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INVITED

Noise Spread Spectrum with Adjustable Notch Frequency in Complex Pulse Coding Controlled DC-DC Converters

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Outline

1. Background
   1-1 Switching Converter
   1-2 EMI Reduction with clock modulation
2. Pulse Coding and Notch Characteristics
   2-1 Pulse coding control
   2-2 Simulation result with PWC control
   2-3 Experimental results of PWC control
3. Automatic PWC Control for Radio Receivers
   3-1 Generating the clock using PLL circuit
   3-2 Adjustable direct generation from input frequency
4. Conclusion

EMI: Electro-Magnetic Interference

PWC: Pulse Width Coding

1. Background

●Our Research about DC-DC converters

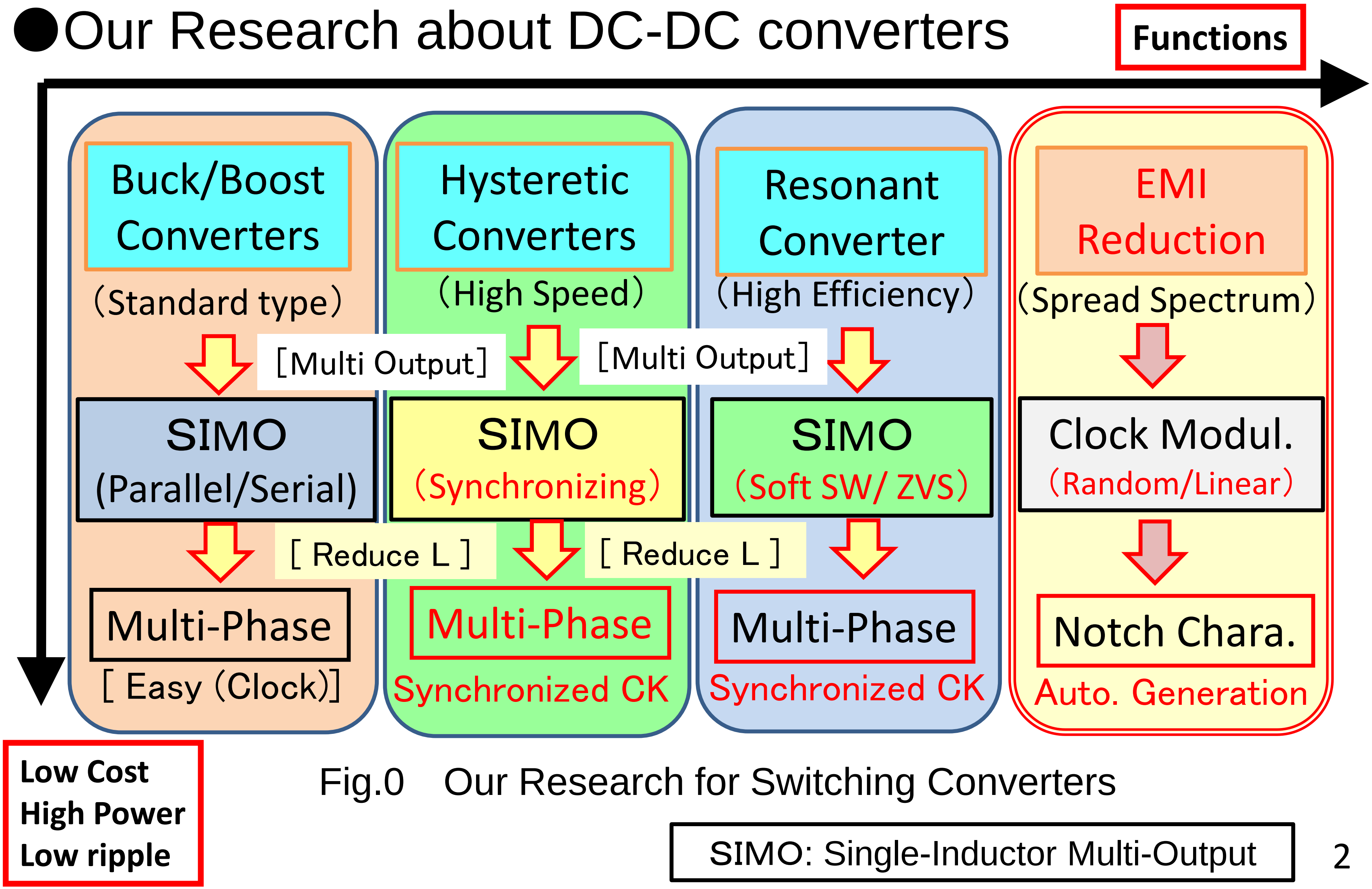
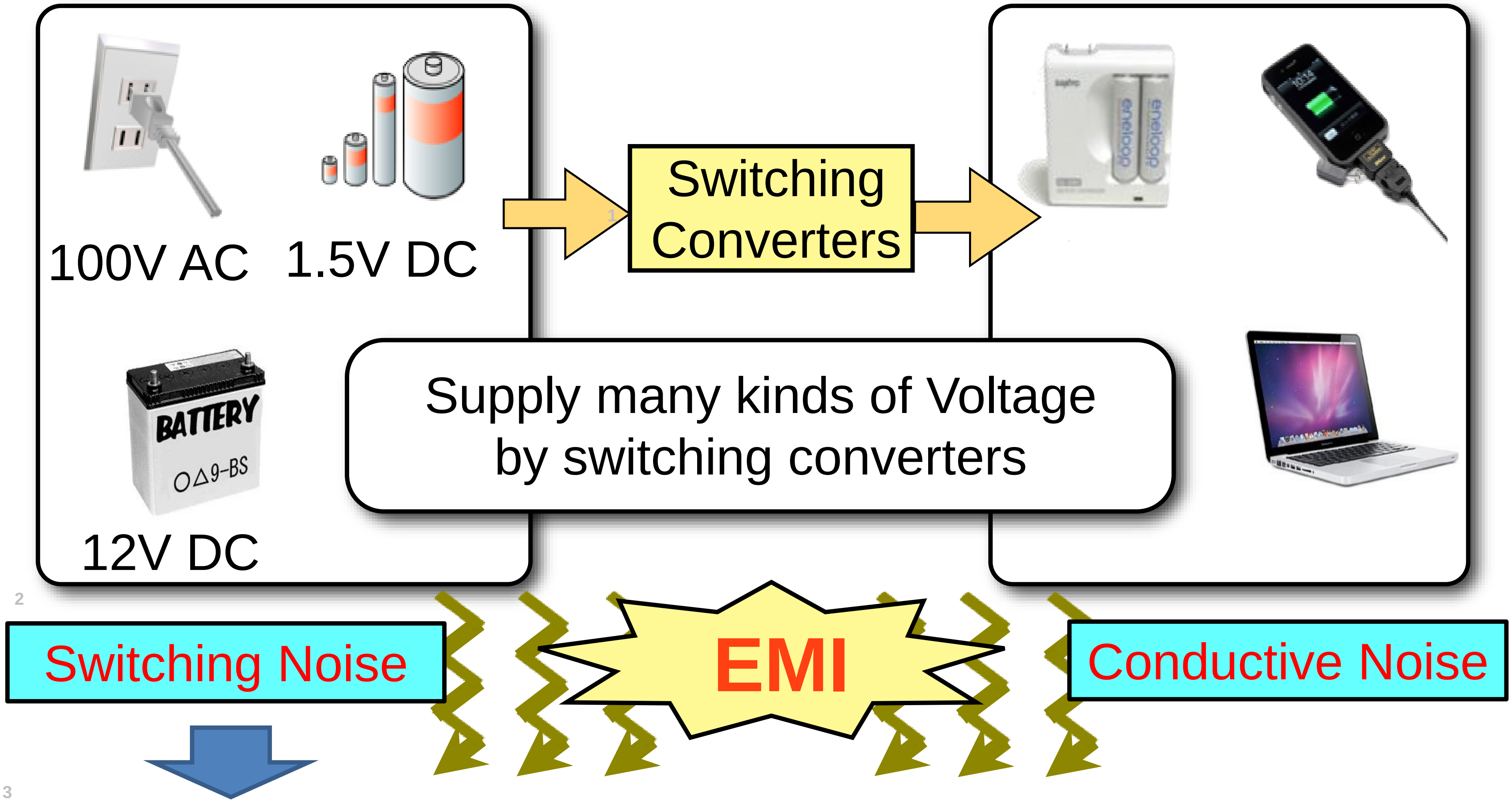


Fig.0 Our Research for Switching Converters

SIMO: Single-Inductor Multi-Output

●Switching noise and EMI trouble



Important to reduce SW noise by decreasing clock spectrum level

Fig.1-1 background (EMI)

EMI: Electro-Magnetic Interference

research process

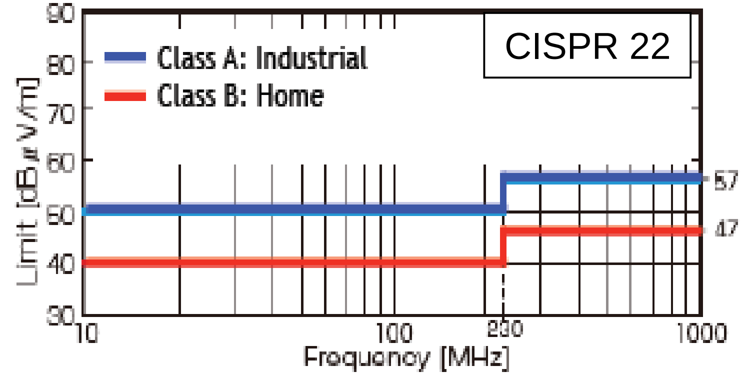
● Reduce clock noise spectrum level below the Standard Level

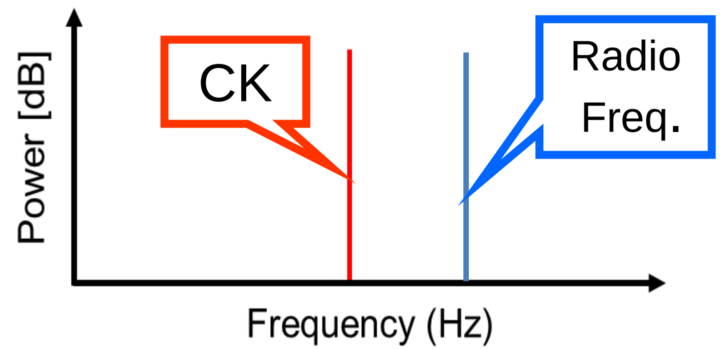
▲ By shaking the clock phase/frequency, spread the clock noise around clock frequency and harmonics.

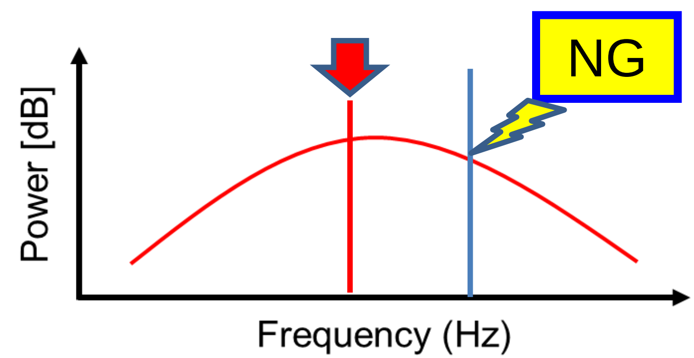
◆ Radio receivers would not like to be affected by spread noise.

