ATS Doctoral Thesis Award

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Study of Multiphase Networks, Noise Reduction for DC-DC Converters, and Stability Test for Electronic Systems

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Outline

1. **Research Background**
   - Motivation, objectives and achievements
2. **Investigation of Multi-Phase Networks**
   - Polyphase filters, complex filters, and quadrature signal generation networks
3. **Noise Reduction for DC-DC Converters**
   - Ringing and ripple reduction techniques
4. **Stability Test for Electronic Systems**
   - Ringing test for passive and active networks
5. **Conclusions**

1. Research Background

Motivation of Study

Performance of a system

Signal to Noise Ratio:

$$\text{SNR} = \frac{\text{Signal power}}{\text{Noise power}}$$

Performance of a device

Figure of Merit:

$$\text{F} = \frac{\text{Output SNR}}{\text{Input SNR}}$$

Common types of noise:

- Electronic noise
- Thermal noise,
- Intermodulation noise,
- Cross-talk,
- Impulse noise,
- Shot noise, and
- Transit-time noise.

Device noise:

- Flicker noise,
- Thermal noise,
- White noise.

System noise:

- Image noise,
- Ripple noise,
- Ringing noise.

1. Research Background

Objectives of Study

- Derivation of transfer function in electronic systems using superposition theorem
- High image rejection ratio and flat pass-band gain for polyphase filters and complex filters
- Low ringing and small ripple for DC-DC Buck converters using linear swept frequency modulation and LC notch harmonic filter methods
- Stability test for electronic networks with and without feedback loops

1. Research Background

Achievements of Study

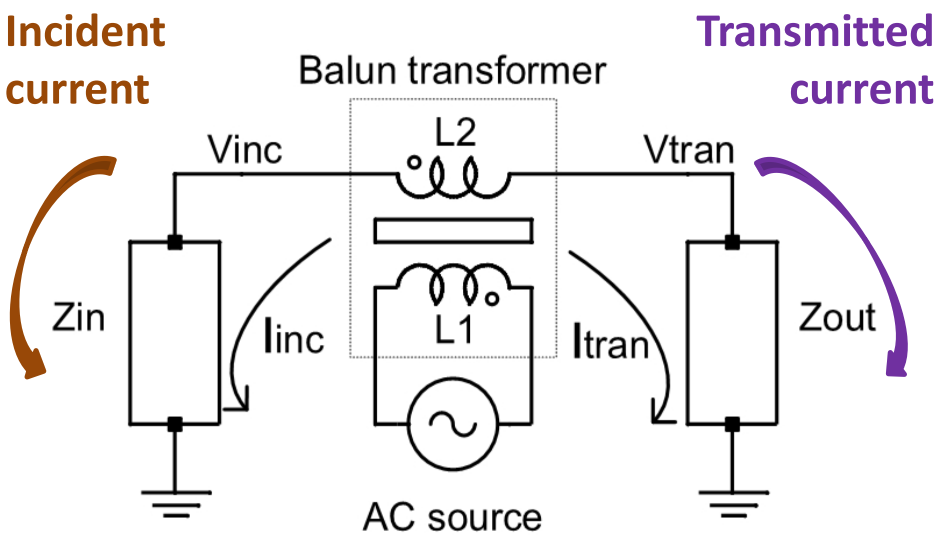
Superposition formula for multi-source networks

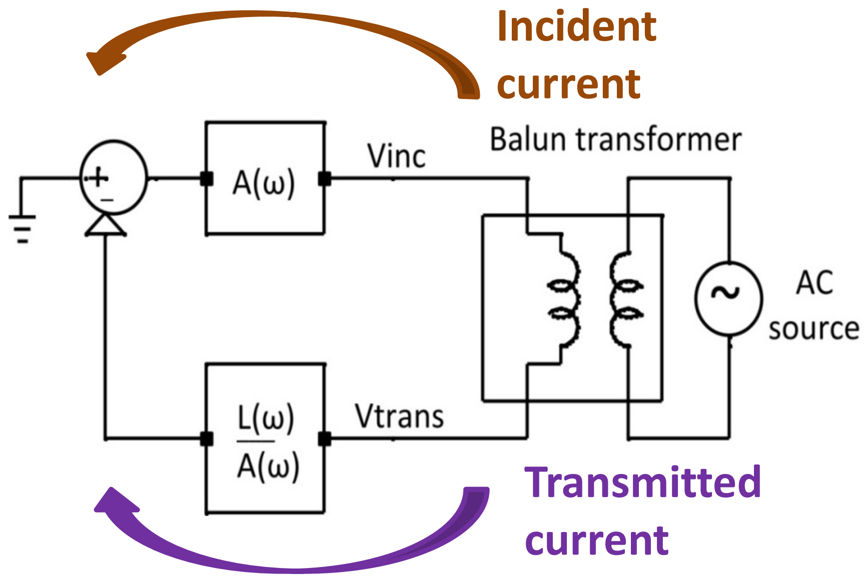
$$V_O(t)\sum_{i=1}^{n}\frac{1}{Z_i}+V_O(t)\sum_{i=1}^{n}\frac{1}{Z_{si}+\dfrac{1}{\sum_{k=1}^{n}\dfrac{1}{Z_{pik}}}}=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

Self-loop function

$$L(\omega)=-\frac{V_{inc}}{V_{trans}}$$

Alternating current conservation for stability test of linear networks





1. Research Background

Limitations of Conventional Methods

- **Conventional Superposition**

→ **Solving for every source (several times).**

- **Conventional Middlebrook's measurement**

→ **Applying only in feedback systems (DC-DC converters).**

- **Conventional replica measurement of loop gain**

→ **Using two identical networks (not real measurement).**

- **Conventional Nyquist's stability condition**

→ **Theoretical analysis for feedback systems (Lab tool)**

2. Investigation of Multi-Phase Networks

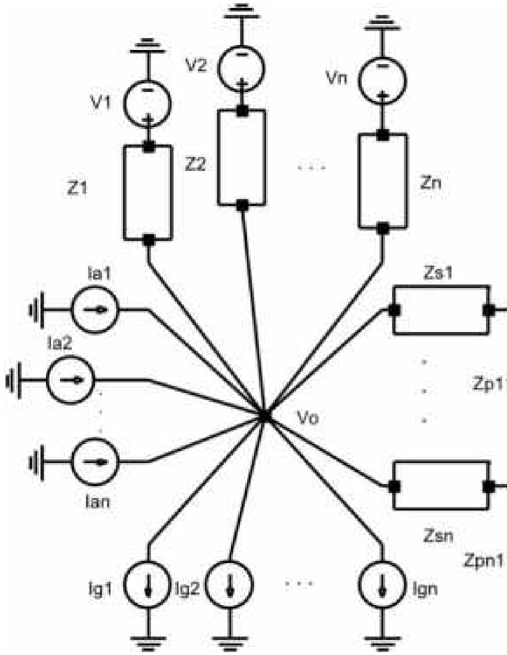
Superposition Theorem for Multi-Source Systems

Superposition formula:

$$V_O(t)\sum_{i=1}^{n}\frac{1}{Z_i}+V_O(t)\sum_{i=1}^{n}\frac{1}{Z_{si}+\dfrac{1}{\sum_{k=1}^{n}\dfrac{1}{Z_{pik}}}}=\sum_{i=1}^{n}\left(\frac{V_i(t)}{Z_i}+I_{ai}(t)-I_{gi}(t)\right)$$

$V_O(t)$: *Voltage at one node*
$V_i(t)$: *Input voltage sources*
$I_{ai}(t)$: *Ahead-toward current sources*
$I_{gi}(t)$: *Ground-toward current sources*
$Z_{i,\ si,\ pi,}(t)$: Impedances at each branch

○ **Multi-source systems, feedback networks (op amps, amplifiers), polyphase filters, complex filters…**

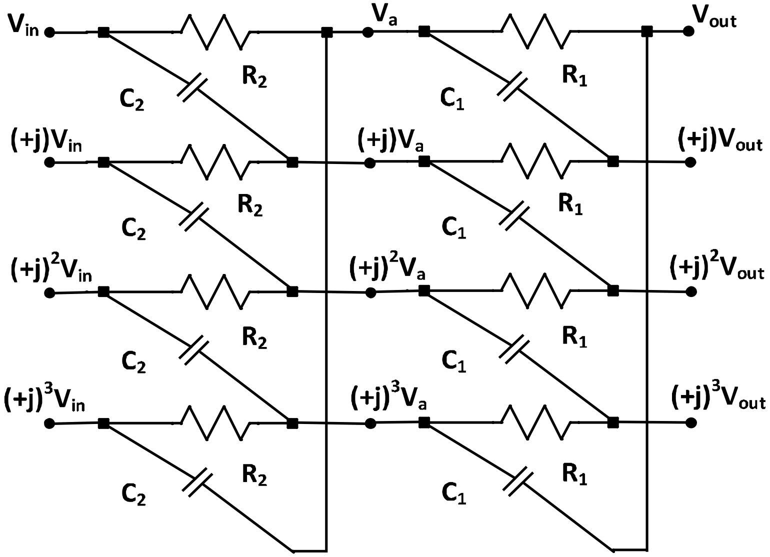


A general multi-source network

2. Investigation of Multi-Phase Networks

Analysis of 2nd–Order Polyphase Filter

Second-order RC polyphase filter



Apply superposition at each node

$$V_{out}\left(\frac{1}{Z_{C1}}+\frac{1}{R_1}\right)=\frac{V_a}{R_1}+\frac{(+j)^3 V_a}{Z_{C1}};$$

$$V_a\left(\frac{1}{Z_{C2}}+\frac{1}{R_2}+\frac{2}{R_1+Z_{C1}}\right)=\frac{V_{in}}{R_2}+\frac{(+j)^3 V_{in}}{Z_{C2}};$$

Transfer function for positive polyphase signal

$$H_P(\omega)=\frac{V_{out}}{V_{in}}=\frac{\left[1+(+j)^3 b_1 j\omega\right]\left[1+(+j)^3 b_2 j\omega\right]}{a_0 (j\omega)^2+a_1 j\omega+1};$$

Transfer function for negative polyphase signal

$$H_N(\omega)=\frac{V_{out}}{V_{in}}=\frac{\left[1+(-j)^3 b_1 j\omega\right]\left[1+(-j)^3 b_2 j\omega\right]}{a_0 (j\omega)^2+a_1 j\omega+1};$$

Here: $b_0=R_1C_1; b_1=R_2C_2;\ a_0=b_0b_1;\ a_1=b_0+b_1+2R_2C_1;$

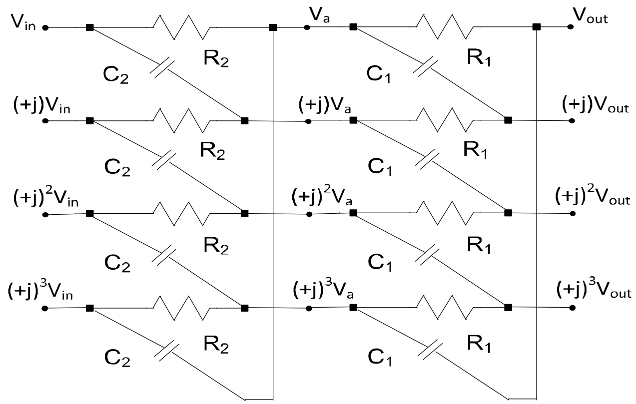
Image rejection ratio (IRR)

$$IRR(\omega)=\frac{|H_P(\omega)|}{|H_N(\omega)|}=\frac{|(1+b_1\omega)(1+b_2\omega)|}{|(1-b_1\omega)(1-b_2\omega)|};$$

2. Investigation of Multi-Phase Networks

Behaviors of 2nd–Order Polyphase Filter

2-order RC polyphase filter

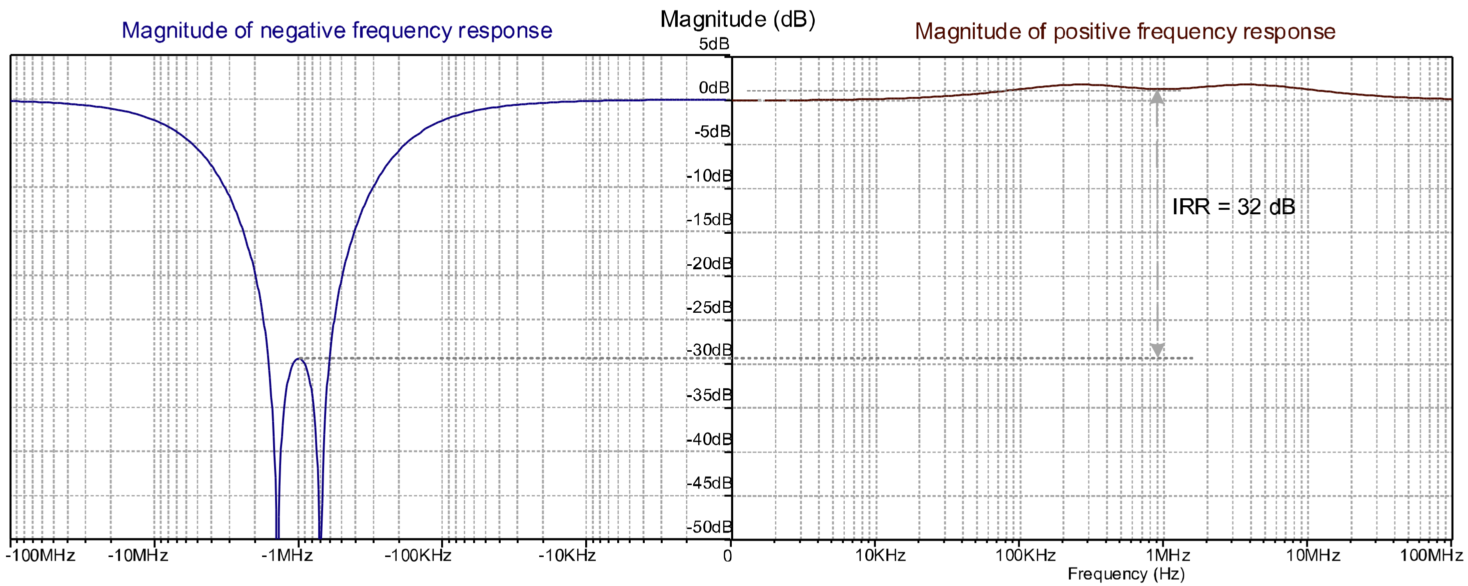


Transfer function in all frequency domain

$$\left|H(\omega)\right| = \frac{(1+b_1\omega)(1+b_2\omega)}{\sqrt{\left(1-a_0\omega^2\right)^2+\left(a_1\omega\right)^2}};\omega \in R$$

Here, R1 = 1 kΩ, C1 = 227 pF, R2 = 1 kΩ, C2 = 114 pF, at f_1 = 700 kHz, f_2 = 1.4 MHz,

Bode plot of transfer function in all frequency domain



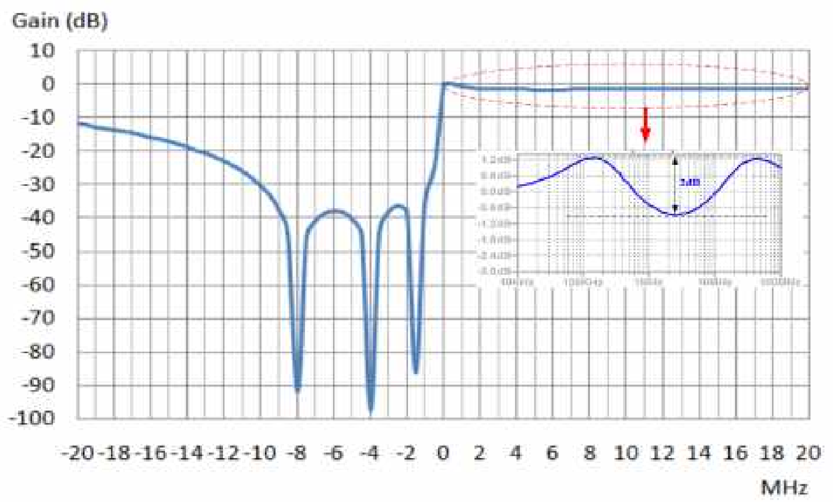
2. Investigation of Multi-Phase Networks

