Analysis and Evaluation Method of RC Polyphase Filter

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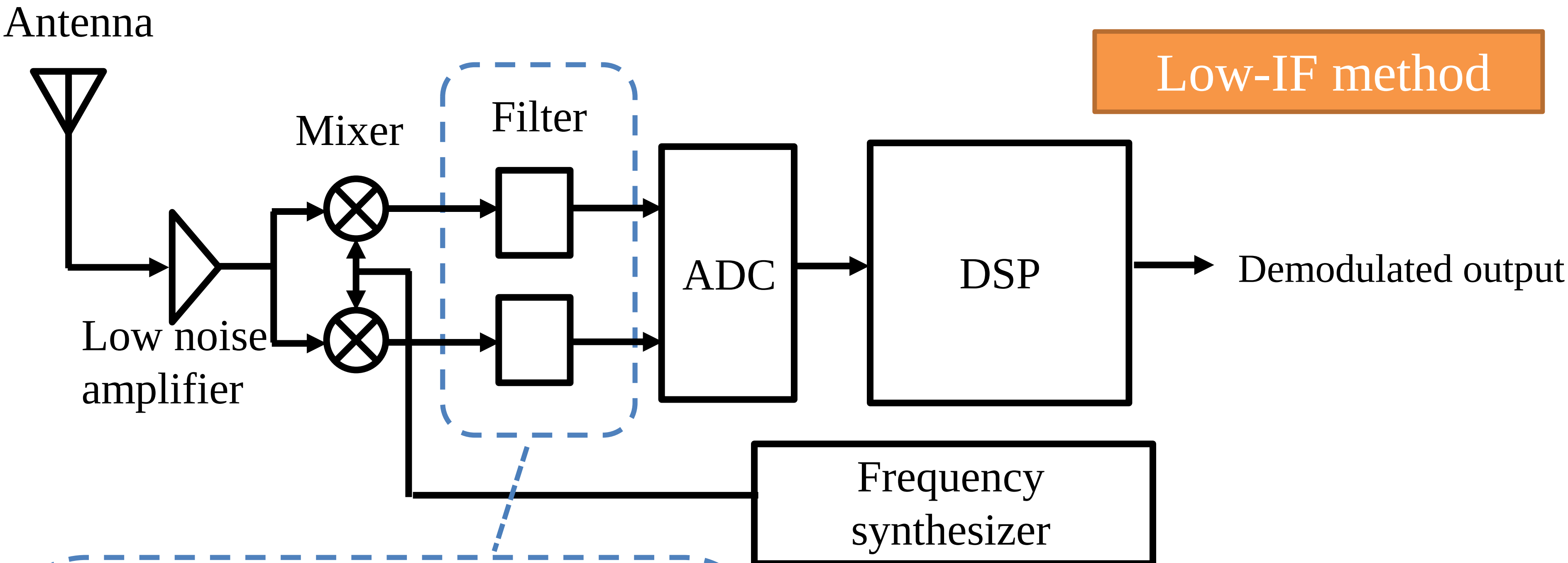
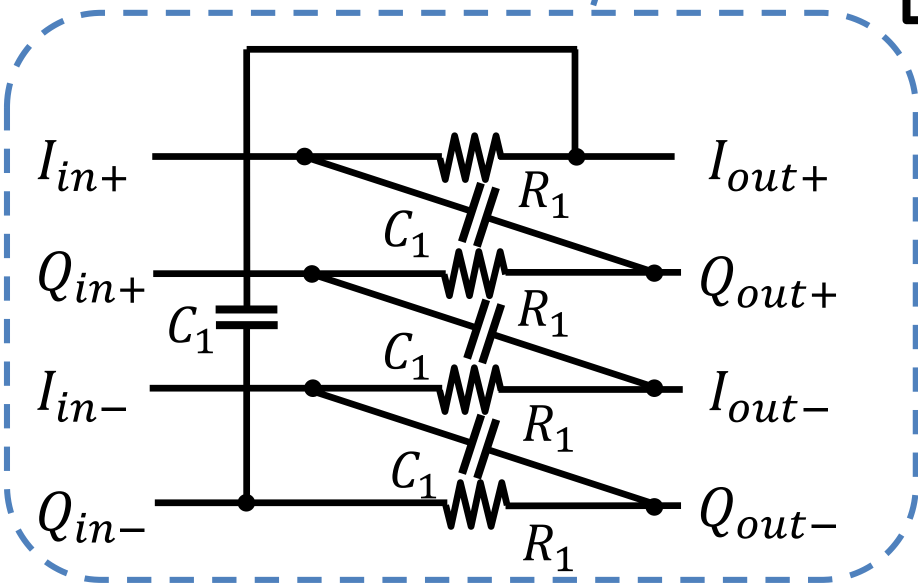
Research Objective





