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# Ringing Test for Tow-Thomas Low-Pass Filters

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# Outline

1. **Research Background**
- Characteristics of adaptive feedback networks

2. **Analysis of Behaviors of High-order Systems**
- Operating regions of high-order systems

3. **Ringing Test for Feedback Amplifiers**
- Stability test for shunt-shunt feedback amplifiers
- Stability test for unity-gain and inverting amplifiers

4. **Ringing test for High-order Systems**
- Stability test for passive and active RLC circuits
- Stability test for Tow-Thomas low-pass filters

5. **Conclusions**

# Effects of Ringing on Circuits

## Performance of a system

**Signal to Noise Ratio:**

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

## Performance of a device

**Figure of Merit:**

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

## Common types of noise:

- **Electronic noise, thermal noise, intermodulation noise, cross-talk, flicker noise, thermal noise...**

**Ringing does the following things:**

- **Causes EMI noise,**
- **Increases current flow,**
- **Decreases the performance, and**
- **Damages the devices.**

**Unstable system**

↓

**STABILITY TEST**

# Objectives of Study

- Derivation of self-loop function based on the proposed comparison measurement
- Investigation of operating region of high-order systems
- Observation of phase margin at unity gain on the Nichols chart

→ Over-damping (high delay in rising time)

→ Critical damping (max power propagation)

→ Under-damping (overshoot and ringing)

# Achievements of Study

## Comparison measurement

- **Shunt-shunt amplifiers**
- **Inverting amplifiers**
- **Unity-gain amplifiers**
- **2nd-order low-pass filters**

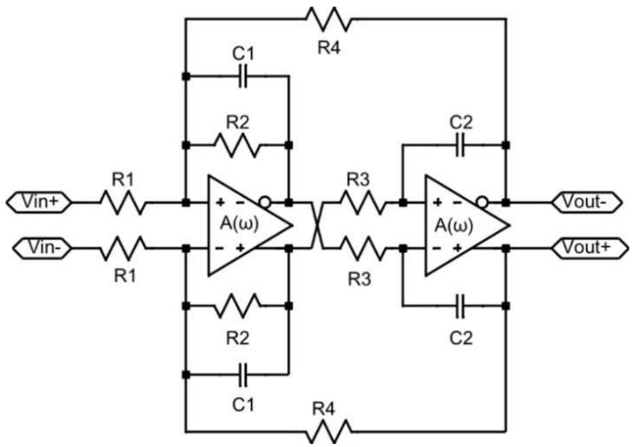
## Transfer function

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

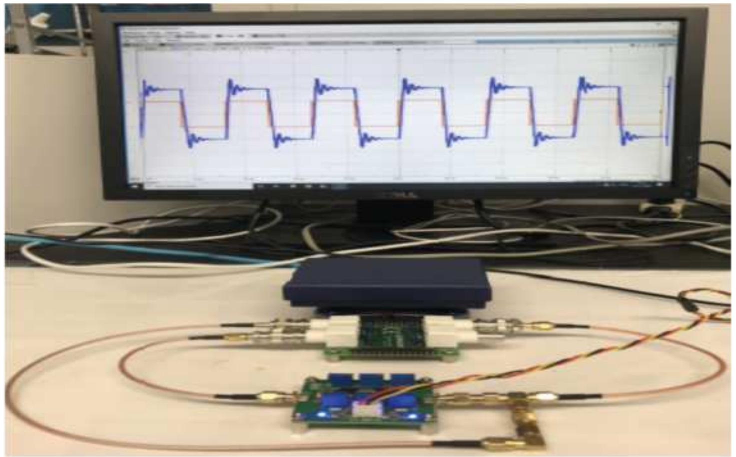
## Self-loop function

$$L(\omega) = \frac{A(\omega)}{H(\omega)} - 1$$

## 2nd-order Tow-Thomas LPF

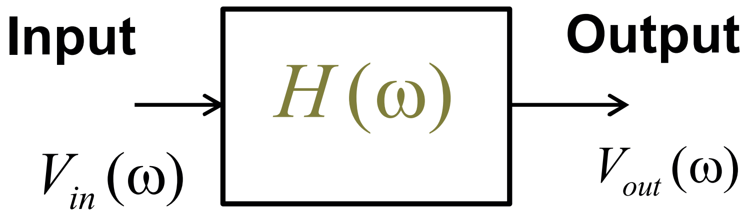



## Implemented circuit



# Definition of Self-loop Function

## Linear system




$V_{in}(\omega)$, $V_{out}(\omega)$: periodic signals with angular frequency variable

## Simplified model for linear systems

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

$A(\omega)$ : Numerator function

$H(\omega)$ : Transfer function

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

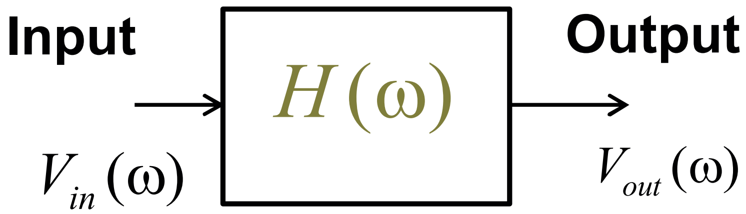
- Polar chart → Nyquist chart
- Magnitude-frequency plot
- Angular-frequency plot

} Bode plots

- Magnitude-angular diagram → Nichols diagram

# Comparison Measurement

## 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

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

## Sequence of steps:

(i) Measurement of numerator function A(ω),

(ii) Measurement of transfer function H(ω), and

(iii) Derivation of self-loop function.

## Self-loop function

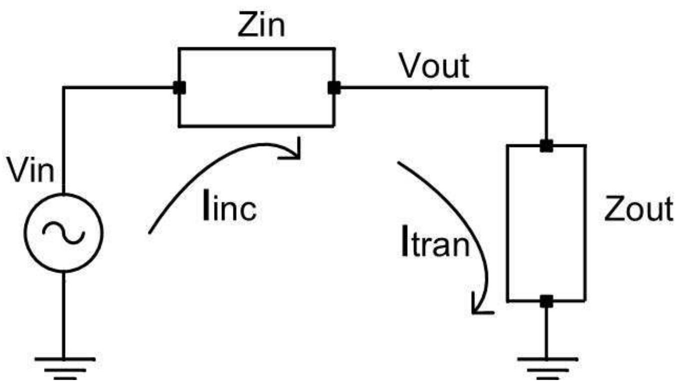
$$L(\omega) = \frac{A(\omega)}{H(\omega)} - 1$$

# Alternating Current Conservation

## 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**

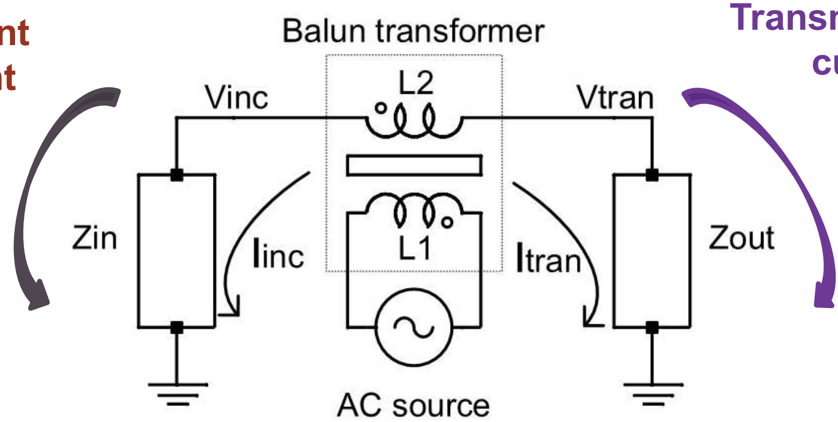
## Self-loop function

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

**10 mH inductance**

Incident current

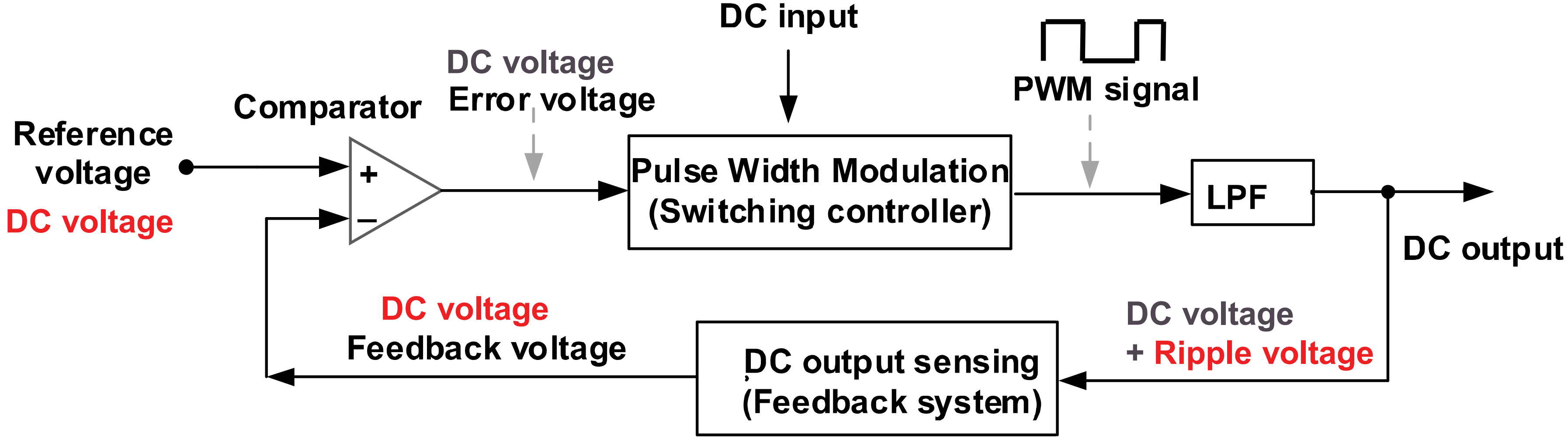
Transmitted current




**Derivation of self-loop function**

# Adaptive Feedback Network

## Block diagram of a typical adaptive feedback system

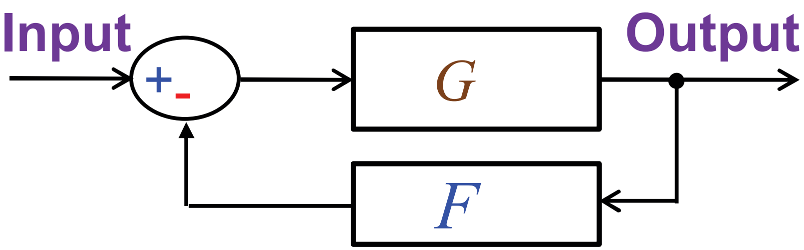



- **Adaptive feedback is used to control the output source along with the decision source (DC-DC Buck converter).**
- **Transfer function of an adaptive feedback network is significantly different from transfer function of a linear negative feedback network.**

**→ Loop gain is independent of frequency variable (referent voltage, feedback voltage, and error voltage are DC voltages).**