Behavior of 4th–Order Polyphase Filter

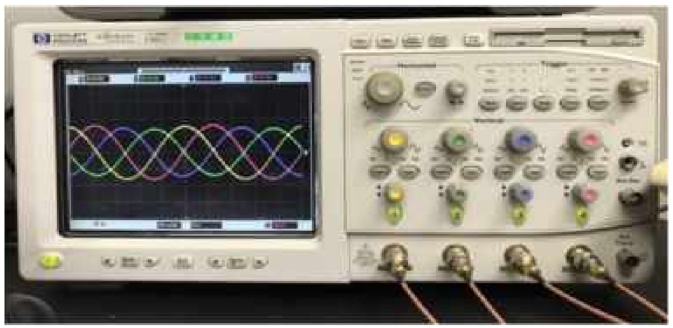
Transfer function

$$H(\omega) = \frac{(1+b_1\omega)(1+b_2\omega)(1+b_3\omega)(1+b_4\omega)}{a_0(j\omega)^4 + a_1(j\omega)^3 + a_2(j\omega)^2 + a_3 j\omega + 1};$$

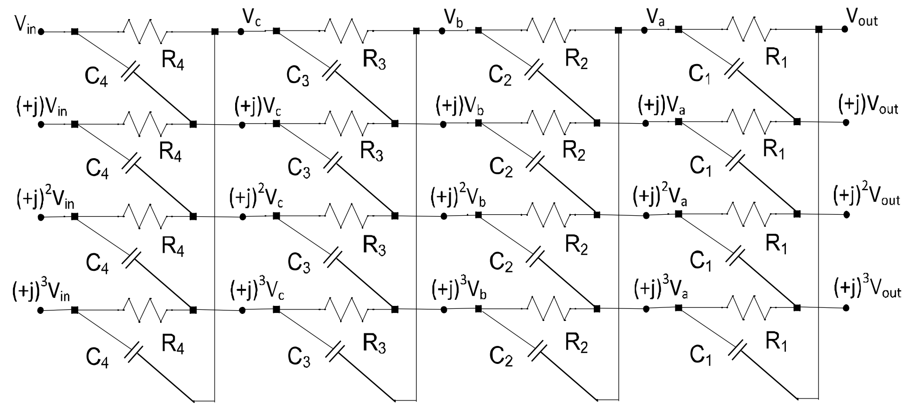
Bode plot of transfer function



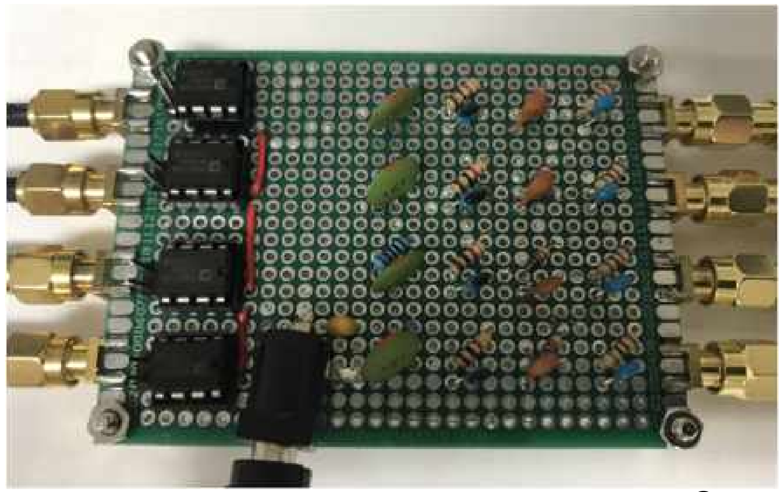
Transient response



Fourth-order RC polyphase filter



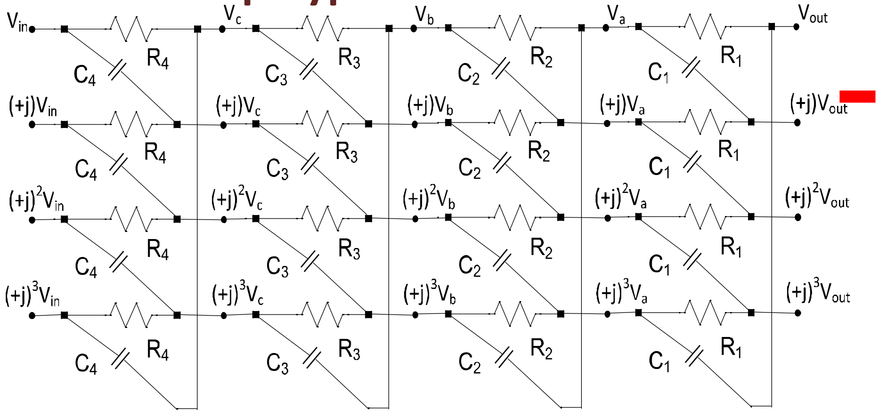
Implemented circuit

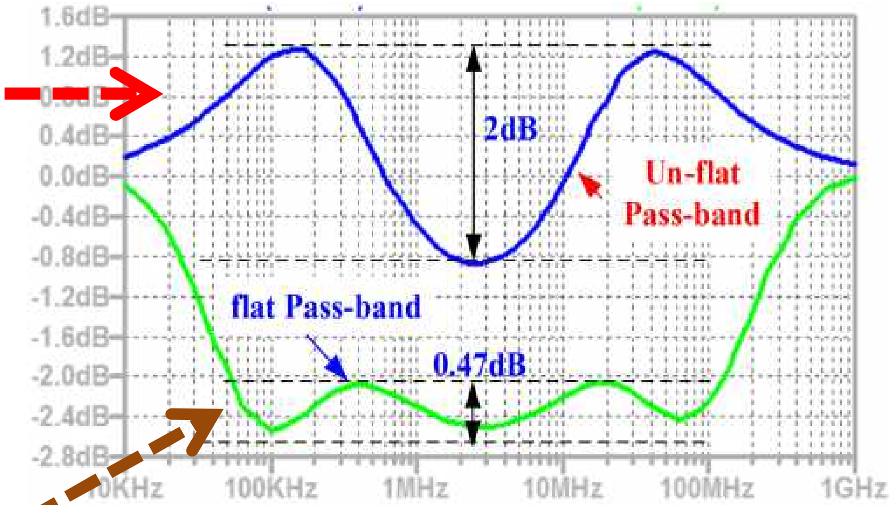


2. Investigation of Multi-Phase Networks

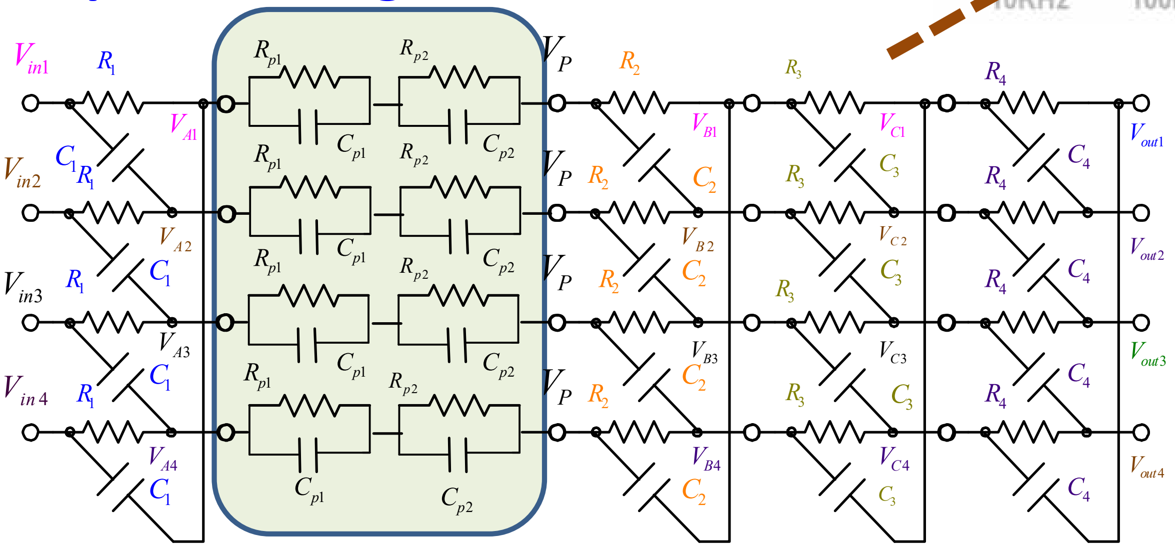
Flat Pass-Band Gain for 4th–Order Polyphase Filter

4th–order polyphase filter





Proposed Design



Two RC band-stop filters

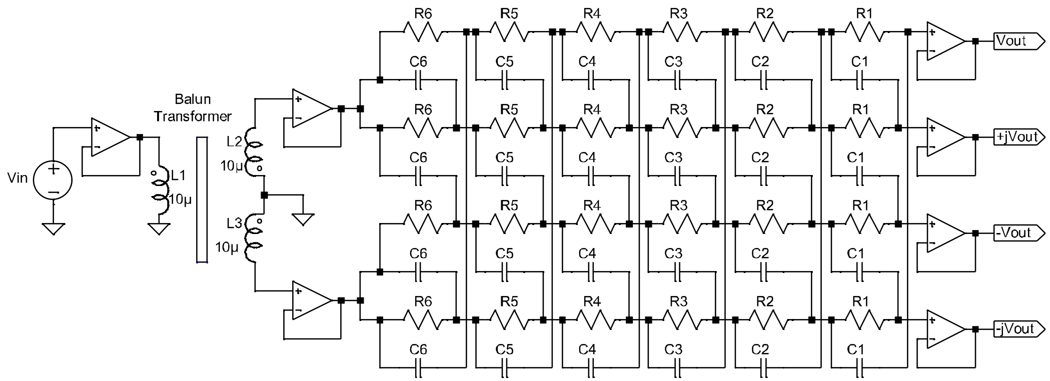
Pass-band Gain Ripple Reduction

from 2dB → 0.47dB

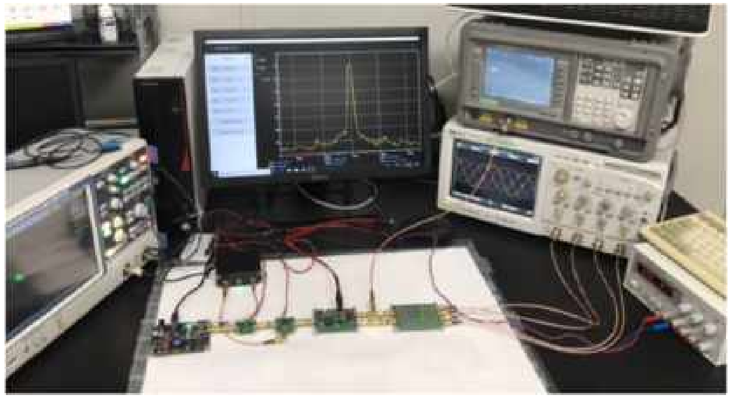
2. Investigation of Multi-Phase Networks

Behavior of 6th-order Quadrature Signal Generation

6th-order polyphase signal generation



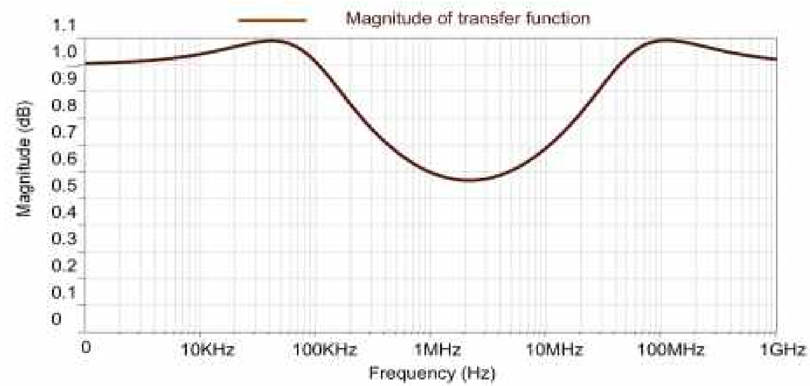
Implemented circuit



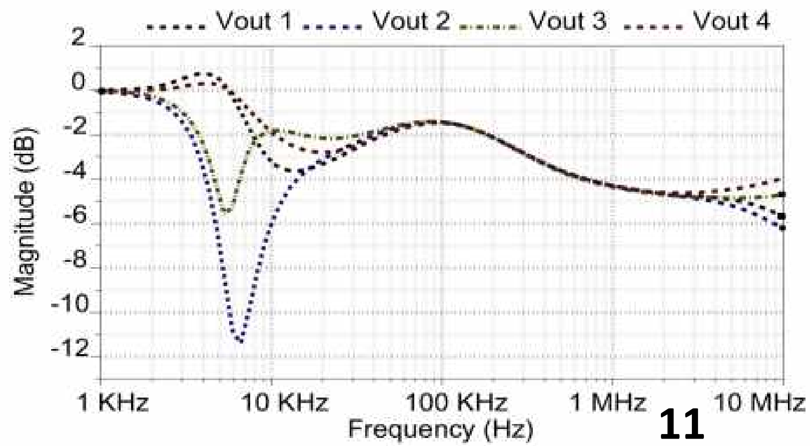
Transfer function

$$H(\omega)=\frac{[1+b_1\omega][1+b_2\omega][1+b_3\omega][1+b_4\omega][1+b_5\omega][1+b_6\omega]}{a_0(j\omega)^6+a_1(j\omega)^5+a_2(j\omega)^4+a_3(j\omega)^3+a_4(j\omega)^2+a_5 j\omega+1};$$

Simulated transfer function



Measured transfer function



2. Investigation of Multi-Phase Networks

Behavior of 4th-order Complex Filter

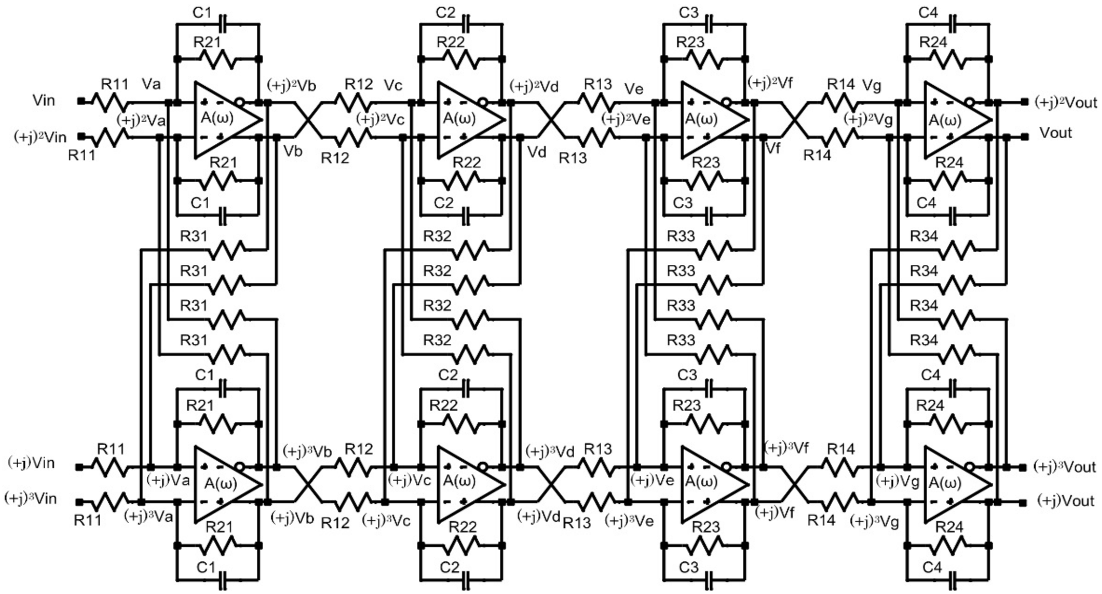
Transfer function for positive polyphase signals

$$H_P(\omega)=\frac{\frac{R_{21}}{R_{11}}}{\left[1+j\left(\frac{\omega}{\omega_{cut1}}+\frac{R_{21}}{R_{31}}\right)\right]}\frac{\frac{R_{22}}{R_{12}}}{\left[1+j\left(\frac{\omega}{\omega_{cut2}}+\frac{R_{22}}{R_{32}}\right)\right]}\frac{\frac{R_{23}}{R_{13}}}{\left[1+j\left(\frac{\omega}{\omega_{cut3}}+\frac{R_{23}}{R_{33}}\right)\right]}\frac{\frac{R_{24}}{R_{14}}}{\left[1+j\left(\frac{\omega}{\omega_{cut4}}+\frac{R_{24}}{R_{34}}\right)\right]};$$