Use RC polyphase filter

- composed of only resistors and capacitors
- Element variation
  - ➡ I, Q signals are not orthogonal

Proposal Measure mismatch characteristics

OUTLINE

- Research background
- RC polyphase filter
- Orthogonal mismatch evaluation method
  - RCPF orthogonal mismatch model
  - Orthogonal mismatch measurement method
- Simulation result
- Conclusion

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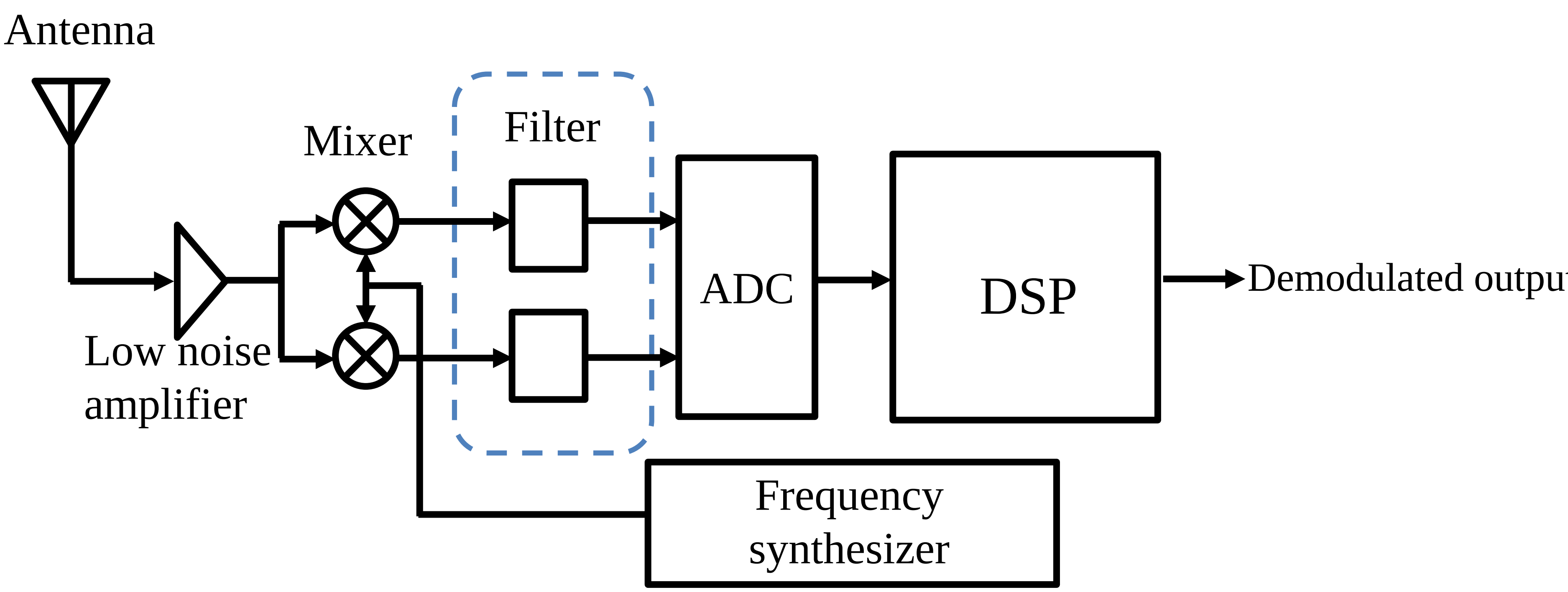
Research Background

