Technical Meeting on Electronic Circuits

Mar. 8 2018 (Thu)

Automatic Notch Frequency Tracking Method with EMI Noise Reduction of Pulse Coding Controlled Switching Converter for Communication Devices

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OUTLINE

- Introduction & Objective
- Conventional Switching Converters
- Pulse Coding Method in Switching Converter
- Automatic PWC Control
    - Relationship with the Clock frequency and the Notch frequency
    - Direct generation of clock pulse from input frequency
    - Simulated Noise Spectrum of PWM Signal
- Automatic PWPC Control
- Conclusion and future work

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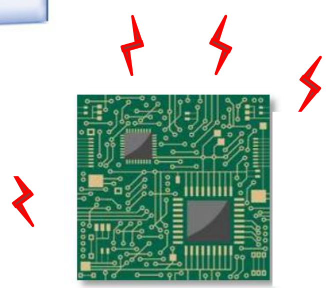
Research Background



Switching converters

Supply many kinds of voltage by switching power

↓

Power of switching converter
has become large

↓

Switching noise has strongly spread
in wide frequency range

↓

Important to reduce switching noise
by decreasing main spectrum level

EMI

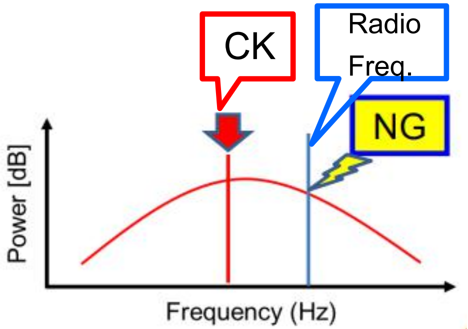
EMI:Electro-Magnetic Interference

Research Objective

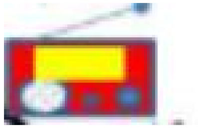
Reduce clock noise by spread spectrum
with shaking clock phase

Trouble

Noise of clock frequency is spread



Some electronic would not like to be affected at special frequency noise



Radio receiver

Research Objective

Spread spectrum with both EMI[1] reduction and control the diffusion of noise

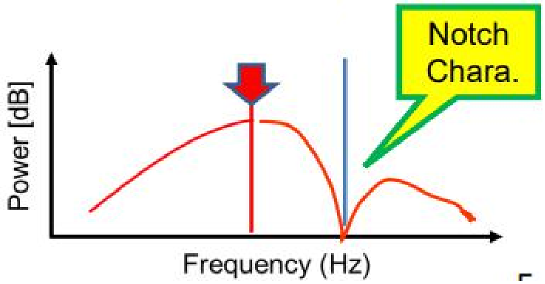
[1]EMI: Electro-Magnetic Interference

Research Summary

Proposed method

Spread spectrum method using pulse coding

Design modulation circuit
in order to generate notch frequency automatically



Achievement

① Reduction of EMI generated from clock
② Noise removal at specific frequency
③ Automatic generation of notch frequency

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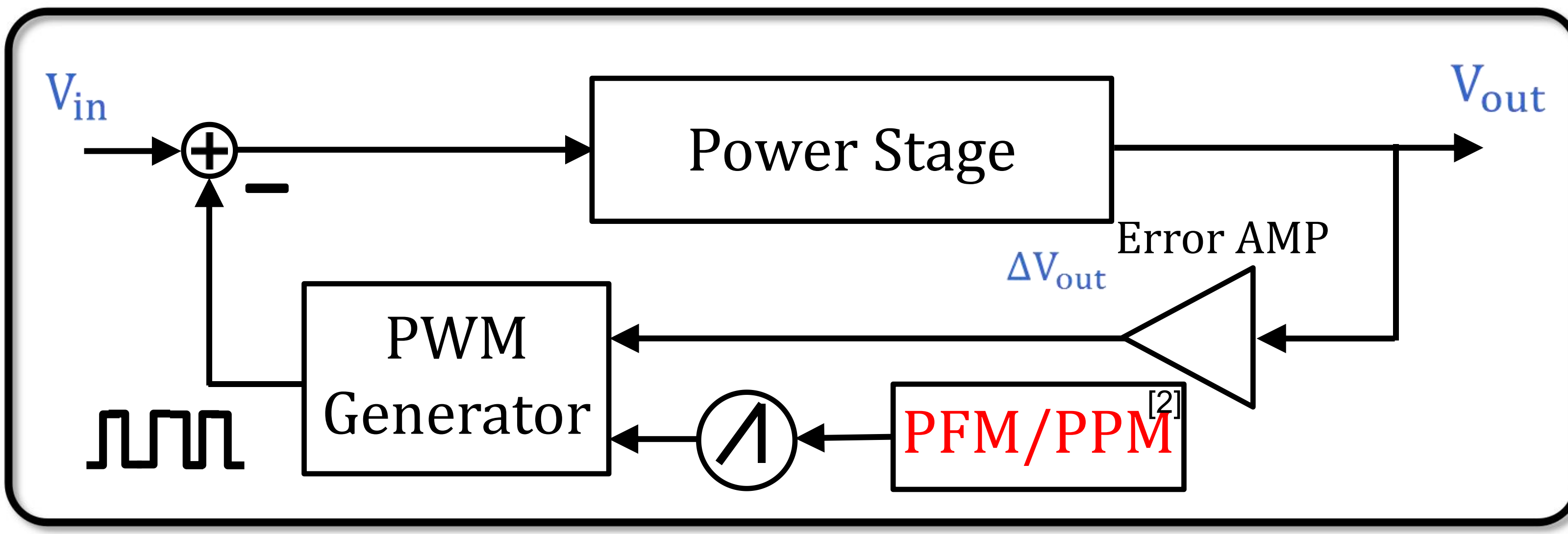
Conventional Switching Converter with Spread Spectrum

Spread Spectrum

Continuous modulation of periodic clock
⇒Reduction of EMI concentrating on fundamental frequency

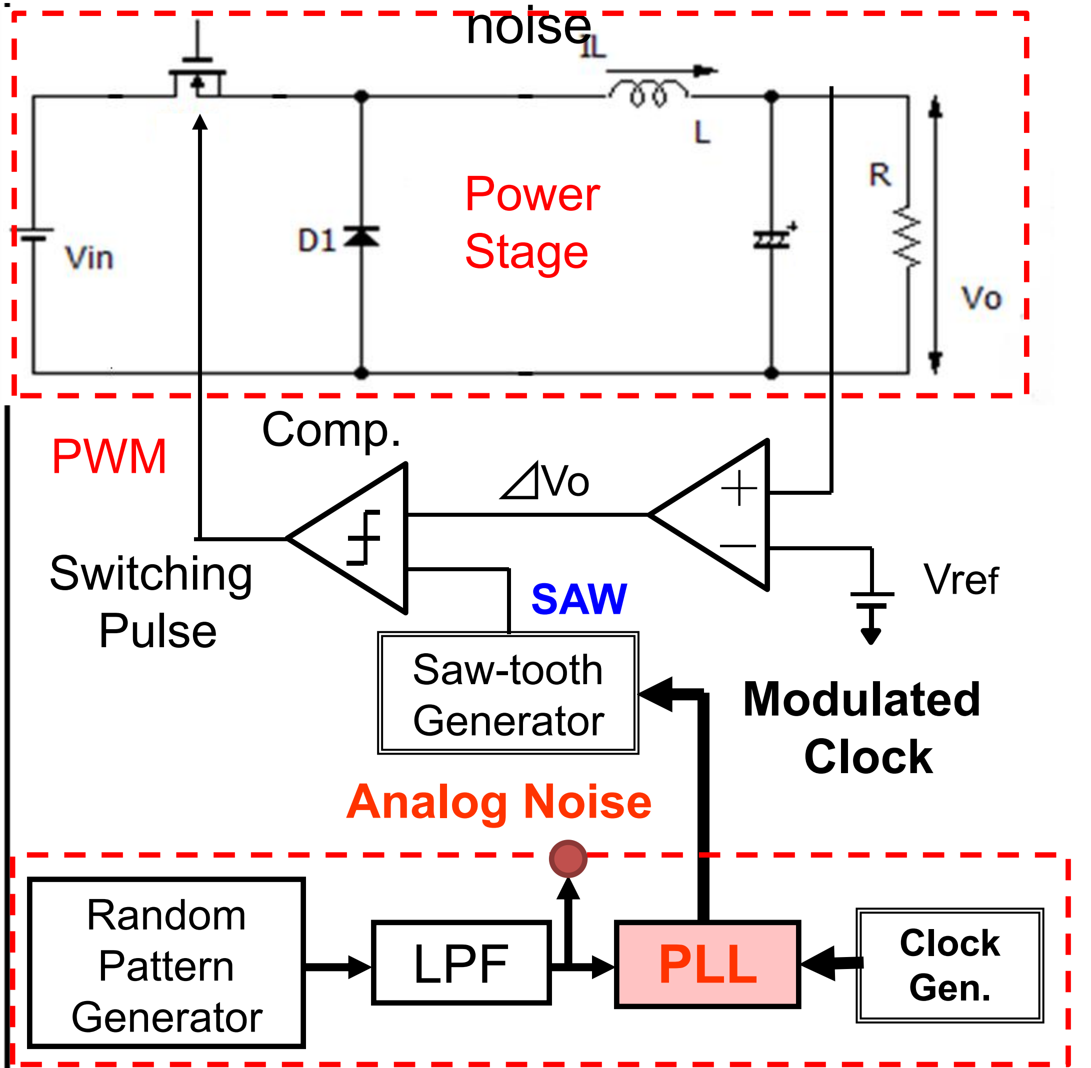


Switching Power

[2] PFM: Pulse Frequency Modulation PPM: Pulse Phase Modulation

Spread Spectrum for EMI Reduction

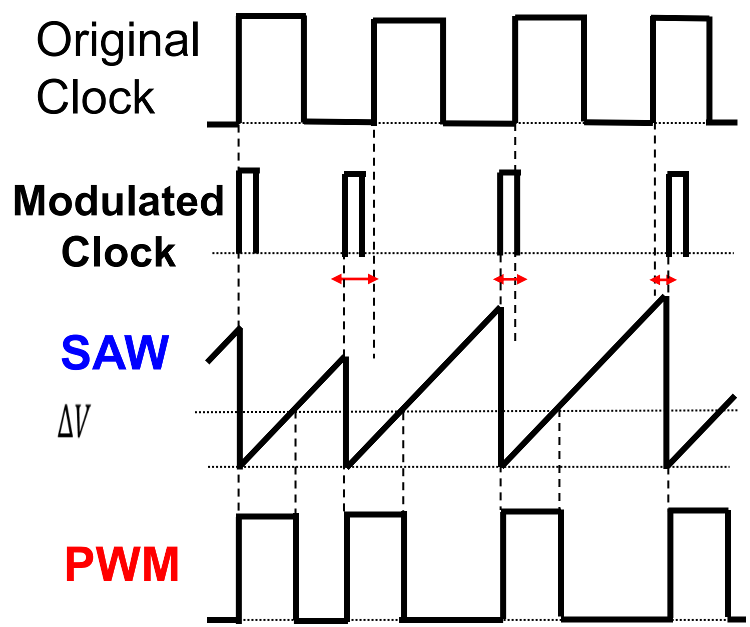
Spread spectrum using pseudo analog noise



Buck converter with modulated clock

To reduce EMI noise, clock pulse is modulated

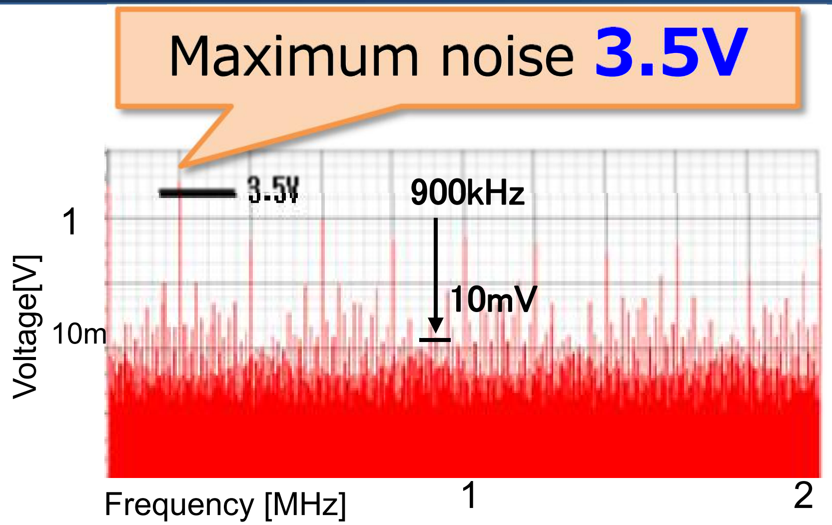
∗ Clock to SAW is modulated by shaking phase using analog noise & PLL[3]