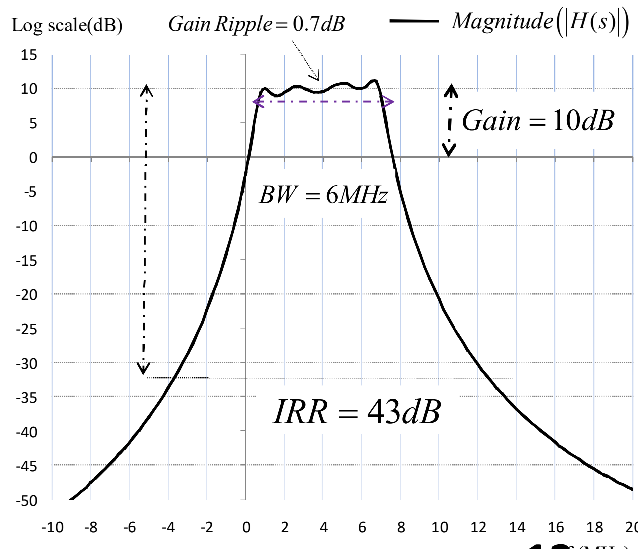
Transfer function for negative polyphase signals

$$H_N(\omega)=\frac{\frac{R_{21}}{R_{11}}}{\left[1+j\left(\frac{\omega}{\omega_{cut1}}-\frac{R_{21}}{R_{31}}\right)\right]}\frac{\frac{R_{22}}{R_{12}}}{\left[1+j\left(\frac{\omega}{\omega_{cut2}}-\frac{R_{22}}{R_{32}}\right)\right]}\frac{\frac{R_{23}}{R_{13}}}{\left[1+j\left(\frac{\omega}{\omega_{cut3}}-\frac{R_{23}}{R_{33}}\right)\right]}\frac{\frac{R_{24}}{R_{14}}}{\left[1+j\left(\frac{\omega}{\omega_{cut4}}-\frac{R_{24}}{R_{34}}\right)\right]};$$

4th-order complex filter



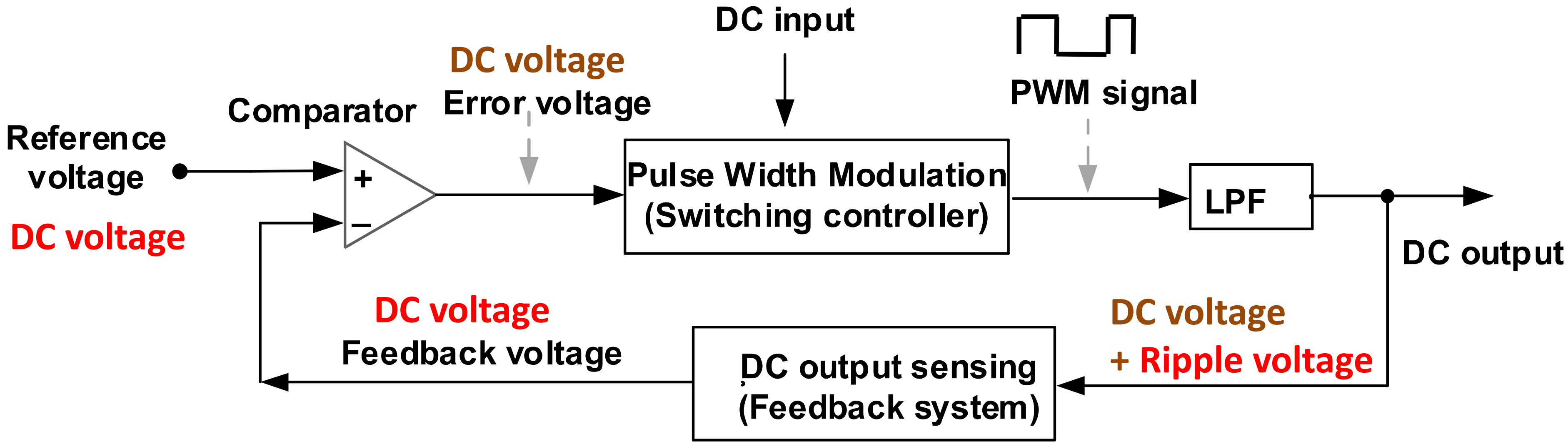
Bode plot of transfer function



3. Noise Reduction for DC-DC Converters

Characteristics of Adaptive Feedback Network

Block diagram of a typical adaptive feedback system



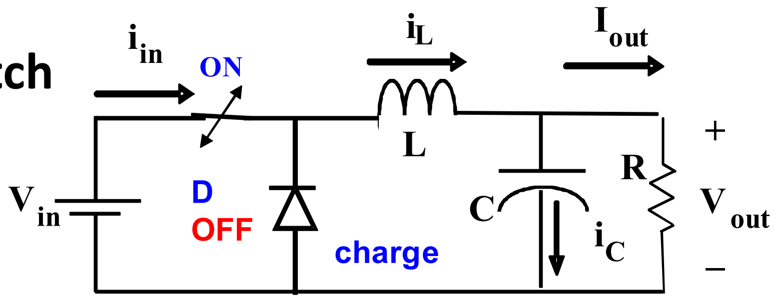
Adaptive feedback is used to control the output source along with the decision source (**DC-DC Buck converter**).

The transfer function of an **adaptive feedback network** is **significantly different from** the transfer function of a **linear negative feedback network**.

3. Noise Reduction for DC-DC Converters

Review of Step-down DC-DC Buck Converter

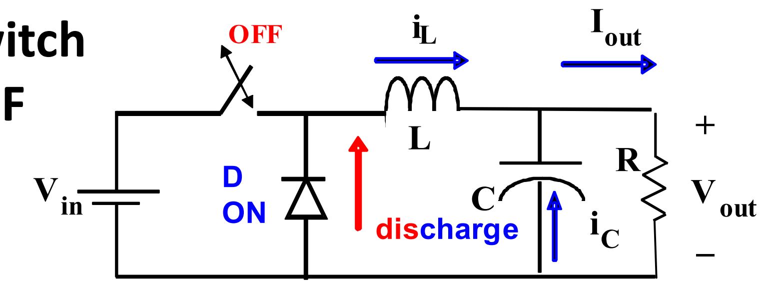
Switch ON



Charging voltage

$$V_{charge}(t)=\left(\begin{array}{l}A_{ch1}e^{\left(-\omega_{2RC}+\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t}\\+A_{ch2}e^{\left(-\omega_{2RC}-\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t}\end{array}\right)$$

Switch OFF



Discharging voltage

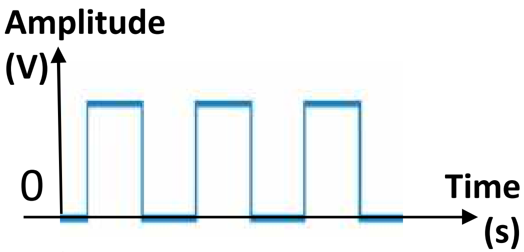
$$V_{discharge}(t)=\left(\begin{array}{l}A_{dis1}e^{\left(\omega_{2RC}+\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t}\\+A_{dis2}e^{\left(\omega_{2RC}+\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t}\end{array}\right)$$

Balanced charge-discharge time condition

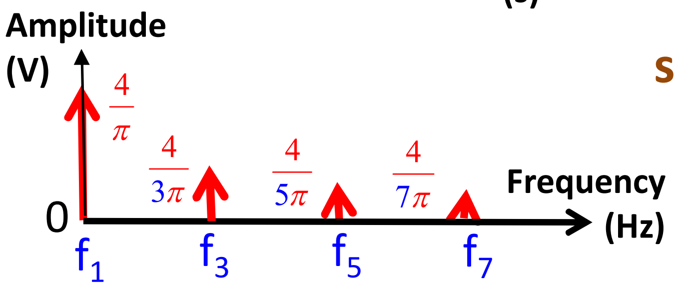
$$|Z_L|=|Z_C|=2R$$

→ **Max power propagation**

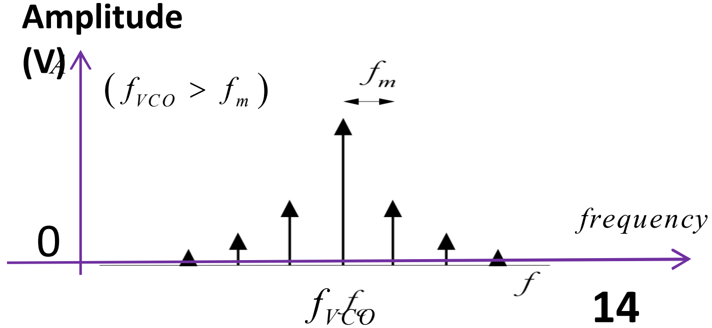
Switching wave



Switching spectrum



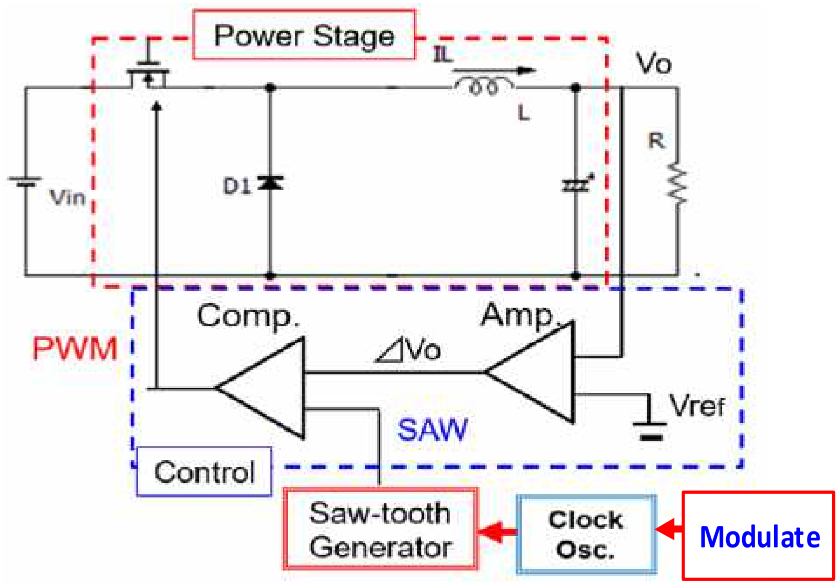
Spread spectrum



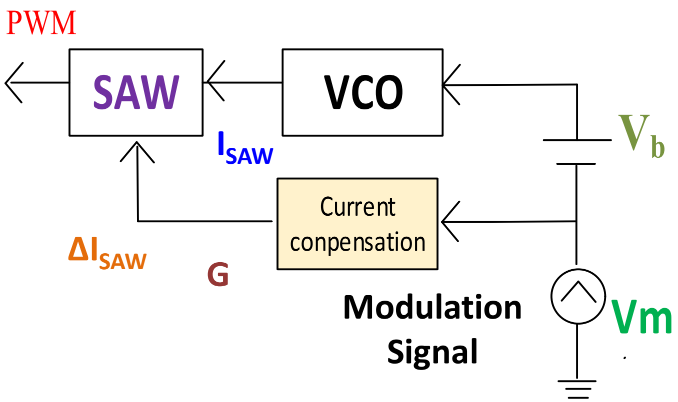
3. Noise Reduction for DC-DC Converters

Ripple Reduction using Linear Swept Frequency Modulation

Block diagram of DC-DC Buck converter

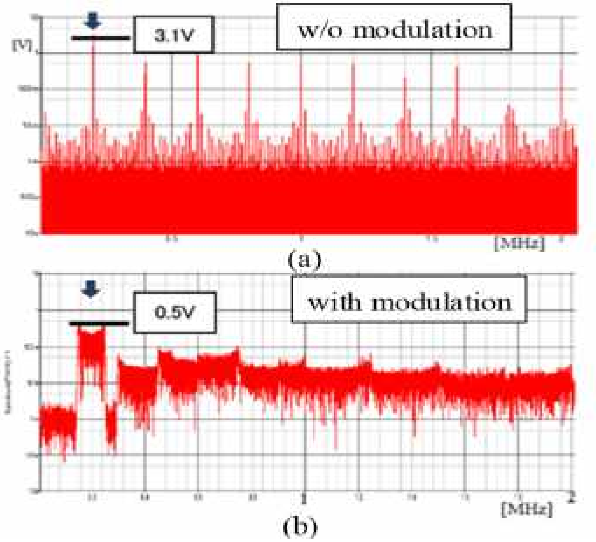


Linear swept frequency modulation



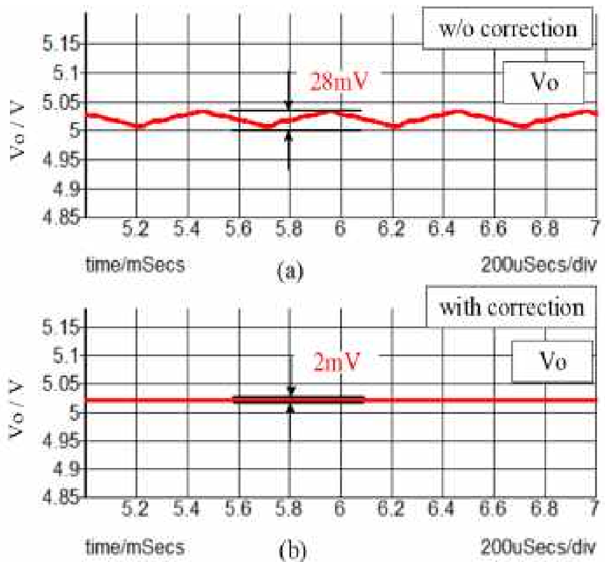
Without frequency modulation

With frequency modulation



Without frequency modulation

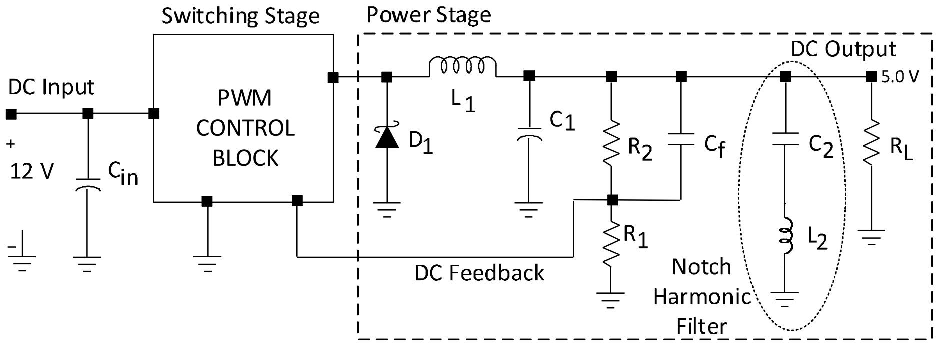
With frequency modulation



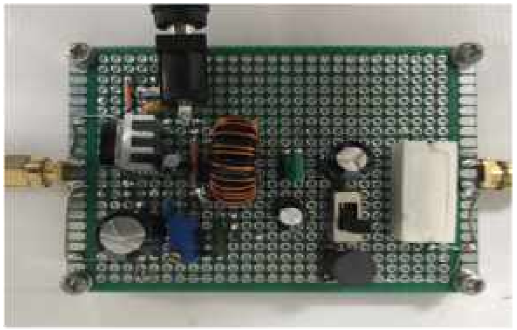
3. Noise Reduction for DC-DC Converters

Ripple Reduction using LC Notch Harmonic Filter

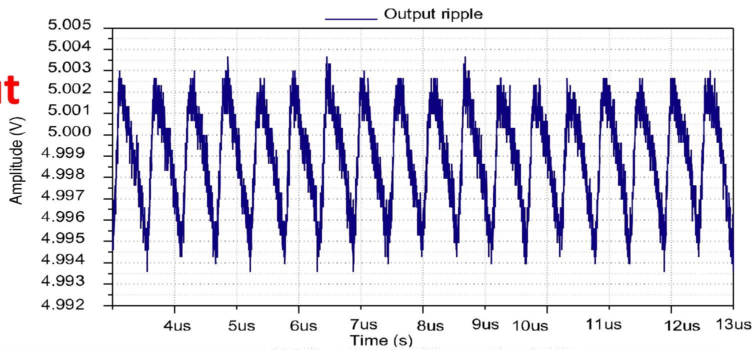
Schematic diagram of DC-DC Buck converter