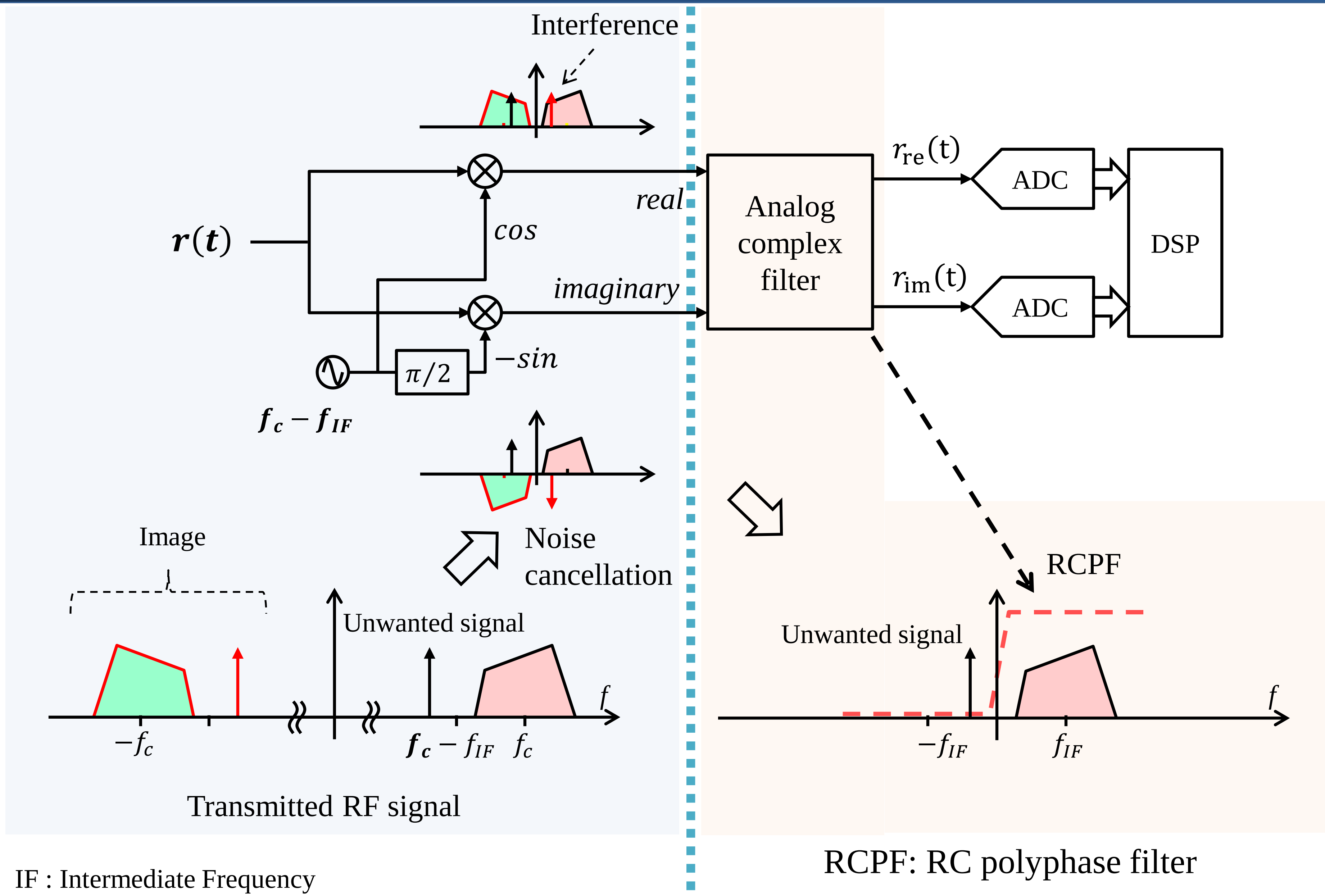
Wireless communication field

Narrowband wireless communication receiver：Low-IF method



Receiver circuit

Low-IF Method



IF : Intermediate Frequency

Our Research Target

Problem

Complex Analog Filter : RC polyphase filter

- Composed of only R's and C's
  - — R, C element variations
  - — I, Q paths mismatch characteristics