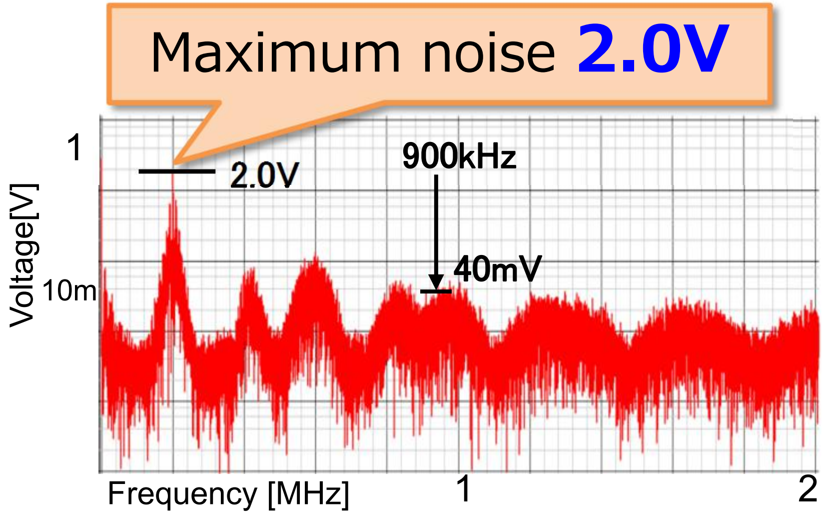
Timing Chart

[3] PLL: Phase Locked Loop

Spread spectrum for EMI Reduction



PWM signal spectrum without EMI reduction



PWM signal spectrum with EMI reduction

◎Simulation conditions

Input : 12V
Output : 6V
Clock frequency: 200kHz

Without EMI reduction

- Noise is concentrated in basic and harmonic frequencies

With EMI reduction

- Peak level of clock frequency is reduced a lot

⇩

Noise is concentrated by diffusion

⇩

Bottom levels are increased NG

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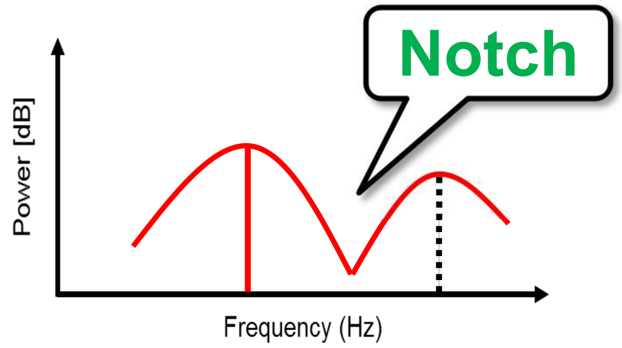
Diffuse Noise to Specific Frequency

Problem

Noise diffusing uniformly
(using analog modulation)



Using digital modulation

Noise diffuses to specific frequency

Frequency band where noise does not spread

Notch band created in important frequency band

- EMI Reduction
- Control of diffused noise

Coding Method

Single coding method

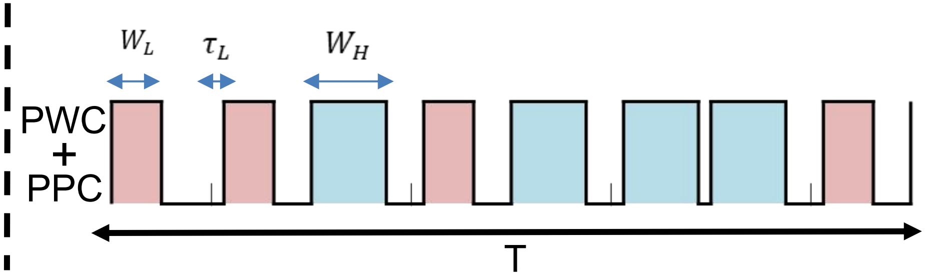
Pulse width・period・position select one to modulation

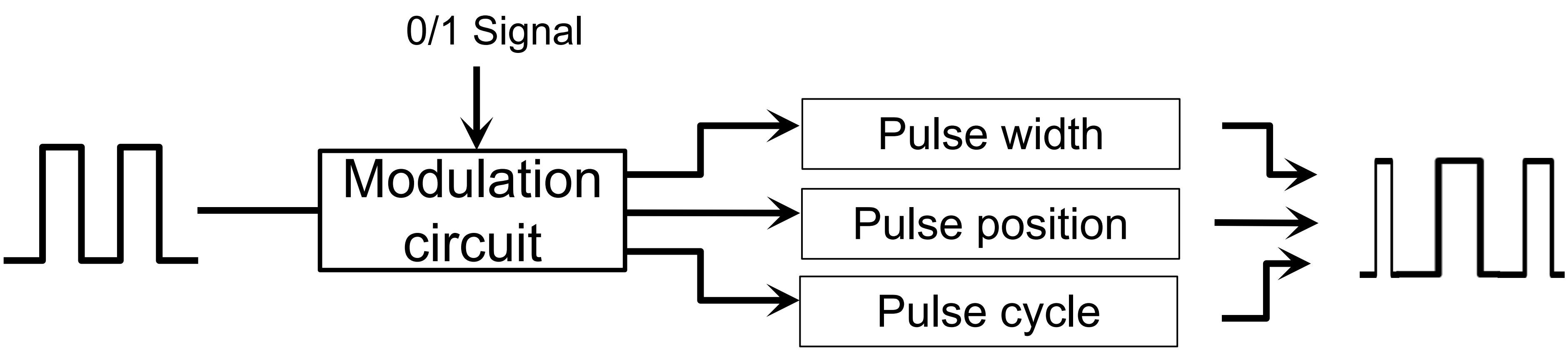
- PWC(Pulse Width coding)method
- PCC(Pulse Cycle coding) method
- PPC(Pulse Phase coding) method

Complex coding method

Pulse width・period・position select two to modulation

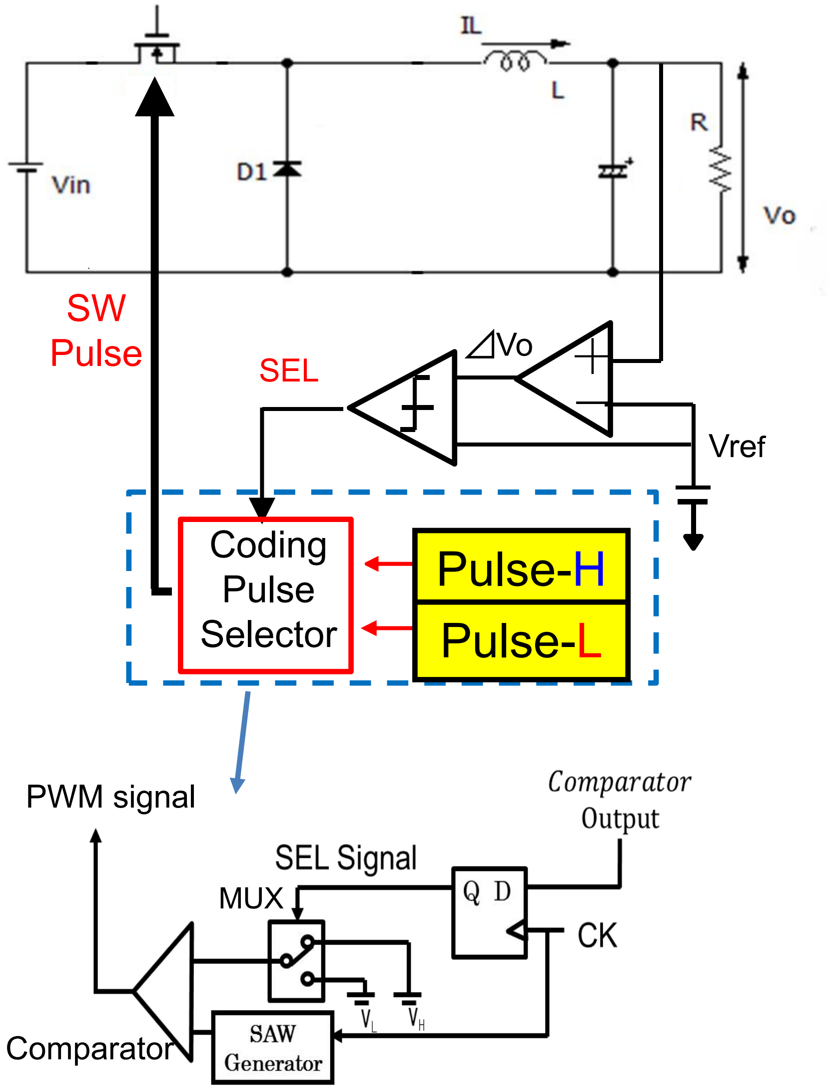
- PWPC（PWC+PPC） method

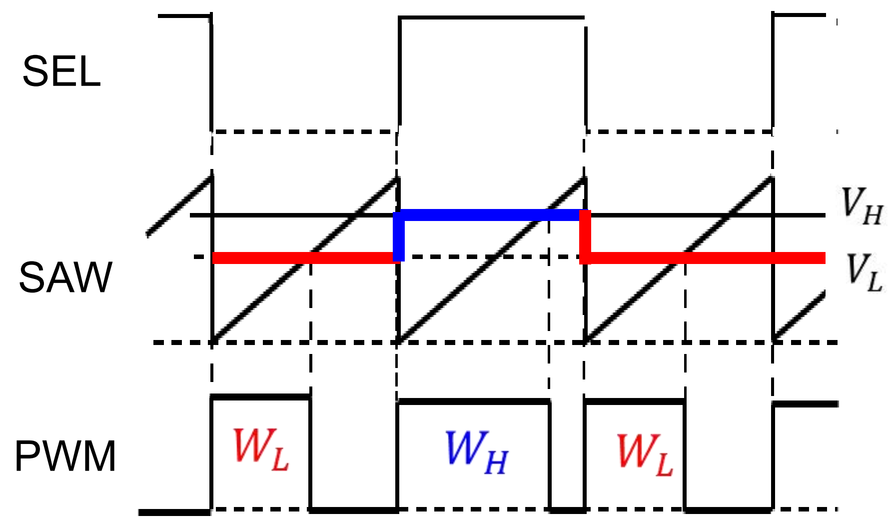




Complex coding method

Pulse Width Modulation in Switching Converter





Input High

①SEL: High
②MUX select V_H
③Generate pulse with long width in comparator

Input Low

①SEL: Low
②MUX select V_L
③Generate pulse with short width in comparator

★ $D_H > D_o > D_L$

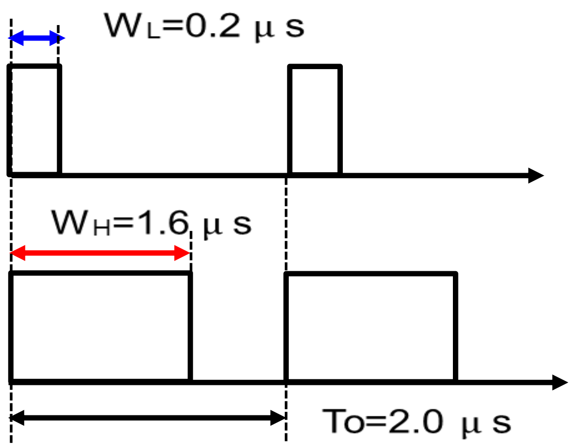
$$D_o = V_o / V_{in}$$

★manually set W_L and W_H

Simulation Result with PWC Control

◎ Condition

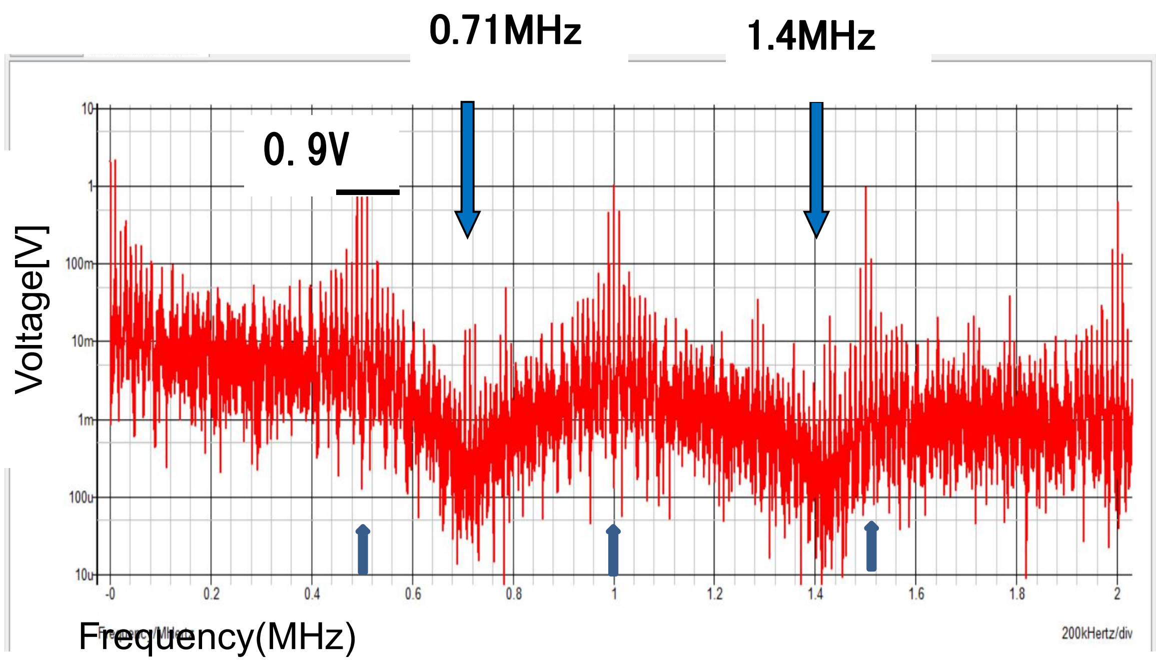
Buck DC-DC converter
V_{in} : 10V
V_{out} : 5V
L : 200 μH
C : 470 μF
I_{out} : 0.25A
f_{ck} : 500kHz



Pulse widths of the coding pulses

Design clock pulse to determine the notch frequency

$$f_n \cong N \times \frac{1}{(W_H - W_L)} \quad [N = 1,2,3,\cdots,n]$$
$$= N \times \frac{1}{1.6\mu s - 0.2\mu s} = 0.71\mathrm{MHz}$$