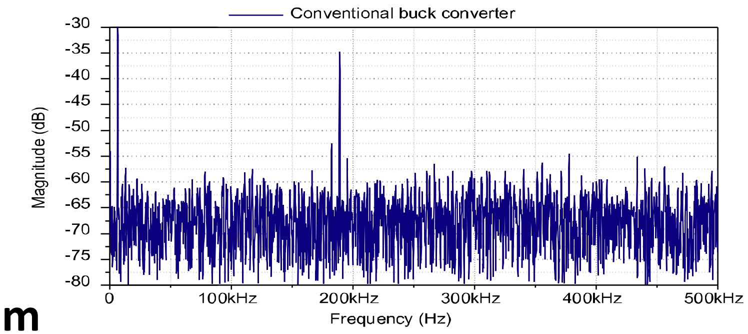
Implemented circuit



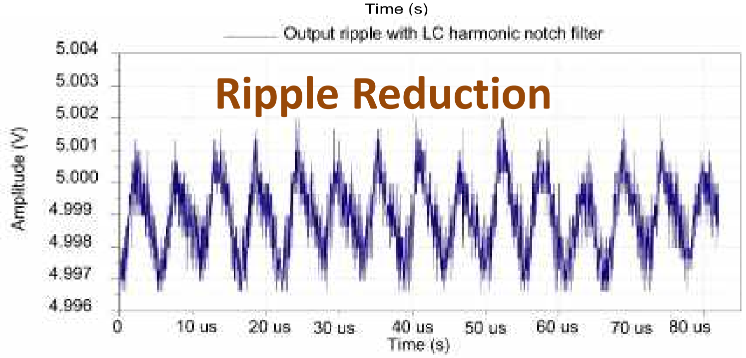
Without notch filter



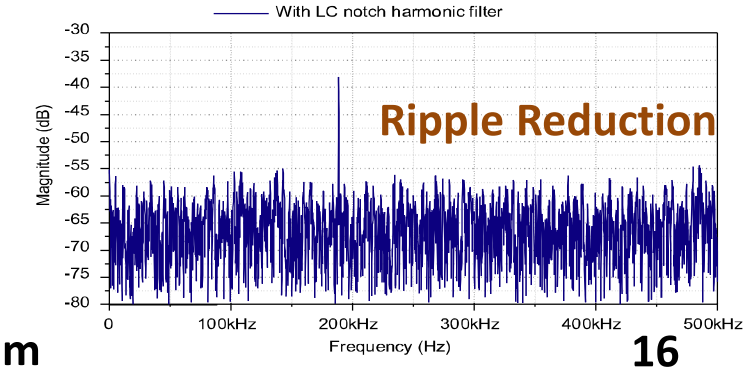
Output spectrum



With notch filter



Output spectrum

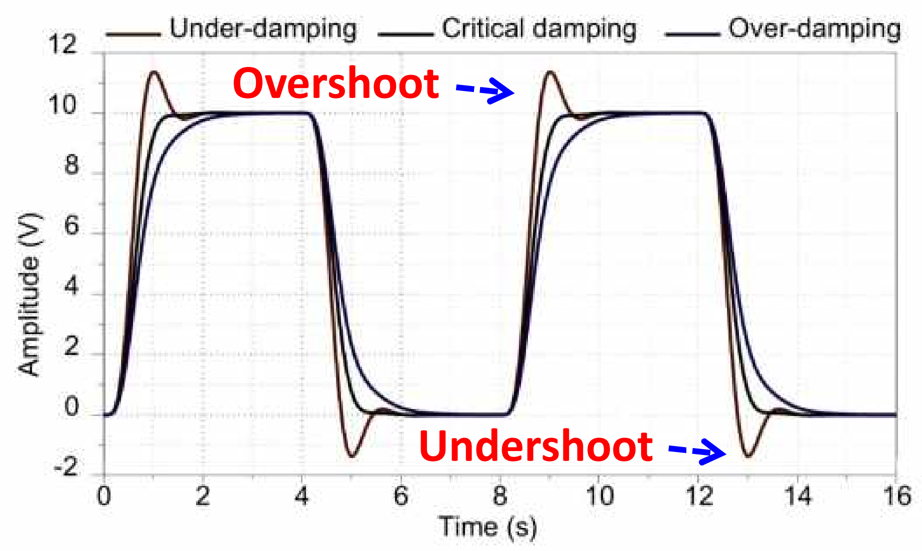


4. Stability Test for Electronic Systems

Damped Oscillation Noise

Large overshoots + ringing + unwanted voltage transients

→ Damped oscillation noise → Unstable system



○ **Ringing occurs in both with and without feedback systems.**

○ **Ringing affects both input and output signals.**

To meet the specified requirements

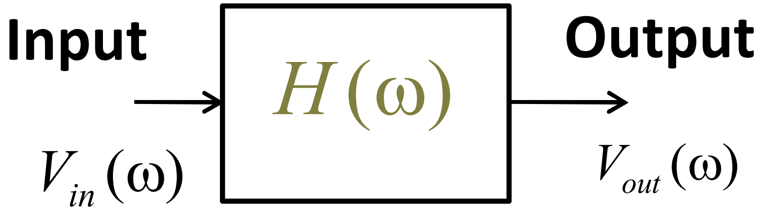
- **High stability**
- **Fast transient response, and**
- **Good steady-state performance.**

→ **STABILITY TEST**

4. Stability Test for Electronic Systems

Self-loop Function in A Transfer Function

Linear system



Model of a linear system

$$H(\omega) = \frac{b_0(j\omega)^n + \ldots + b_{n-1}(j\omega) + b_n}{a_0(j\omega)^n + \ldots + a_{n-1}(j\omega) + a_n}$$

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{A(\omega)}{1 + L(\omega)}$$

$A(\omega)$ **: Open loop function**

$H(\omega)$ **: Transfer function**

$L(\omega)$ **: Self-loop function**

Variable: angular frequency (ω)

- **Polar chart → Nyquist chart**
- **Magnitude-frequency plot**
- **Angular-frequency plot**
- **Magnitude-angular diagram → Nichols diagram**

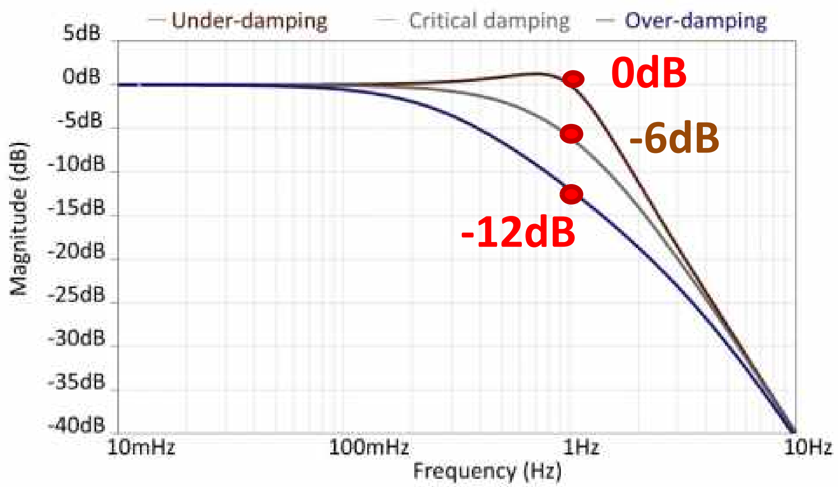
(Magnitude-frequency plot and Angular-frequency plot: **Bode plots**)

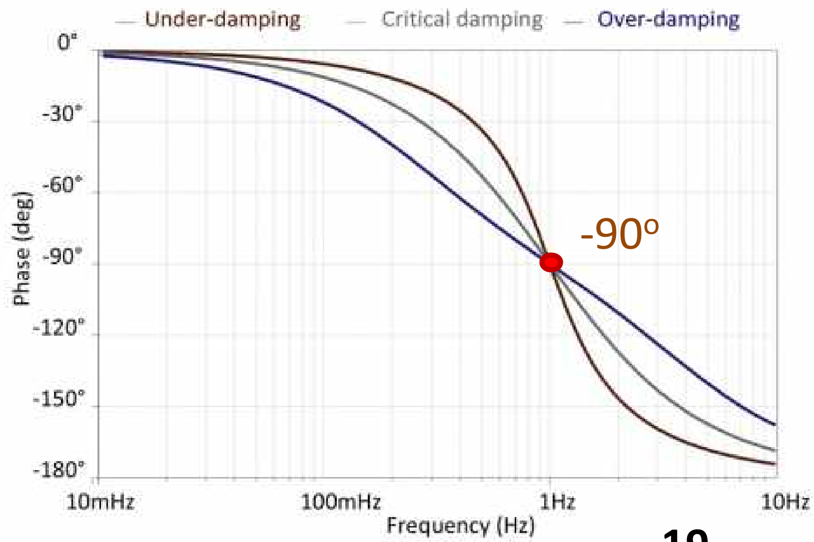
4. Stability Test for Electronic Systems

Behaviors of 2nd-Order Transfer Function

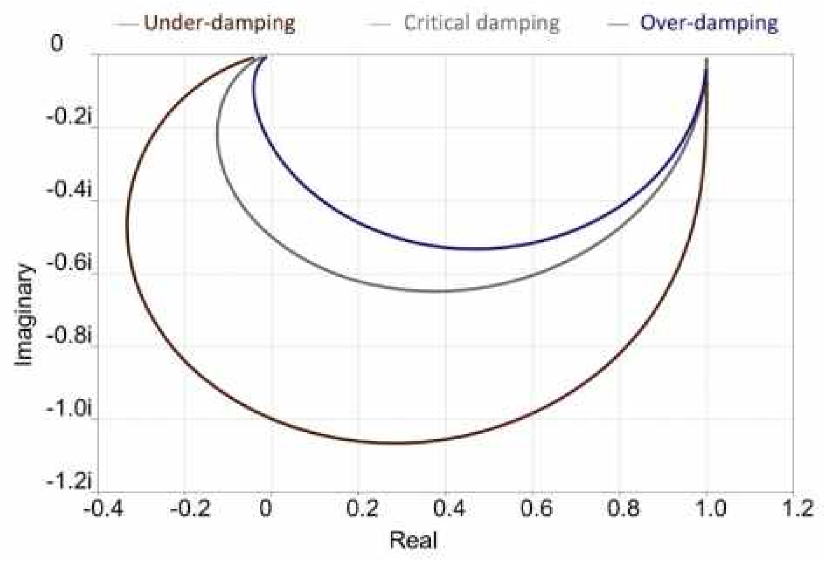
- **Under-damping:** $H_1(\omega) = \dfrac{1}{(j\omega)^2 + j\omega + 1};$
- **Critical damping:** $H_2(\omega) = \dfrac{1}{(j\omega)^2 + 2j\omega + 1};$
- **Over-damping:** $H_3(\omega) = \dfrac{1}{(j\omega)^2 + 3j\omega + 1};$

Bode plot of transfer function





Nyquist chart of transfer function

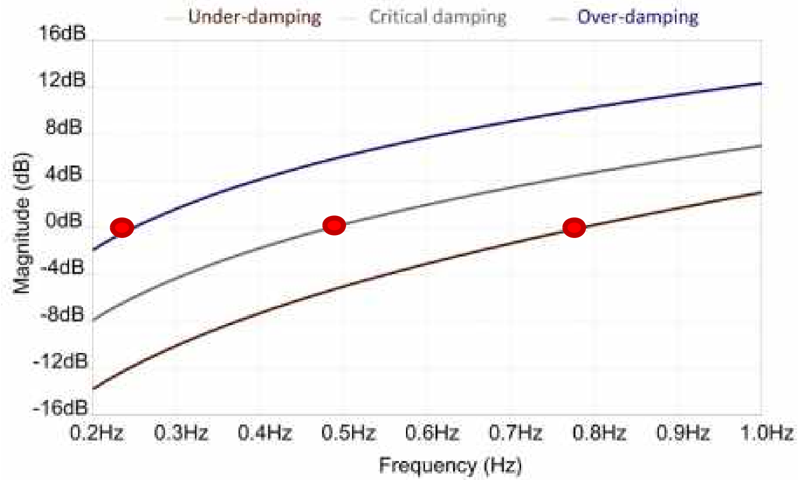


4. Stability Test for Electronic Systems

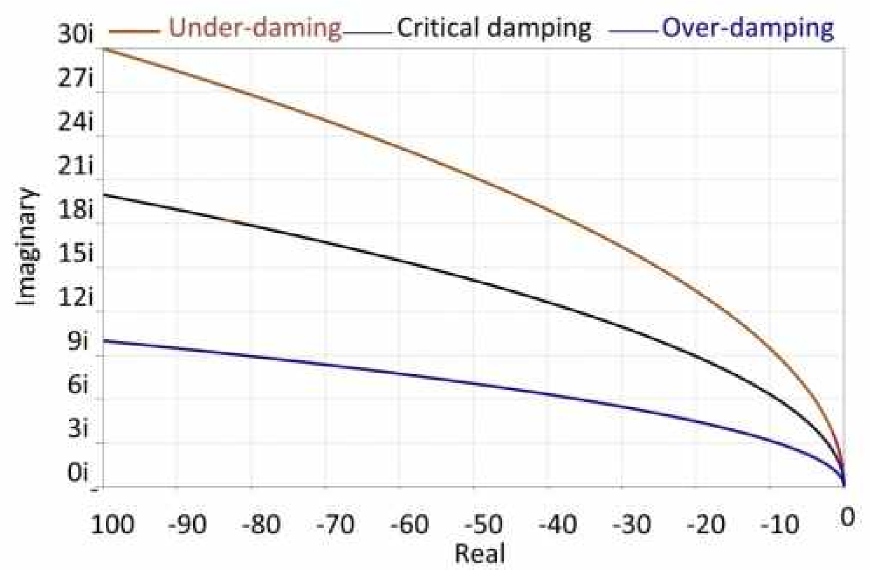
Behaviors of 2nd-Order Self-loop Function

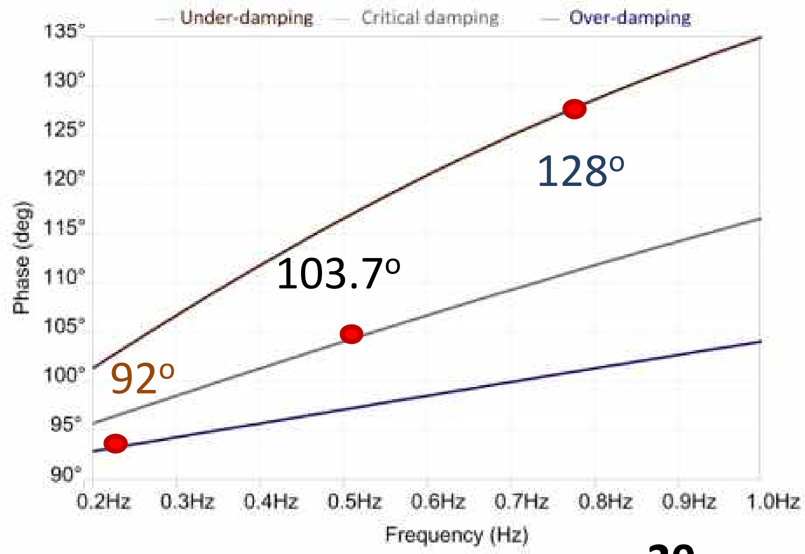
- **Under-damping:** $L_1(\omega) = (j\omega)^2 + j\omega;$
- **Critical damping:** $L_2(\omega) = (j\omega)^2 + 2j\omega;$
- **Over-damping:** $L_3(\omega) = (j\omega)^2 + 3j\omega;$