# Loop Gain in Feedback Systems

## Adaptive feedback system

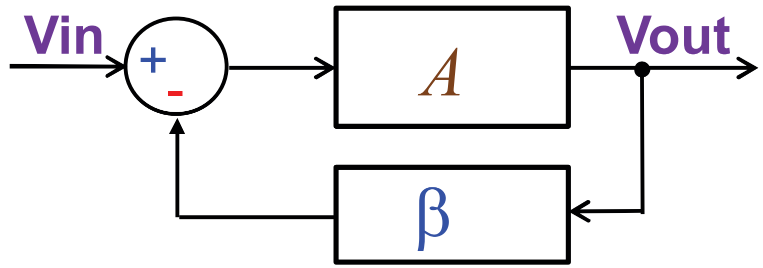



**Transfer function**

$$H = \frac{G}{1+GF} \approx 1$$

**GF : loop gain**

## Inverting amplifier

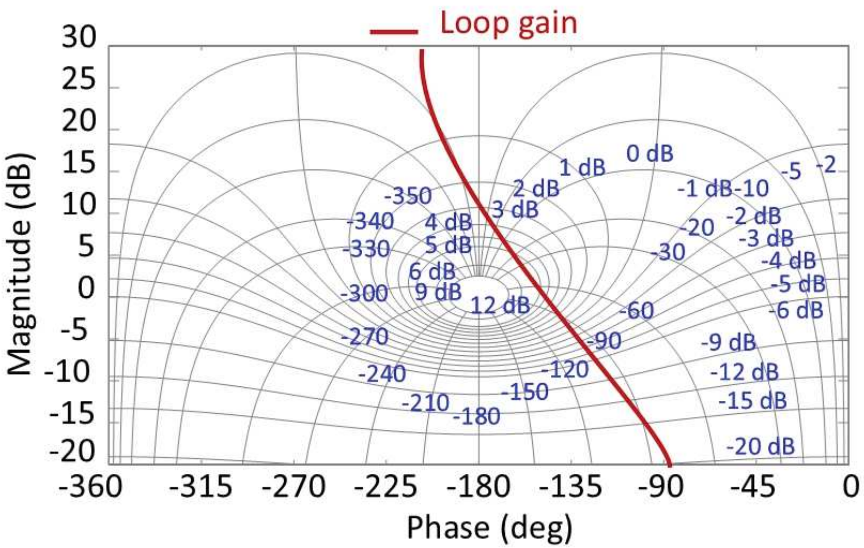



**Transfer function**

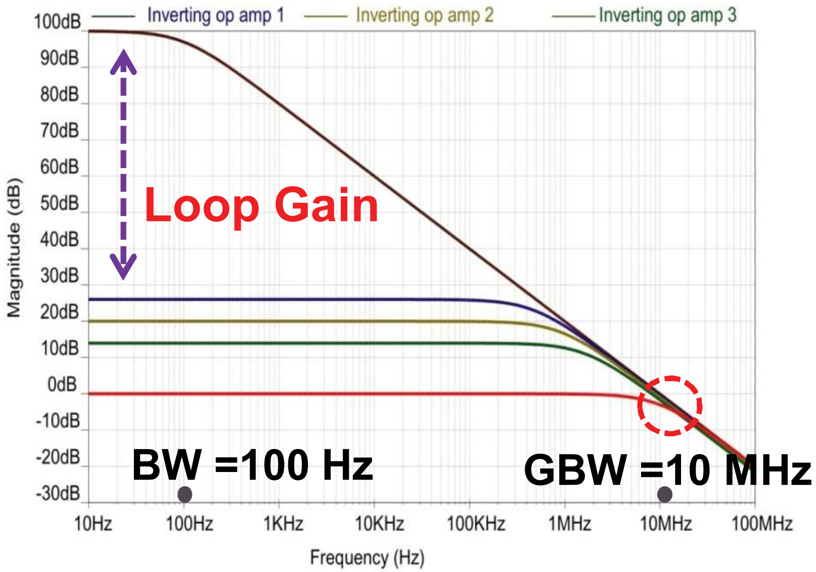
$$H = \frac{A}{1+A\beta} \approx \frac{1}{\beta}$$

**Aβ : loop gain**

### Nichols plot of loop gain




### Gain reduction



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# $2^{nd}$-Order Transfer Function

**Second-order transfer function:** $H(\omega) = \dfrac{1}{1 + a_0 (j\omega)^2 + a_1 j\omega}$

| Case | Over-damping | Critical damping | Under-damping |
|---|---|---|---|
| **Delta** ($\Delta$) | $\frac{1}{a_0} < \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\,2} - 4a_0 > 0$ | $\frac{1}{a_0} = \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\,2} - 4a_0 = 0$ | $\frac{1}{a_0} > \left(\frac{a_1}{2a_0}\right)^2 \Rightarrow \Delta = a_1^{\,2} - 4a_0 < 0$ |
| **Module** $\lvert H(\omega)\rvert$ | $\dfrac{\frac{1}{a_0}}{\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}\sqrt{\omega^2 + \left(\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}\right)^2}}$ | $\frac{1}{a_0}\dfrac{1}{\left[\omega^2 + \left(\frac{a_1}{2a_0}\right)^2\right]} = \frac{1}{2} = -6dB$ | $\dfrac{\frac{1}{a_0}}{\sqrt{\left(\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}\sqrt{\left(\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}\right)^2 + \left(\frac{a_1}{2a_0}\right)^2}}$ |
| **Angular** $\theta(\omega)$ | $-\arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} - \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right) - \arctan\left(\dfrac{\omega}{\frac{a_1}{2a_0} + \sqrt{\left(\frac{a_1}{2a_0}\right)^2 - \frac{1}{a_0}}}\right)$ | $-2\arctan\left(\dfrac{2a_0\omega}{a_1}\right)$ | $-\arctan\left(\dfrac{\omega - \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right) - \arctan\left(\dfrac{\omega + \sqrt{\frac{1}{a_0} - \left(\frac{a_1}{2a_0}\right)^2}}{\frac{a_1}{2a_0}}\right)$ |
| $\omega_{cut} = \dfrac{a_1}{2a_0}$ | $\lvert H(\omega_{cut})\rvert < \dfrac{2a_0}{a_1}$ ; $\theta(\omega_{cut}) > -\dfrac{\pi}{2}$ | $\lvert H(\omega_{cut})\rvert = \dfrac{2a_0}{a_1}$ ; $\theta(\omega_{cut}) = -\dfrac{\pi}{2}$ | $\lvert H(\omega_{cut})\rvert > \dfrac{2a_0}{a_1}$ ; $\theta(\omega_{cut}) < -\dfrac{\pi}{2}$ |

# $2^{nd}$-Order Self-loop Function

**Second-order self-loop function:** $L(\omega) = j\omega\left[a_0 j\omega + a_1\right]$

| Case | Over-damping | | Critical damping | | Under-damping | |
|---|---|---|---|---|---|---|
| **Delta** $(\Delta)$ | $\Delta = a_1^2 - 4a_0 > 0$ | | $\Delta = a_1^2 - 4a_0 = 0$ | | $\Delta = a_1^2 - 4a_0 < 0$ | |
| $\lvert L(\omega)\rvert$ | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | | $\omega\sqrt{(a_0\omega)^2 + a_1^2}$ | |
| $\theta(\omega)$ | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | | $\frac{\pi}{2} + \arctan\frac{a_0\omega}{a_1}$ | |
| $\omega_1 = \frac{a_1}{2a_0}\sqrt{\sqrt{5}-2}$ | $\lvert L(\omega_1)\rvert > 1$ | $\pi - \theta(\omega_1) > 76.3^o$ | $\lvert L(\omega_1)\rvert = 1$ | $\pi - \theta(\omega_1) = 76.3^o$ | $\lvert L(\omega_1)\rvert < 1$ | $\pi - \theta(\omega_1) < 76.3^o$ |
| $\omega_2 = \frac{a_1}{2a_0}$ | $\lvert L(\omega_2)\rvert > \sqrt{5}$ | $\pi - \theta(\omega_2) > 63.4^o$ | $\lvert L(\omega_2)\rvert = \sqrt{5}$ | $\pi - \theta(\omega_2) = 63.4^o$ | $\lvert L(\omega_2)\rvert < \sqrt{5}$ | $\pi - \theta(\omega_2) < 63.4^o$ |
| $\omega_3 = \frac{a_1}{a_0}$ | $\lvert L(\omega_3)\rvert > 4\sqrt{2}$ | $\pi - \theta(\omega_3) > 45^o$ | $\lvert L(\omega_3)\rvert = 4\sqrt{2}$ | $\pi - \theta(\omega_3) = 45^o$ | $\lvert L(\omega_3)\rvert < 4\sqrt{2}$ | $\pi - \theta(\omega_3) < 45^o$ |

# Operating Regions of 2nd-Order System

- **Under-damping:**

$$L_1(\omega) = (j\omega)^2 + j\omega;$$

$$H_1(\omega) = \frac{1}{(j\omega)^2 + j\omega + 1};$$

- **Critical damping:**

$$L_2(\omega) = (j\omega)^2 + 2j\omega;$$

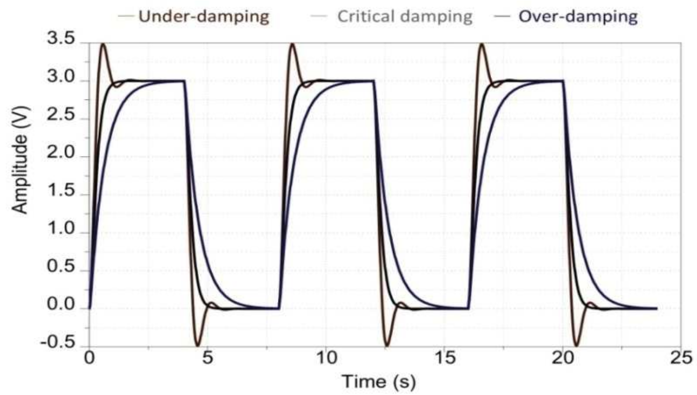
$$H_2(\omega) = \frac{1}{(j\omega)^2 + 2j\omega + 1};$$

- **Over-damping:**

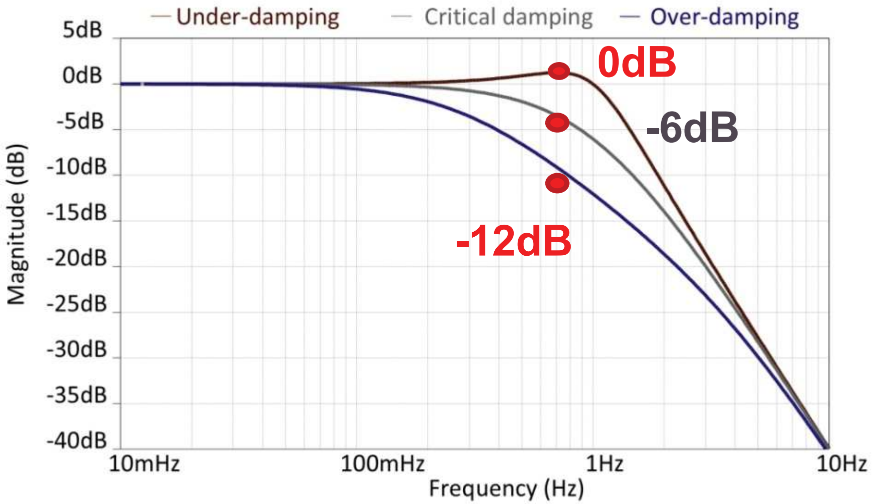
$$L_3(\omega) = (j\omega)^2 + 3j\omega;$$

$$H_3(\omega) = \frac{1}{(j\omega)^2 + 3j\omega + 1};$$

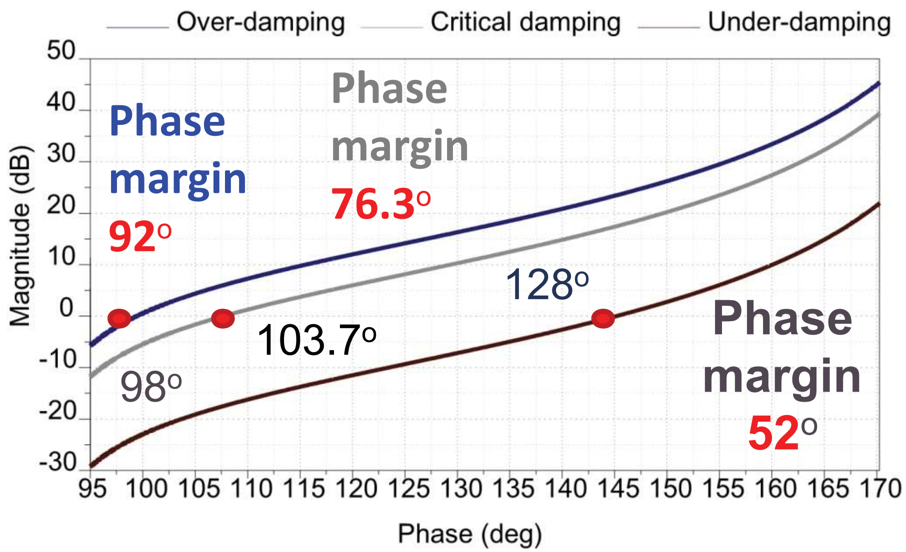
## Transient response




## Bode plot of transfer function




## Nichols plot of self-loop function



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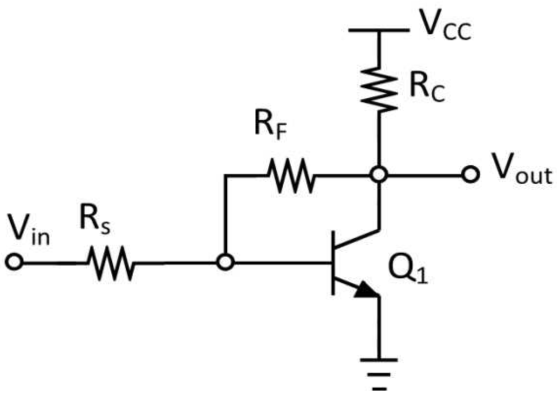
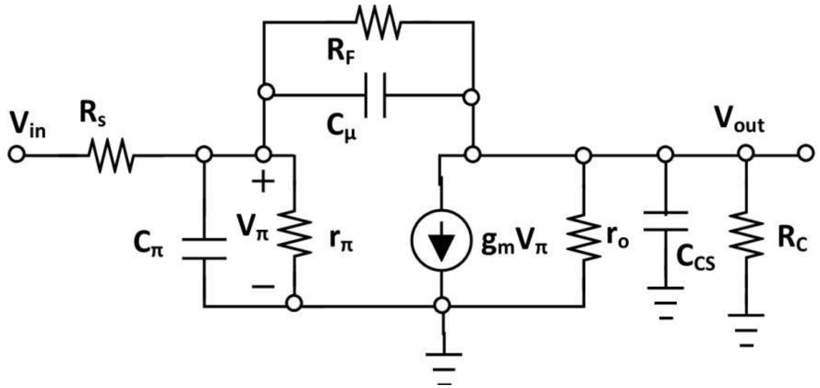
5. Conclusions