PWM signal spectrum using PWC control

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Automatic PWC Control

Set frequency of radio reception

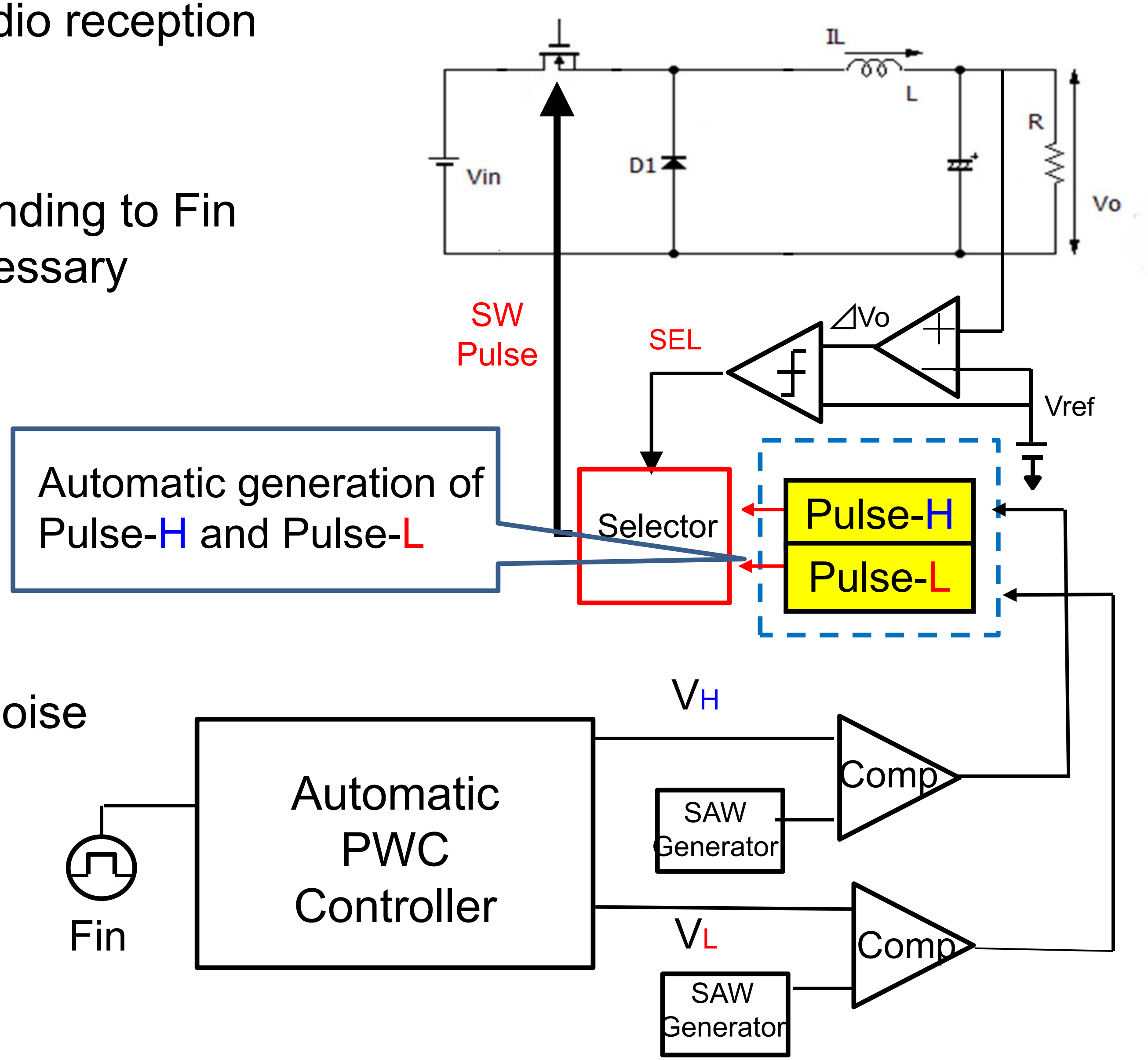
Auto corresponding to Fin change is necessary

Notch frequency

Research objective

Control of diffused noise

Radio receiver



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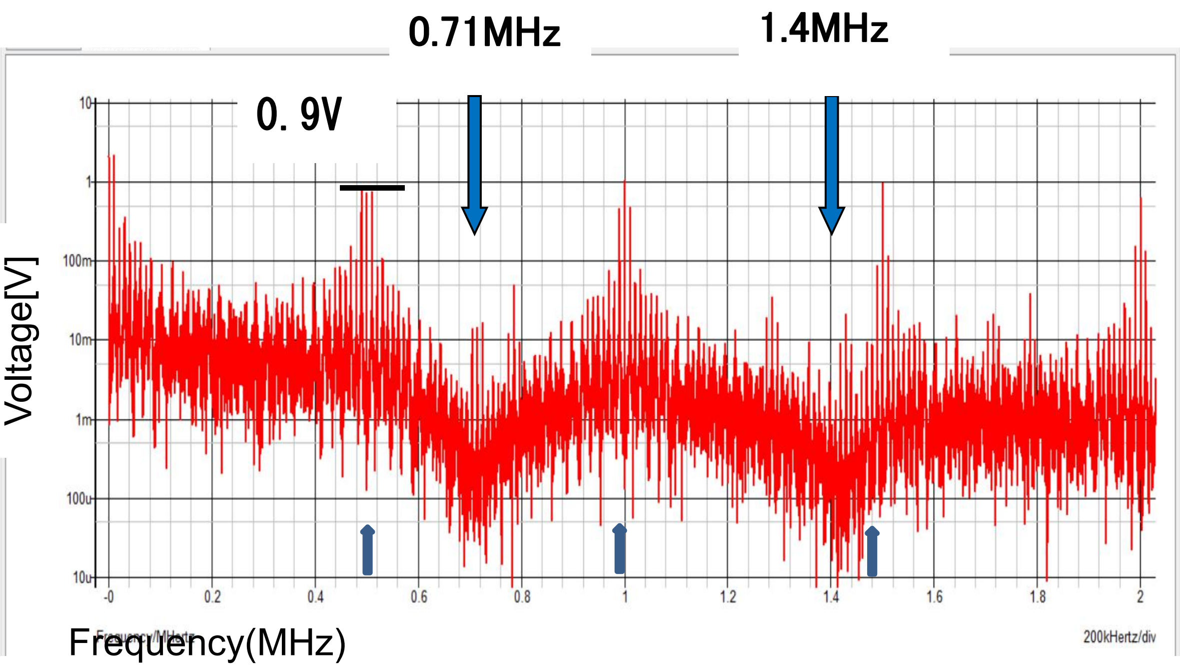
Relationship with Clock and Notch

F_{ck} : 500kHz



PWM signal spectrum using PWC control

Better to generate Fn at middle of Fck

$$F_{ck} < F_n < 2F_{ck}$$

$$NF_{ck} < F_n < (N+1)F_{ck}$$

Optimal

$$F_n = (N+0.5)F_{ck}$$

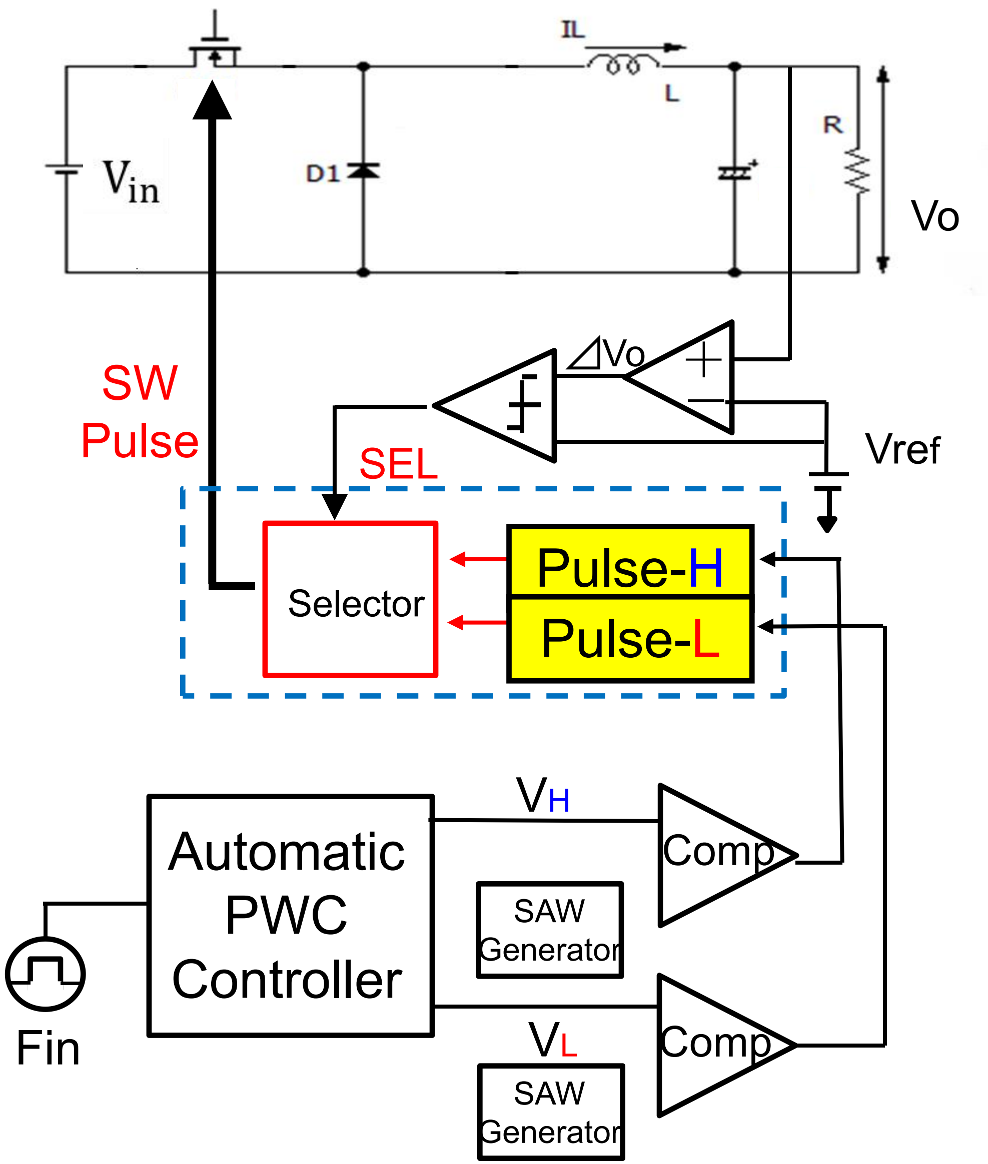
When N=1

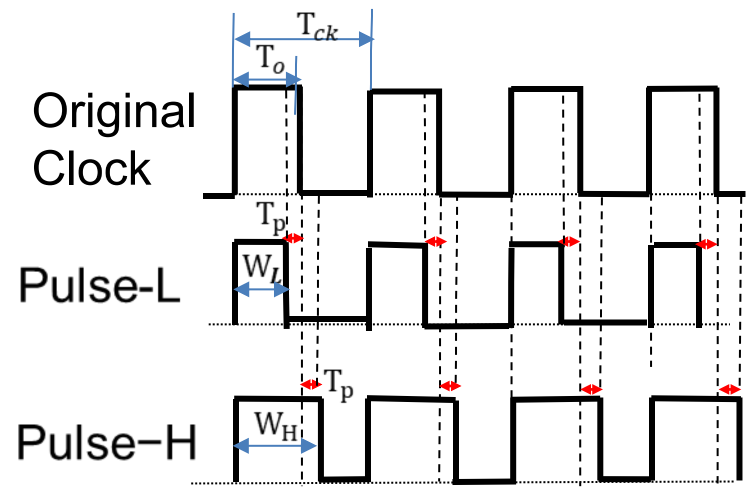
Optimal

$$F_n = 1.5F_{ck}$$

$$\frac{F_n}{3} = \frac{F_{ck}}{2}$$

Relationship between Pulse-H and Pusle-L





Timing Chart

$$T_o = D_o \times T_{ck} = \frac{V_o}{V_{in}} \times T_{ck}$$

$$W_L = T_o - T_p$$

$$W_H = T_o + T_p$$

$$T_n = W_H - W_L = 2 \times T_p$$

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Generating Tck using Direct Calculation

Generate Tck from Tin using:

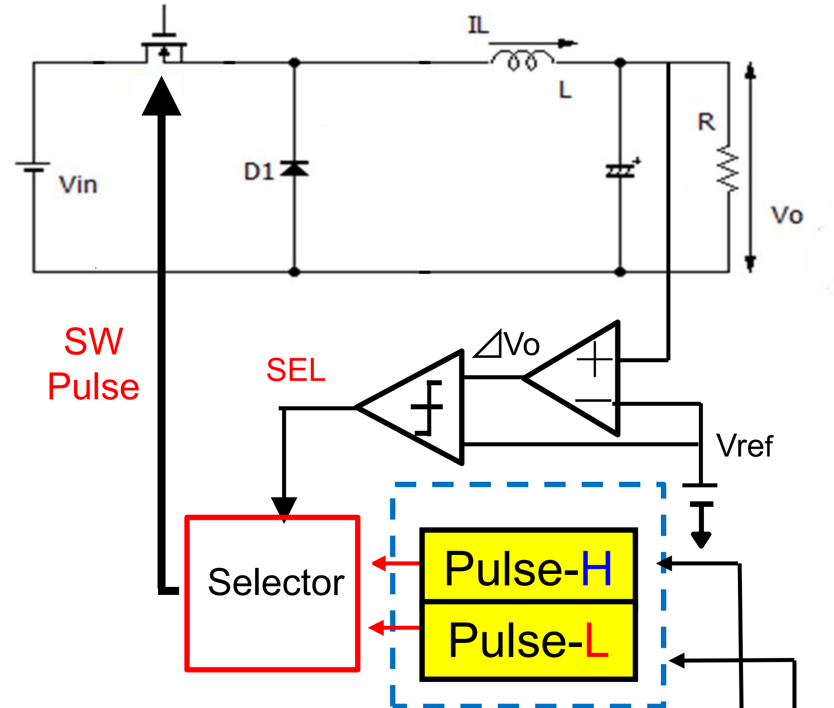
$$F_{in}=(N+0.5)\cdot F_{ck}$$

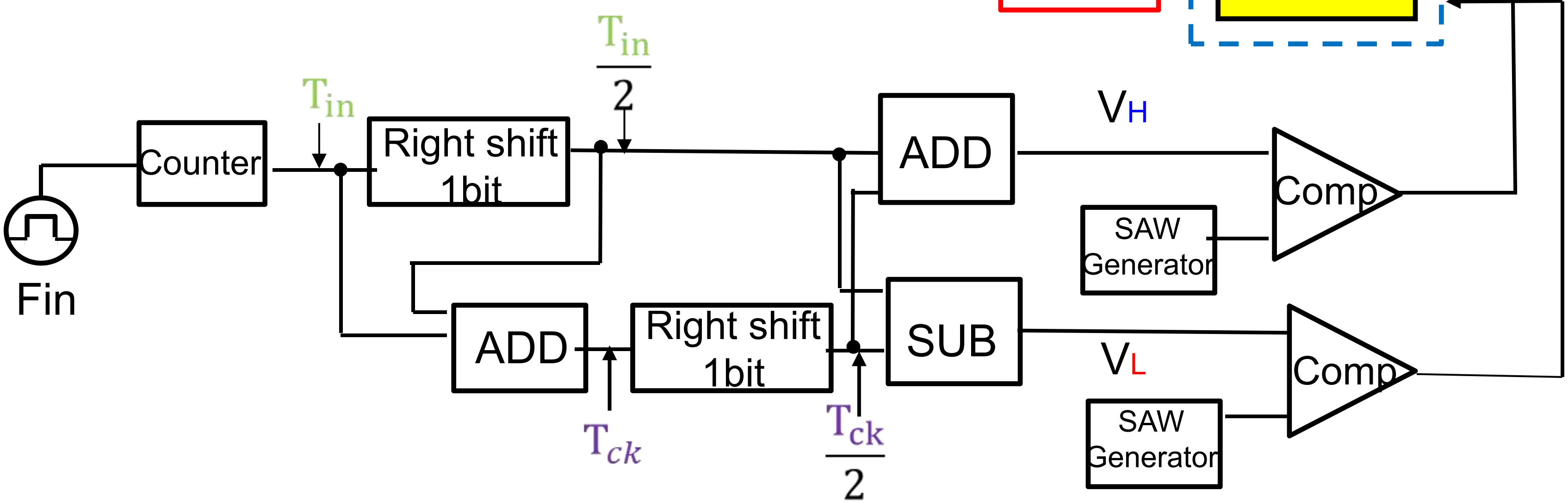
$$T_{ck}=(N+0.5)\cdot T_{in} \quad N=1 \quad D_o=0.5$$

$$W_L = T_o - T_p = D_o \times T_{ck} + \frac{1}{2} T_{in}$$

$$W_H = T_o + T_p = D_o \times T_{ck} - \frac{1}{2} T_{in}$$

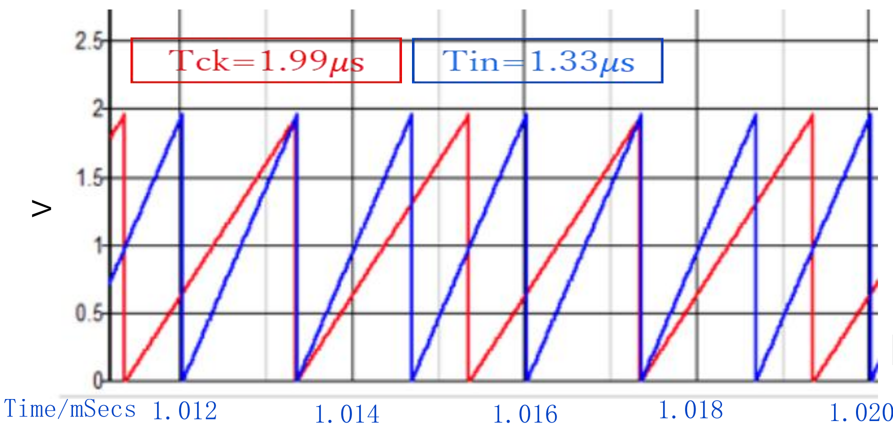
$$T_n = 2 \times T_p$$





Simulation Waveforms of W_H, W_L Generation

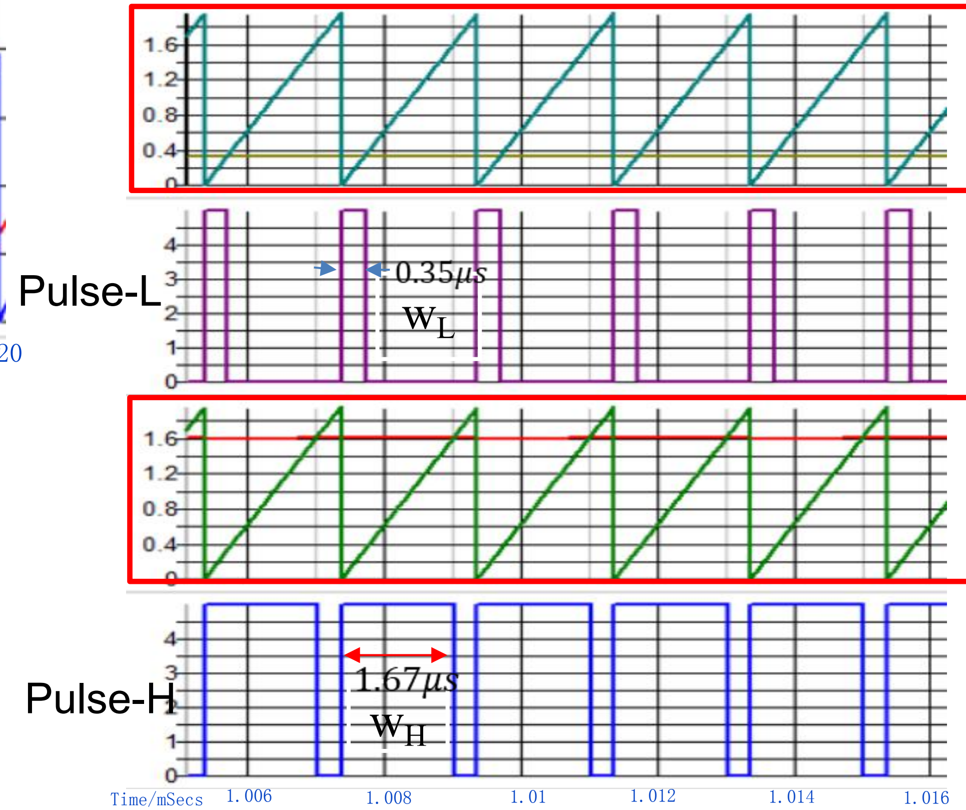
We set $F_{in} = 750kHz$ ➡ Automatic generated $F_{ck} = 500kHz$



Simulation waveform of Tck and Tin

$$T_{ck} = (N + 0.5)T_{in} = 1.5T_{in}$$

Tck compare with V_L or V_H



Simulation waveform of W_H and W_L

Theoretical formula

$W_H = 1.66\mu s$

$W_L = 0.38\mu s$

Simulation result

$W_H = 1.67\mu s$

$W_L = 0.35\mu s$

Well matched

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Simulated Noise Spectrum of PWM Signal Case 1

According to $F_{in} = (N + 0.5)F_{ck}$

Case 1 : Fin=750kHz, N=1⇒Fck=500kHz, W_H=1.66μs, W_L=0.38μs

Result : Fn=750 kHz, Fck=500 kHz, Fck < Fn < 2Fck

◎Condition

Buck DC-DC converter

V_{in} : 10V

V_{out} : 5V

L : 200 μH

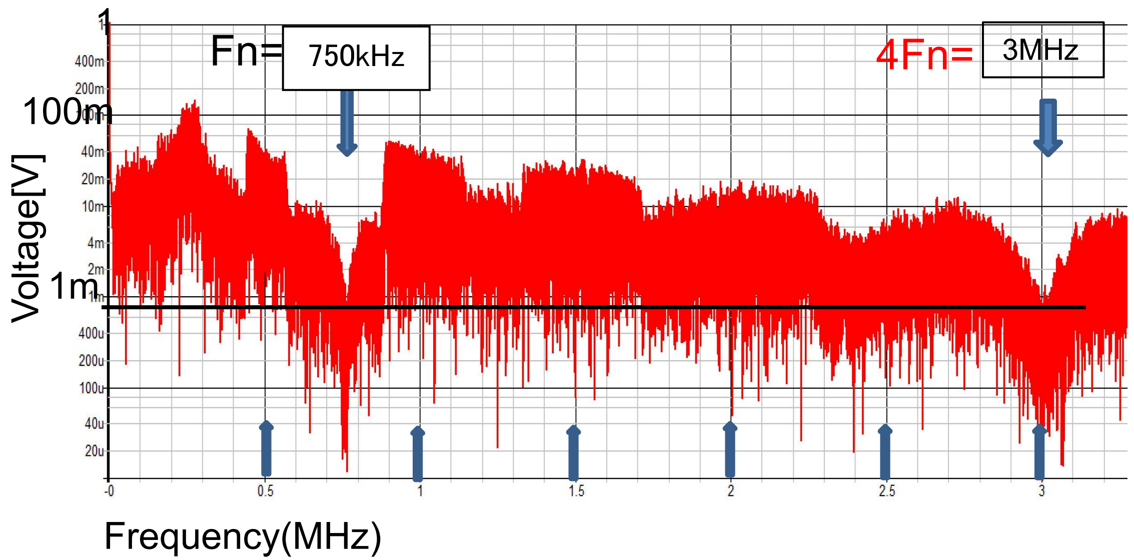
C : 470 μF

I_{out} : 0.25A

◎Result

Fn=750kHz

4・Fn=3.0MHz



Simulated spectrum with EMI reduction

Assume to suppress influence on AM radio in 750kHz
⇒A notch was generated around 750kHz

Simulated Noise Spectrum of PWM Signal Case 2

Case 2:Fin=1.25MHz,N=2 ⇒ Fck=500kHz,W_H=1.40μs,W_L=0.60 μs

Result：Fn=1.27 MHz, Fck=500 kHz, 2Fck ＜ Fn ＜ 3Fck

◎Simulation Result

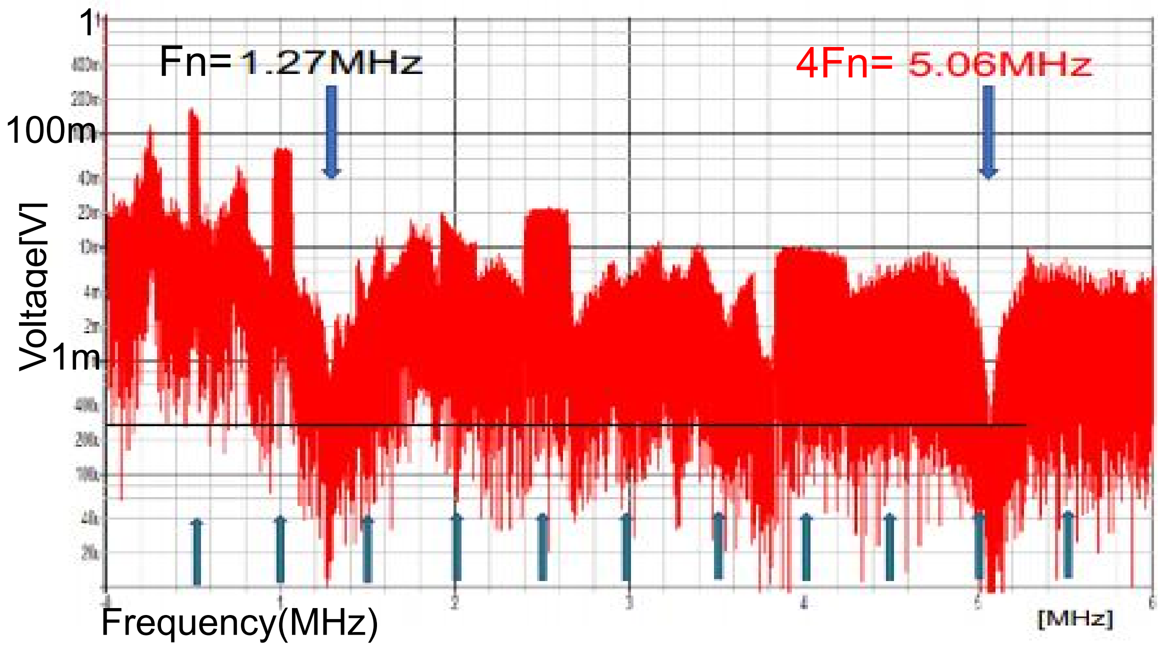
Fn=1.27 MHz

4Fn=5.05 MHz

∗Compare bottom levels

4Fn is deeper than Fn

◎Condition：same



Simulated spectrum with EMI reduction

Transient Response with F_{in} Change in Case 2

◎ Condition (N= 2)