※ Our Objective

★ Develop Spread Spectrum Method both to reduce the EMI noise and







research process

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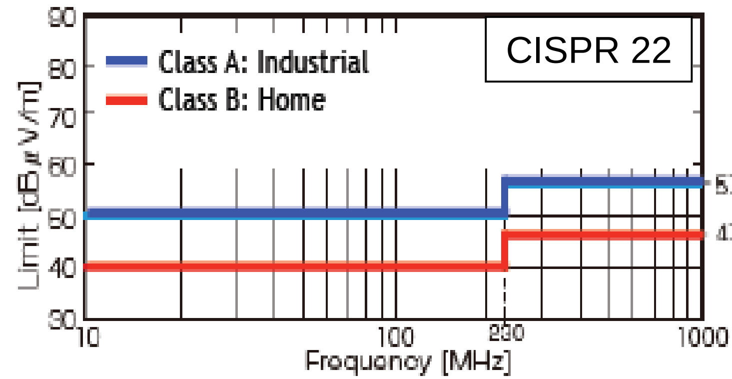
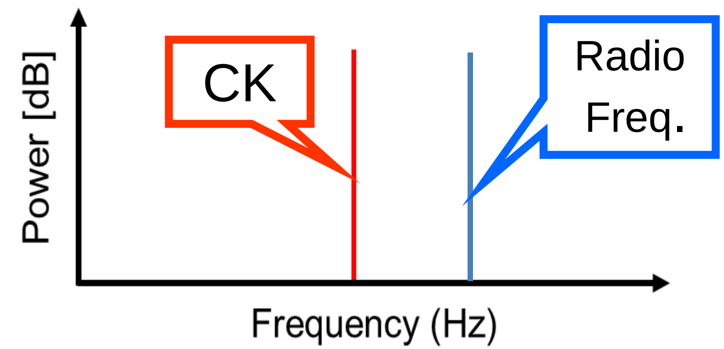
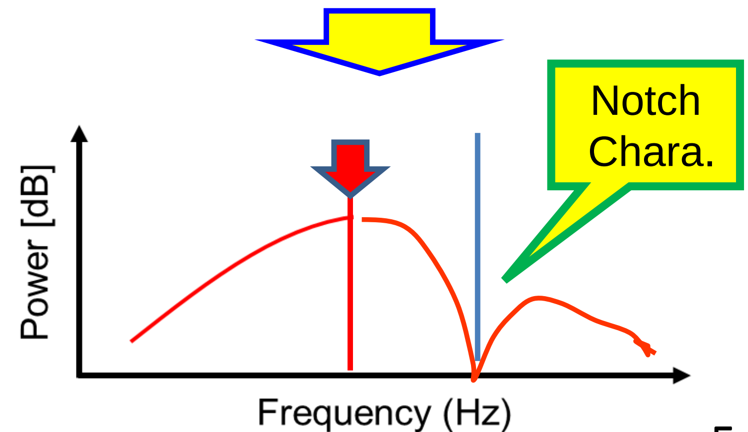






※ Our Objective

★ Develop Spread Spectrum Method both to reduce the EMI noise and to reject noise at desired frequency with Notch Characteristics.

1-1 Switching Converter (Buck type)

- ∗ Output Voltage Vo is compared with Vref and amplified.
- ∗ Amplified voltage ⊿Vo is compared with SAW-tooth signal.
  ⇒ Generate the Pulse Width Modulation (PWM) pulse.
- ∗ Power SW is controlled by the PWM pulse.
- ∗ Inductor Current changes Up/Down to control Vo stable.

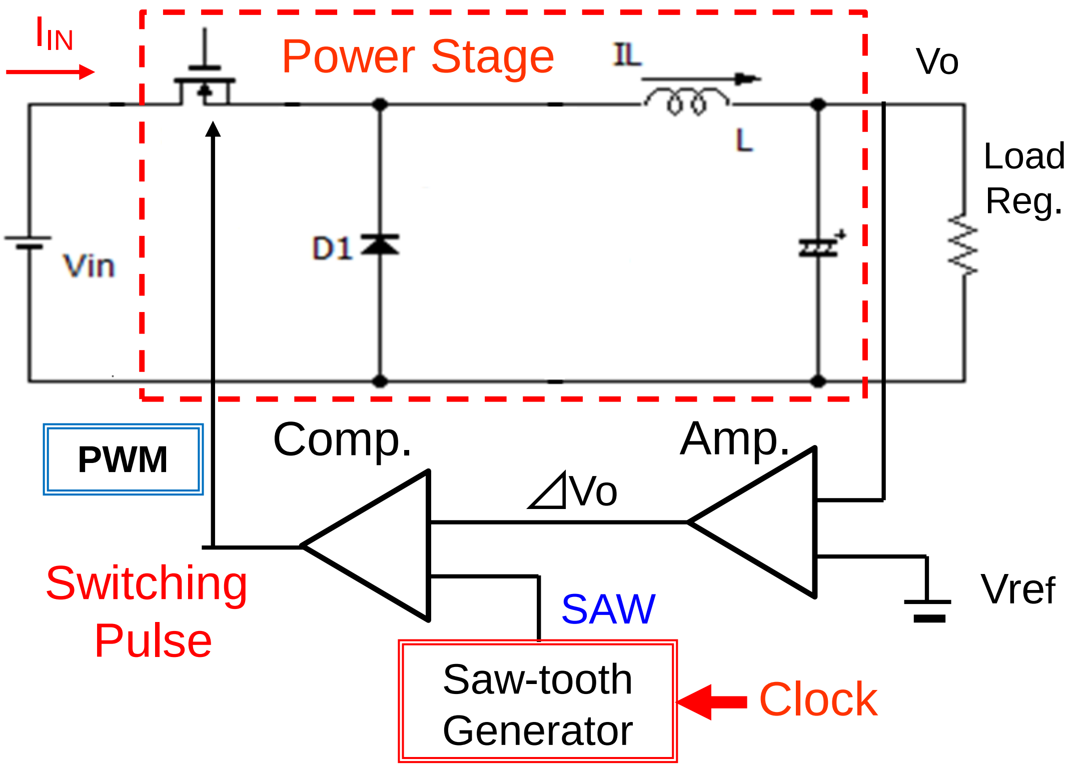


Fig.1-2 Circuit of the Buck converter

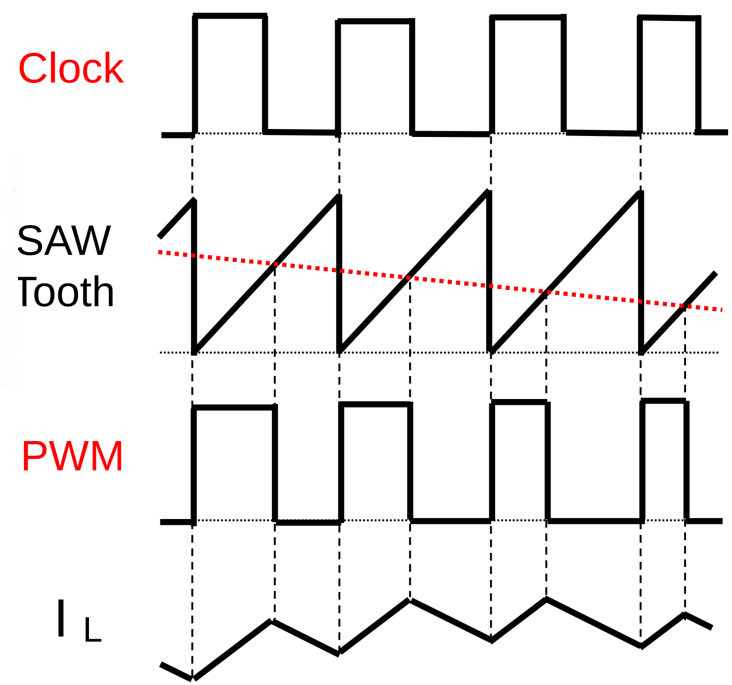


Fig.1-3 Waveforms

● Spectrum of PWM pulse

∗ Electro-Magnetic Interference (EMI) Noise ［from Circuit］

∗ Conductive Current Noise ［Input Current］

∗ Noise Spectrum (PWM pulse)

⇒ High Level spectrum at Fck (=200 kHz) & harmonics.

★Reduce clock frequency spectrum

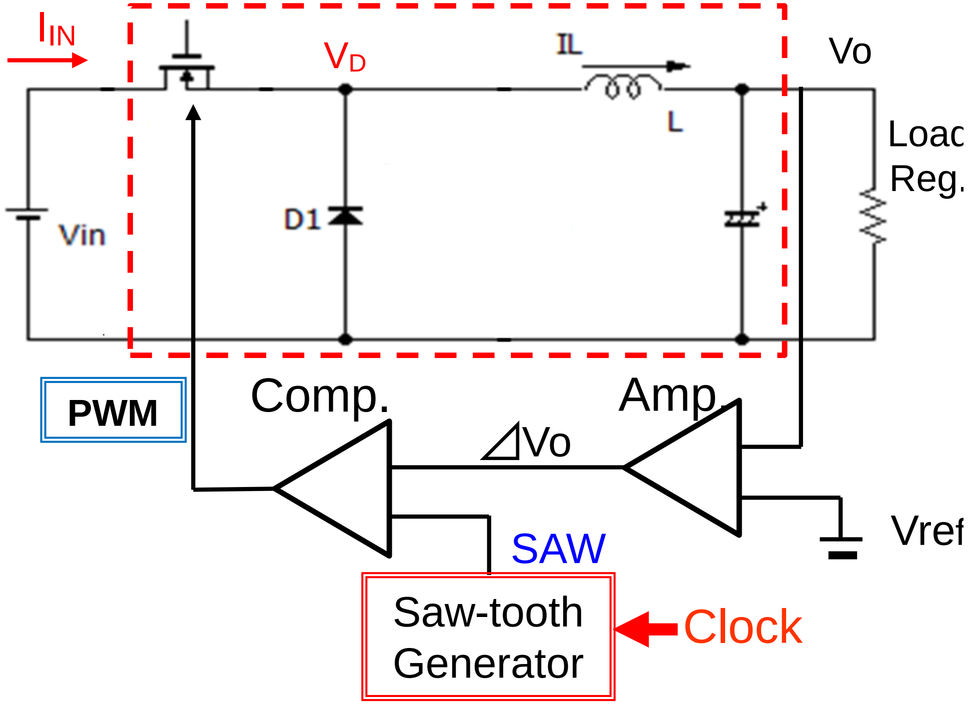


Fig.1-2 Circuit of the Buck converter

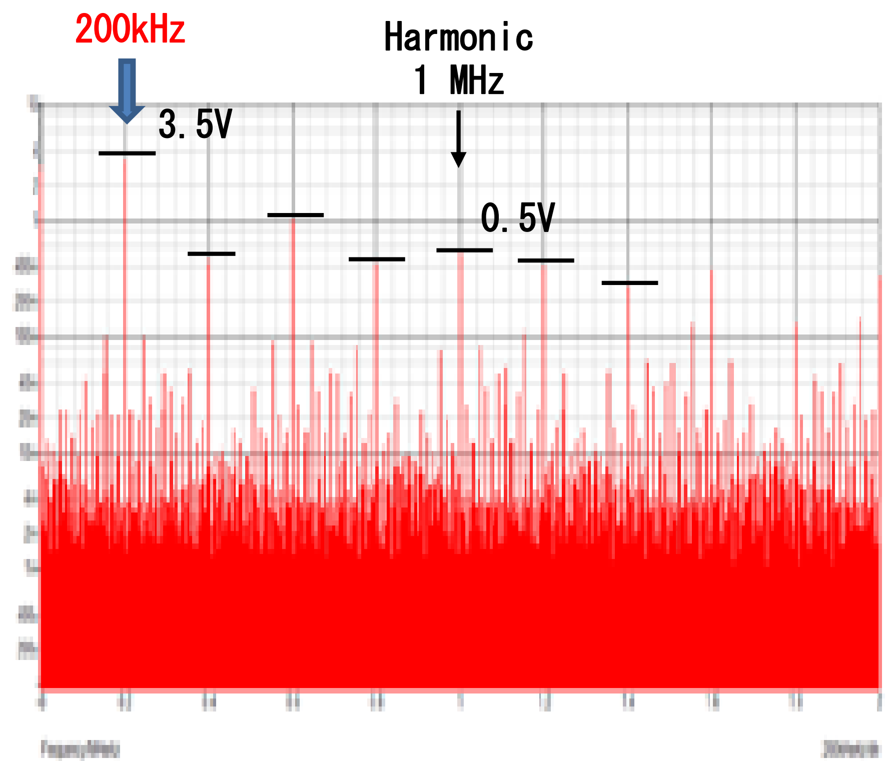


Fig.1-4 Noise Spectrum

1-2 EMI reduction with clock modulation

＊ To reduce EMI noise, clock pulse is modulated.