# Shunt-shunt Feedback Amplifier

## Shunt-shunt feedback amplifier




## Small signal model




**Apply superposition at the nodes $V_\pi$ 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 and self-loop function**

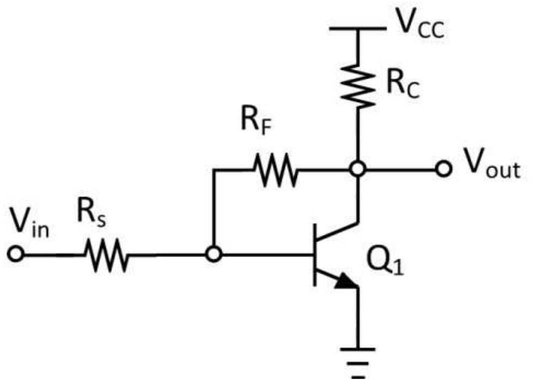
$$H(\omega)=\frac{V_{out}}{V_{in}}=\frac{b_0 j\omega+b_1}{a_0(j\omega)^2+a_1 j\omega+1};\quad L(\omega)=j\omega\left[a_0 j\omega+a_1\right]$$

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

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

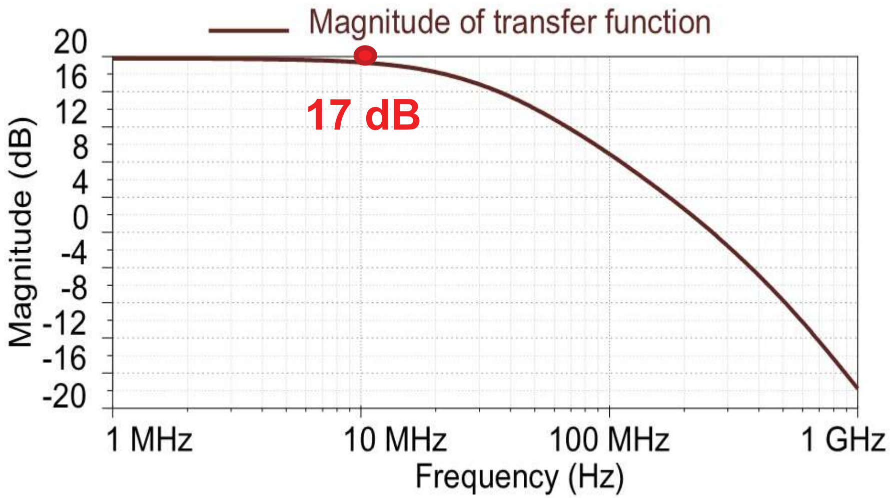
# Characteristics of Shunt-Shunt Feedback Amplifier

## Shunt-shunt feedback amplifier

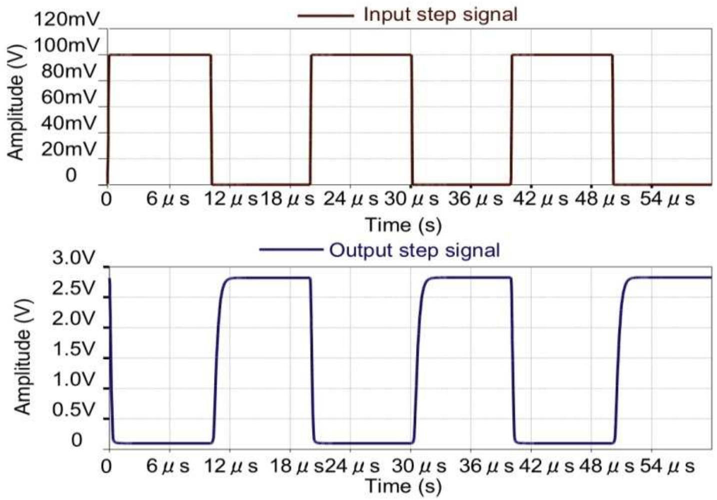



$R_f$ = 1 kΩ, $R_C$ = 10 kΩ, $R_S$ = 950 Ω.

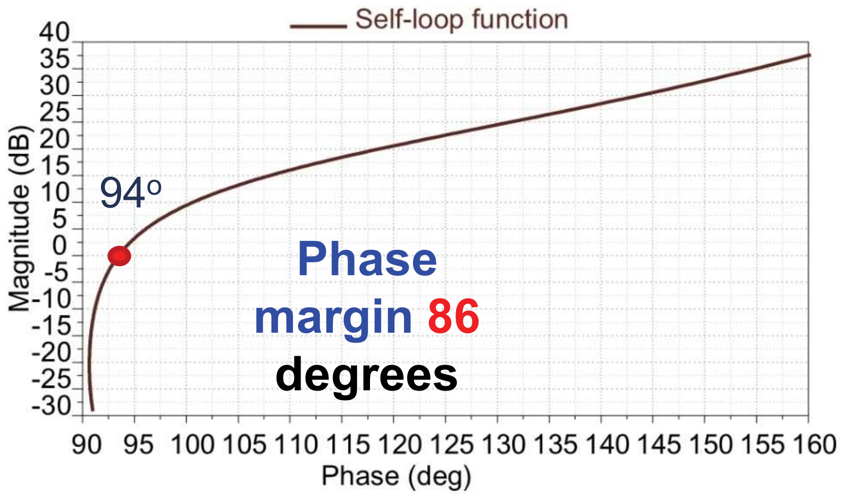
## Bode plot of transfer function




## Transient response




## Nichols plot of self-loop function



# Op Amp without Miller's Capacitor

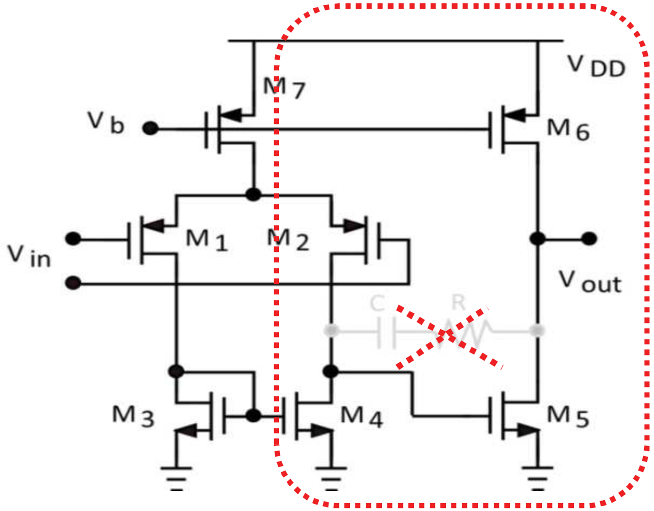
## Open-loop function

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

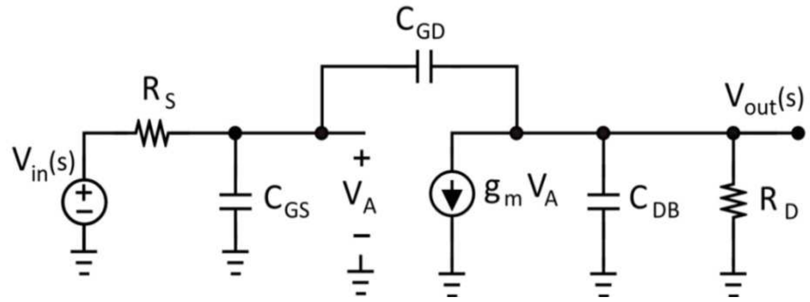
## Self-loop function

$$L_{op}(\omega) = a_0 (j\omega)^4 + a_1 (j\omega)^3 + a_2 (j\omega)^2 + a_3 j\omega;$$

## Without frequency compensation




## Small signal model of 2nd-stage




## Transfer function

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

## Self-loop function

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

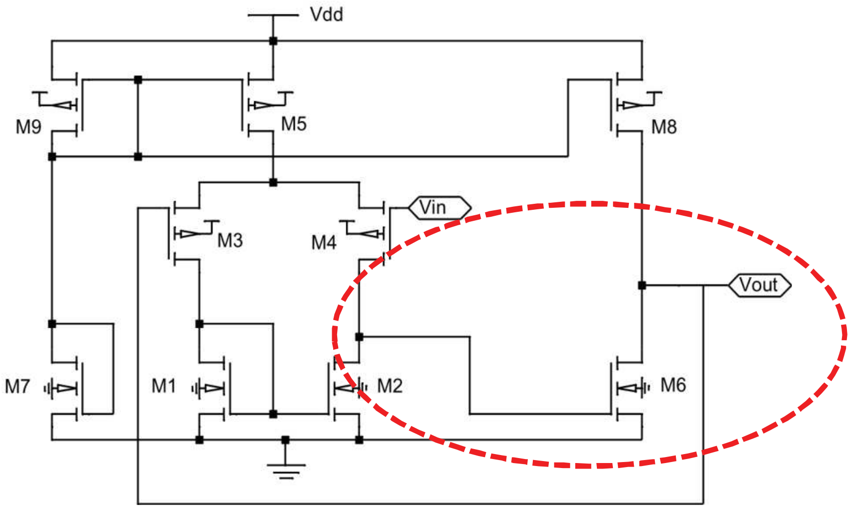
**Where,** $a_0 = R_D C_{GD};\ a_1 = -R_D g_m;$

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

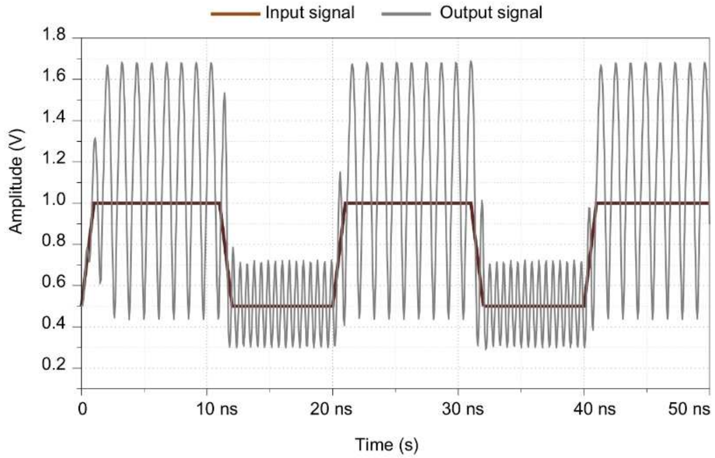
$$b_1 = \left[ R_D (C_{GD} + C_{DB}) + R_S (C_{GS} + C_{GD}) + R_D R_S g_m C_{GD} \right];$$