Proposal

- Measure mismatch characteristics
  - — Evaluation using multi-tone signal

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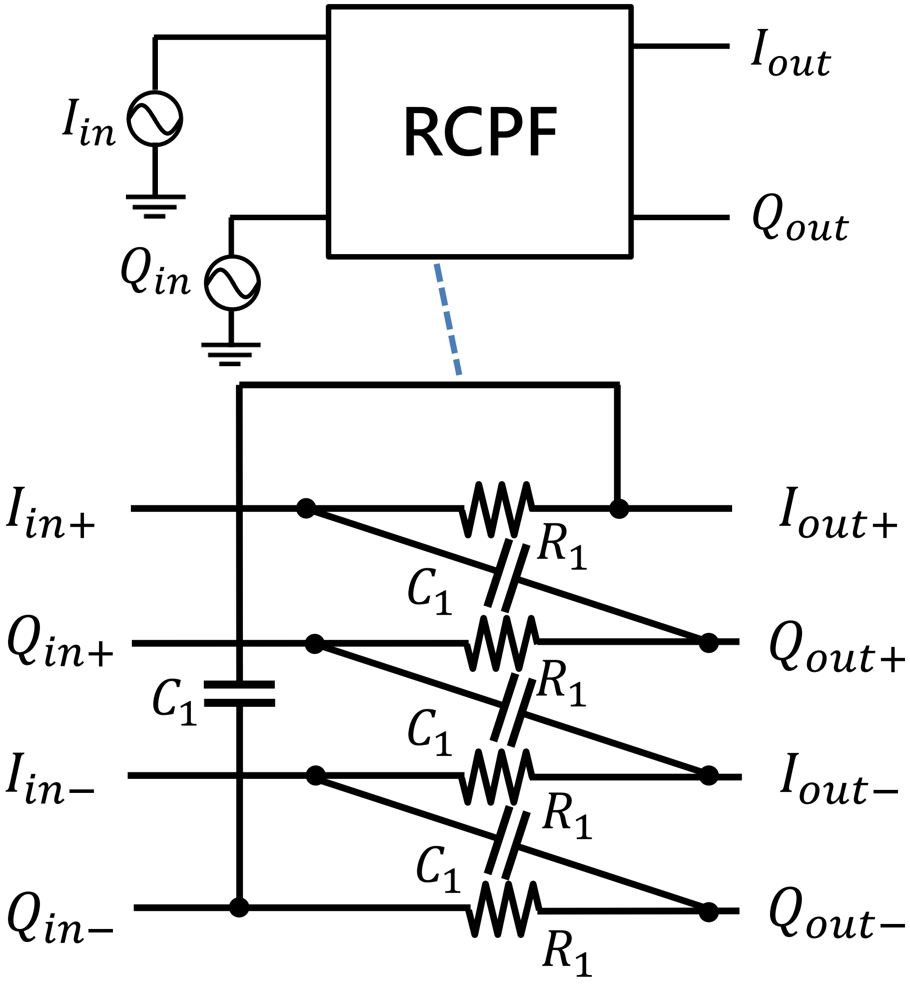
RC Polyphase Filter Circuit