⇒ Clock spectrum is spread and reduced.

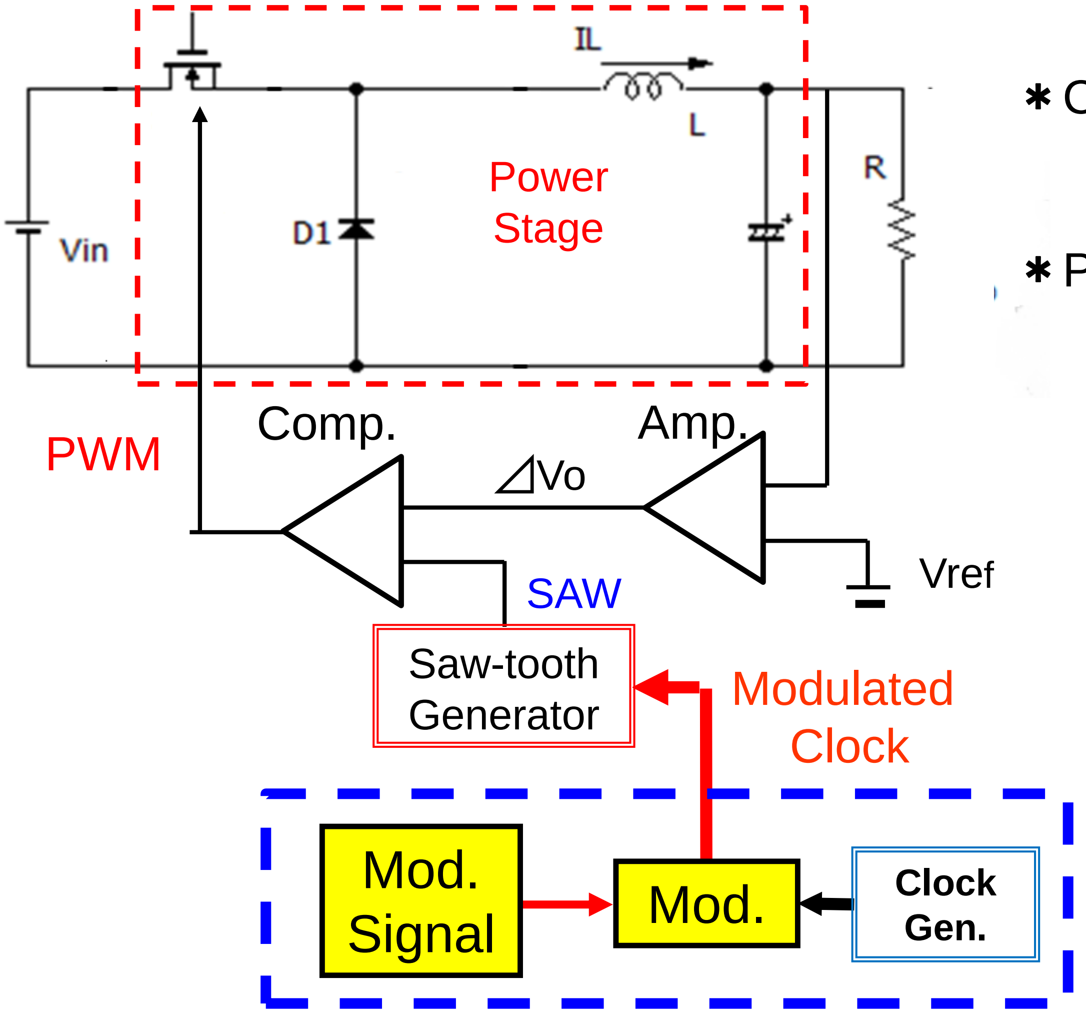


Fig. 1-5 Converter with EMI reduction

＊Clock to SAW generator is modulated by shaking phase or frequency.

＊PWM pulse is modulated and the clock frequency is spread.

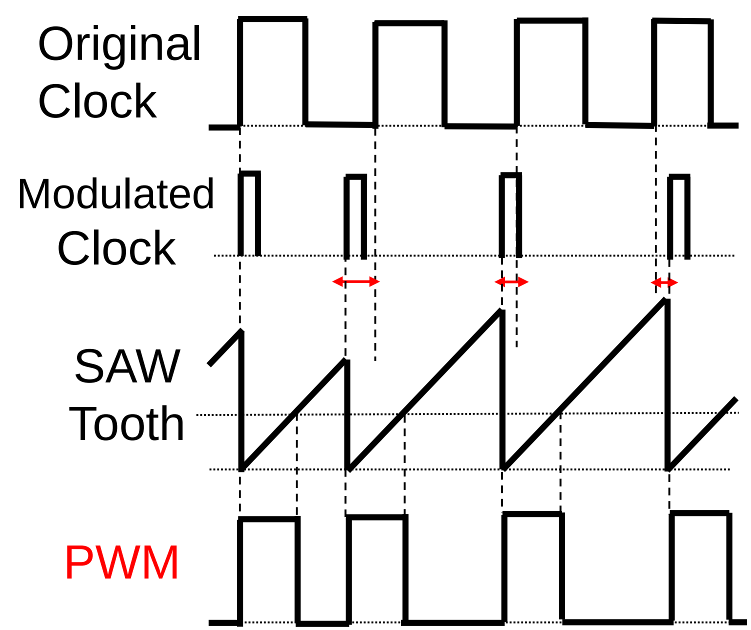


Fig.1-6 Waveforms

* Clock modulation methods:
(1) Random Digital, (2) Linear sweep, (3) Random Analog

1) Random Digital phase modulation:

- Using many shift resistors (> 1,000)
- Need same number of selectors
- Using M-sequence for random signal

*A lot of circuit
*Fast clock
Fs > 200MHz

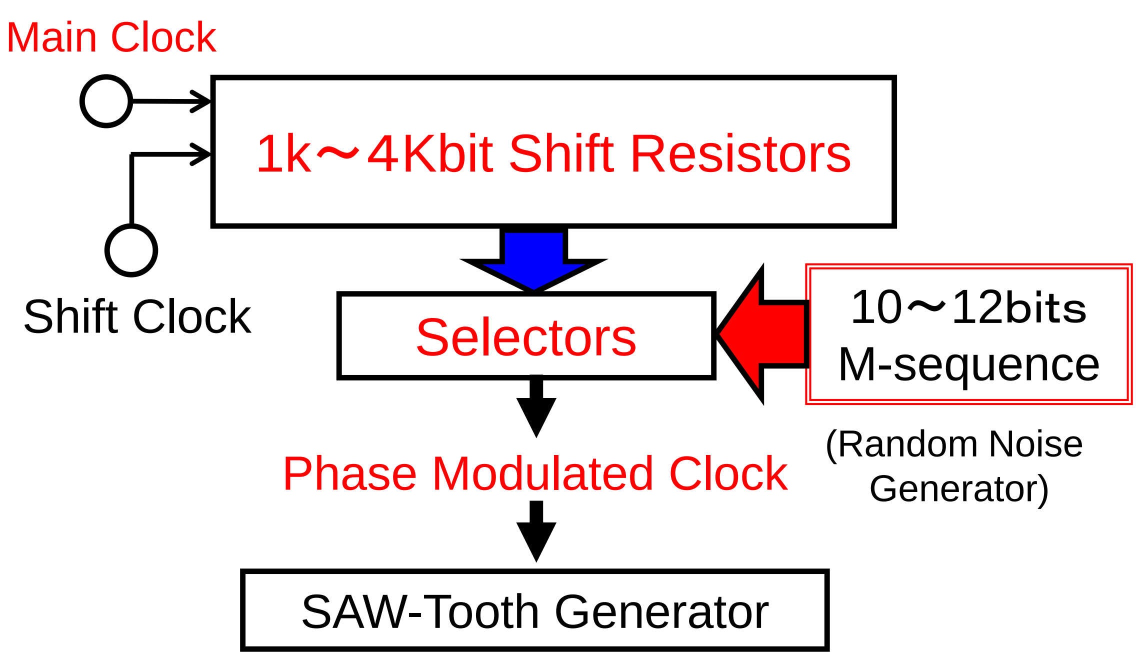


Fig. 1-7 Digital EMI reduction

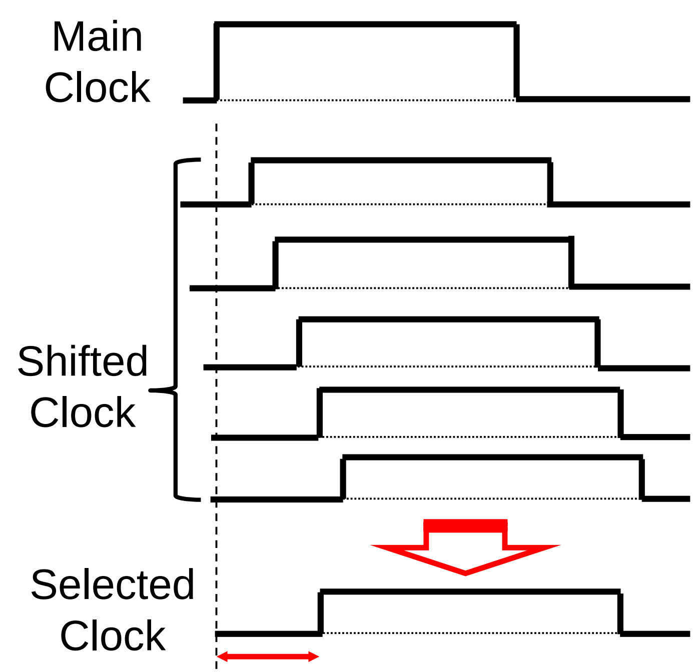


Fig.1-8 Timing chart

2) Linear sweep modulation:

VCO: Voltage Controlled Oscillator

* Clock pulse is generated using VCO.
  - VCO is modulated by Triangular signal with.
* Spectrum of modulated PWM pulse
  - Peak level is reduced and the top shape is flat.