# Unity-Gain Amplifier without Miller's Capacitor

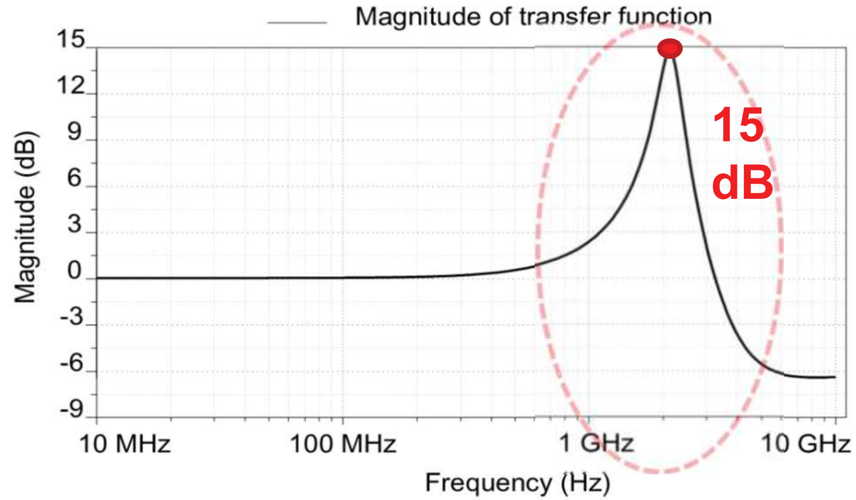
## Unity-Gain Amplifier



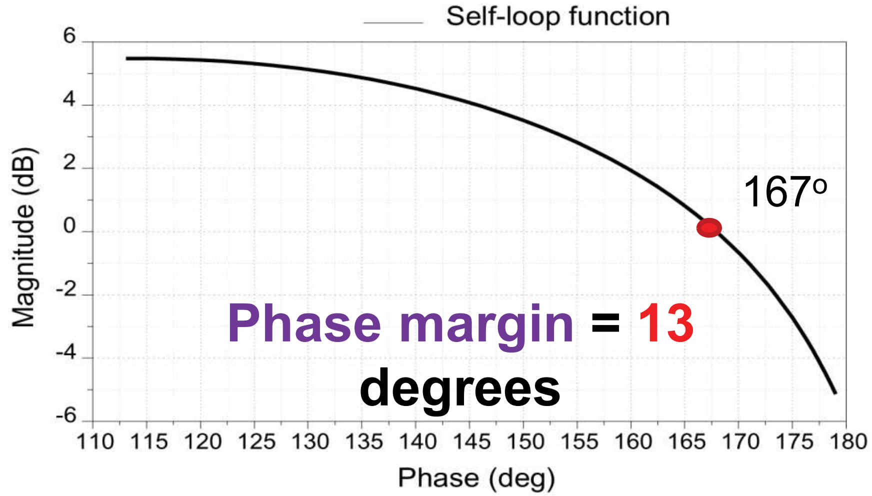

## Transient response




## Bode plot of transfer function




## Nichols plot of self-loop function



# Op Amp with Miller's Capacitor

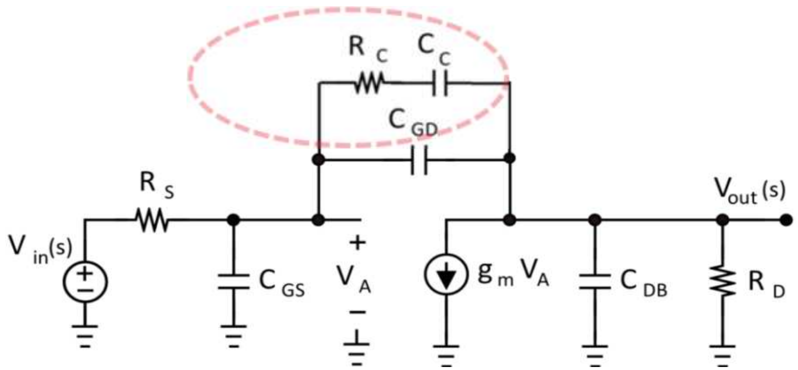
## Open-loop function

$$A_{op}(\omega) = \frac{b_0(j\omega)^5 + b_1(j\omega)^4 + b_2(j\omega)^3 + b_3(j\omega)^2 + b_4 j\omega + b_5}{a_0(j\omega)^6 + a_1(j\omega)^5 + a_2(j\omega)^4 + a_3(j\omega)^3 + a_4(j\omega)^2 + a_5 j\omega + 1};$$

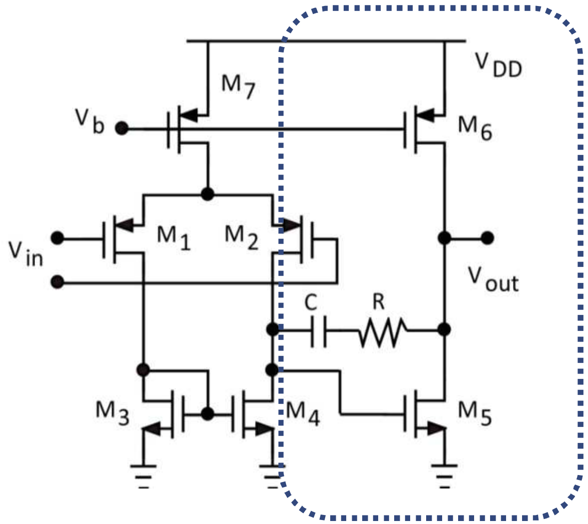
## Self-loop function

$$L_{op}(\omega) = a_0(j\omega)^6 + a_1(j\omega)^5 + a_2(j\omega)^4 + a_3(j\omega)^3 + a_4(j\omega)^2 + a_5 j\omega;$$

## Small signal model of 2nd-stage




## With Miller's capacitor and resistor




## Transfer function

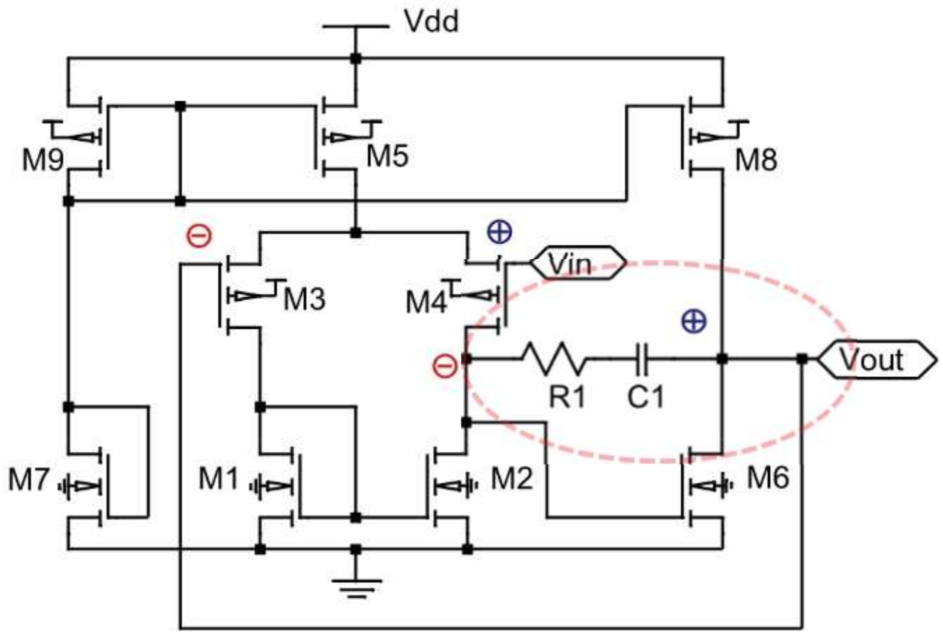
$$H(\omega) = \frac{b_0(j\omega)^3 + b_1(j\omega)^2 + b_2 j\omega + b_3}{a_0(j\omega)^4 + a_1(j\omega)^3 + a_2(j\omega)^2 + a_3 j\omega + 1};$$

## Self-loop function

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

# Unity-Gain Amplifier with Miller's Capacitor

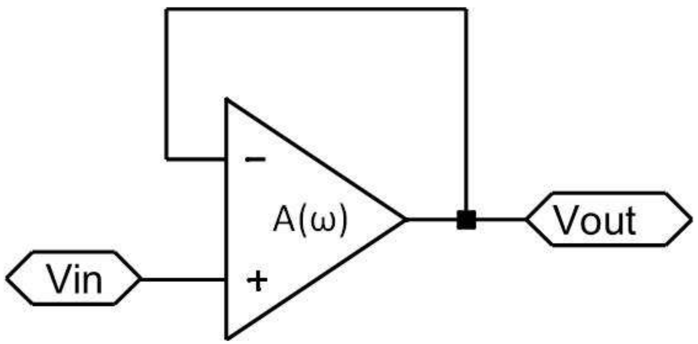
## Unity-gain amplifier with Miller's capacitor




## Transfer function and self-loop function

$$H(\omega)=\frac{1}{1+\frac{1}{A(\omega)}}\approx 1; \quad L(\omega)=\frac{1}{A(\omega)};$$