First-order RCPF

Analog complex filter

【Wireless communication field 】
Image removal filter

HPF + LPF overlay circuit
Hilbert filter characteristics

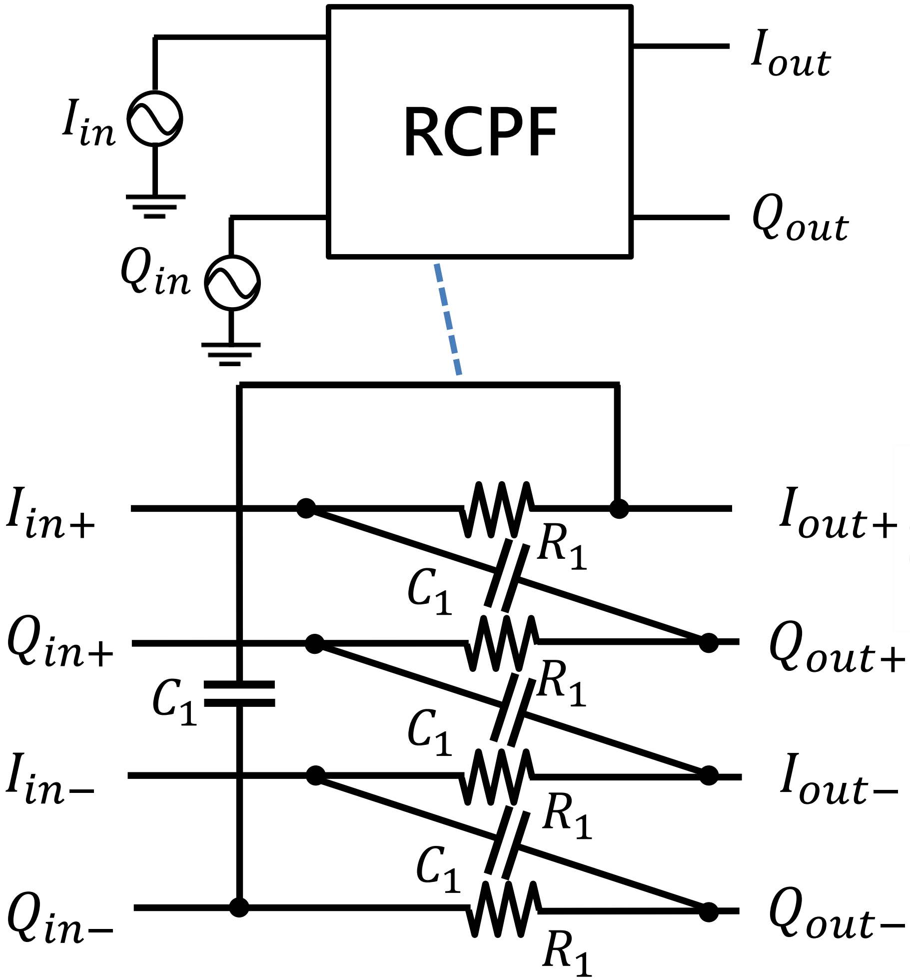
Frequency characteristic :
determined by R and C