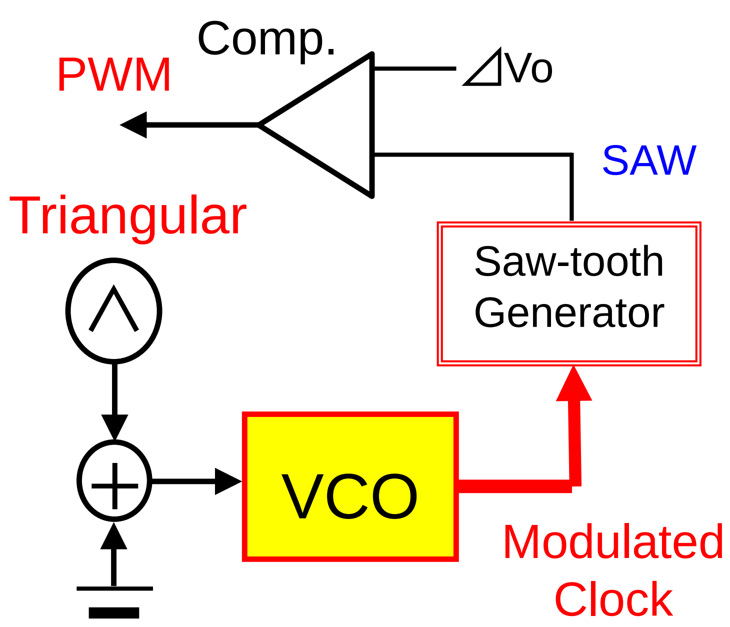


Fig. 1-9 Circuit of Linear Sweep

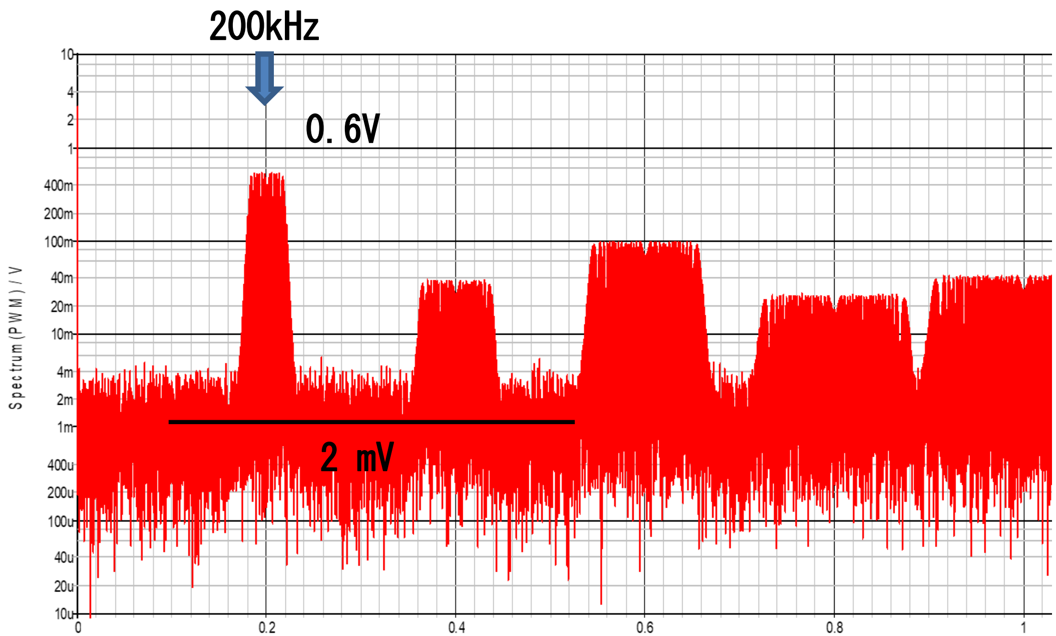


Fig. 1-10 Spectrum with Linear Sweep

(3) Random Analog noise modulation:

＊Pseudo Random Noise + PLL Circuit

- Random pattern is generated from M−sequence (3 bit) through LPF ⇒ pseudo random analog noise (Fig.1-12)
- Output of PLL circuit is the clock with random frequency.

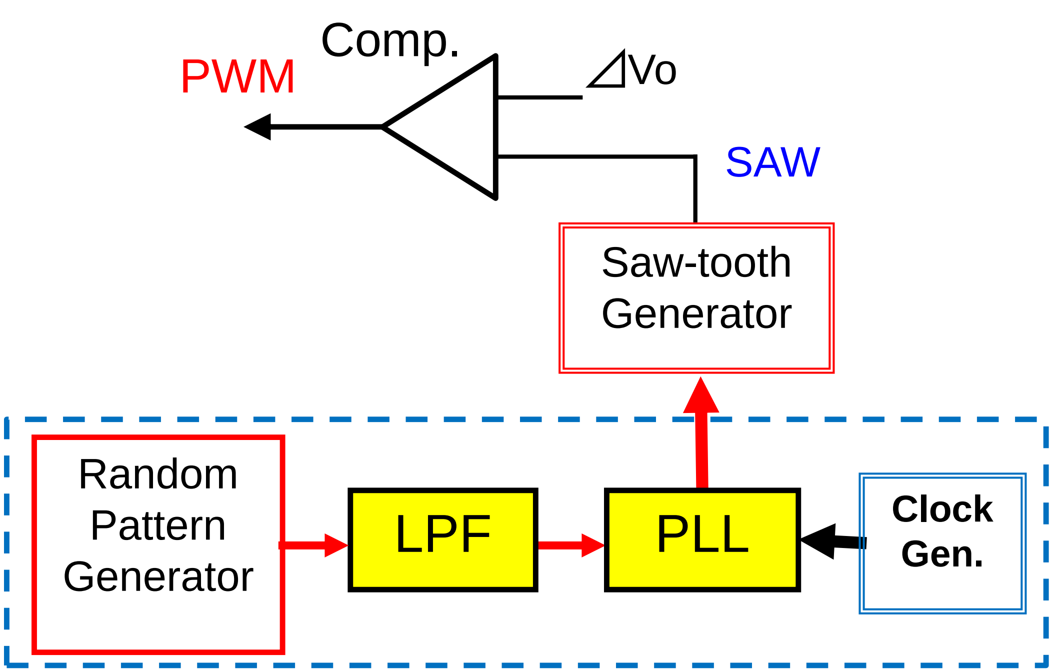


Fig. 1-11 Spectrum with Linear Sweep

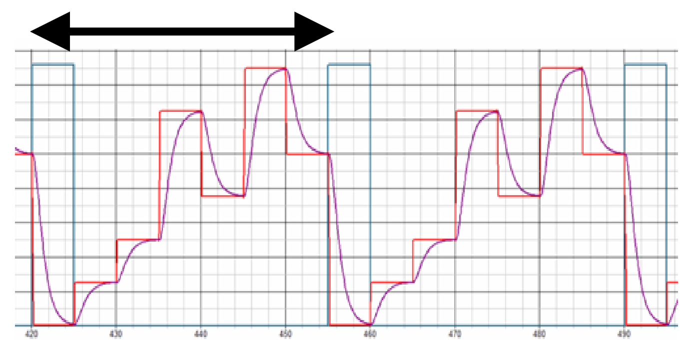


Fig. 1-12 pseudo random noise

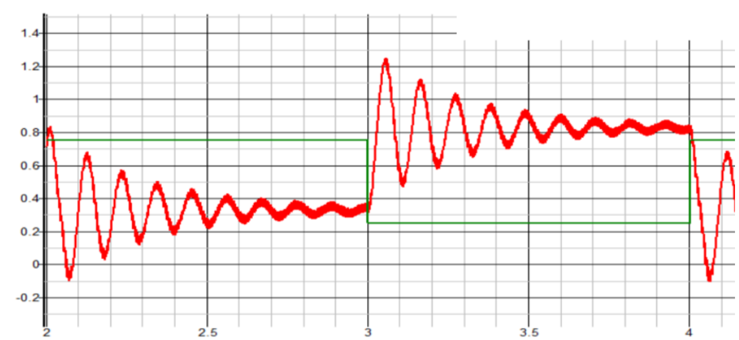


Fig. 1-13 PLL characteristics

- Simulated noise spectrum with EMI reduction
- Peak level is reduced to 2.0V (－4.9 dB)
- Harmonics are much reduced. (ex. －20 dB at 1.0 MHz)
- Output Voltage Ripple Vo is about 13 mVpp. (=0.3%)

◆ Bottom levels increase high!

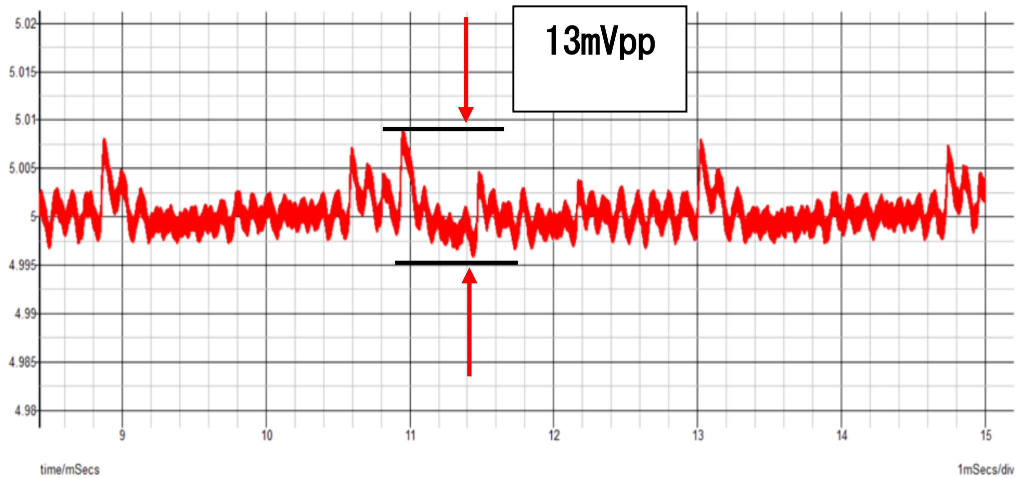
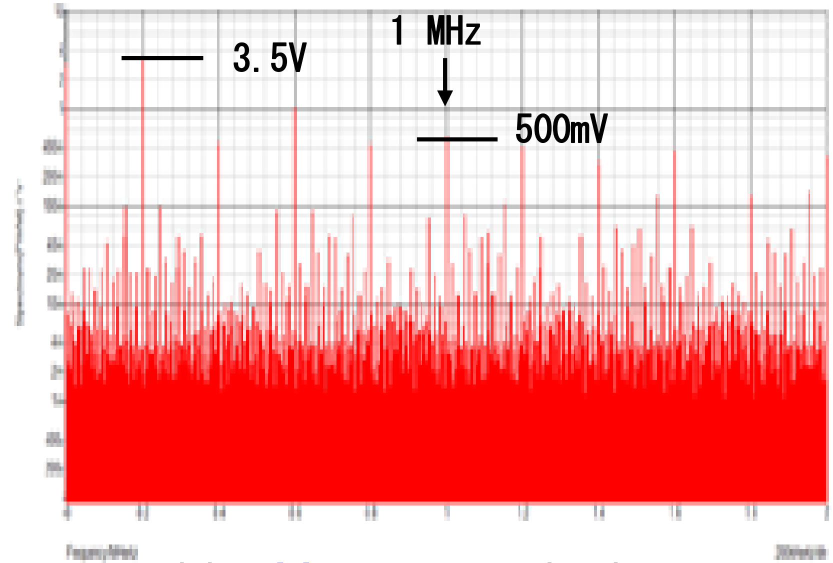
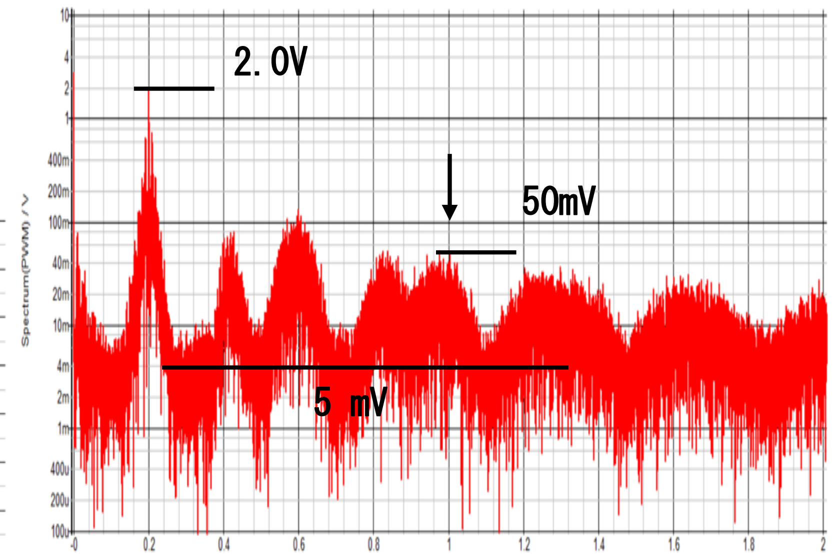


Fig.1-15 Output Voltage Ripple



(a) **Without** EMI reduction



(b) **With** EMI reduction

Fig.1-14 Comparison of Spectrum

Outline

1. Background
   1-1 Switching Converter
   1-2 EMI Reduction with clock modulation

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   2-1 Pulse coding control
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   2-3 Experimental results of PWC control

3. Automatic PWC Control for Radio Receivers
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4. Conclusion

PWC: Pulse Width Coding

2. Pulse Coding and Notch Characteristics

2-1 Pulse coding control

★ Switching Converter with Pulse Coding

∗ Make SEL signal
by comparing ⊿Vo vs. Vr

・Select Pulse-H or Pulse-L.