Bode plot of self-loop function



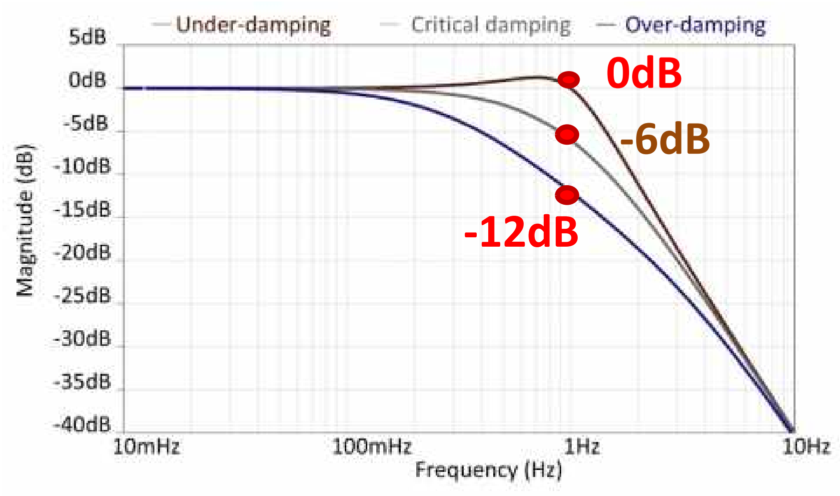
Nyquist chart of self-loop function



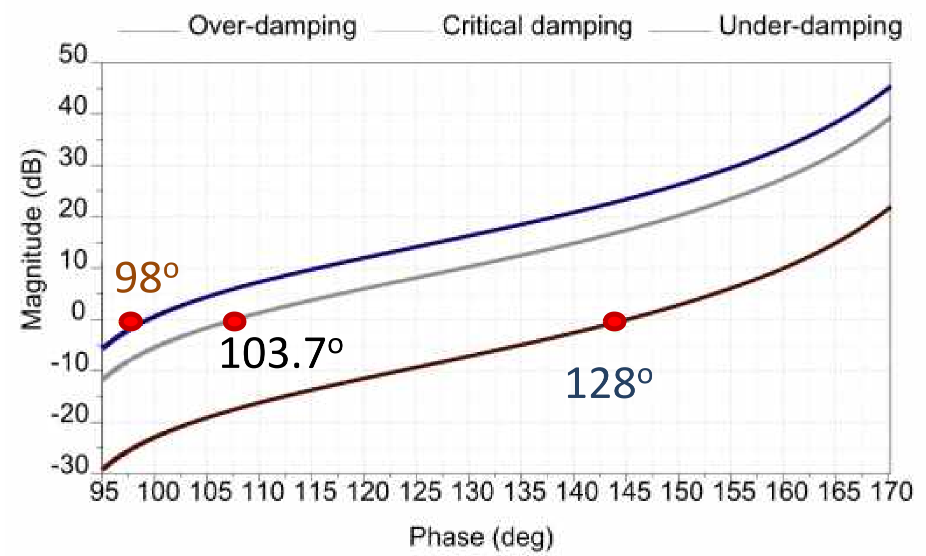


4. Stability Test for Electronic Systems
Operating Regions of 2nd-Order System

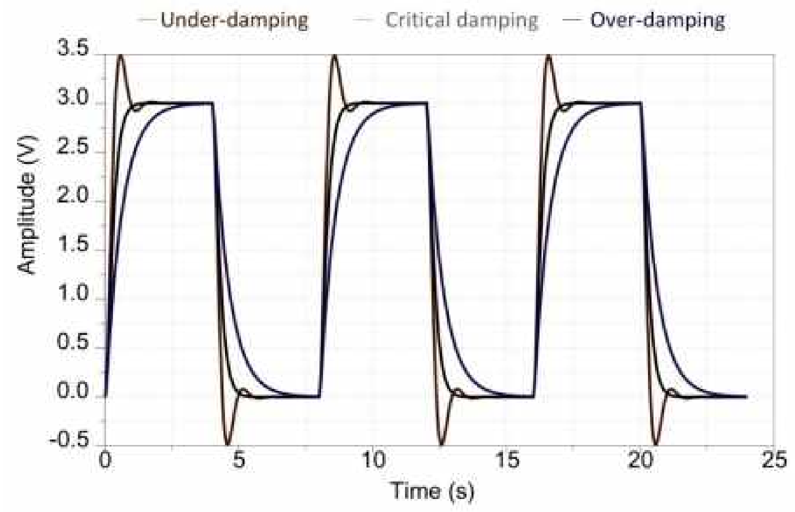
Magnitude response of transfer function



Magnitude-angular response of self-loop function



Transient response



Over-damping:

→Phase margin is 88 degrees.

Critical damping:

→Phase margin is 76.3 degrees.

Under-damping:

→Phase margin is 52 degrees.

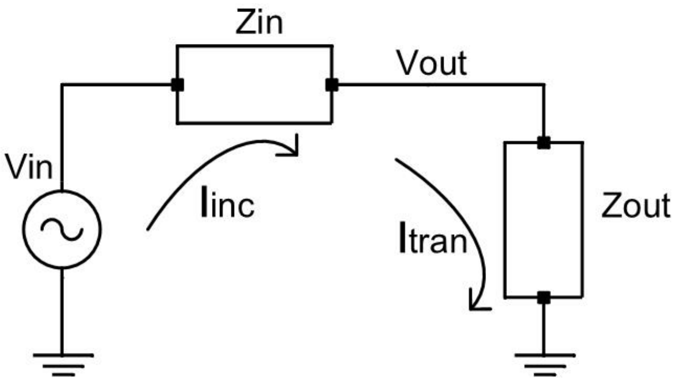
4. Stability Test for Electronic Systems

Alternating Current Conservation for Passive Networks

Transfer function

$$H(\omega) = \frac{V_{out}(\omega)}{V_{in}(\omega)} = \frac{1}{1 + \dfrac{Z_{in}}{Z_{out}}}$$

$$\Rightarrow L(\omega) = \frac{Z_{in}}{Z_{out}};$$



Simplified linear system

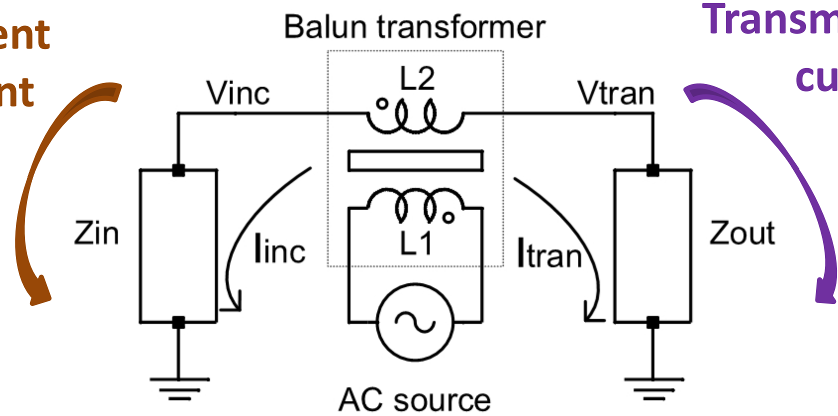
Self-loop function

$$\frac{V_{inc}}{Z_{in}} = -\frac{V_{trans}}{Z_{out}} \Rightarrow L(\omega) = -\frac{V_{inc}}{V_{trans}} = \frac{Z_{in}}{Z_{out}}$$

10 mH inductance

Incident current

Transmitted current

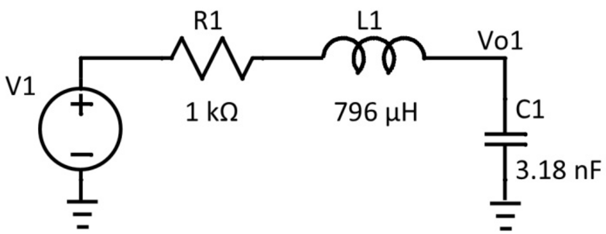


Derivation of self-loop function

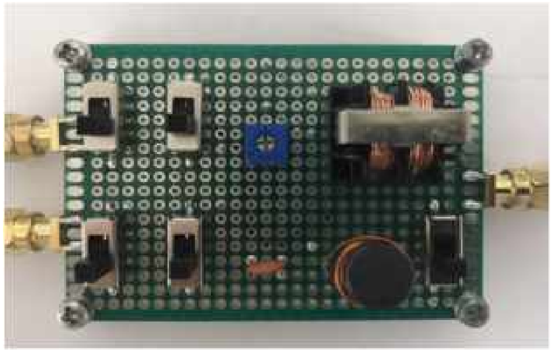
4. Stability Test for Electronic Systems

Stability Test for 2rd-Order Passive RLC LPF

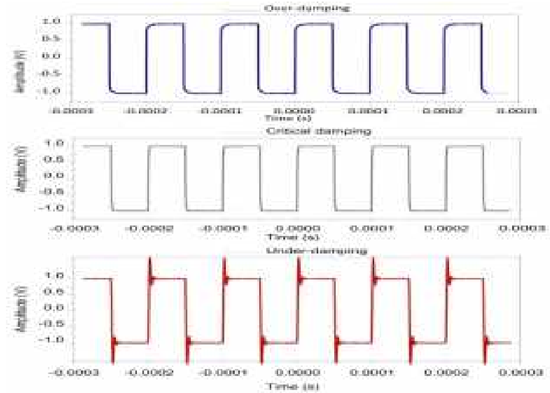
Passive RLC Low-pass Filter



Implemented circuit

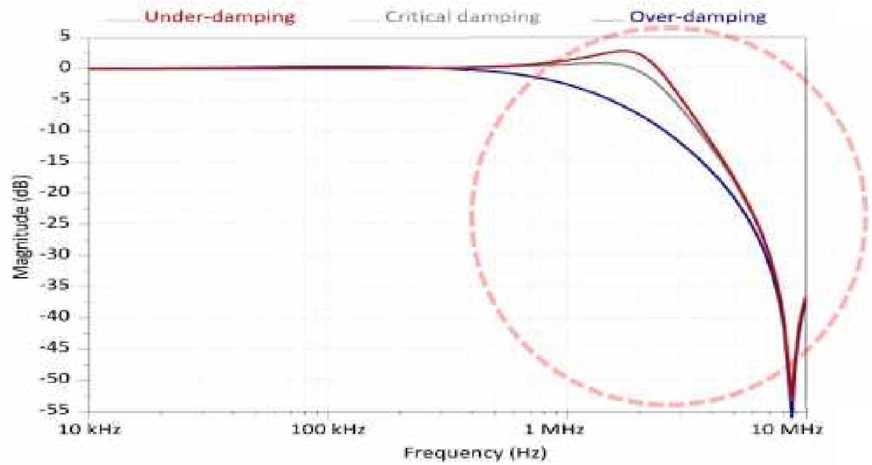


Transient responses



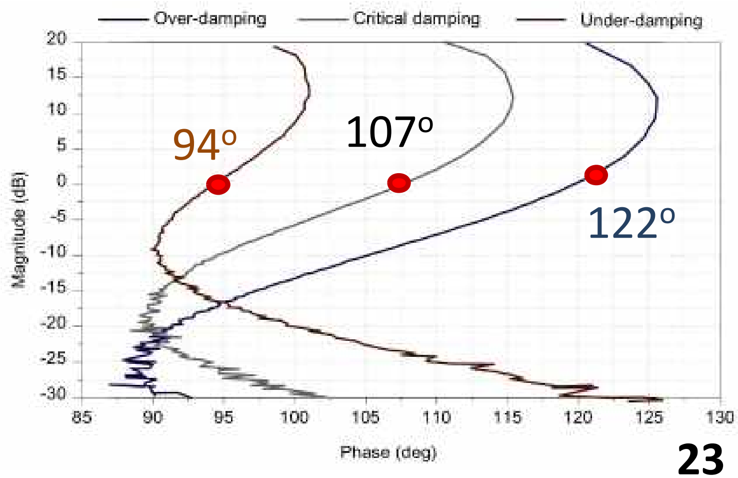
Transfer function

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$



Self-loop function

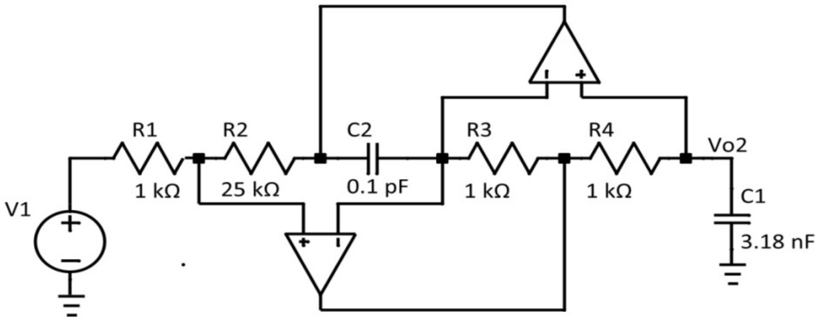
$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$



4. Stability Test for Electronic Systems

Stability Test for 2rd-Order Active Ladder LPF

Active ladder low-pass filter



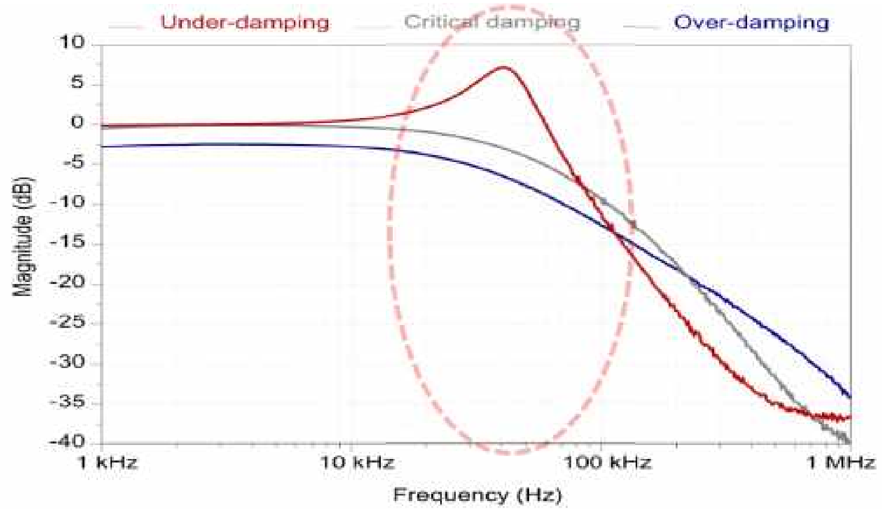
Implemented circuit

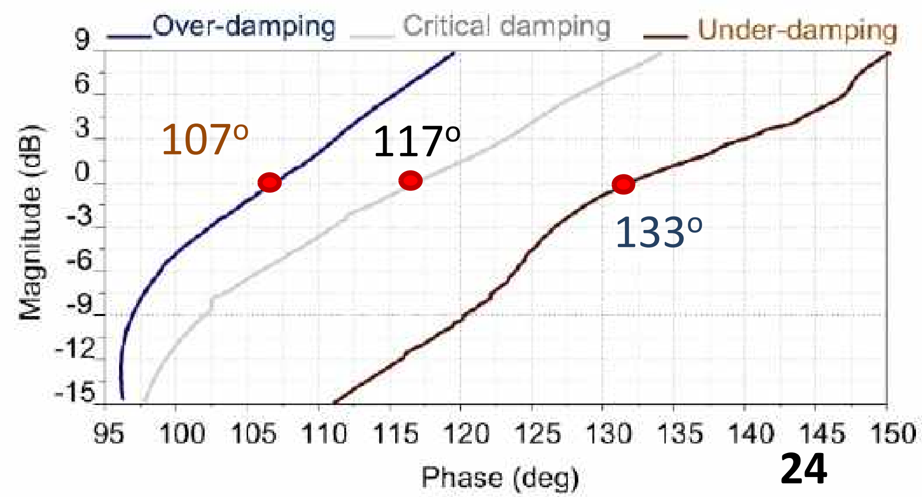
Transfer function

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

Self-loop function

$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$





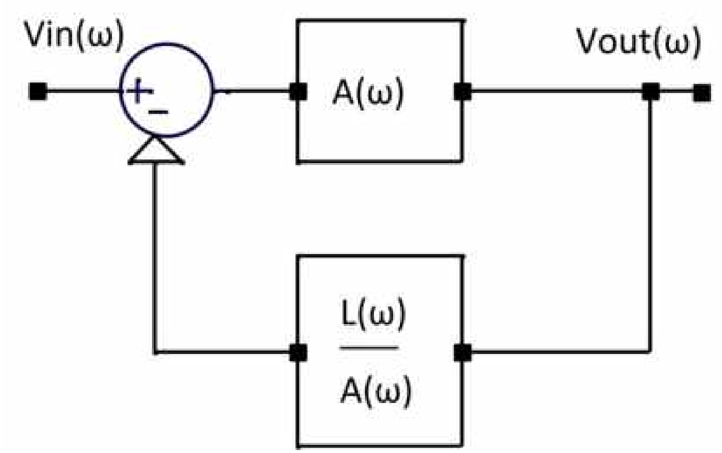
4. Stability Test for Electronic Systems

Alternating Current Conservation for Active Networks

Transfer function

$$H(\omega)=\frac{V_{out}(\omega)}{V_{in}(\omega)}=\frac{A(\omega)}{1+L(\omega)}$$