$F_{in} = 1.25\text{MHz}$ ➡ $F_{in} = 1\ MHz$

$F_{in} = 1.25\text{MHz}$ ➡ $F_{in} = 750kHz$

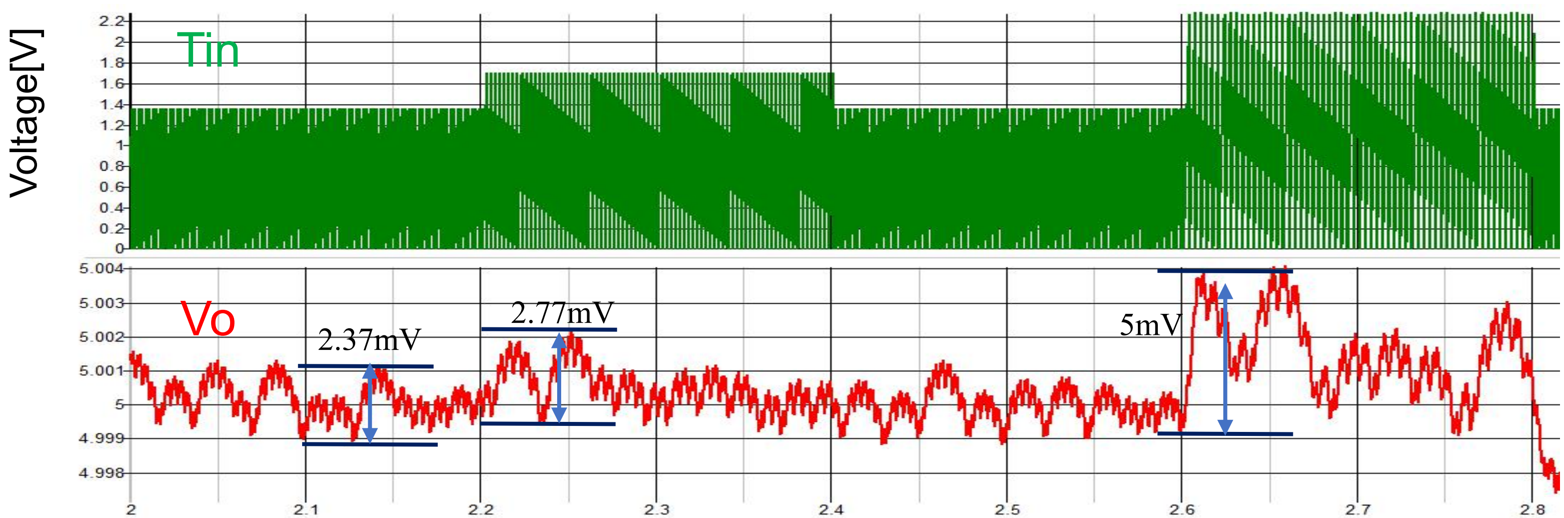
Settling Time≈ 0μs

◎ Output stability

Ripple: $2.37mV_{pp}$ at $F_{in} = 1.25MHz$
$2.77mV_{pp}$ at $F_{in} = 1MHz$
$5mV_{pp}$ at $F_{in} = 750kHz$

Static ripple is about 0.1% of the output voltage V_o

stable



Transient response with Fin change

Response speed is important when tuning or switching communication channels

Simulated Noise Spectrum of PWM Signal Case 3

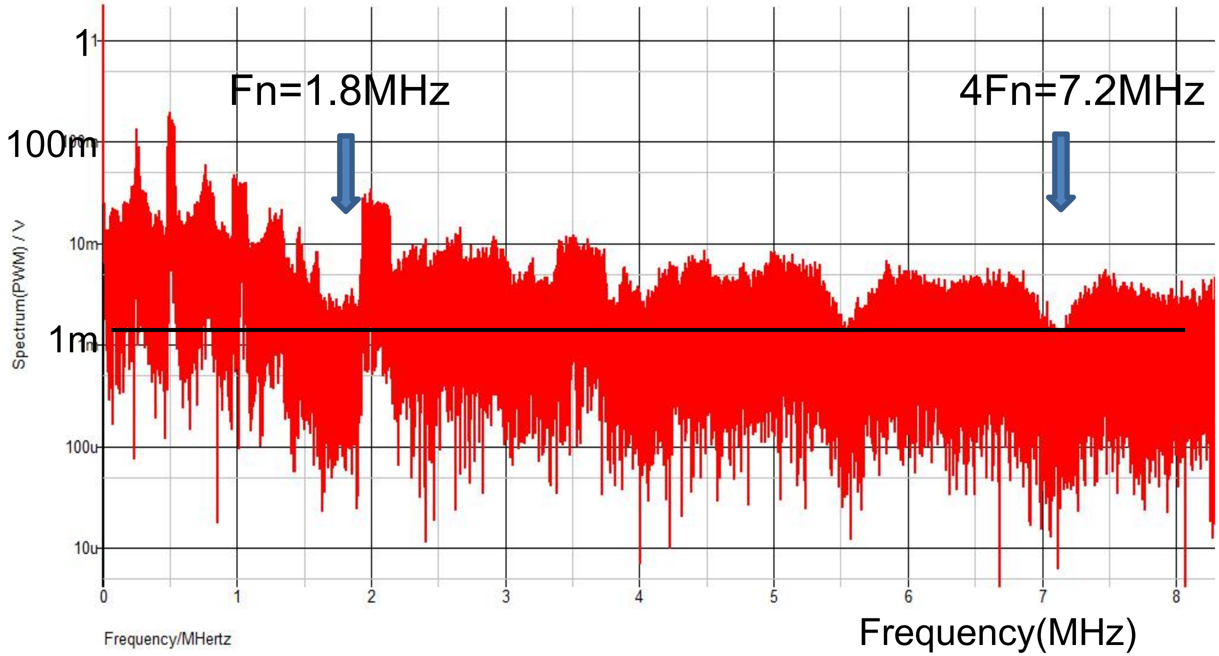
Case3 : Fin=1.75MHz, N=3⇒Fck=500kHz, W_H=1.29µs,W_L=0.72µs

Result：Fn=1.8 MHz, Fck=500 kHz, 3Fck ＜ Fn ＜ 4Fck

◎Simulation Result

Fn=1.8 MHz
4Fn=7.2 MHz

＊Compare bottom levels
Almost equal



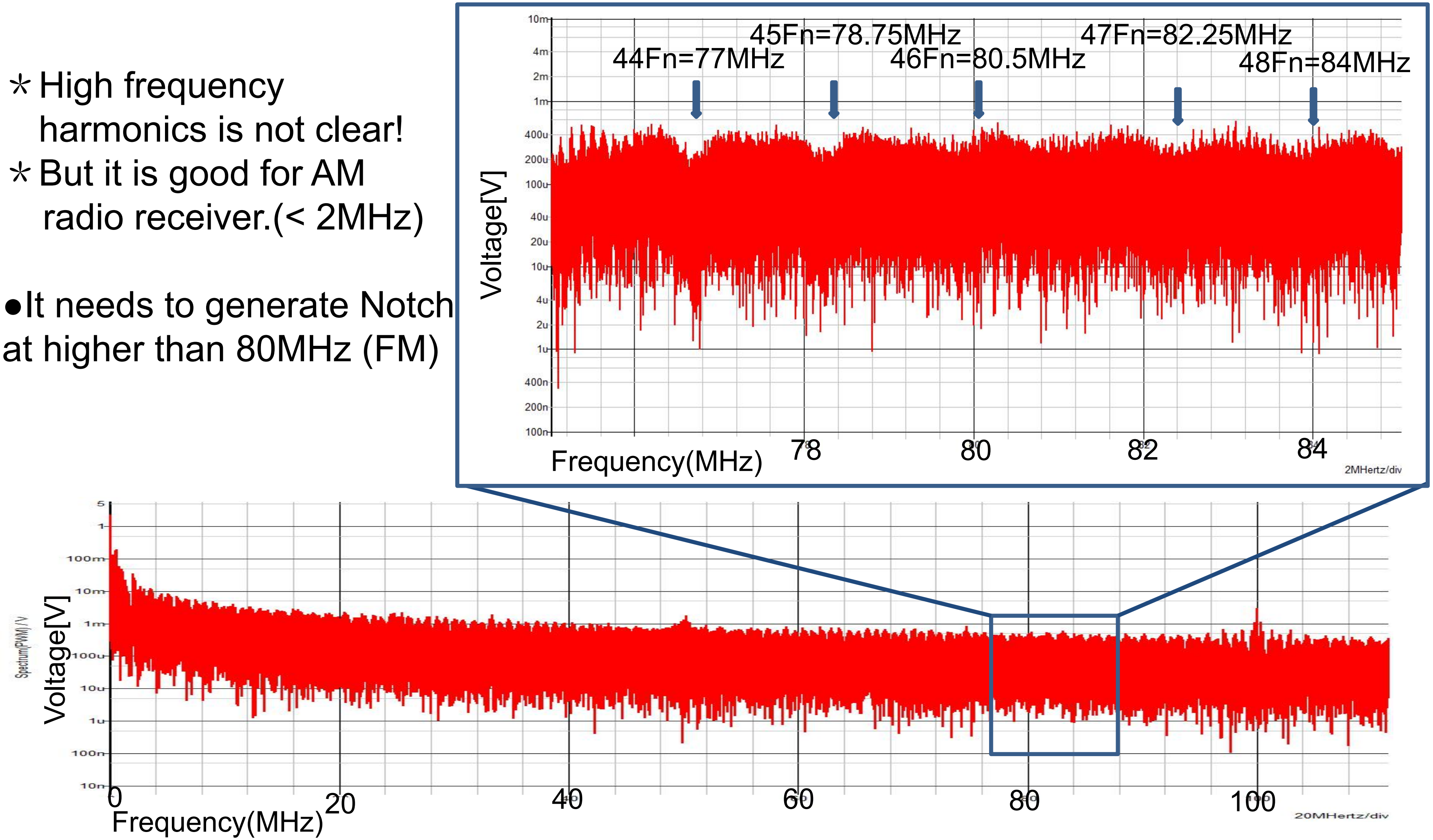
◎Condition： same

Simulated spectrum with EMI reduction

Simulated Noise Spectrum of PWM Signal Case 3

* High frequency harmonics is not clear!
* But it is good for AM radio receiver.(< 2MHz)

●It needs to generate Notch at higher than 80MHz (FM)



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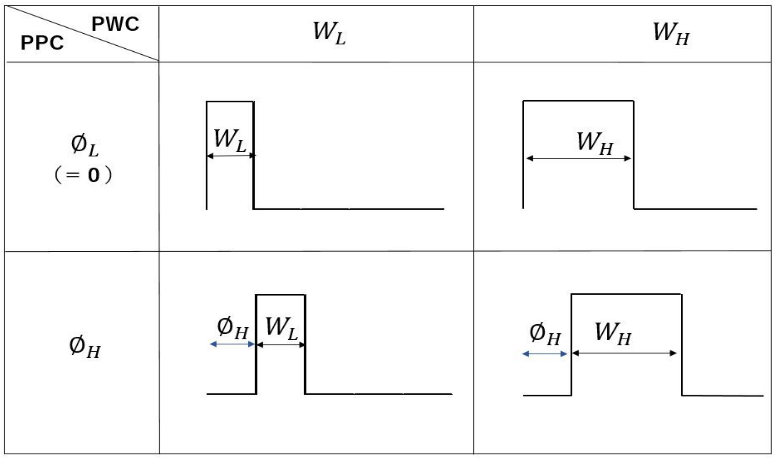
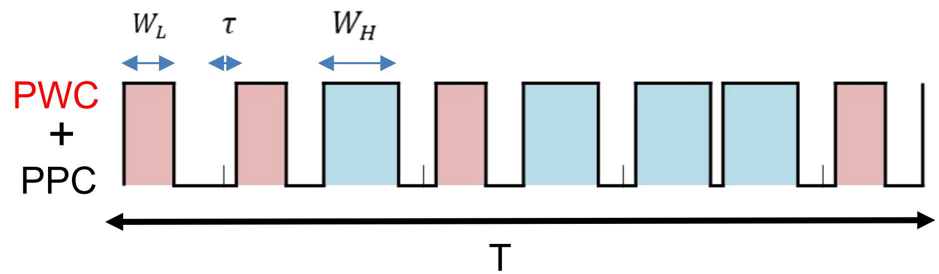
PWPC Method

Complex coding method

PWPC (Pulse width coding + Pulse phase coding) method





Theoretical formula

$$f_{notch1} = \frac{n}{(W_H - W_L)}$$

$$f_{notch2} = \frac{n}{2|\tau_H - \tau_L|}$$

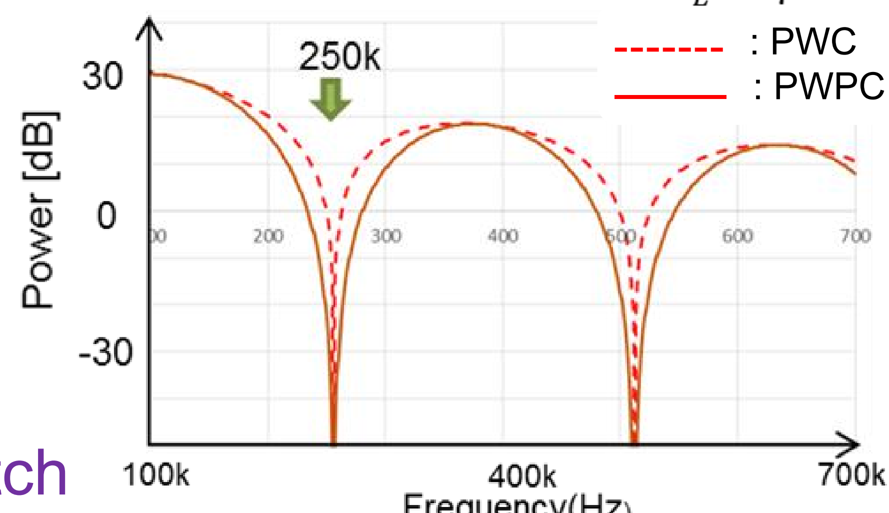
Set $f_{notch1} = f_{notch2}$ ➡ Big Notch

Condition:

$W_H = 7\mu s$

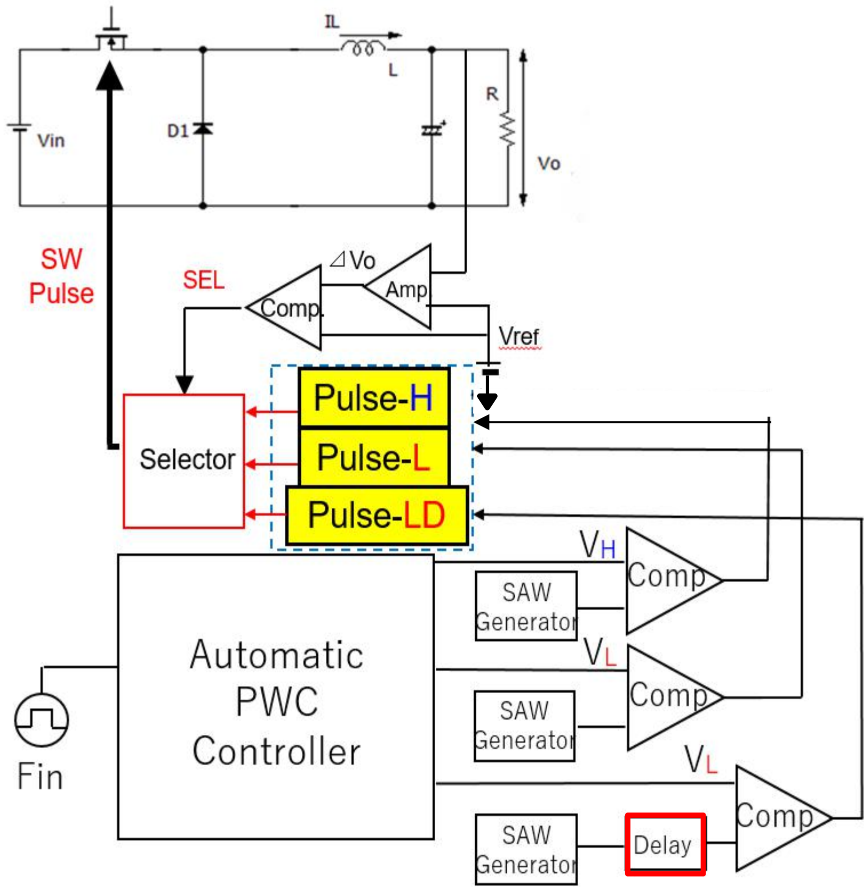
$W_L = 3\mu s$

Expect

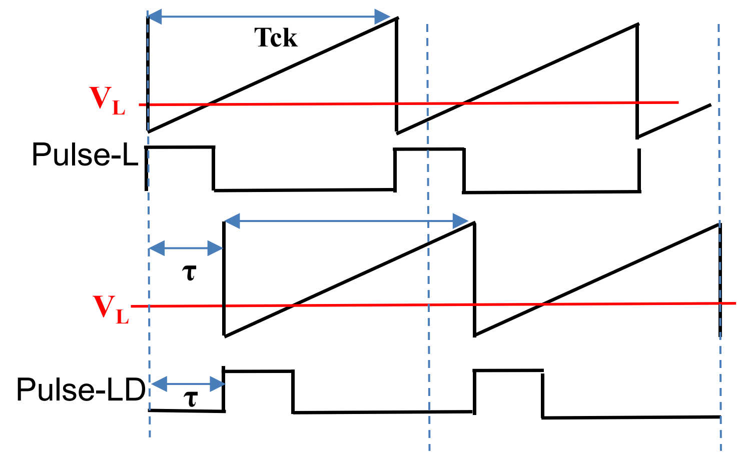


Automatic Generation of Notch Frequency with PWPC Control

Automatic pulse generation



Pulse coding of PWPC method



Design timing in PWPC method

$$W_H = To + Tp = Do \times Tck + 0.5Tin$$

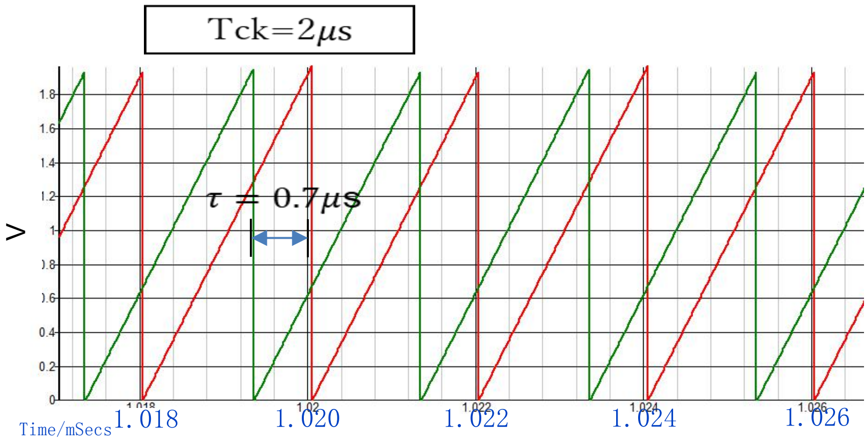
$$W_L = To - Tp = Do \times Tck - 0.5Tin$$

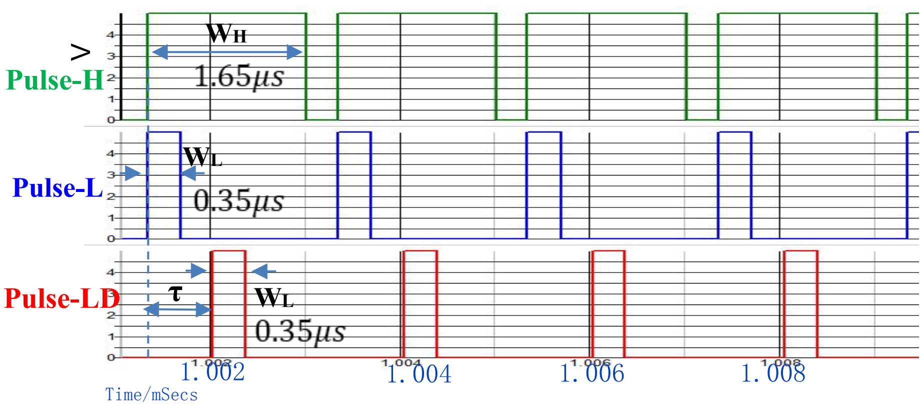
$$\tau = (W_H - W_L)/2 = 0.5 \times Tin$$

Simulation Waveforms of W_H, W_L Generation

We set $F_{in} = 750kHz$ ➡ Automatic generated $F_{ck} = 500kHz$

$f_{notch1} = f_{notch2}$ ➡ $\frac{n}{(W_H - W_L)} = \frac{n}{2|\tau_H - \tau_L|}$ ➡ $\tau_H - \tau_L = \tau = \frac{W_H - W_L}{2} = \frac{T_{in}}{2}$





Simulation waveform of Tck and delay Tck

Simulation waveform of Pulse-H, Pusle-L and delay Pulse-L

Theoretical formula result

$W_H = 1.67\mu s$
$W_L = 0.33\mu s$
$\tau = 0.67\mu s$

Well matched

Simulation result

$W_H = 1.66\mu s$
$W_L = 0.38\mu s$
$\tau = 0.70\mu s$

Simulated Noise Spectrum of PWPC Control

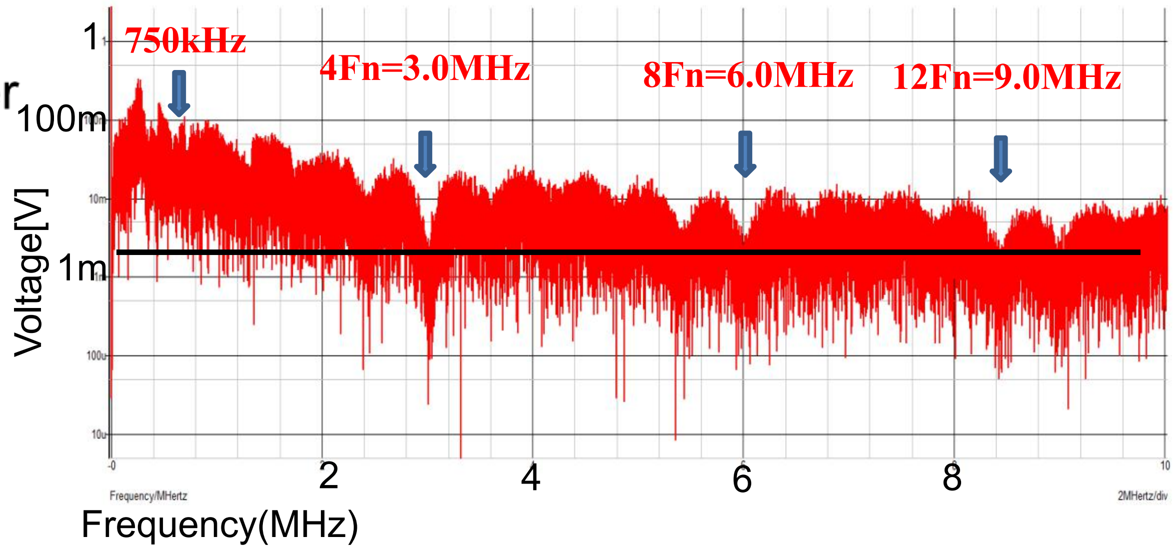
According to $F_{in} = (N + 0.5)F_{ck}$

Fin=750kHz , N=1⇒ Fck=500kHz,W_H=1.67μs,W_L=0.33 μs

Fn=750 kHz, Fck=500 kHz, Fck ＜ Fn ＜ 2Fck

◎ Condition

Buck DC-DC converter
V_{in}： 10V
V_{out}： 5V
L： 200 μ H
C： 470 μ F
I_{out}： 0.25A
F_{in}： 750kHz



Simulated spectrum with EMI reduction

PWPC characteristic: There are many harmonics of 4NFn

（N ＝1,2,3・・・）

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Conclusion

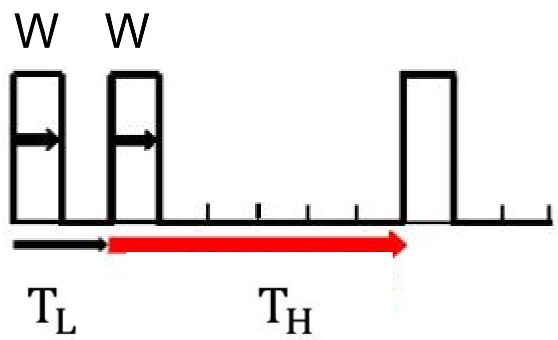
- Developed pulse coding control in order to generate notch characteristics at desired frequency
- Analyze spread spectrum with notch characteristics
- Automatic generate the notch frequency from Fin

Using $F_{\mathrm{in}} = (N + 0.5)F_{\mathrm{ck}}$, discussion on direct generation of notch in N=1,2,3 situation using PWC control

Automatic generating of notch frequency with PWPC control

Future Work

- Notch generation using PCC(Pulse Cycle Coding) method



- Investigate why the large notch at 4Fn appear.
- Extend 4Fn in order to high frequency notch generation using PWPC method

Thank you for Listening

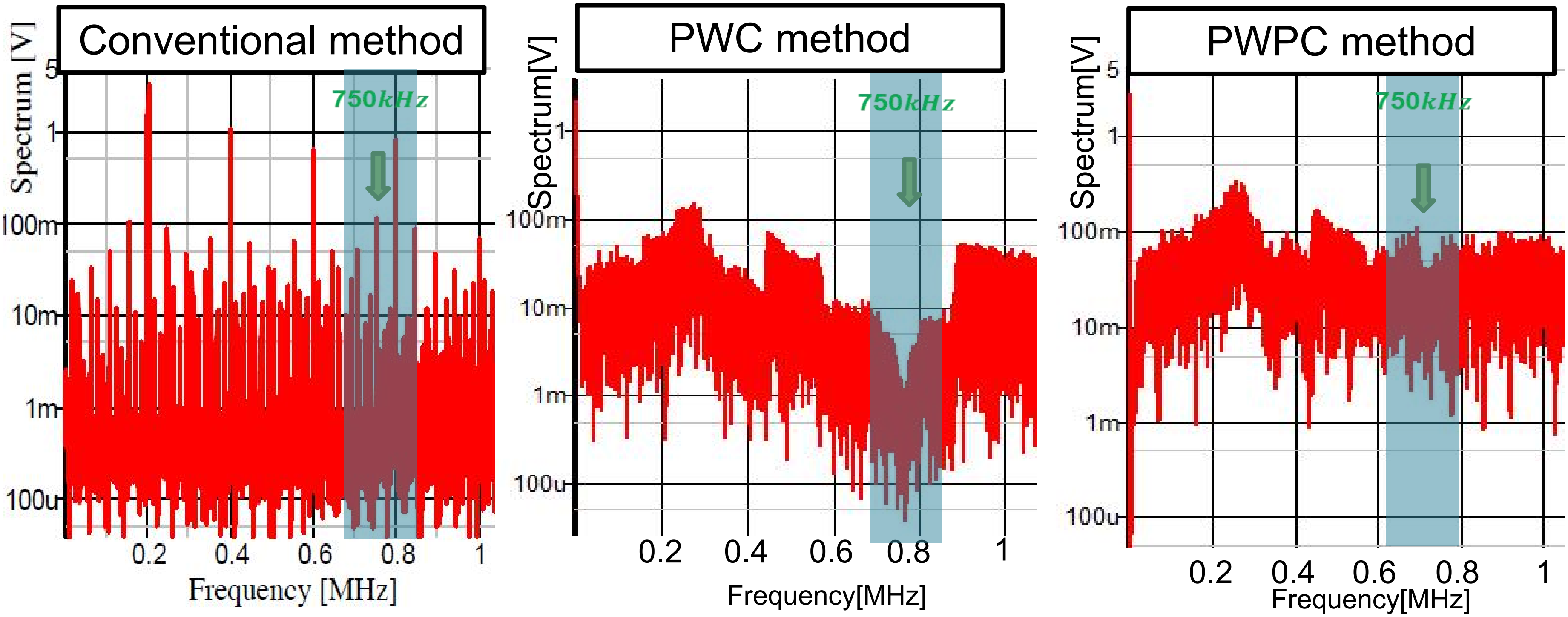
Q and A

Q1: Is there any way to get broad notch? Get the width and depth of notch, is it available?
A: In order to get the notch more deep, we come up with PWC, PWPC method, compared with there two method, we found in low frequency, PWC method is better to create deep notch. Also want to consider the PCC method to expect deep notch. I have not consider about to expand the width of notch, I will consider about it in the later.