Pulse-H : with H-Duty ratio

∗ In order to control Vo,
duty ratios of coding pulses
are very important.

★ $D_H > D_O > D_L$ ･･･ (1)

$D_O = V_O / V_{in}$

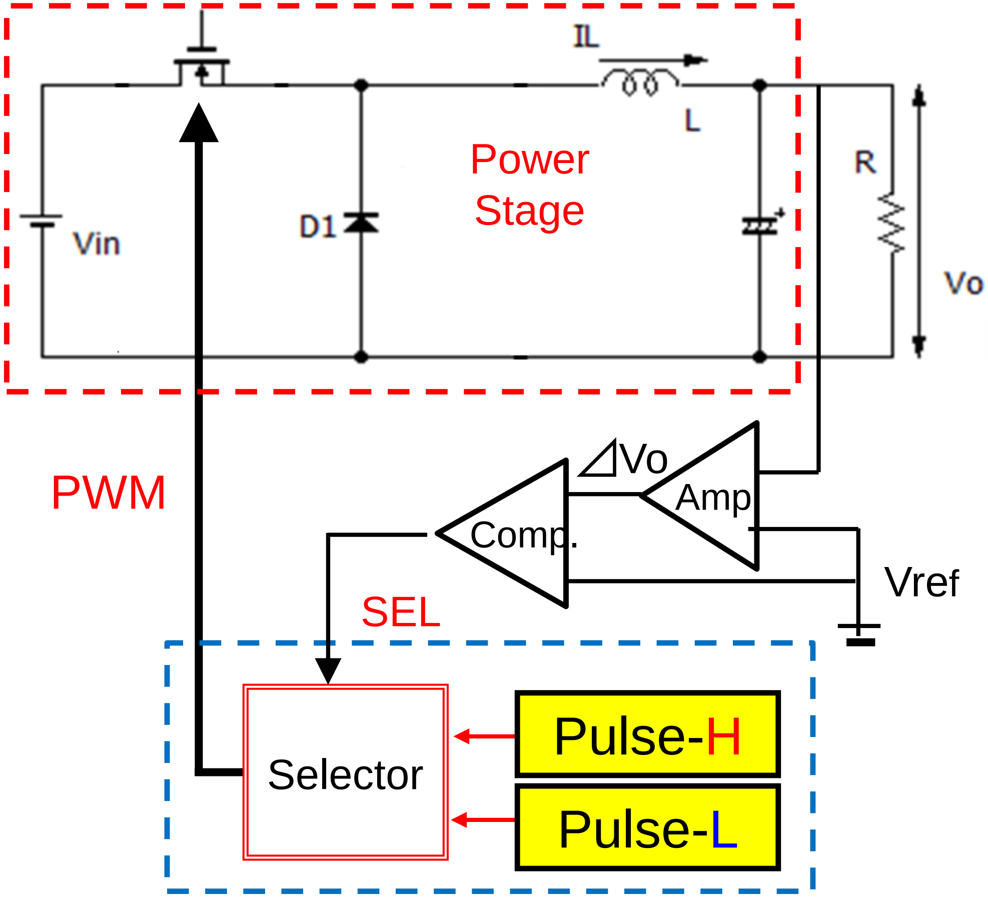

Fig.2-1 Switching Converter with Pulse Coding

★ Pulse Coding control

1) Pulse Width Coding (PWC)

- Pulse width is different.
- Notch frequency: Fn

$$Fn = N/(W_H - W_L) \quad \cdots (2)$$

2) Pulse Phase Coding (PPC)

- Pulse phase is different.

$$Fn = N/(2 \cdot \tau) \quad \cdots (3)$$

3) Pulse Cycle Coding (PCC)

- Pulse cycle (period) is different.

$$Fn = N/(T_L - T_S) \quad \cdots (4)$$

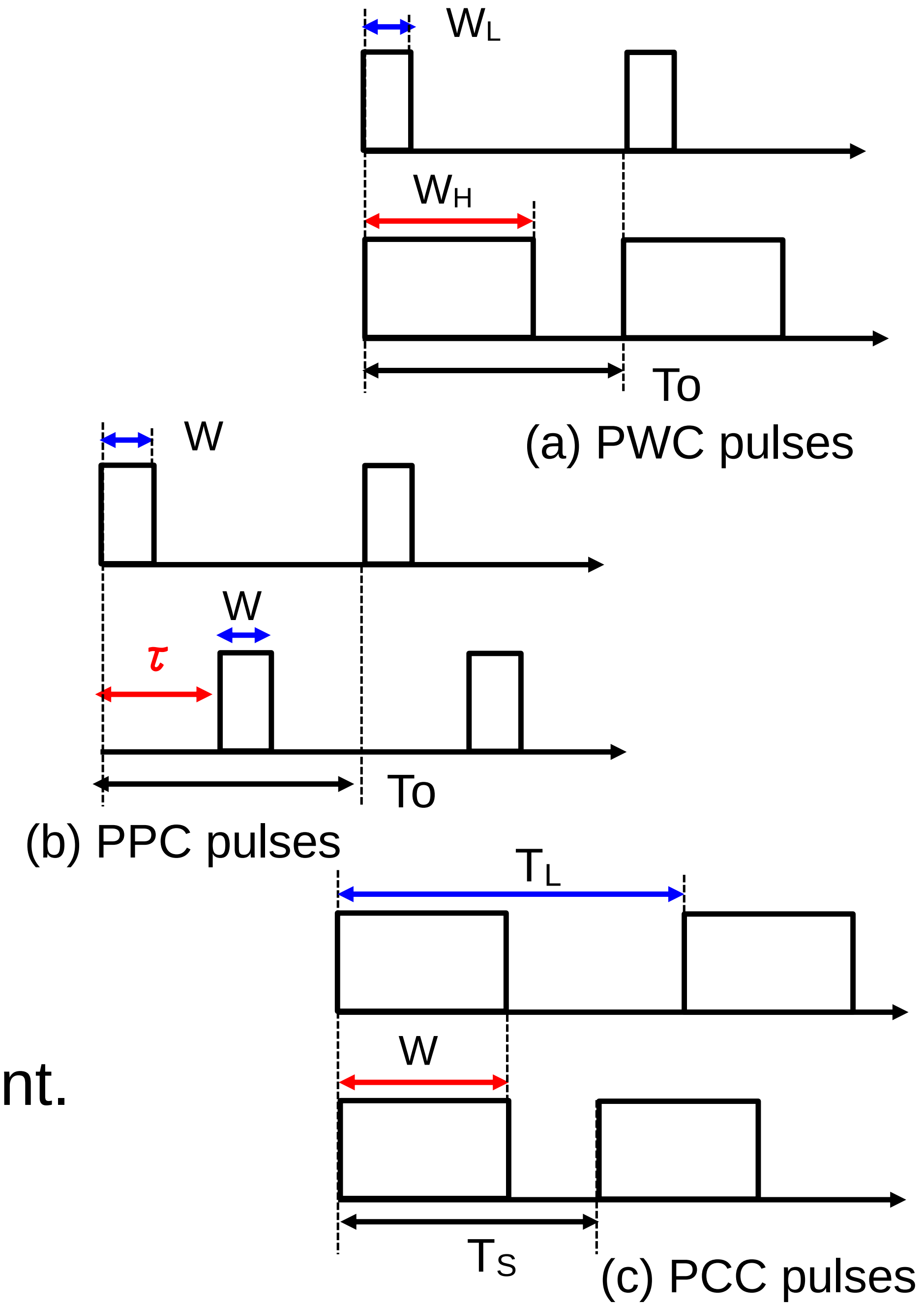

Fig.2-2 Pulse Coding control

★ Complex Pulse Coding control

1) Pulse Width & Phase Coding (PWPC)

- Pulse width & phase are different.
- Notch frequency: Fn

$Fn1 = N/(2 \cdot \tau)$

$Fn2 = M/(T_L - T_S)$

2) Double notch characteristics

When set $\tau = (T_L - T_S) / 2$ ··· (5)