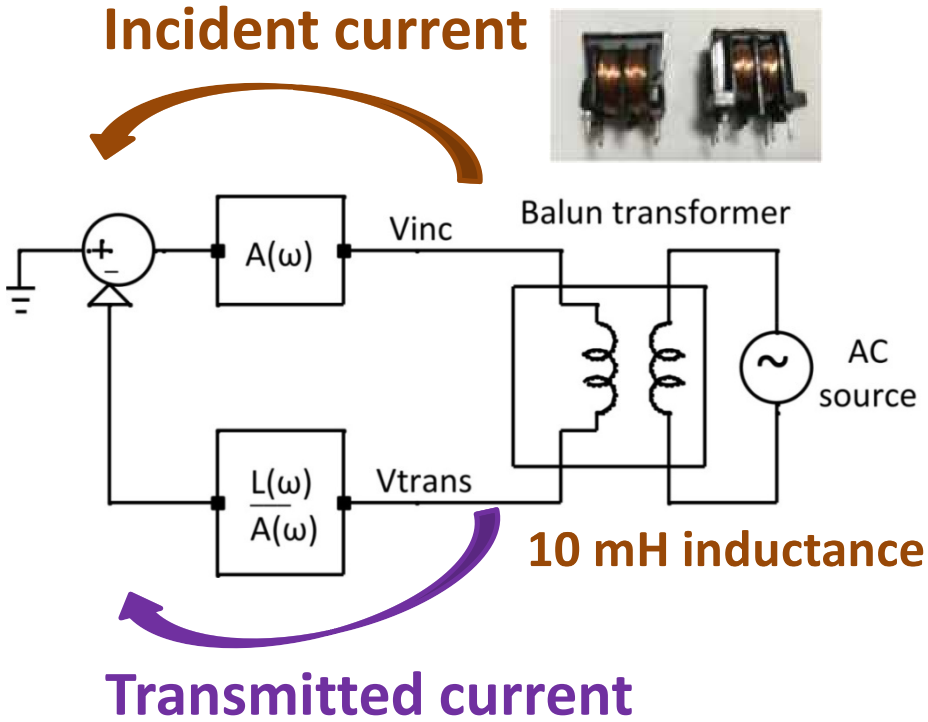
$$\Rightarrow V_{out}(\omega)=A(\omega)\left[V_{in}(\omega)-\frac{L(\omega)}{A(\omega)}V_{out}(\omega)\right]$$



Signal flow graph

Self-loop function

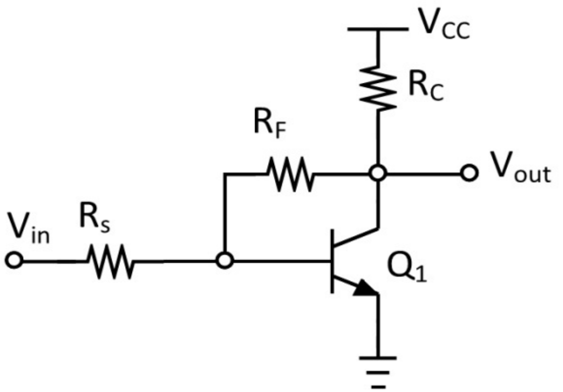
$$\frac{V_{inc}}{A(\omega)}=-\frac{L(\omega)}{A(\omega)}V_{trans}\Rightarrow L(\omega)=-\frac{V_{inc}}{V_{trans}}$$



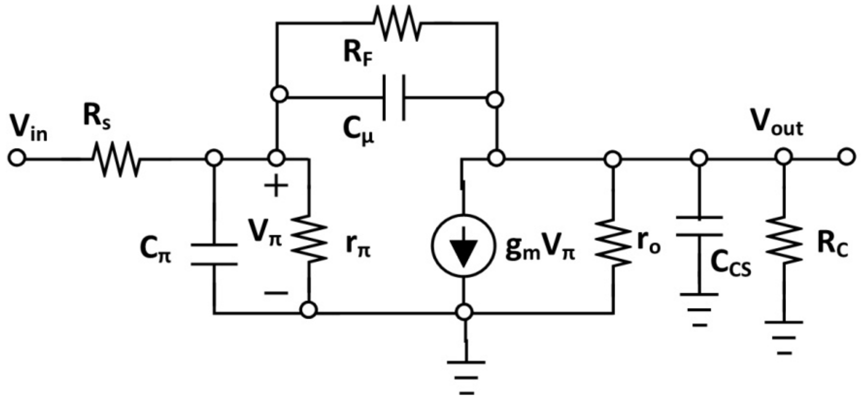
4. Stability Test for Electronic Systems

Analysis of Shunt-Shunt Feedback Amplifier

BJT shunt-shunt feedback amplifier



Small signal model



Apply superposition at the nodes V_π and V_{out}, we have

$$V_\pi\left(\frac{1}{R_s}+\frac{1}{r_\pi}+\frac{1}{Z_{C\pi}}+\frac{1}{R_F}+\frac{1}{Z_{C\mu}}\right)=\frac{V_{in}}{R_s}+\frac{V_{out}}{Z_{C\mu}};\quad V_{out}\left(\frac{1}{Z_{C\mu}}+\frac{1}{Z_{CCS}}+\frac{1}{R_C}+\frac{1}{r_o}\right)=V_\pi\left(\frac{1}{Z_{C\mu}}+\frac{1}{R_F}-g_m\right);$$

Transfer function H(ω) and self-loop function L(ω)

$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{b_0 j\omega+b_1}{a_0(j\omega)^2+a_1 j\omega+1};\quad L(\omega)=j\omega\left[a_0 j\omega+a_1\right]$$

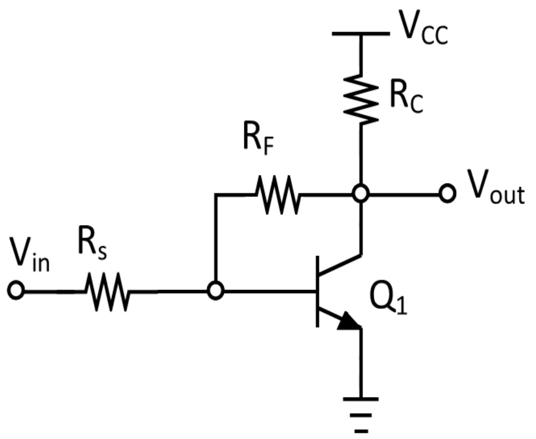
Where, $b_0=R_L C_{GD1};\ b_1=-R_L g_{m1};\ a_0=R_S R_L\left(C_{GD1}C_{GS1}+C_{GD1}C_{DB1}+C_{DB1}C_{GS1}\right);$

$$a_1=R_L\left(C_{GD1}+C_{DB1}\right)+R_S\left(C_{GS1}+C_{GD1}\right)+R_S R_L g_{m1} C_{GD1};$$

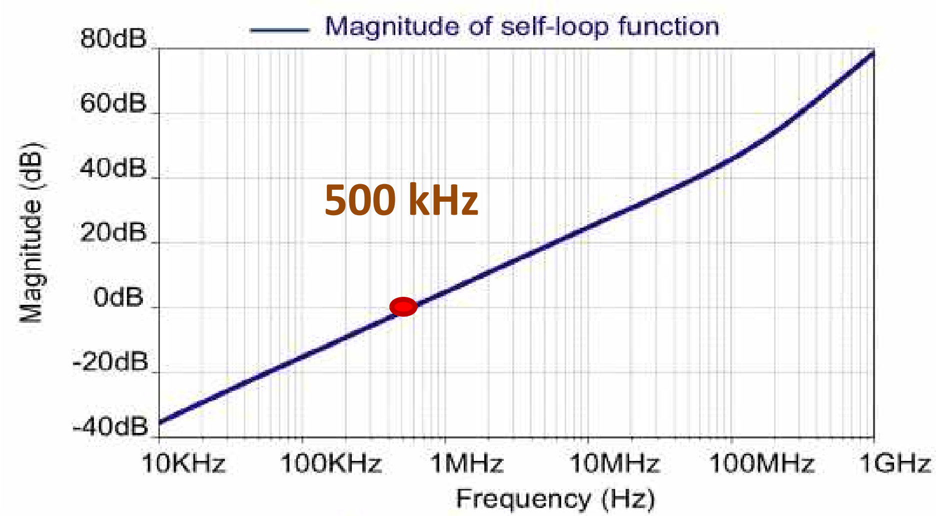
4. Stability Test for Electronic Systems

Stability Test of Shunt-Shunt Feedback Amplifier

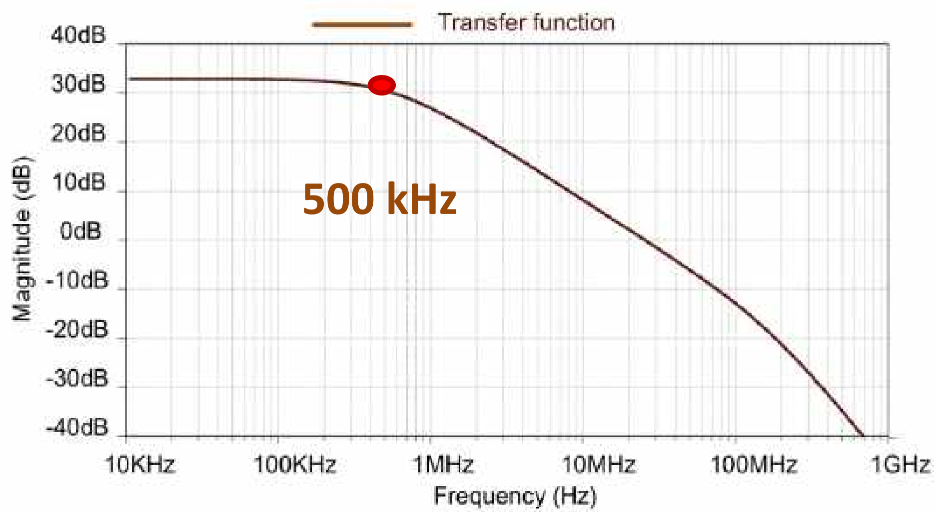
BJT shunt-shunt feedback amplifier

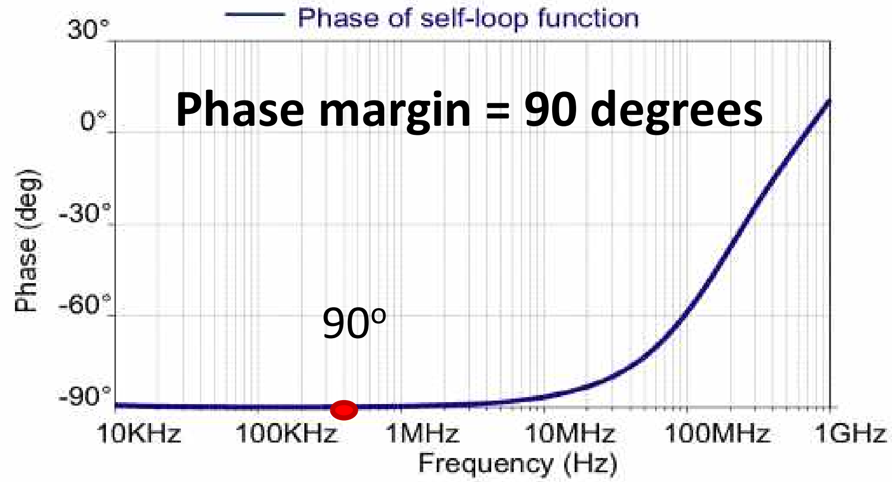


Bode plot of self-loop function L(ω)



Bode plot of transfer function H(ω)

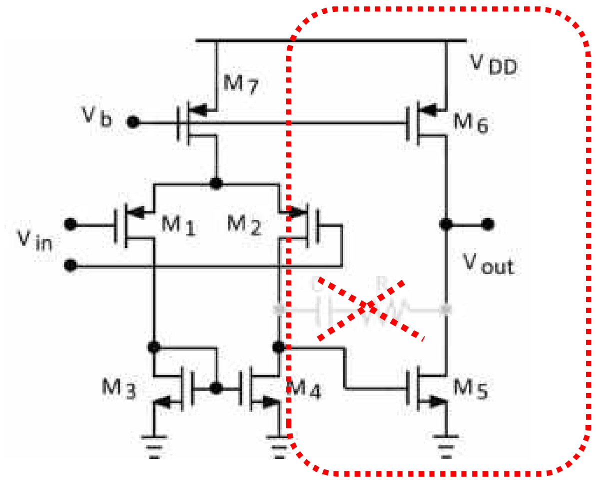




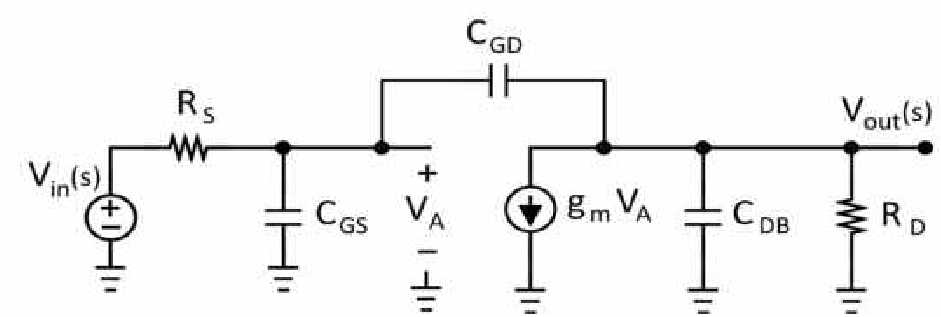
4. Stability Test for Electronic Systems

Analysis of Op Amp without Miller's Capacitor

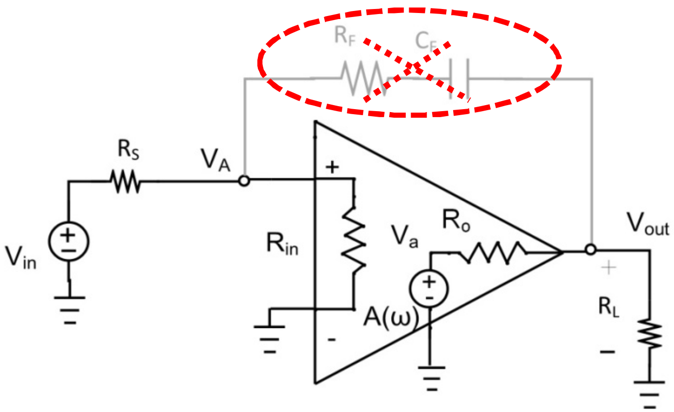
Without frequency compensation



Small signal model



Simplified model



Transfer function H(ω) and self-loop function L(ω)

$$H(\omega) = \frac{b_0 j\omega + b_1}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega$$

Where,

$$b_0 = R_D R_S \left[(C_{GD} + C_{DB})(C_{GS} + C_{GD}) - C_{GD}^2 \right]$$

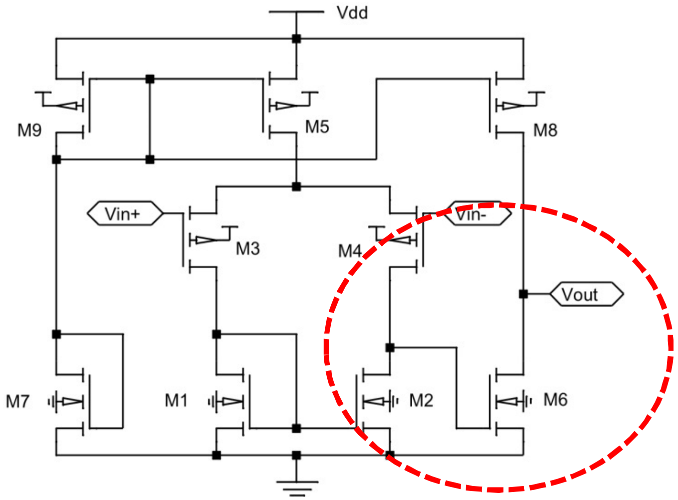
$$b_1 = \left[R_D (C_{GD} + C_{DB}) + R_S (C_{GS} + C_{GD}) + R_D R_S g_m C_{GD} \right]$$

$$a_0 = R_D C_{GD}; \; a_1 = -R_D g_m;$$

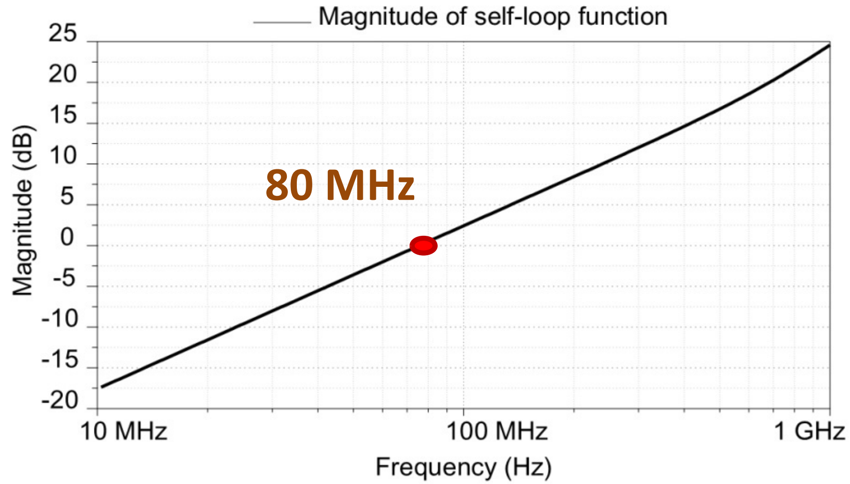
4. Stability Test for Electronic Systems