## Simplified model




**Under-damping:**

**R1= 2 kΩ, C1 = 1 pF**

**Critical damping:**

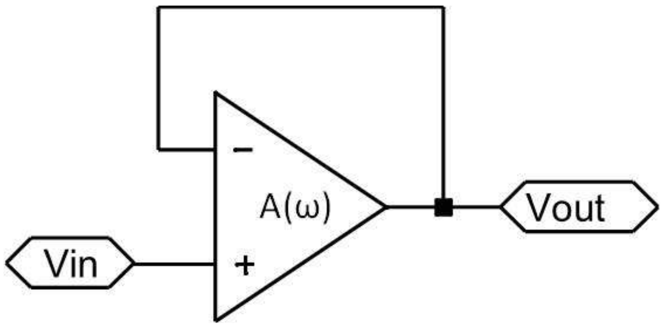
**R1 = 3.5 kΩ, C1 = 0.2 pF**

**Over-damping:**

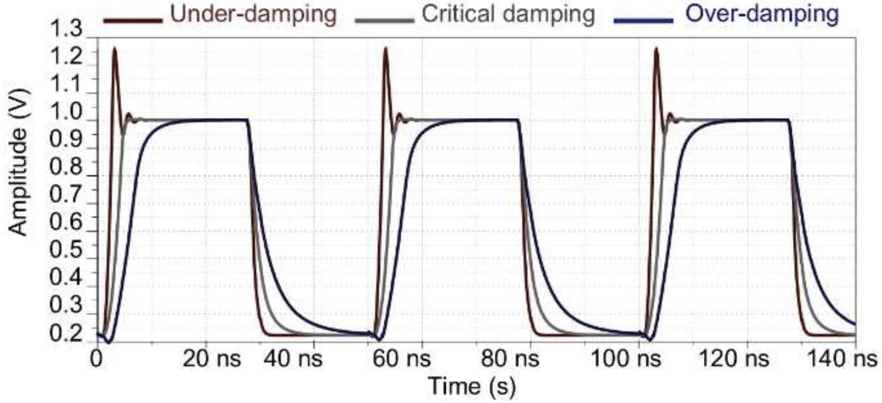
**R1 = 3.5 kΩ, C1 = 0.8 pF**

# Behaviors of Unity-Gain Amplifier

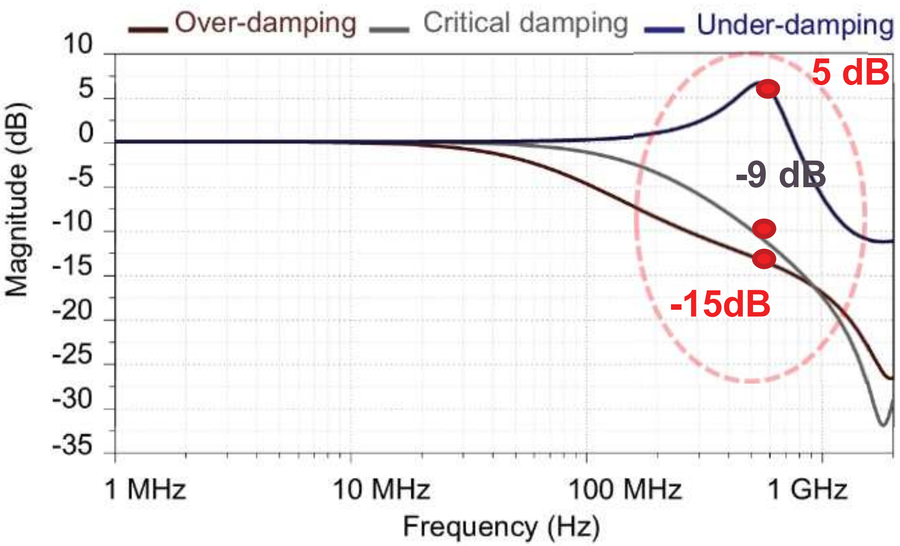
## Model of unity gain amplifier



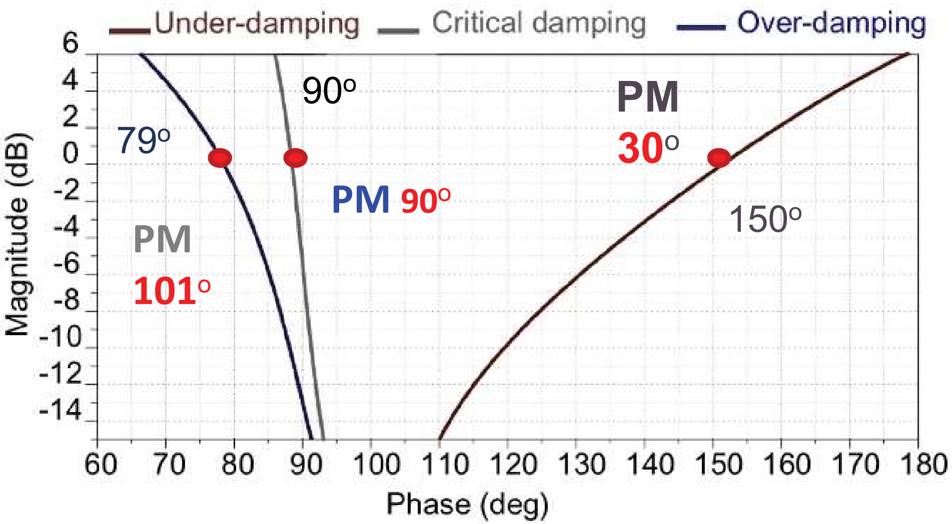

## Simulated transient response




## Bode plot of transfer function

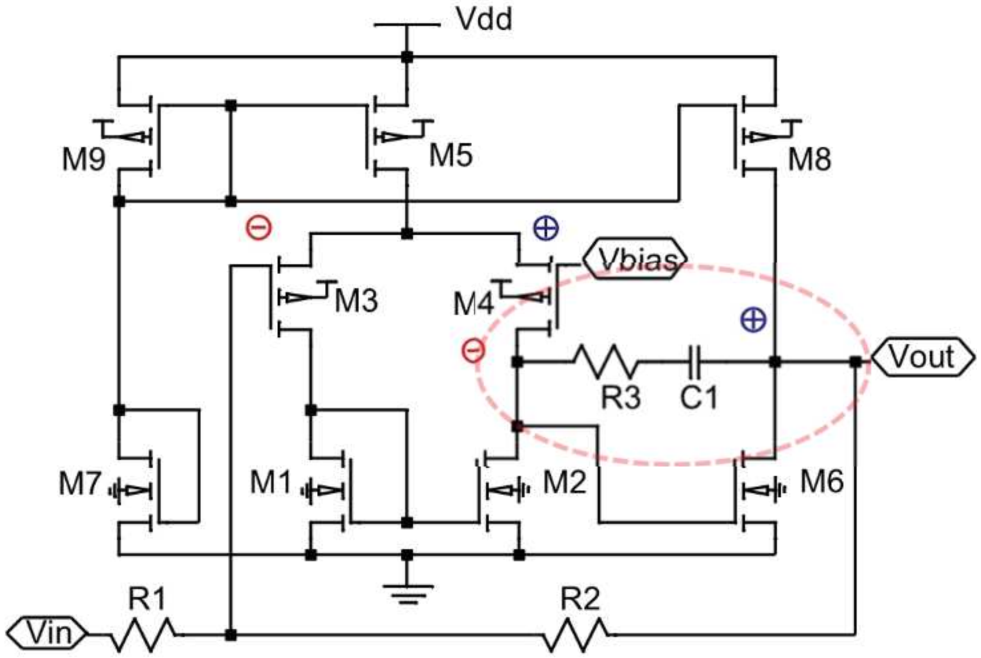



## Nichols plot of self-loop function

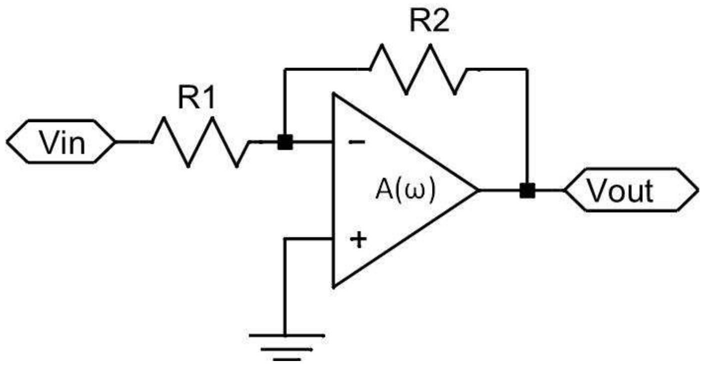


# Inverting Amplifier with Miller's Capacitor

## Inverting amplifier




## Simplified model




**Under-damping:**

**R3= 2 kΩ, C1 = 1 pF**

**Critical damping:**

**R3 = 3.5 kΩ, C1 = 0.2 pF**

**Over-damping:**

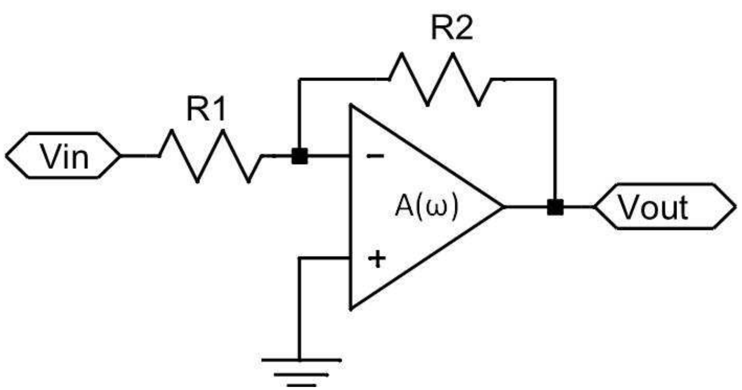
**R3 = 3.5 kΩ, C1 = 0.8 pF**

**Transfer function and self-loop function**

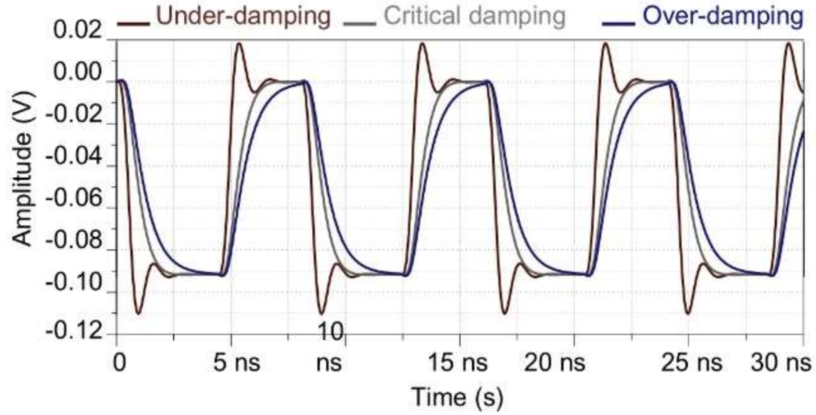
$$H(\omega)=\frac{-\dfrac{R_2}{R_1}}{1+L(\omega)}\approx-\frac{R_2}{R_1};\ L(\omega)=\frac{1}{A(\omega)}\left(1+\frac{R_2}{R_1}\right);$$

# Behaviors of Inverting Amplifier

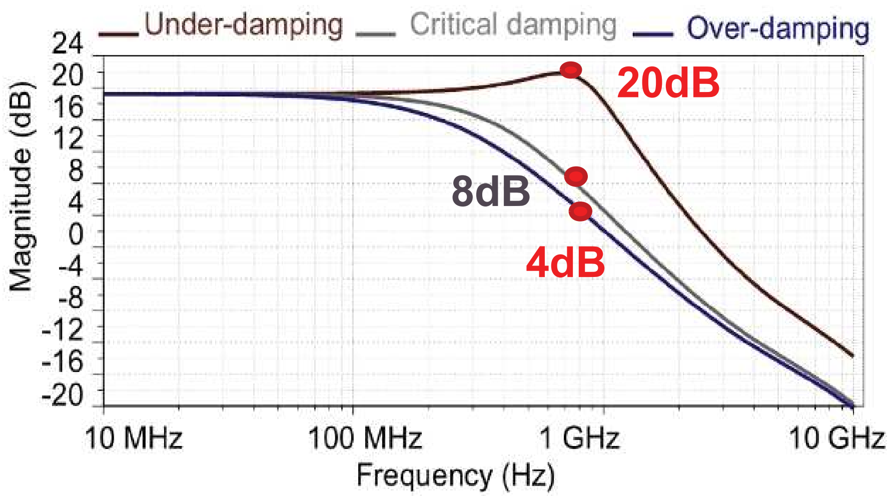
## Model of inverting amplifier



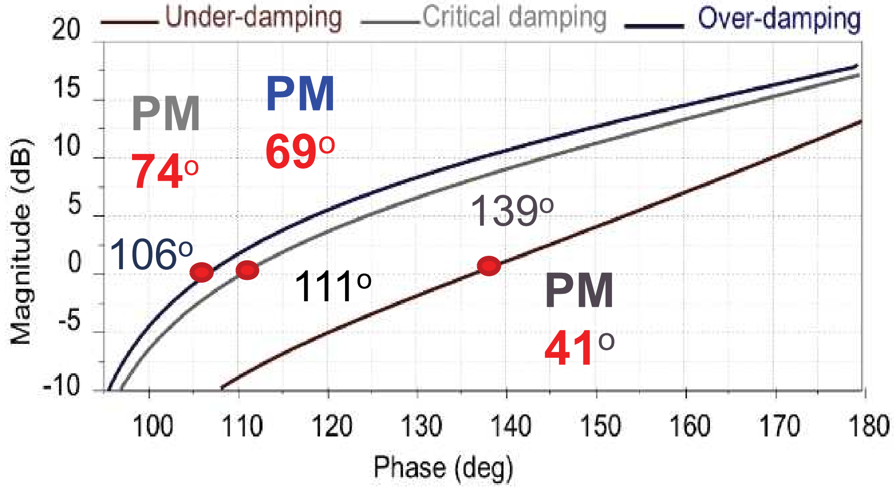

## Simulated transient response




## Bode plot of transfer function




## Nichols plot of self-loop function

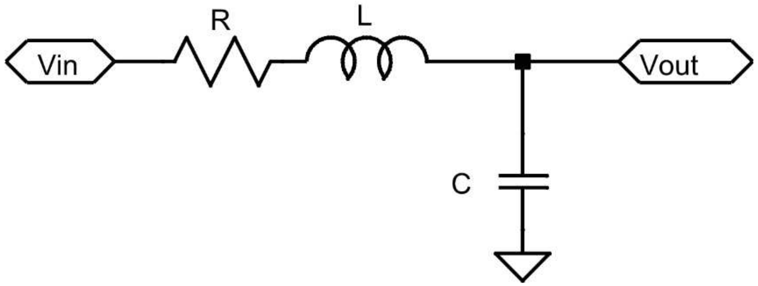


# Outline

1. Research Background
   - Characteristics of adaptive feedback networks
2. Analysis of Behaviors of High-order Systems
   - Operating regions of high-order systems
3. Ringing Test for Feedback Amplifiers
   - Stability test for shunt-shunt feedback amplifiers
   - Stability test for unity-gain and inverting amplifiers
4. **Ringing test for High-order Systems**
   - **Stability test for passive and active RLC circuits**
   - **Stability test for Tow-Thomas low-pass filters**
5. Conclusions

# Analysis of 2nd-Order Passive RLC LPF

## Passive RLC Low-pass Filter




## Transfer function

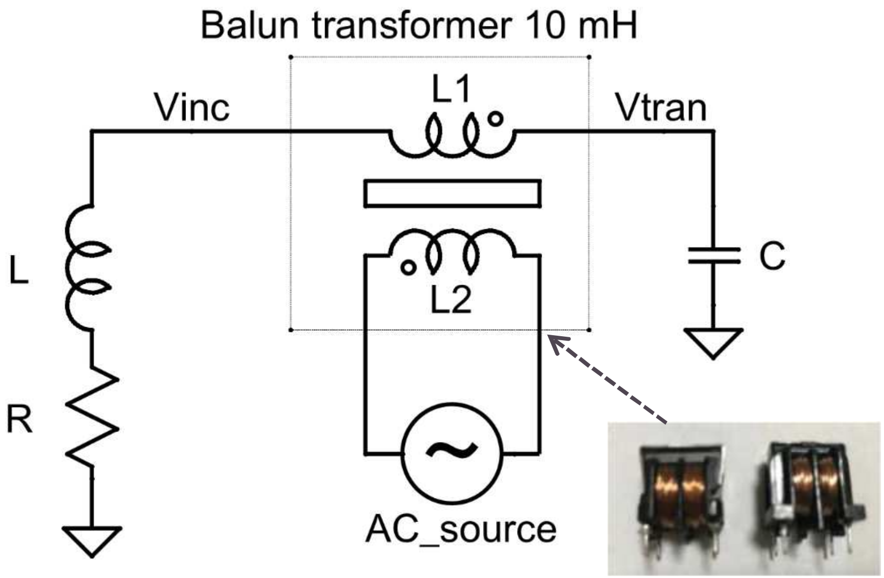
$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{a_0 (j\omega)^2 + a_1 j\omega + 1};$$