then Fn1 = Fn2. : Double Notch

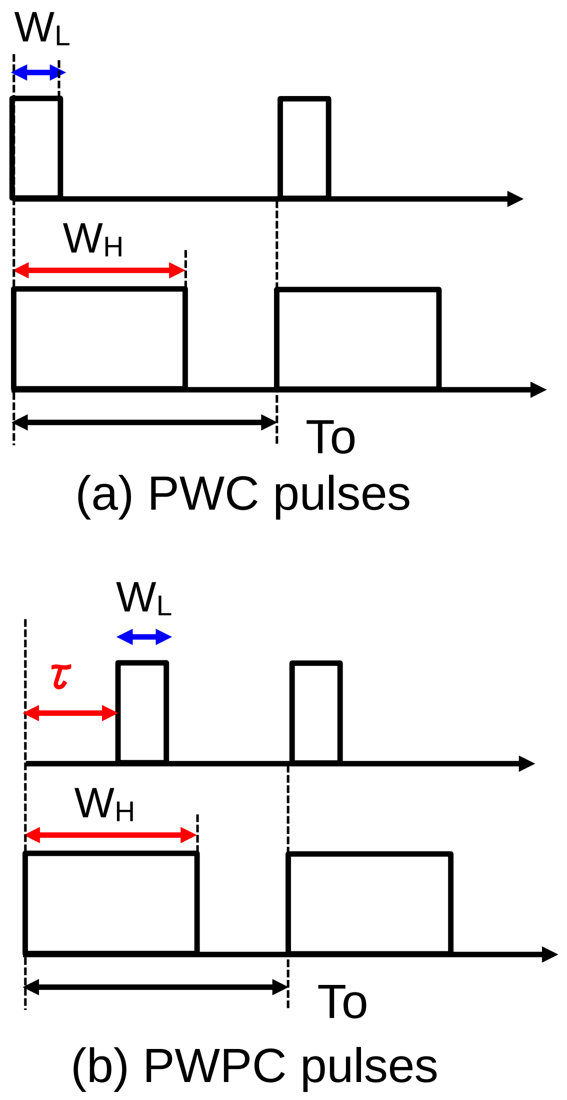

Fig.2-3 PWPC control

2-2 Simulation result with PWC control

● Simulation results with PWC control

∗ Condition: Vi=10V, Vo=5V, Fck=500kHz

∗ Pulses: H-Pulse W_H=1.7us, D_H =0.85
L-Pulse W_L =0.4us, D_L =0.2

∗ Static Ripple:⊿Vo＜2mV @Io=0.25A

∗ Overshoot = 2.5 mV @⊿Io=0.125A

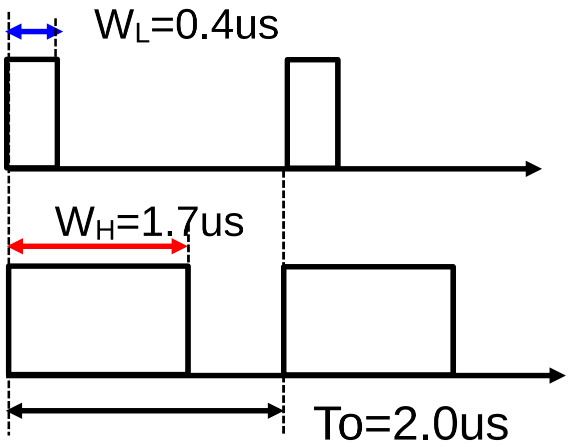

Fig.2-4 PWC Pulses

Fig.2-5 Signals with PWC control

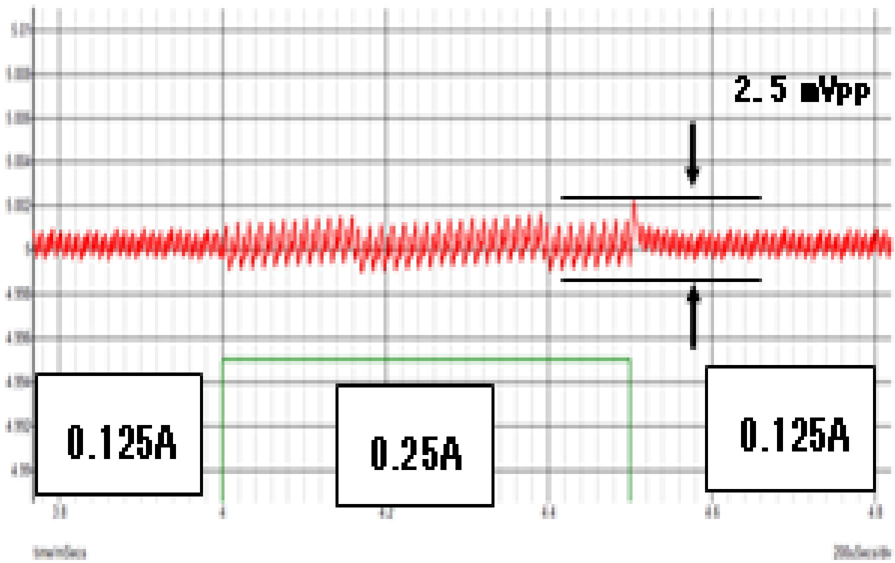

Fig.2-6 Output ripple with PWC control

● Noise Spectrum with PWC control of PWM pulse

* Notch Freq. : $F_N = N/(W_H - W_L)$ = N/1.3us = 0.77, 1.5 MHz

  Peak Level Reduction: 3.5V ⇒ 0.9V (−11.8 dB)

* Frequency relation : Fck < Fn < 2Fck

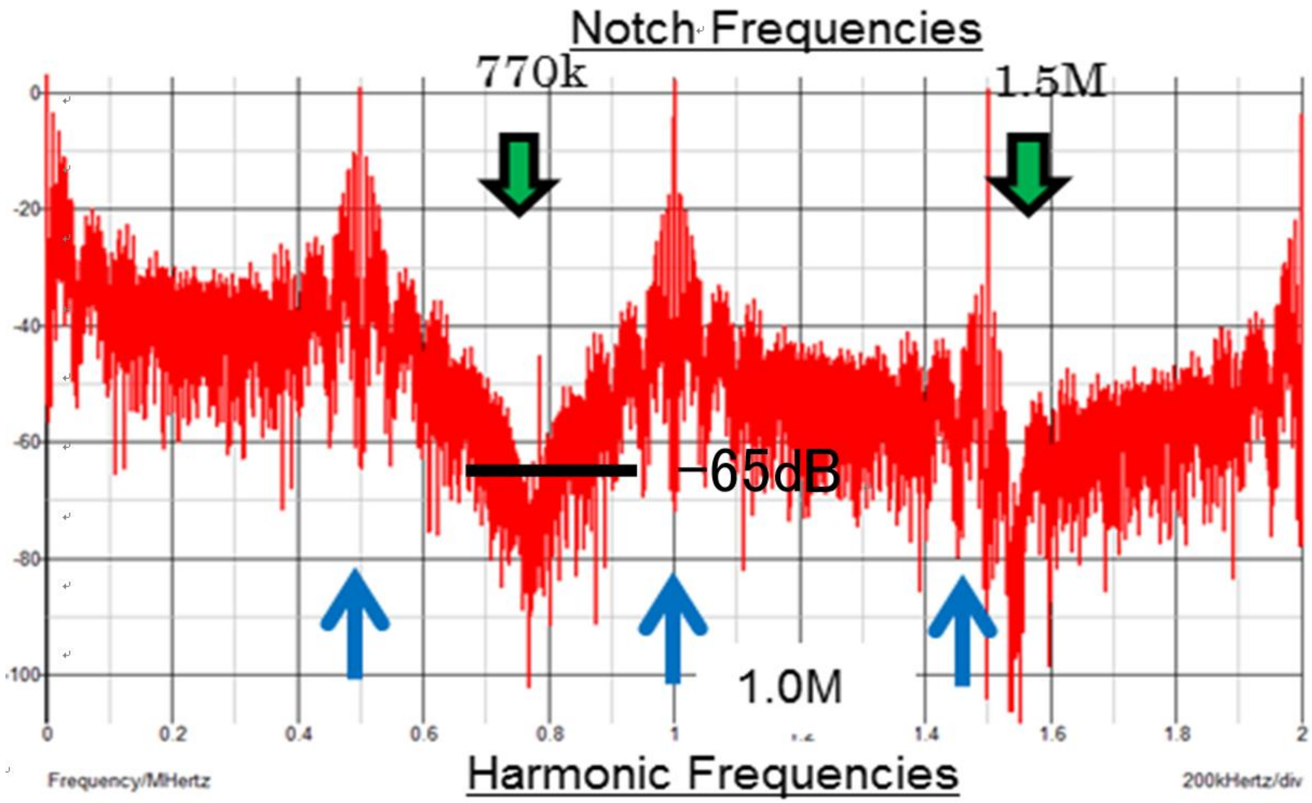

Fig. 2-7 Noise Spread Spectrum with PWC control

● Noise Spectrum with PWPC control :

∗ Conditions: Vi=10V, Vo=5.0V, Fck=1.4 MHz (Tck=714 ns)

W_H =480 ns, W_L = 320 ns, $\tau = (W_H - W_L)/2 = 80$ ns

∗ Notch Frequency: F_N = 1/160ns= 6.25 MHz

Bottom Level: V_B : −65dB ⇒ −75 dB (−10dB)

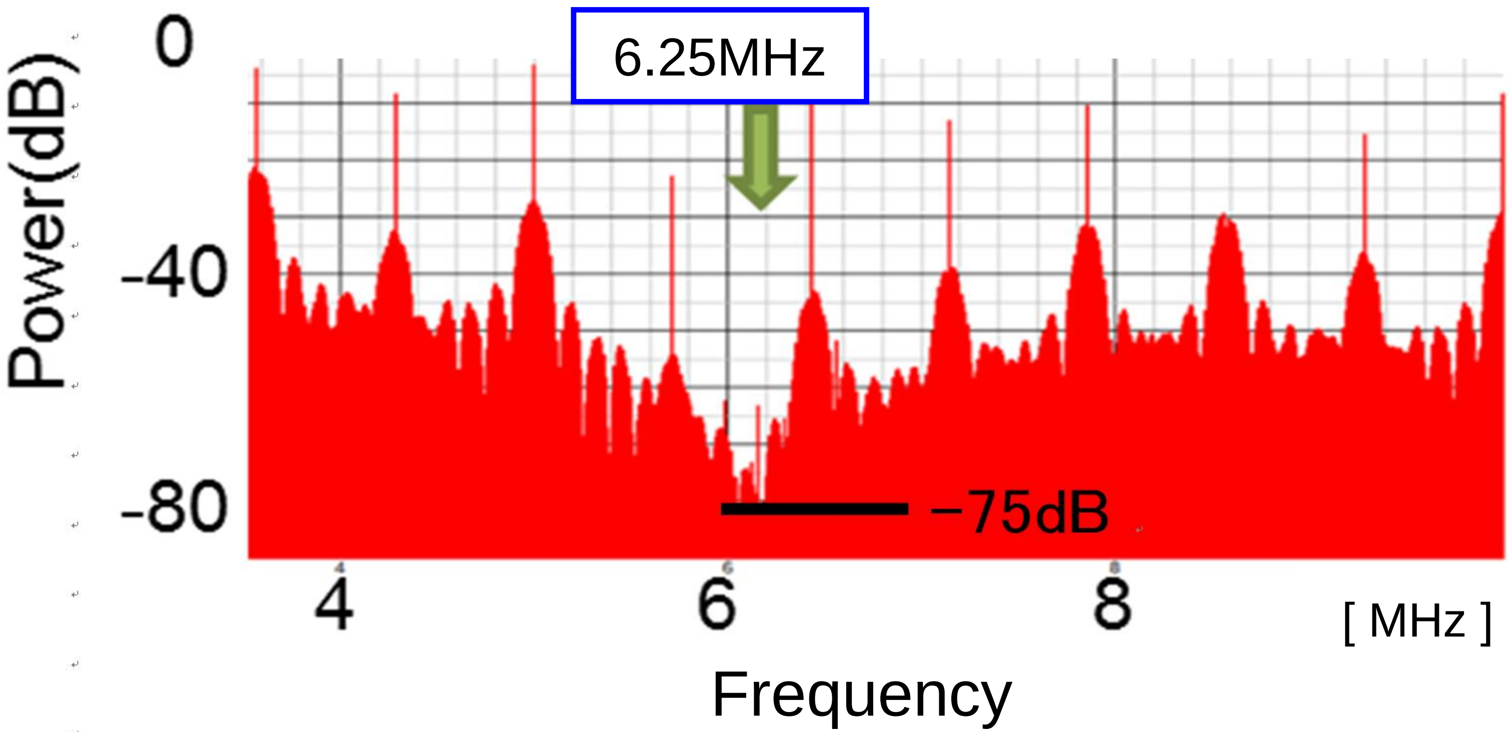

Fig.2-8 Noise Spectrum of PWPC control

2-3 Experimental result with PWC control

* Conditions : W_H =5.0 ns, W_L =1.0 ns, Tck=160 kHz
* Notch Frequency: Fn=1／(5.0−1.0) us = 250 kHz
* Relation: Fck ＜ Fn=274 kHz ＜ 2･Fck