Q2: Can you tell me the effect of notch frequency depending on the current load change?
A: In the communication devices, there are many changes of the receiving signal and the input frequency, Response speed is important when tuning or switching communication channels. If let the current load change, the change of output voltage is small, it means the system is stable.

Spectrum Comparison with Proposed Method

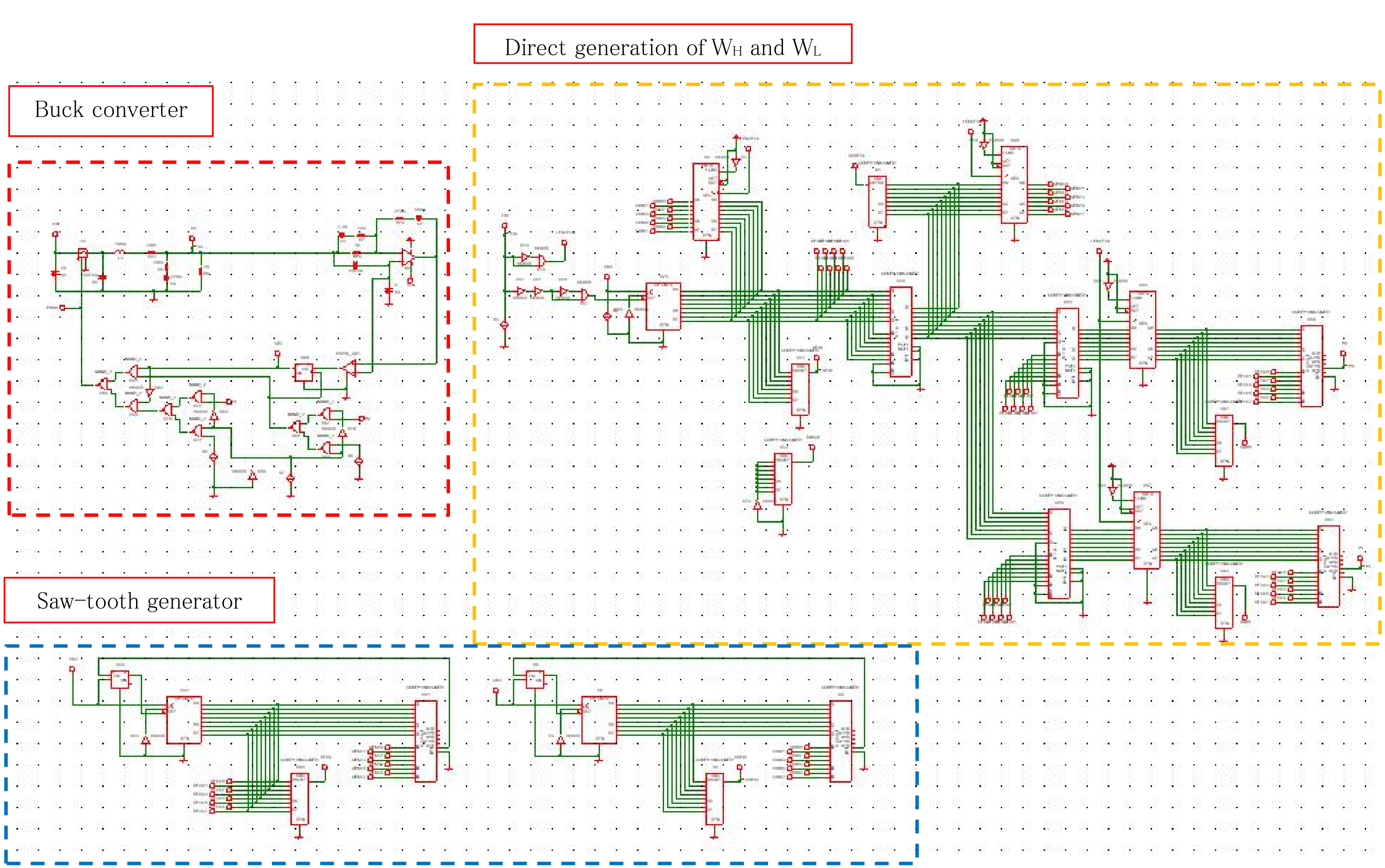
- Assumed to suppress the influence on AM radio
  ⇒A notch is generated around 750 kHz
- Compared with PWC, PWPC and conventional method



$f_{clock} = 500kHz$
$f_{notch} = 750kHz$

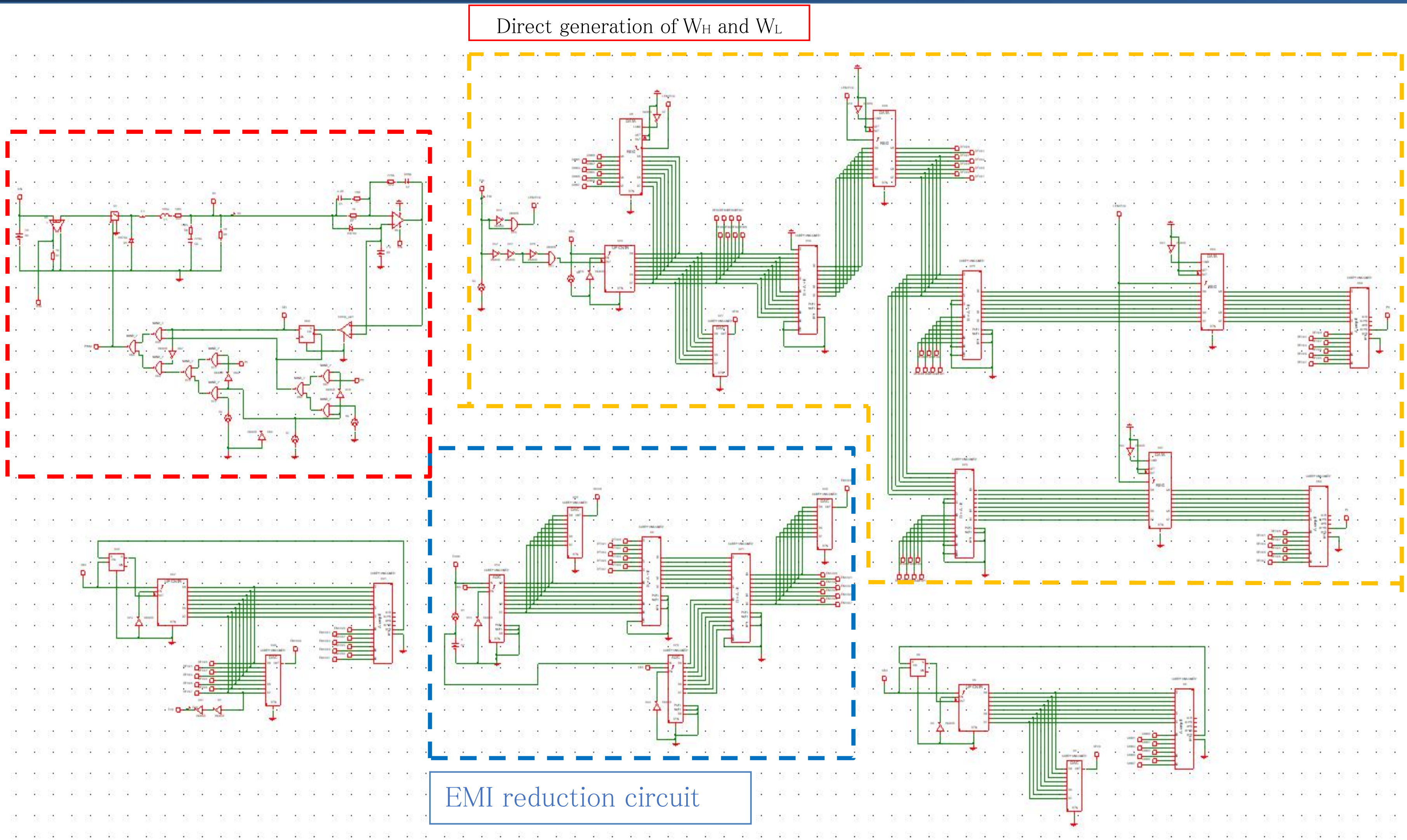
Spectrum reduced compared with the conventional method!!

Automatic Notch Generation using Direct method (N=1)

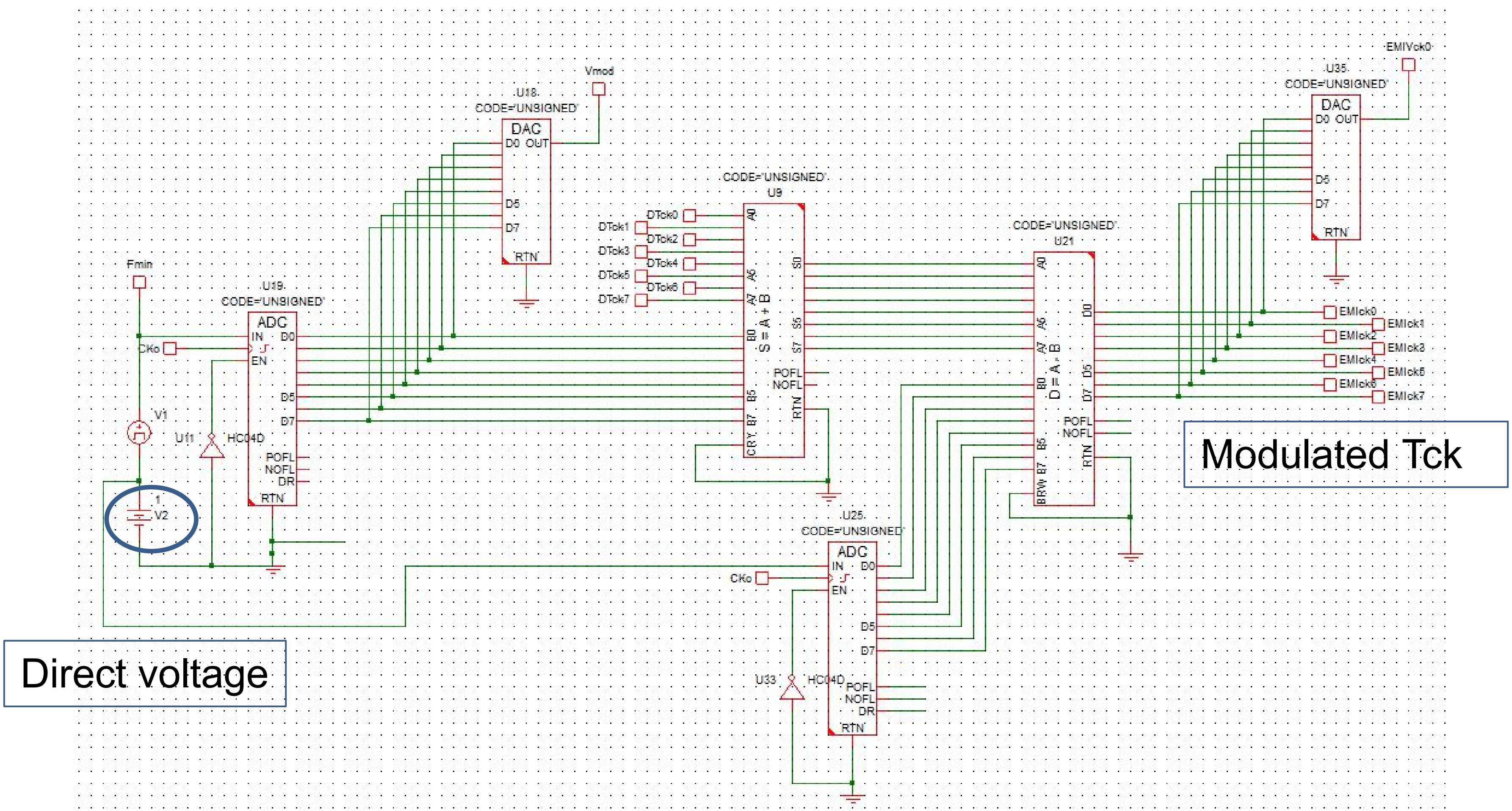


No CPU!