## Self-loop function

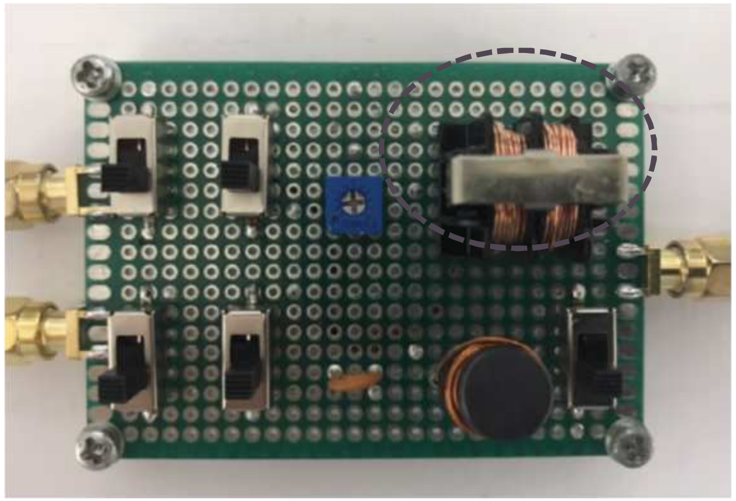
$$L(\omega) = a_0 (j\omega)^2 + a_1 j\omega;$$

**where,** $a_0 = LC; a_1 = RC;$

## Derivation of self-loop function

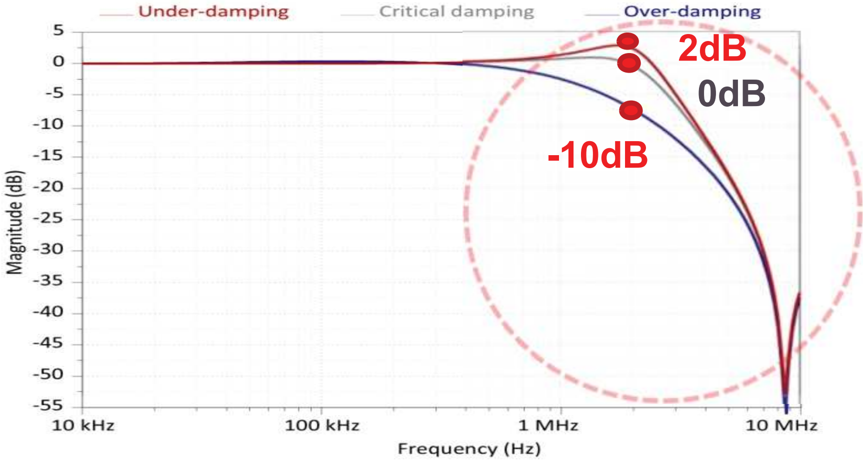



## Implemented circuit

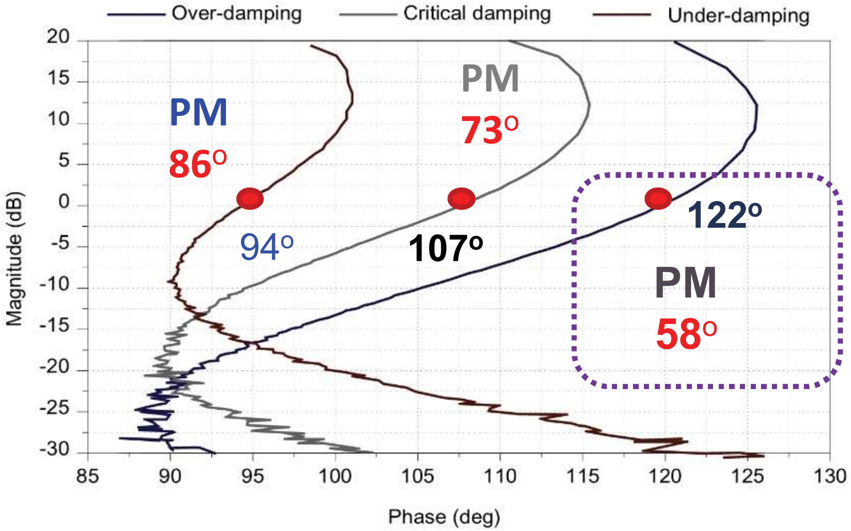


# Measurement Results for 2nd-Order Passive RLC LPF

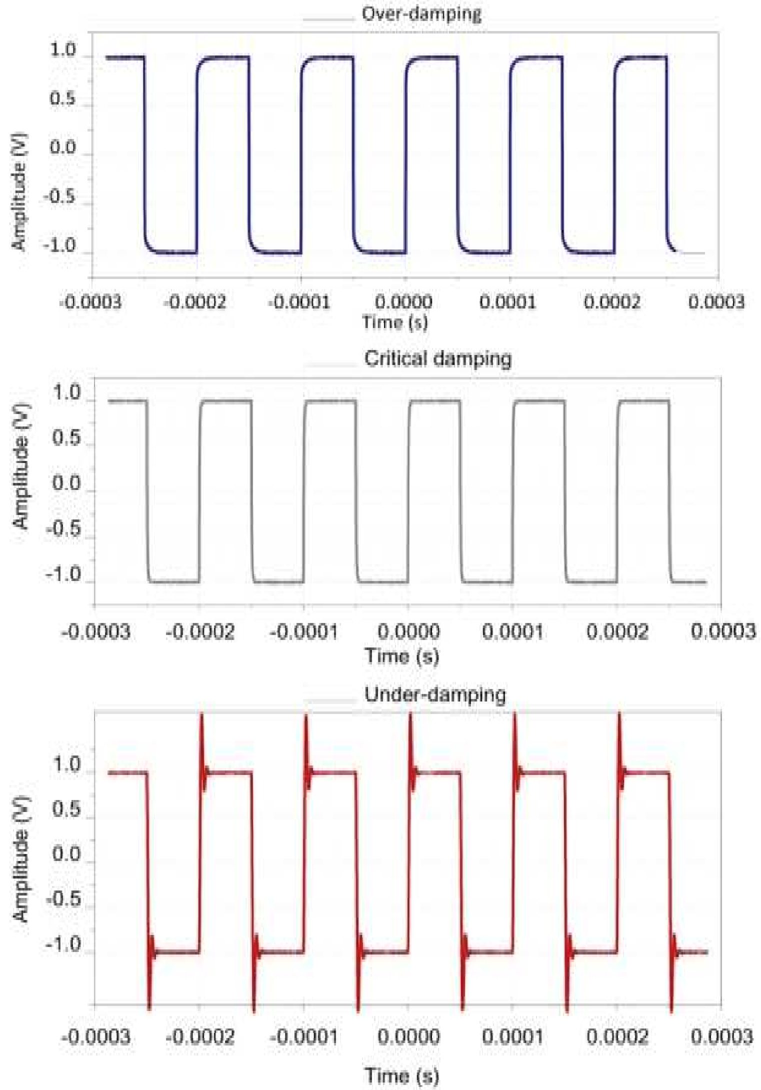
## Bode plot of transfer function




## Nichols plot of self-loop function

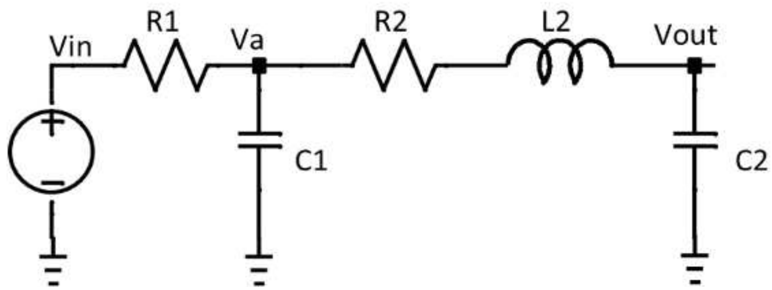



## Transient responses

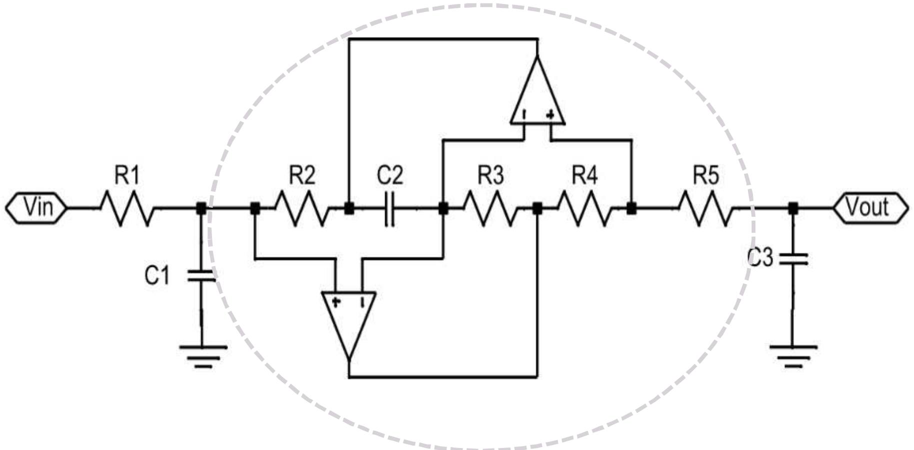


# Analysis of Active 3rd-Order Ladder LPF

## Passive 3rd-order ladder LPF




## Active 3rd-order ladder LPF




General impedance converter

## Transfer function & self-loop function

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

$$L(\omega) = j\omega\left[a_0(j\omega)^2 + a_1 j\omega + a_2\right]$$

**where,** $b_0 = L_2C_2;\ b_1 = R_2C_2;$

$$a_0 = R_1C_1L_2C_2;\ \ a_1 = R_1C_1R_2C_2 + L_2C_2;$$

$$a_2 = R_1\left(C_1 + C_2\right) + R_2C_2;$$

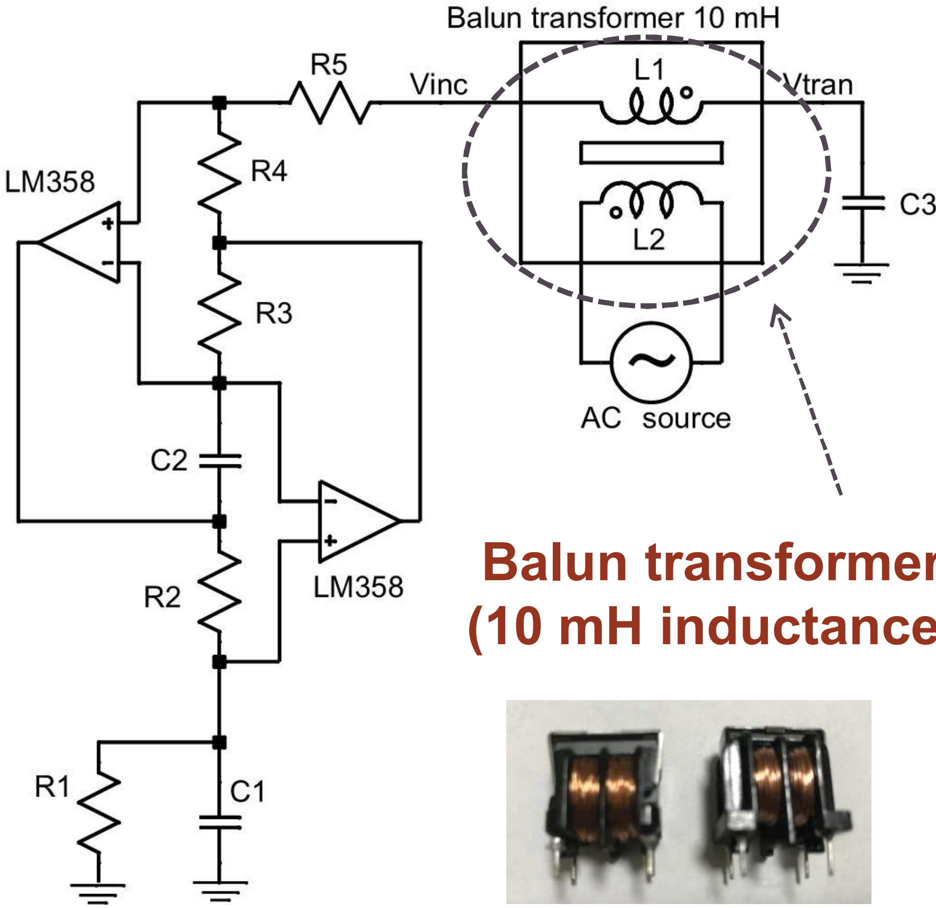
**R1 = 100 Ω, R2 = 50 kΩ,**

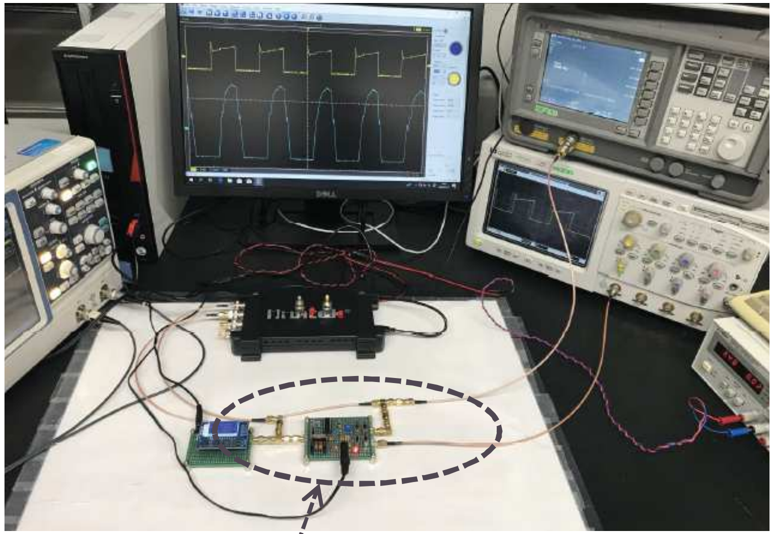
**R3 = R4 = 50 kΩ, C1 = 5 nF, C2 = 10 nF, C3 = 3.18 nF, at $f_0$ = 100 kHz.**