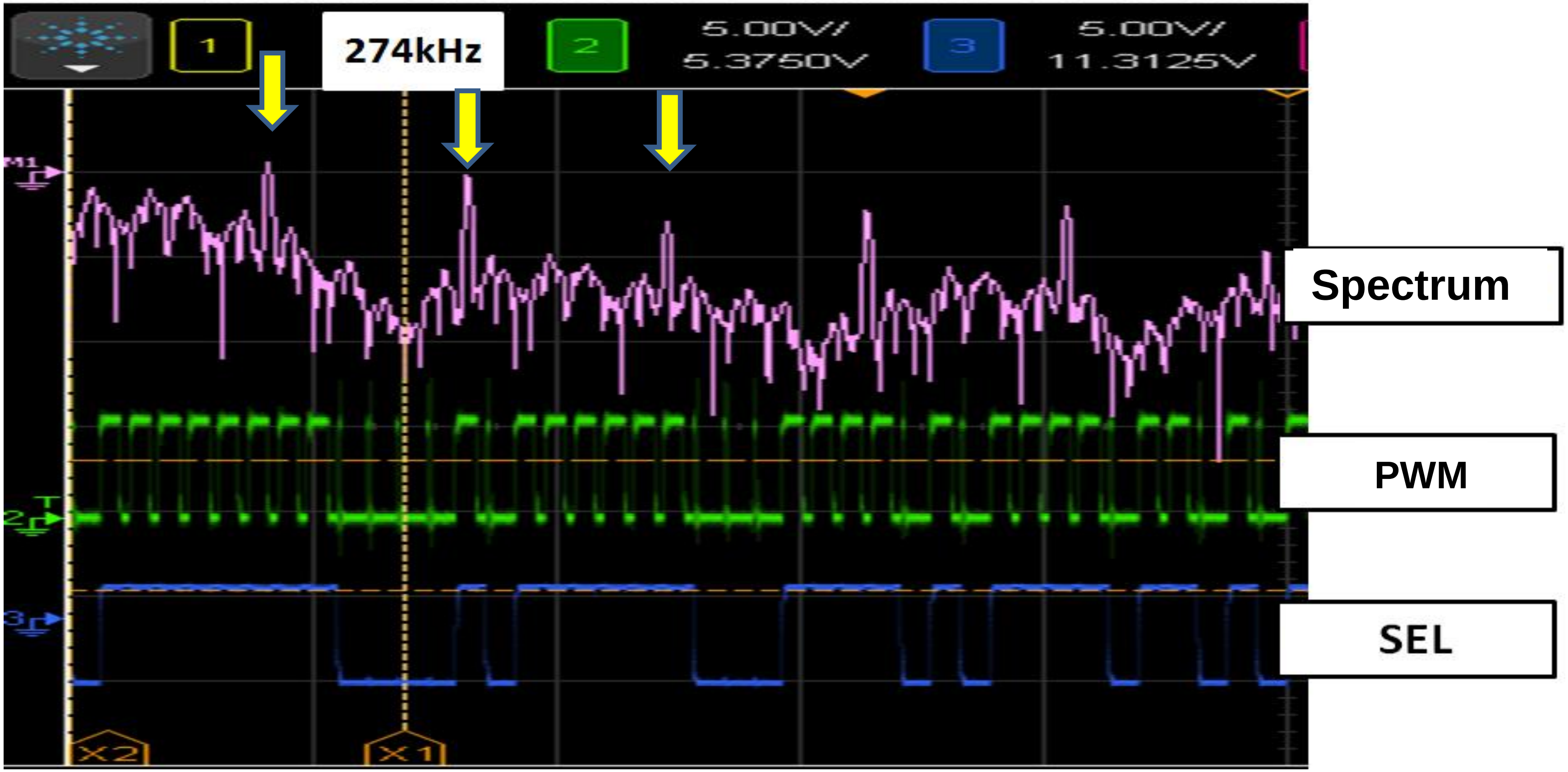

Fig.2-9 Noise spectrum & major signals with PWC

- Experimental result 2 with PWC

  ＊Conditions 2: W_H =2.0 ns, W_L =1.0 ns, Fck=420 kHz

  ＊Notch Freq.：F_N =1／(2.0－1.0) us = 1.0 MHz

  ＊Relation: 2･Fck ＜ Fn=1.05 MHz ＜ 3･Fck

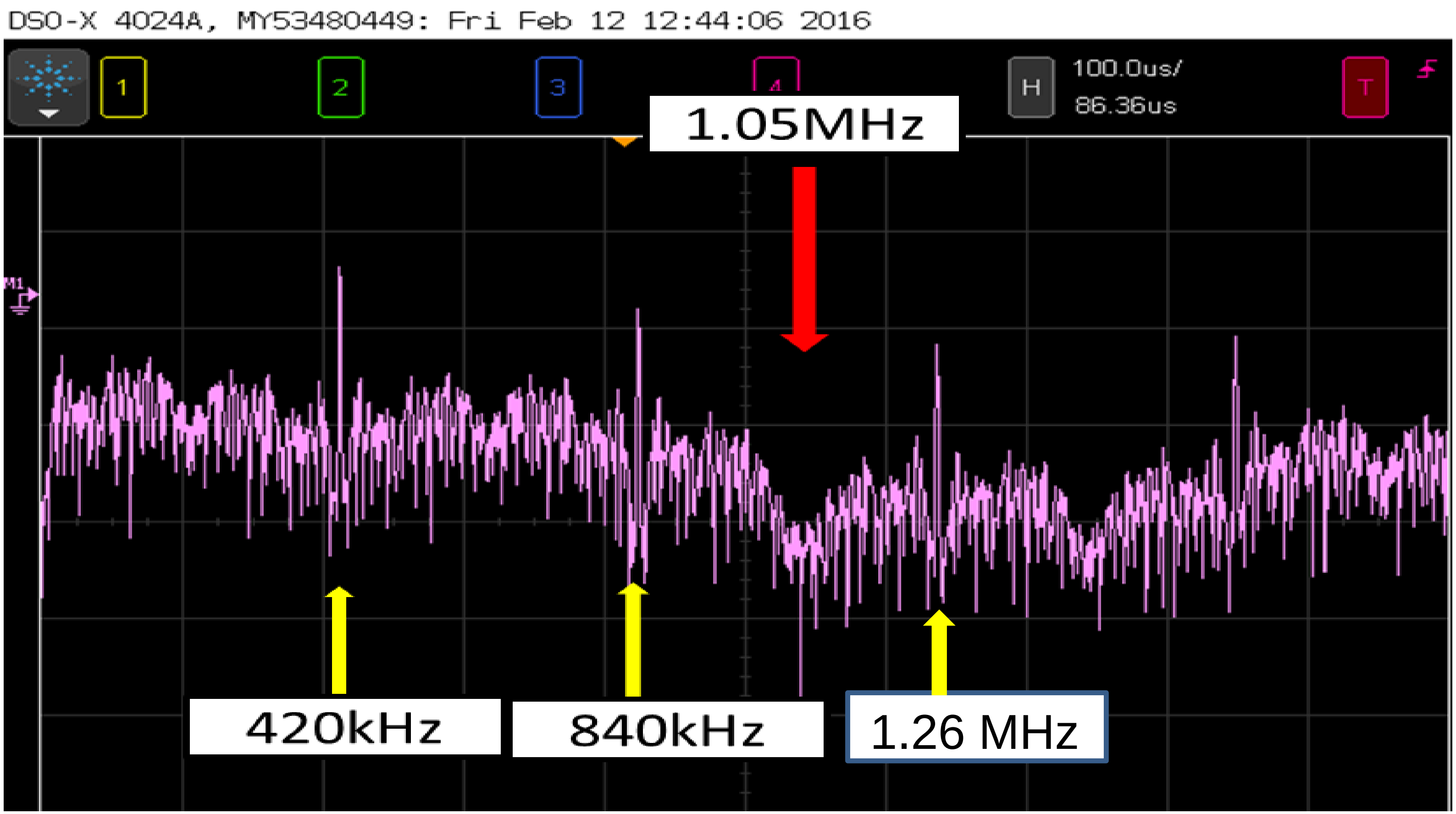

Fig. 2-10 Another noise spectrum with PWC 2

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   3-2 Adjustable pulse generation from input frequency
4. Conclusion

3. Automatic PWC Control for Radio Receiver

3-1 Generating clock pulse & coding pulses

● Relations among Fin, Fck, Fn and W_H, W_L

∗ Better to generate Fn at middle of Fck :

- N=1: $Fck < Fn < 2 \cdot Fck$
- N=2: $2 \cdot Fck < Fn < 3 \cdot Fck$

$\therefore$ $Fn = (N+0.5) \cdot Fck \Rightarrow Tck = Tn \cdot (N+0.5)$ ･･･(7)

∗ Static duty ratio Do and Coding pulses

- $Do = Vo / Vin$、 $Tn = W_H - W_L = Tin$ ･･･(8)
- $W_H = Do \cdot Tck + Tin/2$, $W_L = Do \cdot Tck - Tin/2$ ･･･(9)

★ After generating Tck from Tin,

W_H & W_L are set with Eq. (9).

★ Case: N=1, Do=0.5

$$Tck = Tin \cdot (N+0.5) = 1.5 \cdot Tin \Rightarrow 2 \cdot Tck = 3 \cdot Tin \qquad \cdots(10)$$

● How to generate Fck from Fin

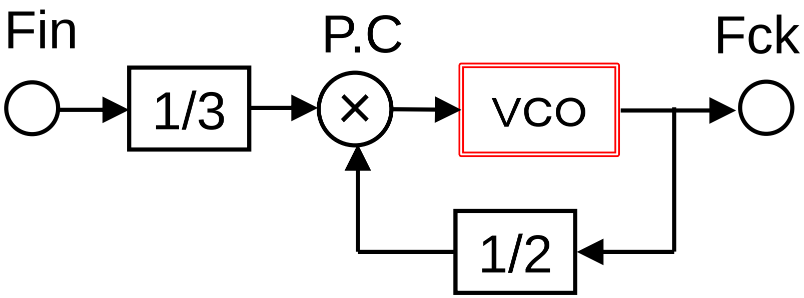
(A) using PLL circuit (B) Using Direct calculation

(A) Generating Tck using PLL circuit : (Presentation IPS01-03 [Sun])