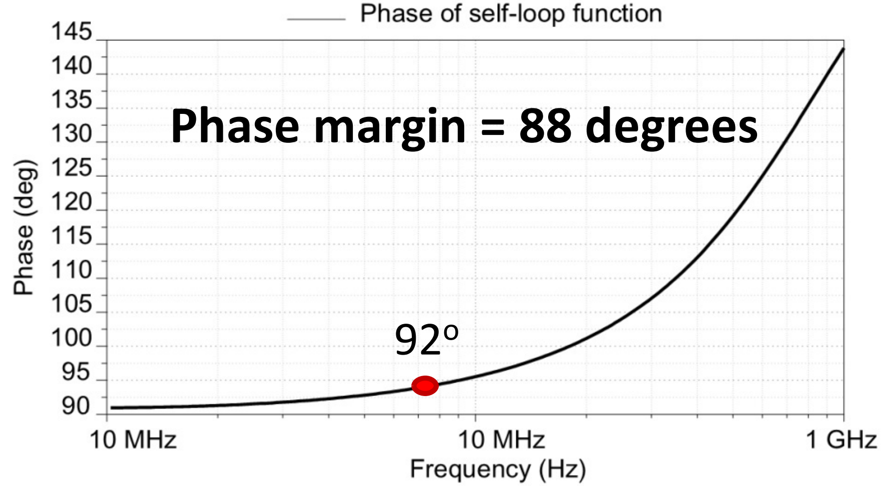
Stability Test of Op Amp without Miller's Capacitor

Op amp without frequency compensation

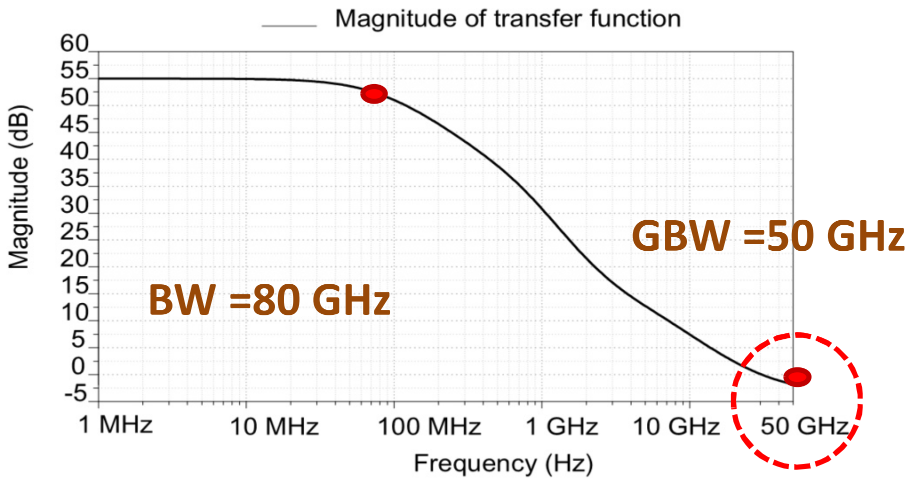


Bode plot of self-loop function L(ω)





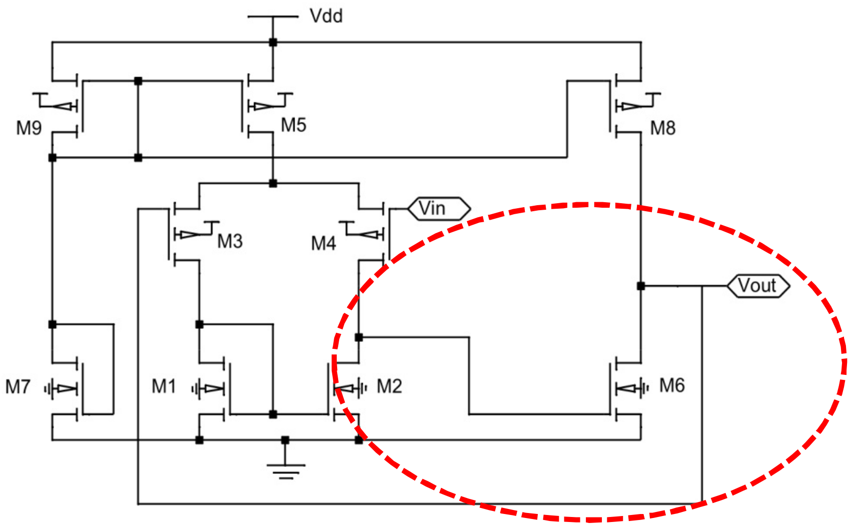
Bode plot of transfer function H(ω)



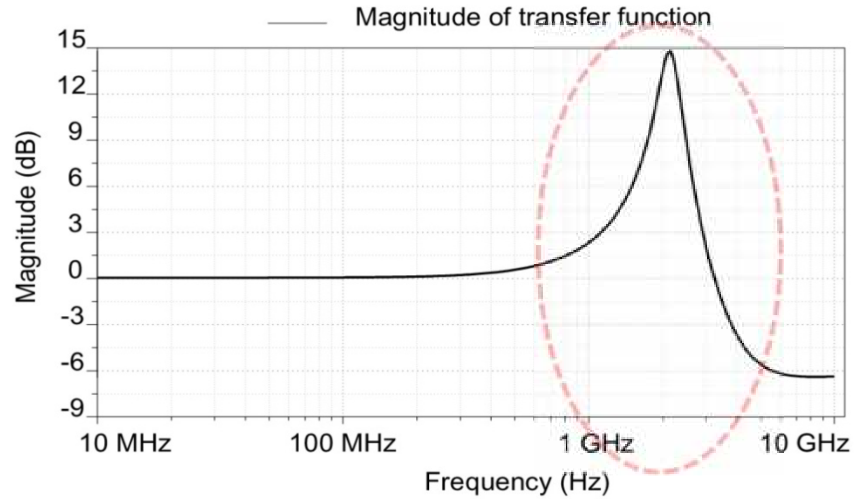
4. Stability Test for Electronic Systems

Unity-Gain Amplifier without Miller's Capacitor

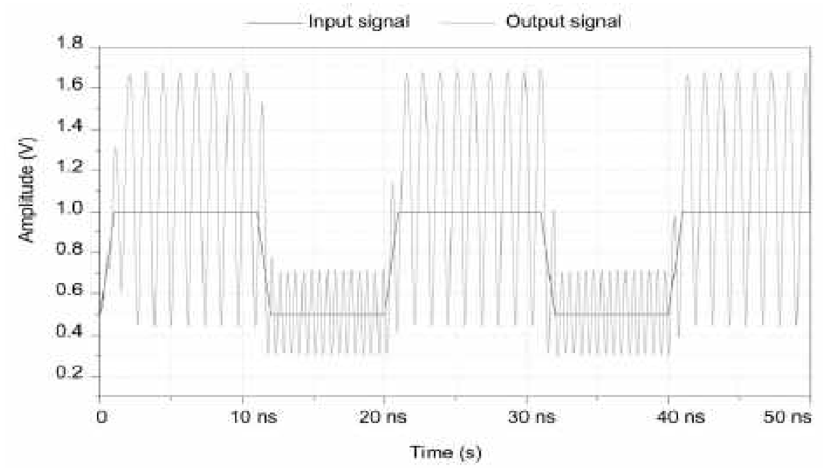
Unity-Gain Amplifier



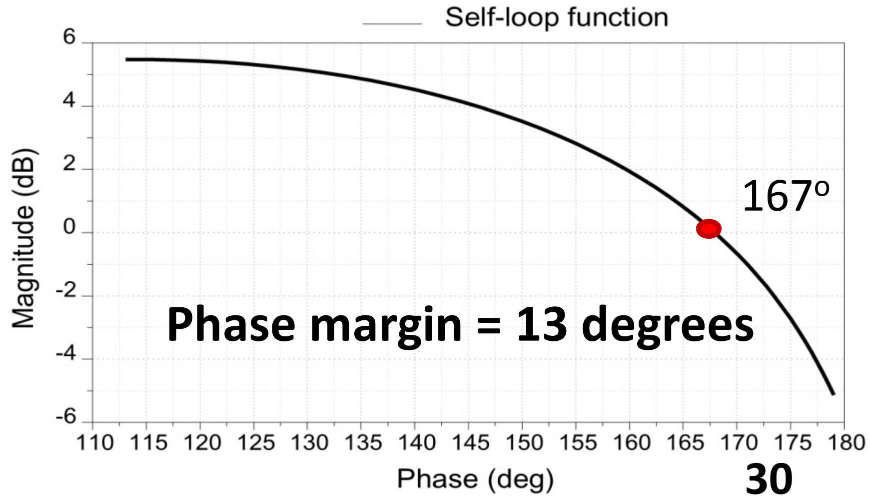
Bode plot of transfer function H(ω)



Transient response



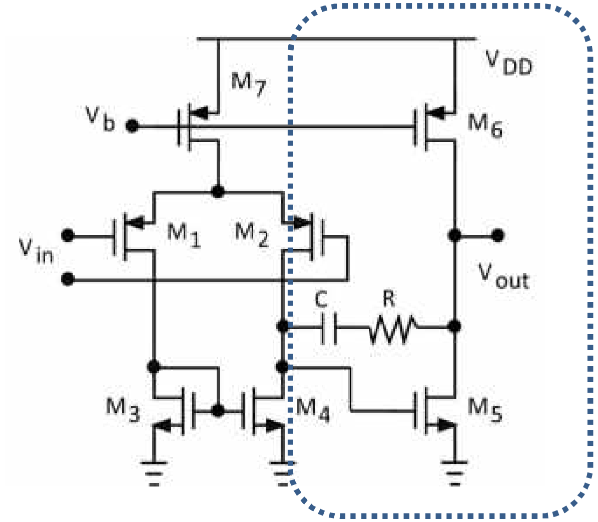
Nichols plot of self-loop function L(ω)



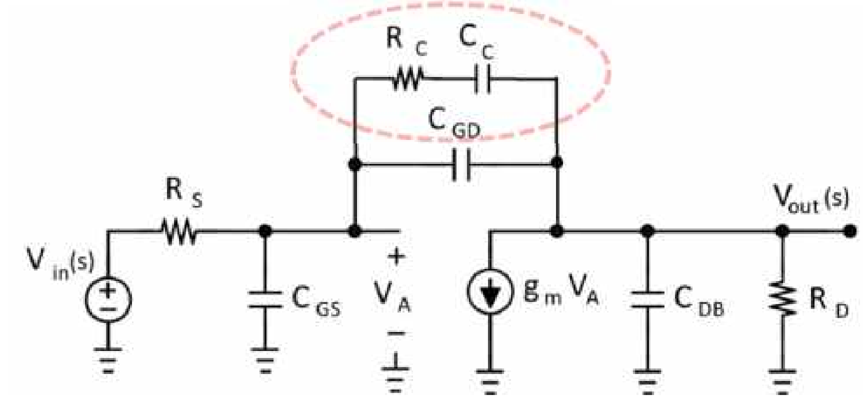
4. Stability Test for Electronic Systems

Two-stage Op Amp with Frequency Compensation

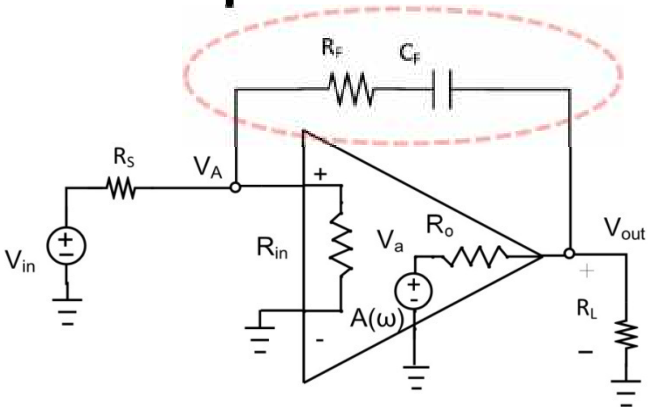
With Miller's capacitor and resistor



Small signal model



Simplified model



Transfer function H(ω)

$$H(\omega) = \frac{b_0 (j\omega)^3 + b_1 (j\omega)^2 + b_2 j\omega + b_3}{a_0 (j\omega)^4 + a_1 (j\omega)^3 + a_2 (j\omega)^2 + a_3 j\omega + 1};$$

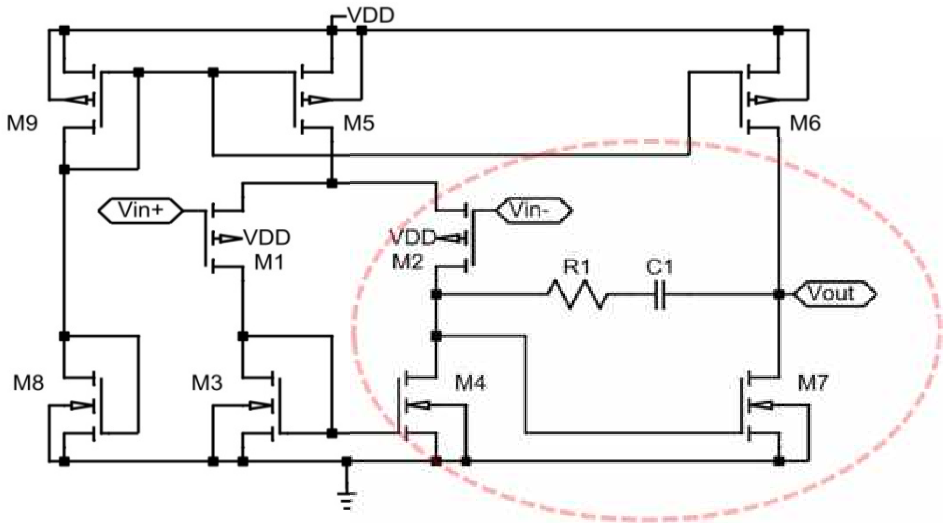
Self-loop function L(ω)

$$L(\omega) = a_0 (j\omega)^4 + a_1 (j\omega)^3 + a_2 (j\omega)^2 + a_3 j\omega$$

4. Stability Test for Electronic Systems

Behaviors of Op Amp with Frequency Compensation

Model of two-stage op amp



Under-damping:

R1= 2 kΩ, C1 = 1 pF

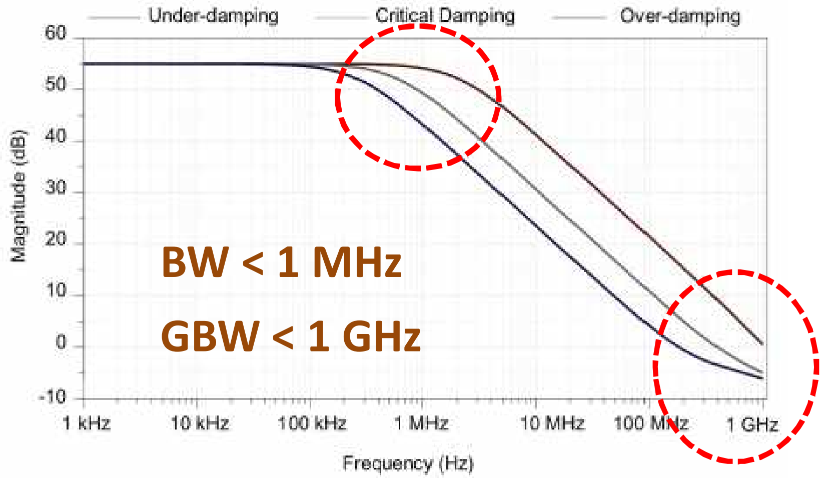
Critical damping:

R1 = 3.5 kΩ, C1 = 0.2 pF

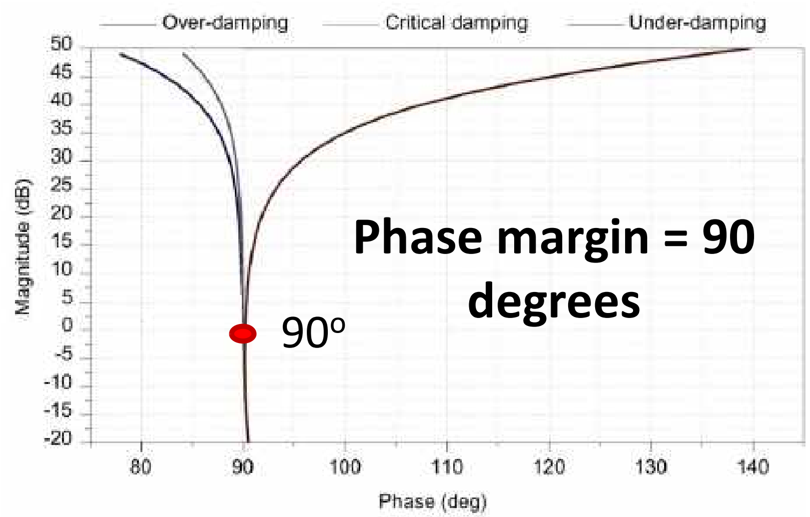
Over-damping:

R1 = 3.5 kΩ, C1 = 0.8 pF

Bode plot of transfer function H(ω)



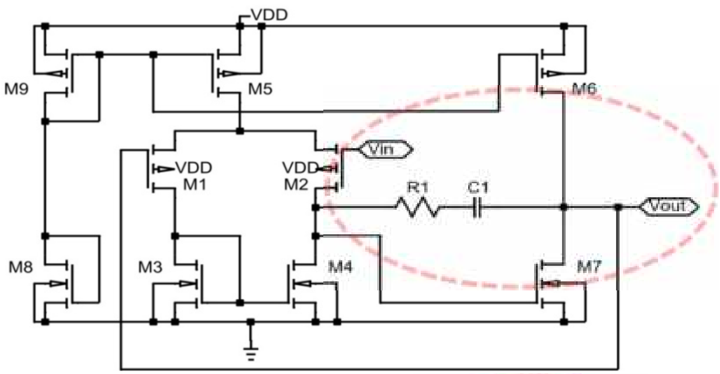
Nichols plot of self-loop function L(ω)



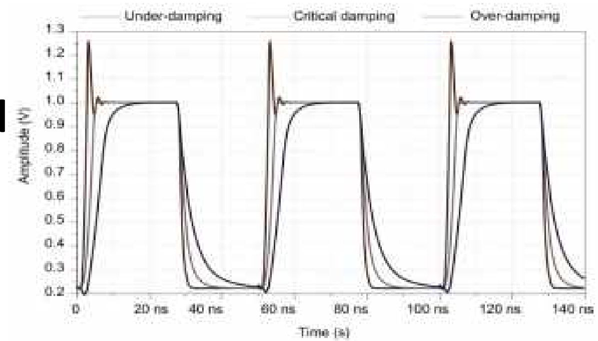
4. Stability Test for Electronic Systems

Stability Test for Op Amp with Miller's Capacitor

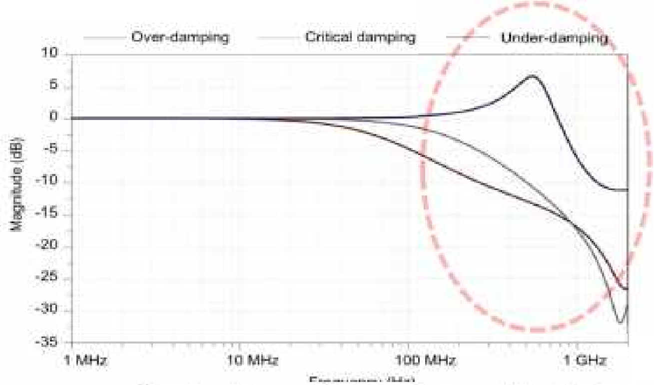
Unity-gain amplifier with Miller's capacitor



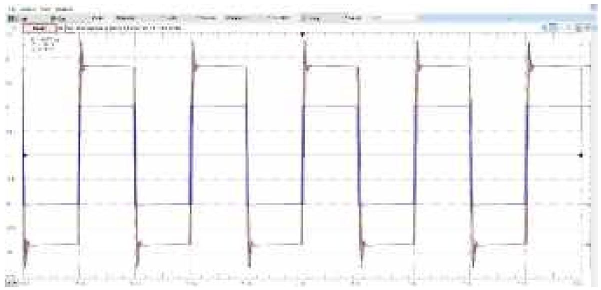
Simulated transient response



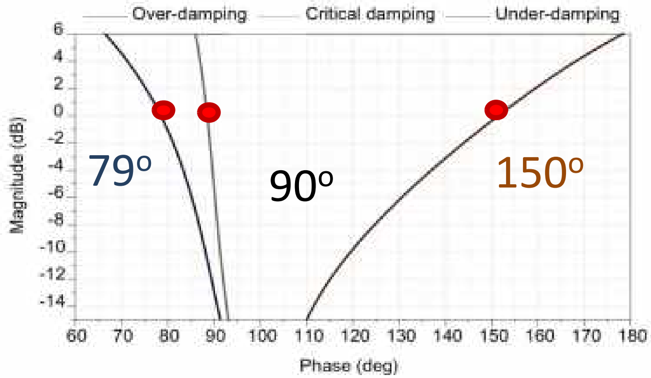
Bode plot of transfer function



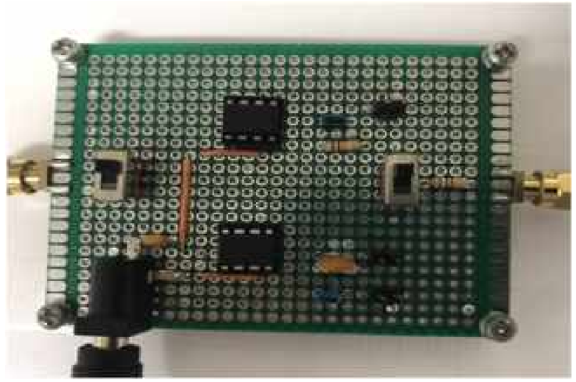
Measured transient response



Nichols plot of self-loop function



Implemented circuit



4. Stability Test for Electronic Systems

Stability Test for 3rd-Order Sallen-Key LPF

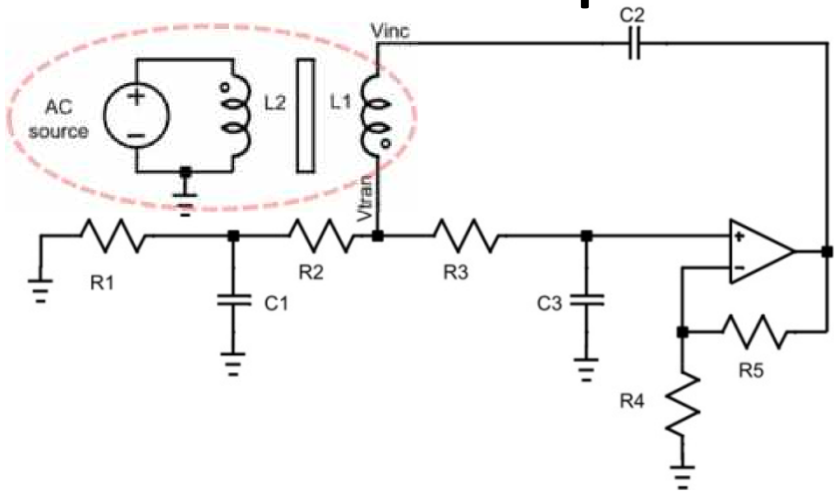
Transfer function

$$H(\omega) = \frac{b_0}{a_0(j\omega)^3 + a_1(j\omega)^2 + a_2 j\omega + 1};$$

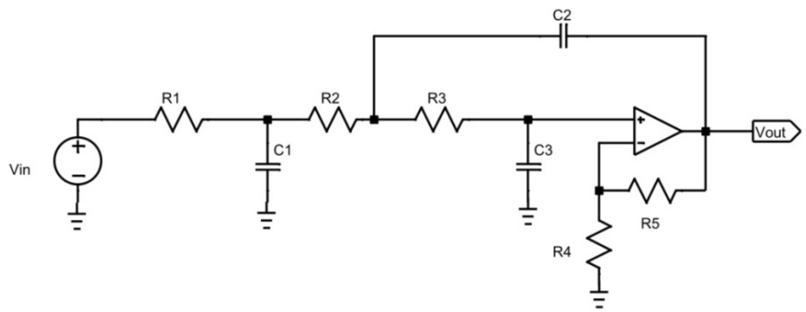
Self-loop function

$$L(\omega) = a_0(j\omega)^3 + a_1(j\omega)^2 + a_2 j\omega;$$

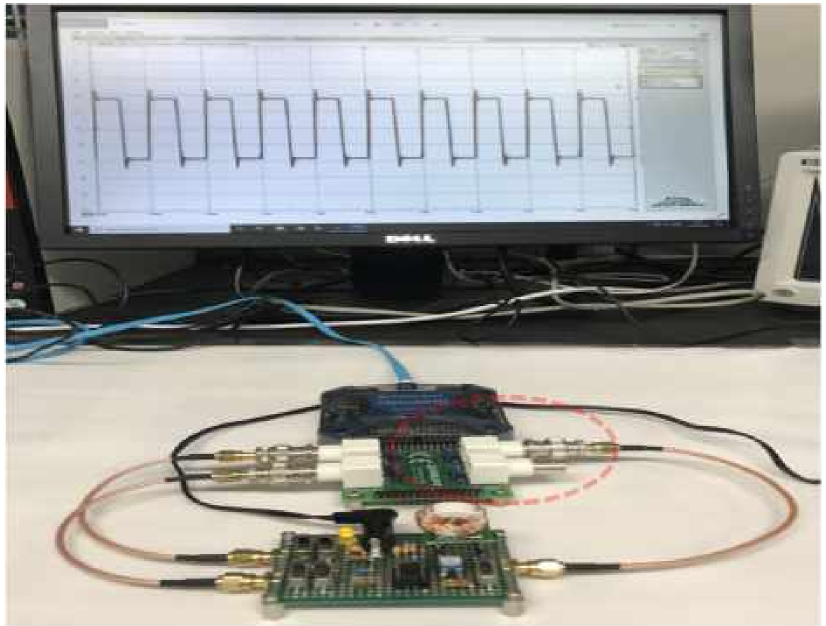
Derivation of self-loop function



Single ended 3rd -order Sallen-Key LPF



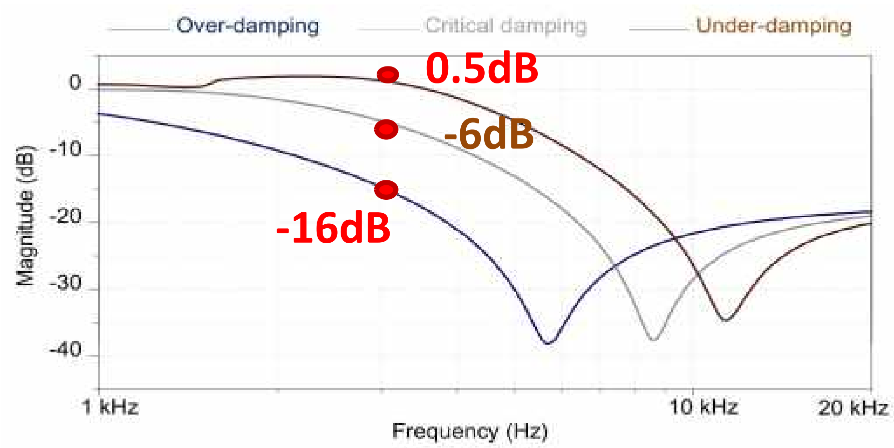
Implemented circuit



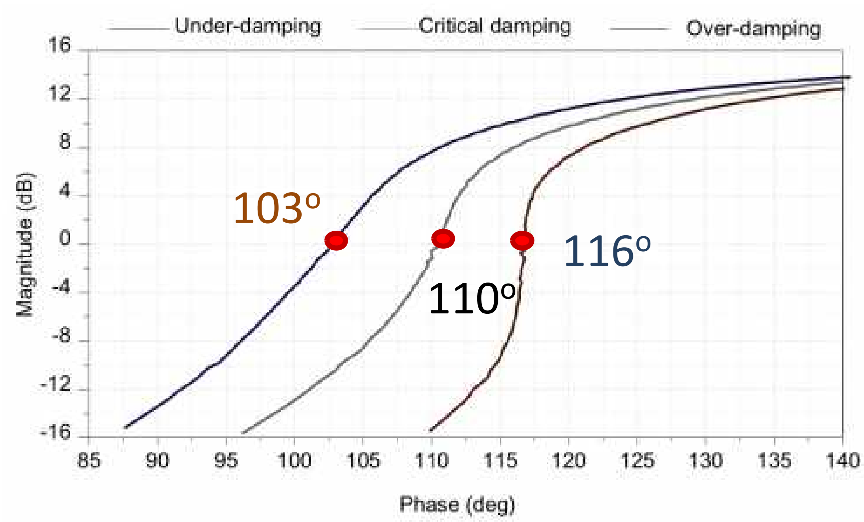
4. Stability Test for Electronic Systems

Measurement Results of 3rd-order Sallen-Key LPF

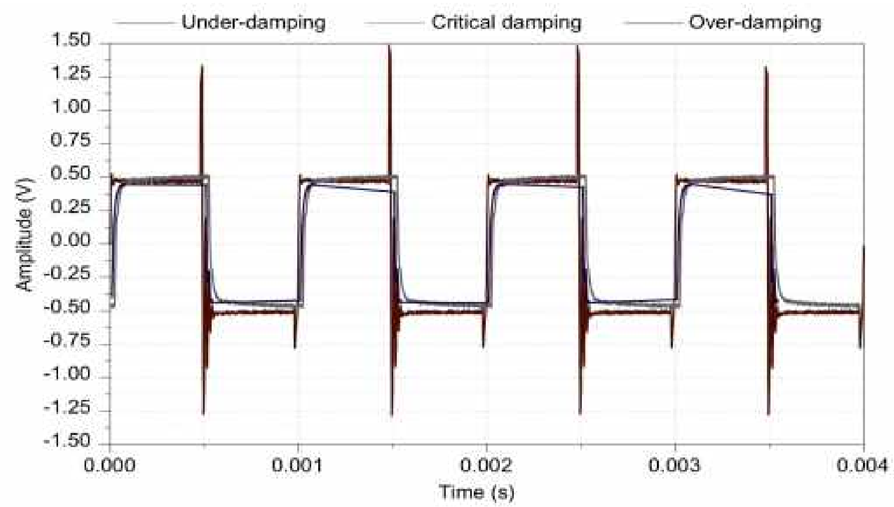
Bode plot of transfer function



Nichols plot of self-loop function



Transient response



Over-damping:

→Phase margin is 77 degrees.

Critical damping:

→Phase margin is 70 degrees.

Under-damping:

→Phase margin is 64 degrees.

5. Conclusions

This work:

- **Investigation of system noise: image noise, ripple noise, and ringing noise**
- **Proposal of superposition formula for deriving transfer function in multi-source networks**
- **Derivation of transfer function and image rejection ratio for high-order polyphase filters and complex filters in all frequency domain**
- **Flat pass-band gain for 4th-order polyphase filter using two RC band-stop filters**
- **Implementations of 4th-order polyphase filter and 6th-order quadrature signal generation network.**
- **Ripple reduction for DC-DC buck converter using linear swept frequency modulation, and LC notch harmonic filter**

5. Conclusions

- **Implementation** of a DC-DC buck converter with LC notch harmonic filter
- **Proposal** of an alternating current conservation for deriving self-loop function in feedback networks
- **Stability test** for feedback amplifier networks: shunt-shunt feedback amplifier, two-stage op amp with and without frequency compensation
- **Stability test** for filter networks: RLC low-pass filter, active ladder low-pass filter, 3-order Sallen-Key low-pass filter

Future of work:

- **Stability test** for **parasitic components** in transmission lines, printed circuit boards, physical layout layers
- **Investigation** of **I/Q mismatches** and **DC offsets** in multi-phase networks

References

[1] M. Tran, Y. Sun, N. Oiwa, Y. Kobori, A. Kuwana, H. Kobayashi, "Mathematical Analysis and Design of Parallel RLC Network in Step-down Switching Power Conversion System", JMEIS, J. Mech. Elect. Intel. Syst. vol. 3, no. 2, May 2020.

[2] M. Tran, N. Kushita, A. Kuwana, H. Kobayashi, "Mathematical Model and Analysis of 4-Stage Passive RC Polyphase Filter for Low-IF Receiver", JMEIS, J. Mech. Elect. Intel. Syst. vol. 3, no. 2, May 2020.

[3] M. Tran, Y. Sun, Y. Kobori, A. Kuwana, H. Kobayashi, "Design Proposal for Inductor Type Buck Converter in Bluetooth Receiver Chip with Overshoot Cancellation and Ripple Reduction Technique", J. Special Issue on 5th Int. Symp. of GUMI and 9th ICAMDE AMM, 2020. (accepted)

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Thank you very much!

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