- **Over-damping (R5 = 0.5 kΩ),**
- **Critical damping (R5 = 1 kΩ), and**
- **Under-damping (R5 = 2 kΩ).**

# Measurement Set Up for 3rd-Order Ladder LPF

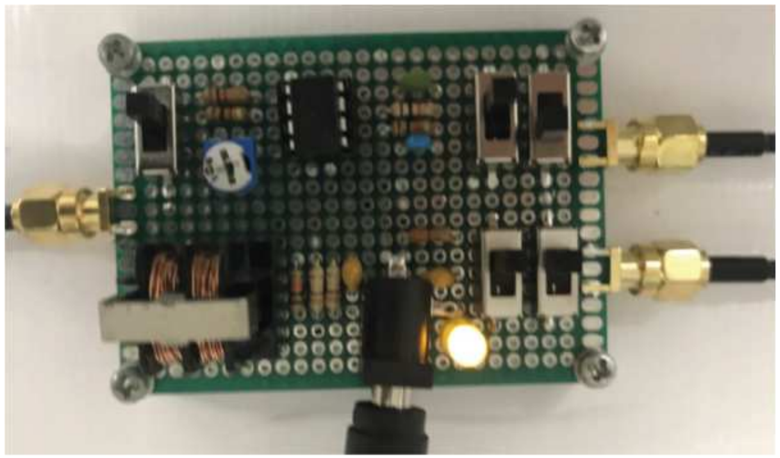
## Measurement of self-loop function



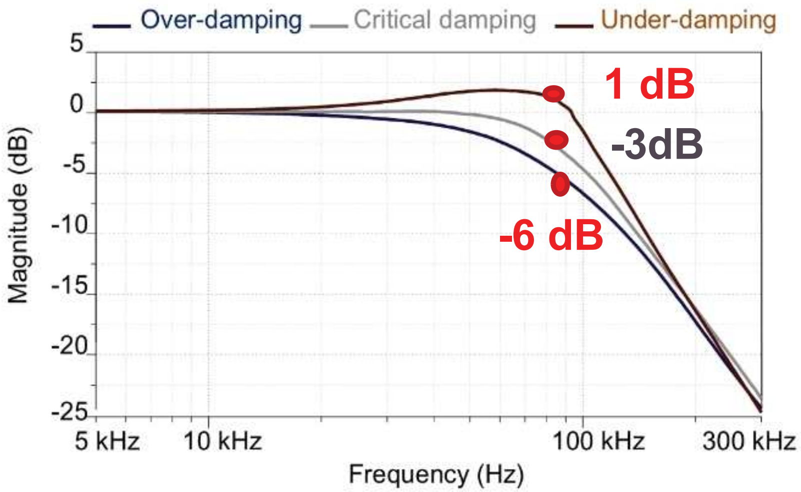
System under test

**Balun transformer (10 mH inductance)**

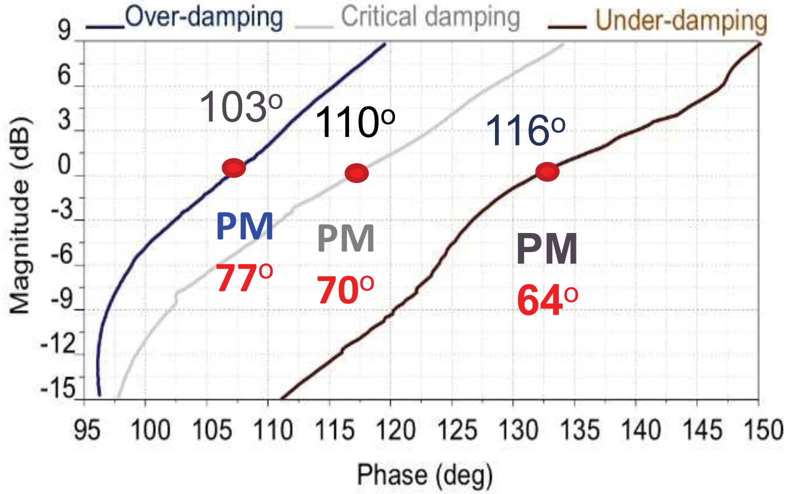


# Measurement Results of 3rd-order Ladder LPF

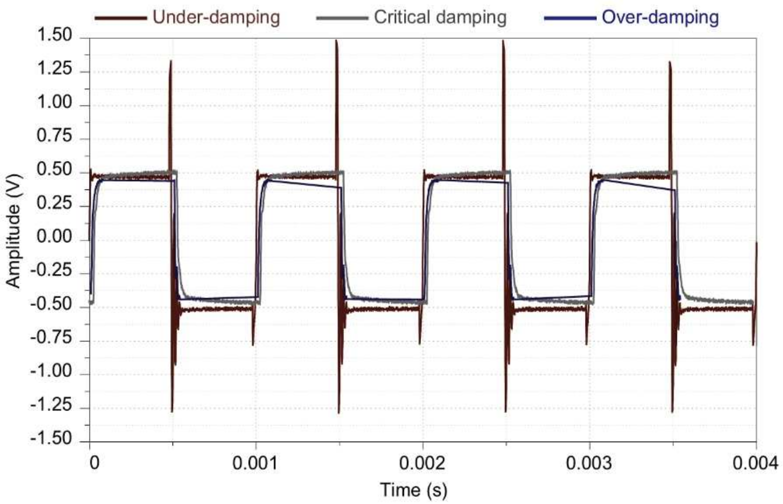
## Bode plot of transfer function




## Nichols plot of self-loop function




## Transient response




**Over-damping:**

→**Phase margin is 77 degrees.**

**Critical damping:**

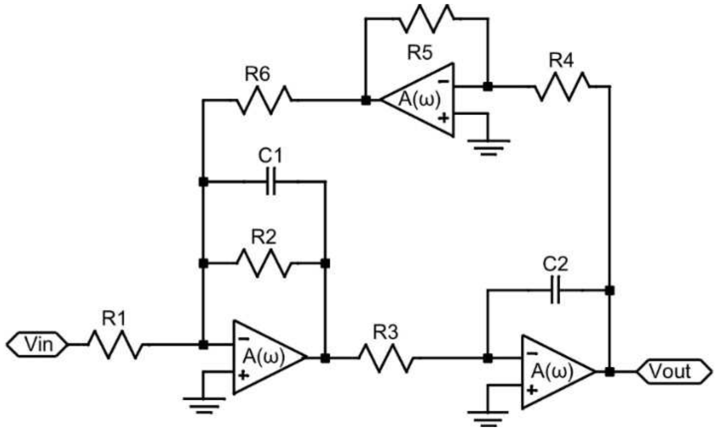
→**Phase margin is 70 degrees.**

**Under-damping:**

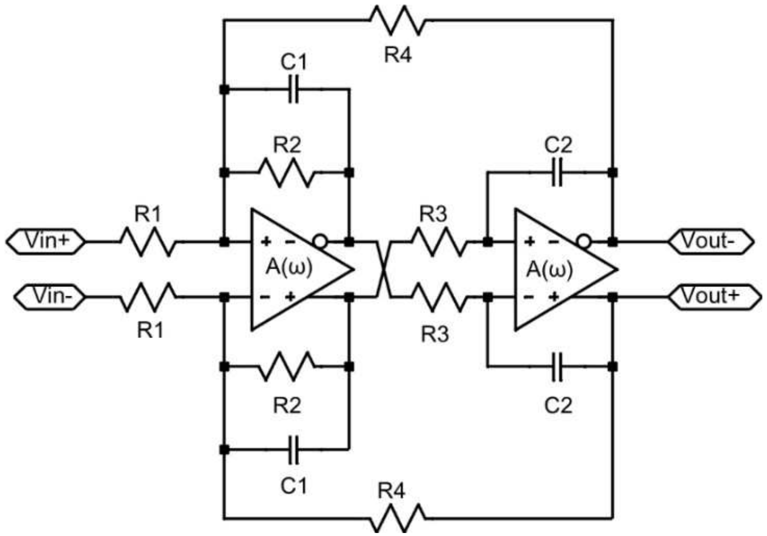
→**Phase margin is 64 degrees.**

# Analysis of 2nd-Order Tow-Thomas LPF

## Single ended Tow-Thomas LPF




## Fully differential Tow-Thomas LPF




## Transfer function & self-loop function

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

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

**where,** $b_0 = \frac{R_4 R_6}{R_1 R_5};$

$$a_0 = \frac{R_3 R_4 R_6 C_1 C_2}{R_5}; a_1 = \frac{R_3 R_4 R_6 C_2}{R_2 R_5};$$