∗ Use VCO and generate Fck= (2/3)·Fin

∗ Generate coding pulses W_H , W_L from Tin & Tck

$$W_H = Tin/2 + Tck/2、W_L = Tin/2 - Tck/2 \qquad \cdots(9')$$



P.C : Phase Comparator
VCO: Voltage Controlled Oscillator

Fig. 3-1 PLL circuit with VCO

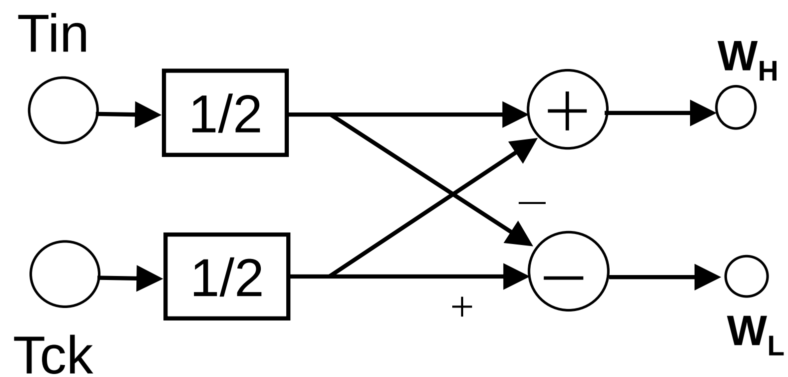


Fig. 3-2 Generating W_H & W_L

∗ Simulation result: Fin =500 kHz

・Noise spectrum: Fck= 330 kHz, Fn=520 kHz

・Step Response with Fin change: @ Fin=0.5MHz ⇔ 1.0MHz

Ripple=15mVpp, Undershoot=－15mV

Settling time (recovery time): Ts = 0.15 ms

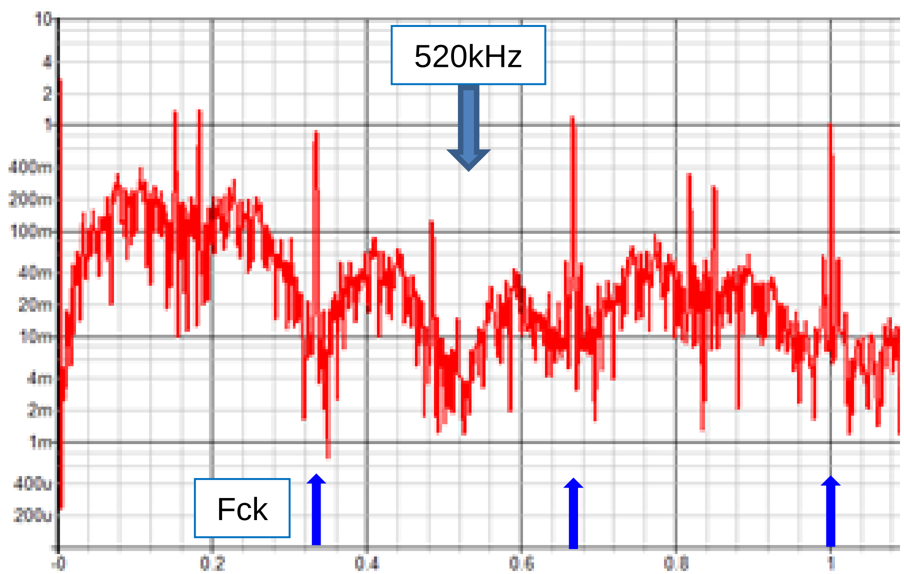


Fig. 3-3 Noise spectrum with auto generated coding pulses

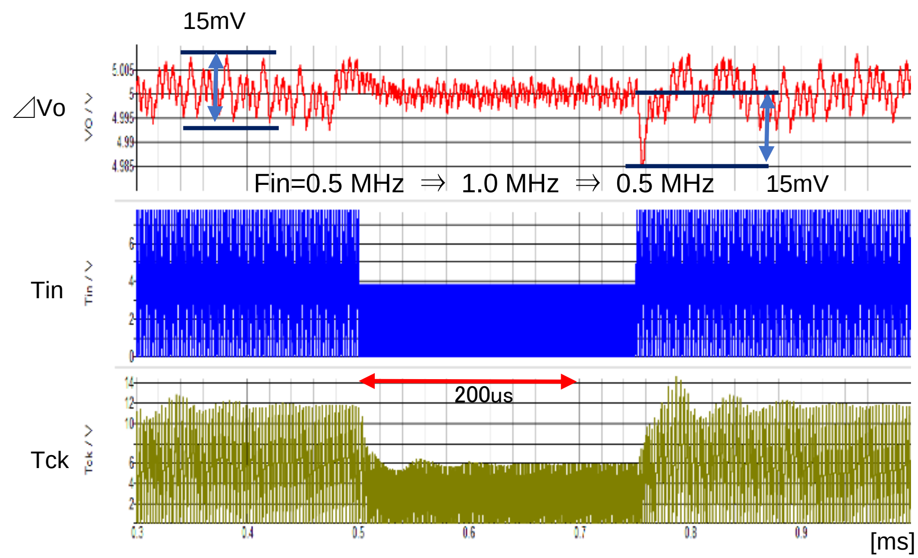


Fig. 3-4 Transient response with Fin change

(B) Generating Tck using Direct calculation

＊Generate Tck from Tin using Eq. 10 : $Tck = 1.5 \cdot Tin$ (N=1)

・Measure Tin and generate Tck using digital/analog circuit.

＊Calculate coding pulses W_H & W_L from Tin & Tck

$$W_H = Tin/2 + Tck/2,\quad W_L = Tin/2 - Tck/2 \quad \cdots (9')$$

●Simulation result: Fin=750 kHz

・Static voltage ripple: ⊿Vo = 3mV @ Fin= 750kHz

・Step Response: when Fin = 1.25M ⇔ 1.0M ⇔ 0.75MHz

⊿Vo = Over/Undershoot = 4mV, Settling time≒0 ms

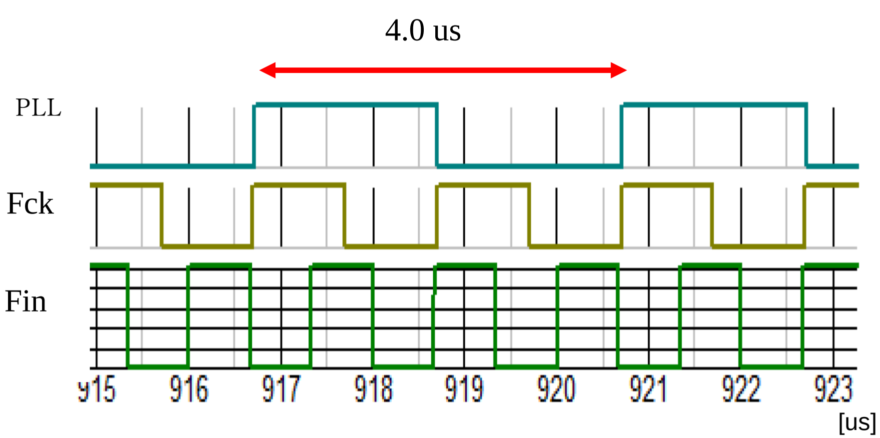


Fig. 3-5 Direct generation of Tck

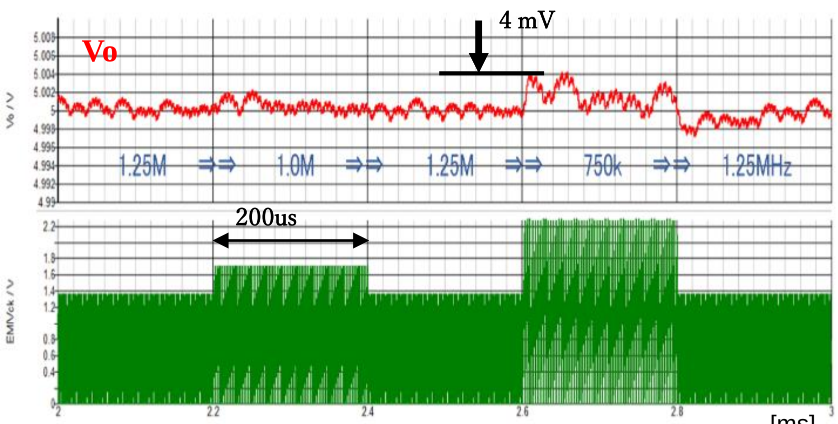


Fig. 3-6 Transient response with Fin change

● Noise spectrum with Linier sweep EMI reduction

∗ Case 1: Fin= 750 kHz, N=1

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

∗ Case 2: Fin=1.25 MHz, N=2

- Fn=1.27 MHz, Fck=500 kHz, 2Fck < Fn < 3Fck

● There appears the large notch at 4·Fn

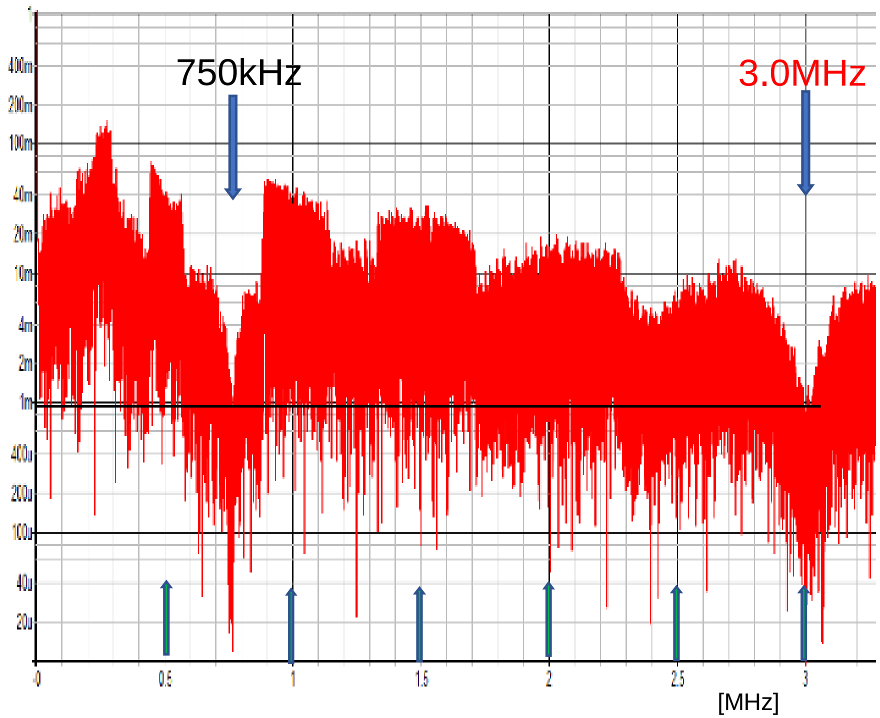


Fig. 3-7 Noise spectrum (N=1)

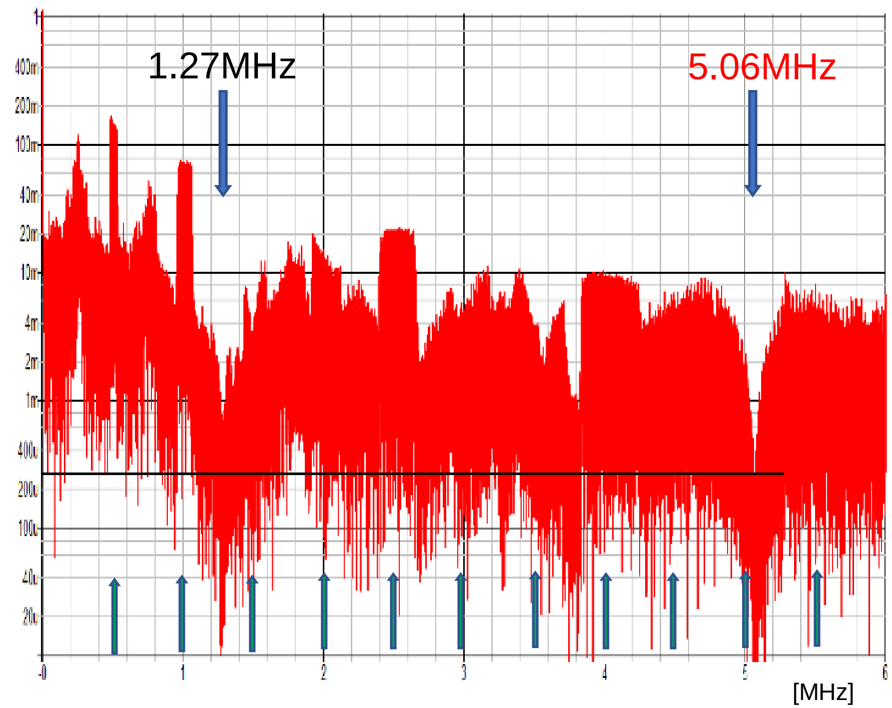


Fig. 3-8 Noise spectrum (N=2)

Conclusion

★ Developed Pulse Coding Control in order to generate notch characteristics at desired frequency.

1. Theoretical Notch Frequency:
   - PWC : $F_N = N/(W_H - W_L)$
   - PPC : $F_N = N/(2\tau)$
   - PCC : $F_N = N/(T_L - T_S)$

   ＊Complex Pulse Coding
   PWPC=PWC+PPC

2. Experimental Noise Spectrum with PWC :
   - Notch appears at Fn = (N+0.5)･Fck

3. Automatic notch generating method:

   1) Generate Fck from Fin : Fck=2/3･Fin (or Tck=1.5･Tin)
      (A) using PLL circuit (B) using Direct Calculation

   2) Make W_H & W_L from Tin & Tck and set Fn:
      ⇒ W_H =Tin/2＋Tck/2、W_L =Tin/2 －Tck/2

●Future Work:
Investigate why the large notch at 4･Fn appear.

Thank you for your kind attention!

Is there any question?