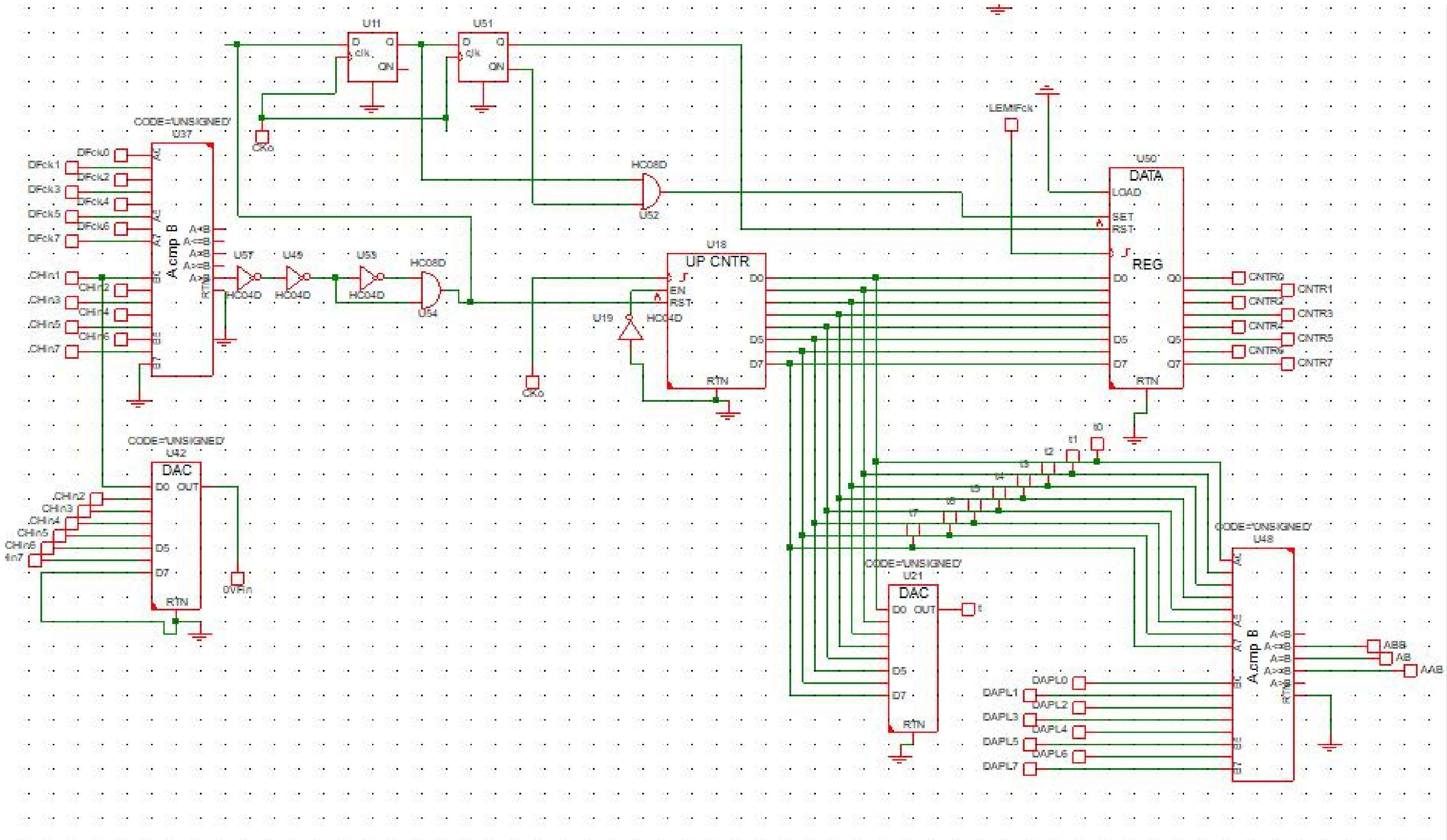
Automatic Notch Generation using Direct method with EMI Reduction（N=2)



EMI Reduction



Produce the delay of Tck



Application of Automatic Generation of the Notch Frequency

Switching frequency and harmonics used in in-vehicle DC-DC converter must not overlap reception frequency bands of AM, FM of radio

demand

Reception frequency from radio receiver ≈ Notch frequency

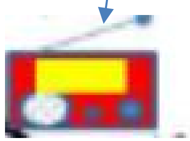
Frequency band where noise does not spread

Goal

Automatic generation of notch frequency

It is possible to greatly reduce influence on other electronic devices

DC-DC converter



Radio receiver

Set frequency of radio reception

Auto correspond to Fin change is necessary

Transient Response with F_{in} Change in Case 3

◎ Condition

$F_{in} = 1.75\text{MHz} \Rightarrow F_{in} = 1.5MHz$

◎ Output stability

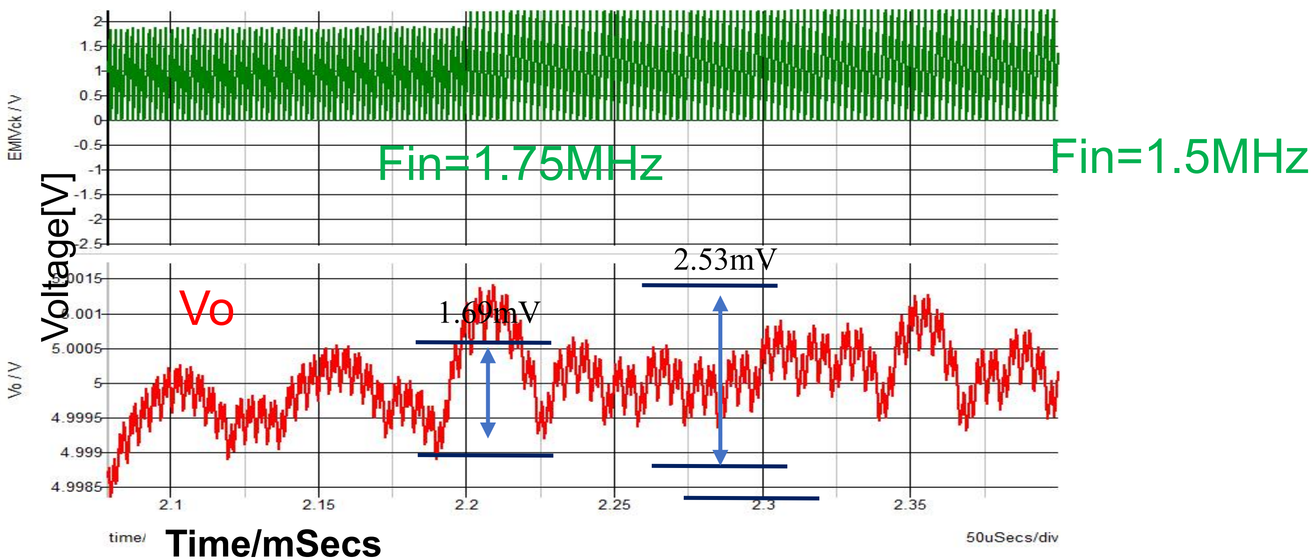
Ripple: $1.69mV_{pp}$ at $F_{in} = 1.75MHz$
$2.53mV_{pp}$ at $F_{in} = 1.5MHz$

Static ripple: $2.53mV_{pp}$

V_o : $5.0V$

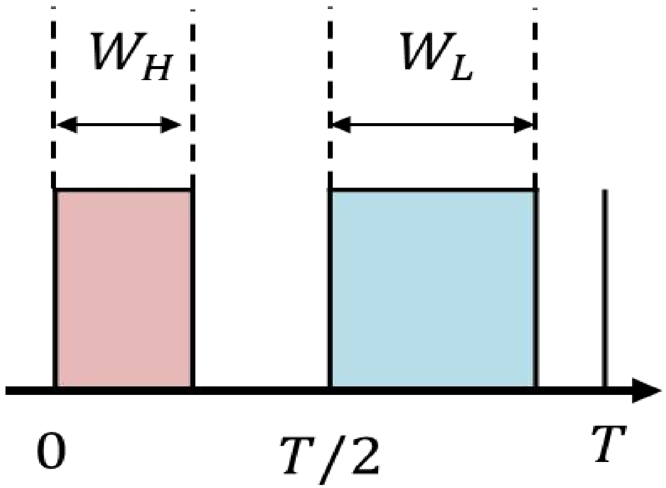
Static ripple is about 0.05% of the output voltage V_o

stable



Transient response with Fin change in N=3 situation

Expression Analysis of Coding Waveform



$$f(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$$

$$= \int_0^{W_H} e^{-j\omega t} dt + \int_{T/2}^{W_{L+T/2}} e^{-j\omega t} dt$$

$$= -\frac{1}{j\omega}\{\cos(\omega W_H) - j\sin(\omega W_L) - \cos(\omega W_L) + j\sin(\omega W_L)\}$$

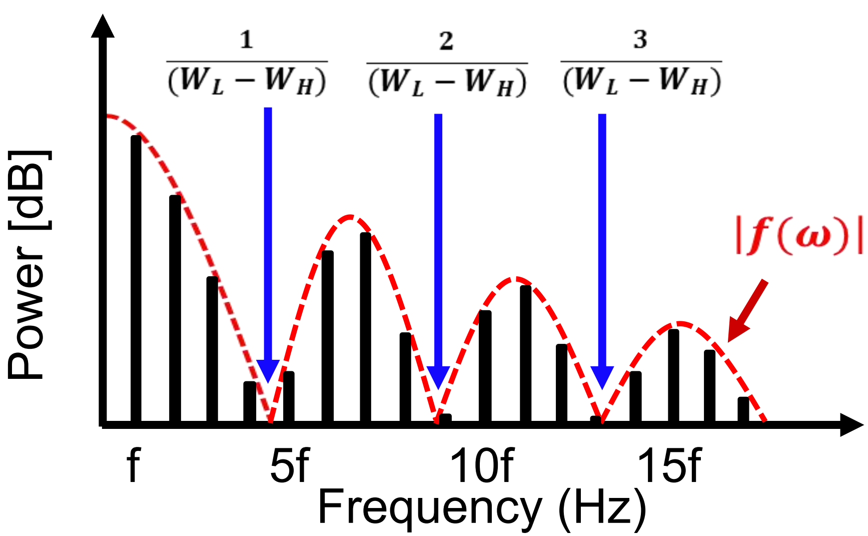
$$|f(\omega)| = \frac{1}{\omega}\sqrt{2 - 2\cos(\omega W_H - \omega W_L)}$$

From the double theorem

$$= \frac{1}{\omega}\sqrt{4\sin^2\{(\omega W_L - \omega W_H)/2\}}$$

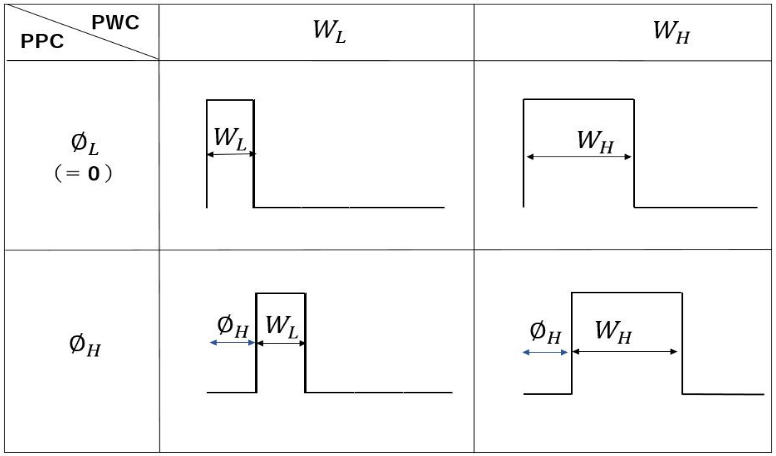
$$= \frac{(W_L - W_H)\left|\sin\{\frac{\omega}{2}(W_L - W_H)\}\right|}{\frac{\omega}{2}(W_L - W_H)}$$

$$= \boldsymbol{(W_L - W_H)\left|sinc\{\frac{\omega}{2}(W_L - W_H)\}\right|}$$



$$f_{notch} \cong N \times \frac{1}{(W_H - W_L)}$$

Expression Analysis of Coding Waveform



$$f(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$$

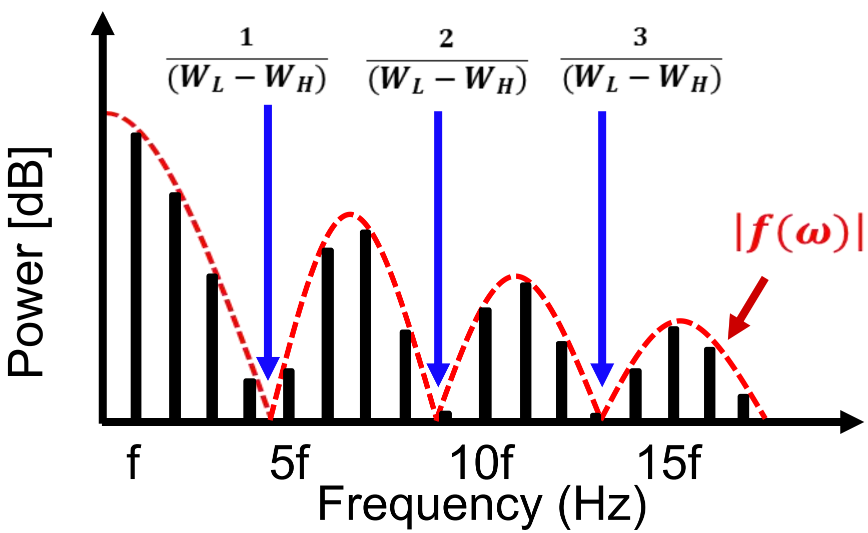
$$= \frac{1}{\omega}\{\mathrm{jcos}(\omega(\tau_H - \tau_L)) + \sin(\omega(\tau_H - \tau_L))$$

$$- \mathrm{jcos}(\omega(\tau_H - \tau_L - W)) - sin(\omega(\tau_H - \tau_L - W)$$

$$- \mathrm{jcos}(\omega(\tau_L - \tau_H)) - sin(\omega(\tau_L - \tau_H)$$

$$+ \mathrm{jcos}(\omega(\tau_L - \tau_H - W) + sin(\omega(\tau_L - \tau_H - W)$$

$$|f(\omega)| = 2|\tau_L - \tau_H| \left| sinc\left\{(2|\tau_L - \tau_H|)\frac{\omega}{2}\right\}\right| \left| sin\left\{W\frac{\omega}{2}\right\}\right|$$



$$f_{notch} \cong N \times \frac{1}{2|\tau_H - \tau_L|}$$

PWPC Method

Expression analysis of PWPC method

$$|f(\omega)| = (2|\tau_L - \tau_H|)\left|sinc\left\{(2|\tau_L - \tau_H|)\frac{\omega}{2}\right\}\right|\left|sin\left\{(W_L - W_H)\frac{\omega}{2}\right\}\right|$$

◎Condition
W_L = 7us
W_H = 3us

Let $W_2 - W_1 = 2|\tau_L - \tau_H|$

The square of sin

$$|f(\omega)| = \frac{sin^2\left(\frac{\omega}{2}(W_L - W_H)\right)}{\omega/2}$$