### Component parameters

**GBW = 10MHz, Ao = 100000,**

**fo = 25kHz, C1 =1 nF, C2 = 100 pF,**

**R1= R4 = R5 = 1kΩ, R3 = 100 kΩ, R6 = 5 kΩ.**

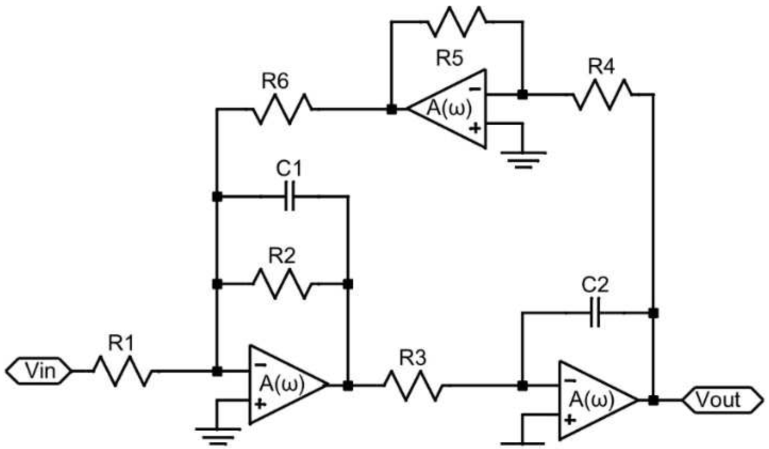
**Under-damping: R2 = 10 kΩ,**

**Critical damping: R2 = 3.5 kΩ,**

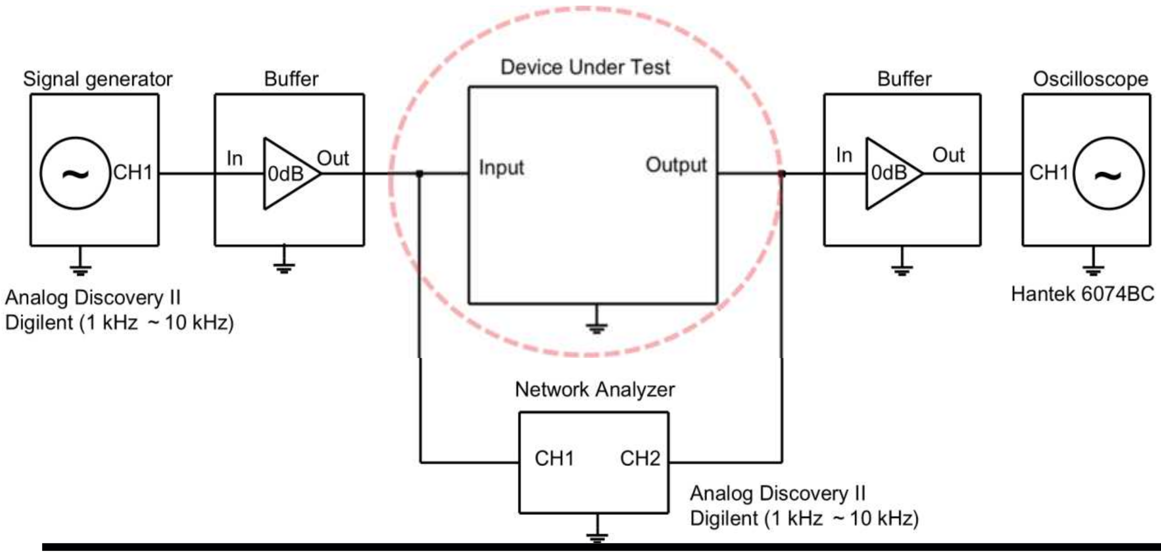
**Over-damping: R2 = 10 kΩ**

# Measurement set up for Tow-Thomas LPF

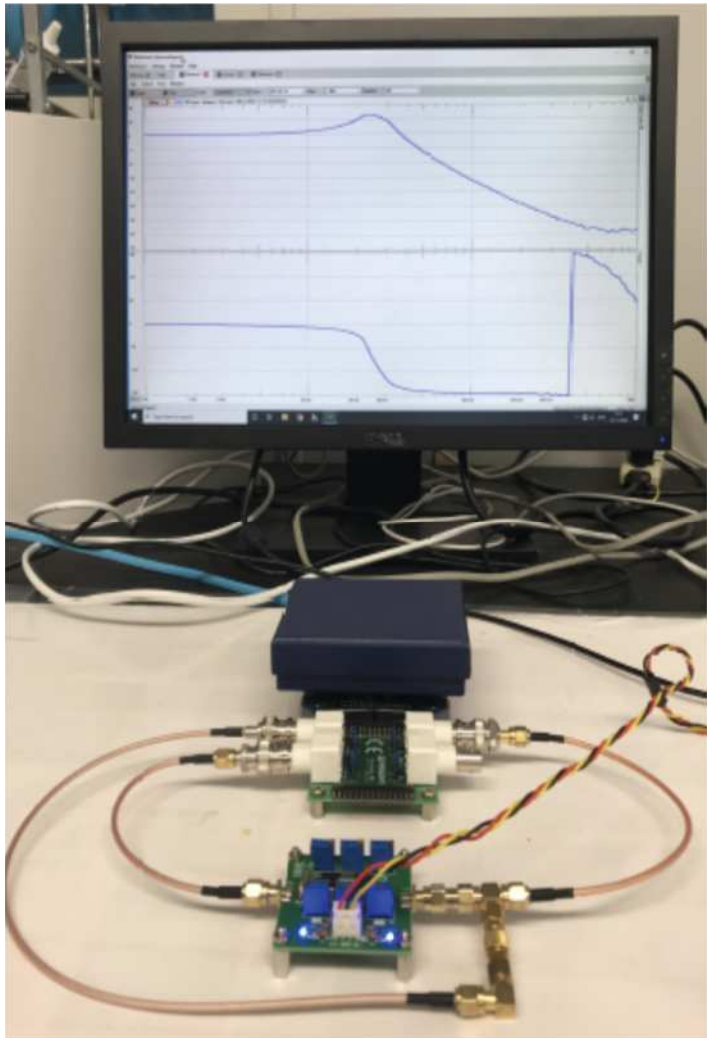
## Schematic of Tow-Thomas LPF




## System Under Test

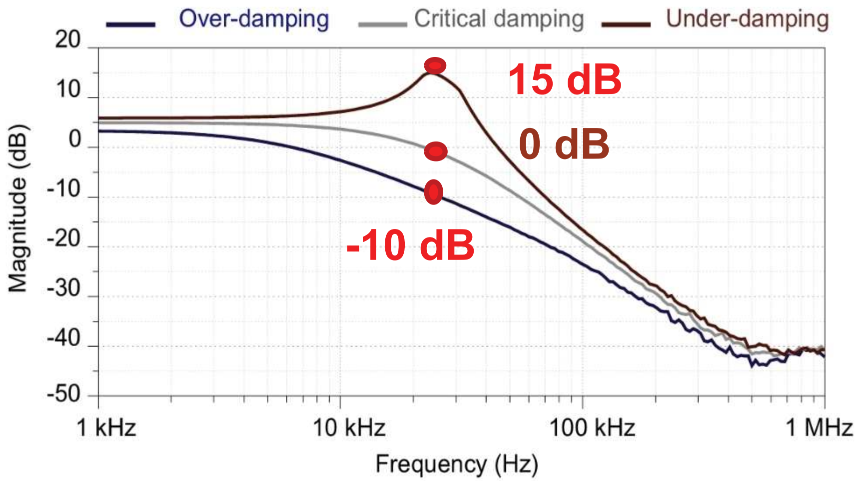



## Measurement set up

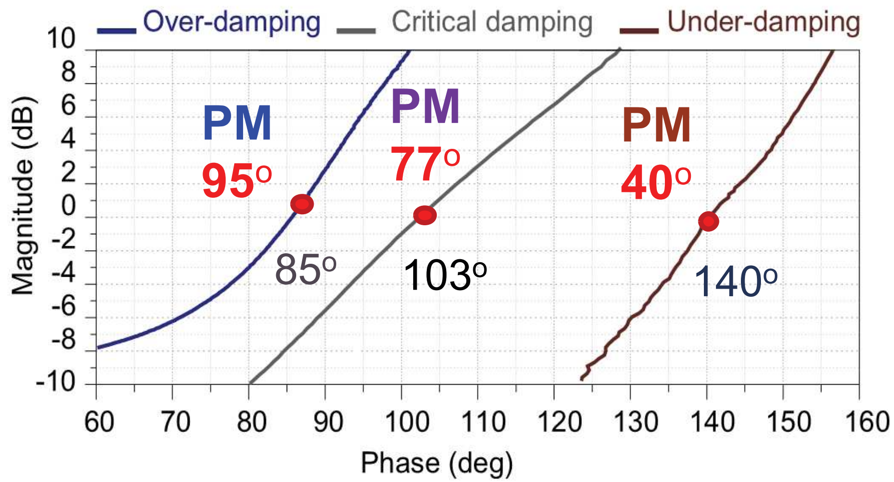


# Measurement Results of Tow-Thomas LPF

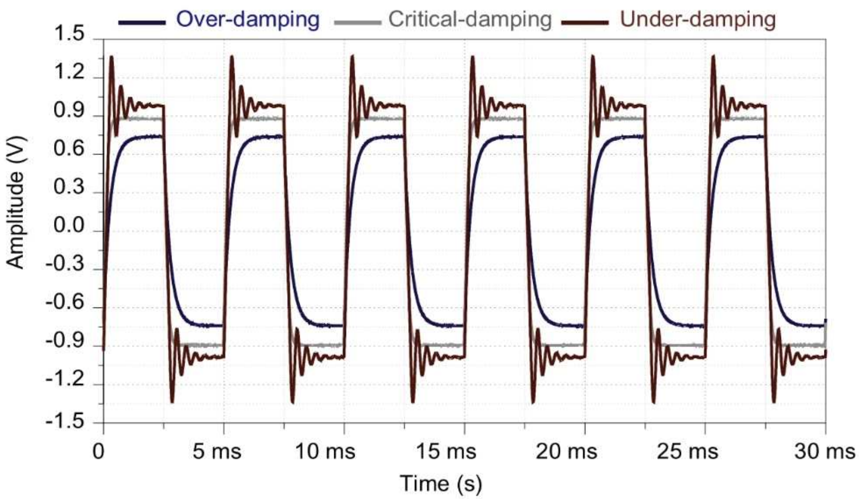
## Bode plot of transfer function




## Nichols plot of self-loop function




## Transient response




**Over-damping:**

→**Phase margin is 95 degrees.**

**Critical damping:**

→**Phase margin is 77 degrees.**

**Under-damping:**

→**Phase margin is 40 degrees.**

# Outline

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- Stability test for Tow-Thomas low-pass filters
5. Conclusions

## Limitations of Existing Methods

- **Middlebrook's measurement of loop gain**

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

- **Replica measurement of loop gain**

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

- **Nyquist's stability condition**

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

- **Nichols chart of loop gain**

→ **Only used in feedback control theory (Lab tool).**

# Merits of Self-loop Function

| Features | Comparison measurement | Alternating current conservation | Replica measurement | Middlebrook's method |
|---|---|---|---|---|
| Main objective | Self-loop function | Self-loop function | Loop gain | Loop gain |
| Transfer function accuracy | Yes | Yes | No | No |
| Breaking feedback loop | No | Yes | Yes | Yes |
| Operating region accuracy | Yes | Yes | No | No |
| Phase margin accuracy | Yes | Yes | No | No |
| Passive networks | Yes | Yes | No | No |

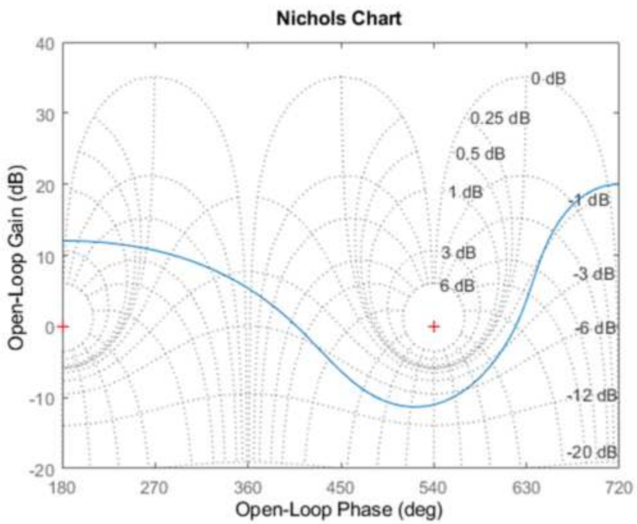
# Limitations of Loop Gain on Nichols Chart

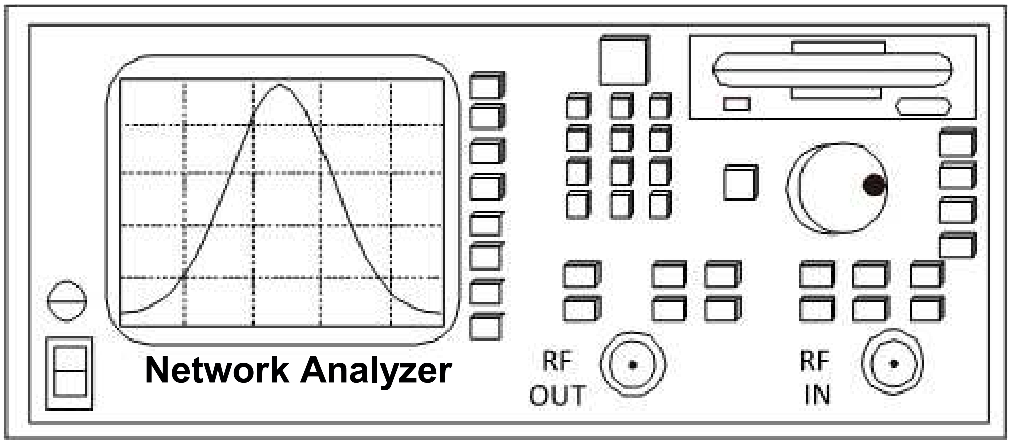
- **Loop gain is independent of frequency variable.**

→**Loop gain in adaptive feedback network is significantly different from self-loop function in linear negative feedback network.**

**Nichols chart is only used in MATLAB simulation.**

**Nichols chart isn't used widely in practical measurements (only used in control theory).**




https://www.mathworks.com/help/control/ref/nichols.html

**(Technology limitations)**

# Conclusions

**This work:**

- **Proposal of comparison measurement for deriving self-loop function in a transfer function**

  **→ Observation of self-loop function can help us optimize the behavior of a high-order system.**

- **Implementation of circuit and measurements of self-loop functions for high-order networks.**

  **→ Theoretical concepts of stability test are verified by laboratory simulations and practical experiments.**

**Future work:**

- **Stability test for parasitic components in transmission lines, printed circuit boards, physical layout layers**

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# Thank you very much!


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Laboratory