【Element variation】

Notch position deviation

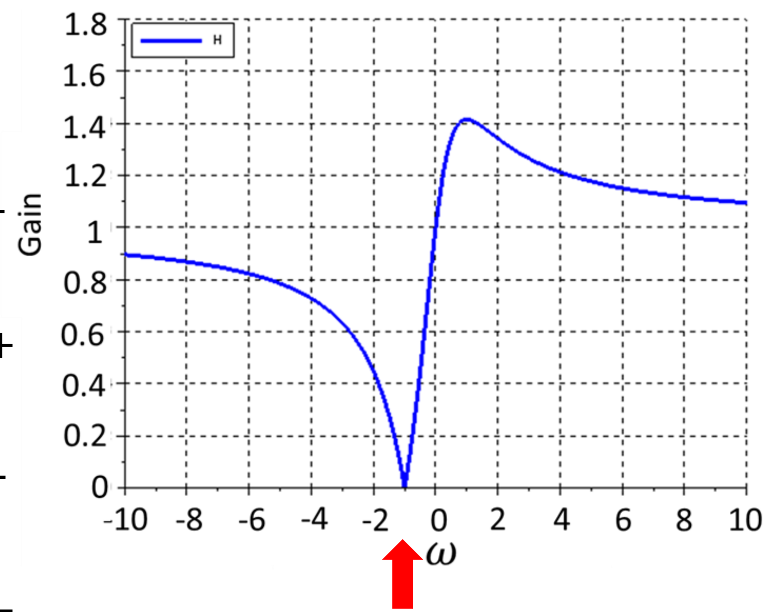
→ Attenuation change

RC Polyphase Filter



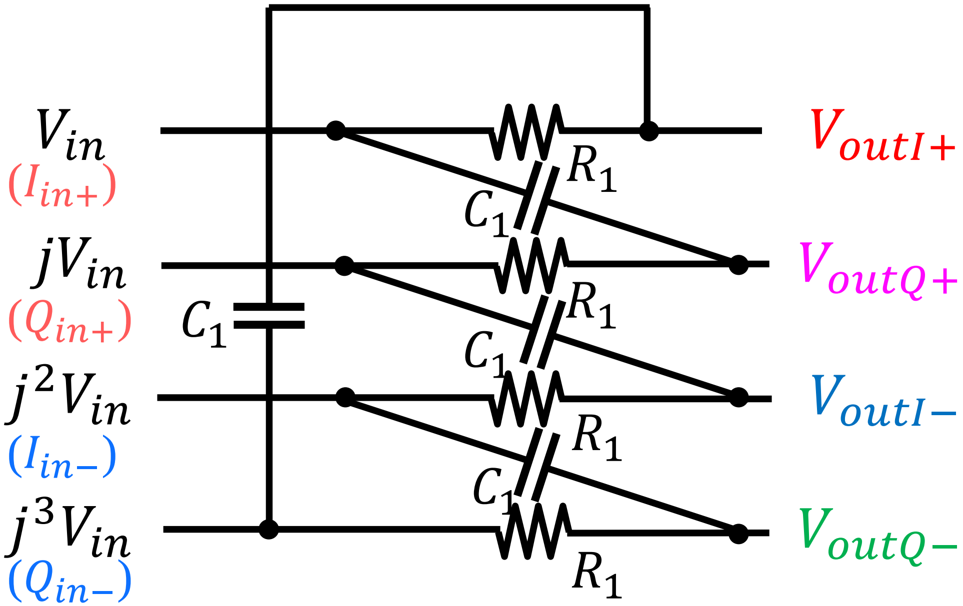
$R_1 = 1k\Omega$、$C_1 = 10pF$

Frequency characteristic :
Determined by R_1 and C_1

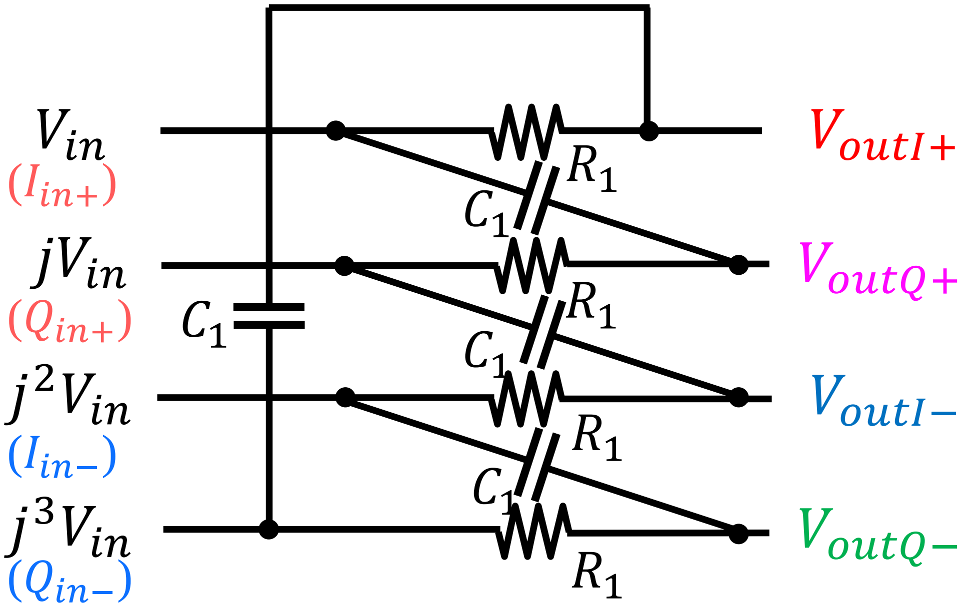


$\omega_{zero} = 1/(R_1 C_1)$

RC Polyphase Filter I/O relationship



RC Polyphase Filter I/O relationship



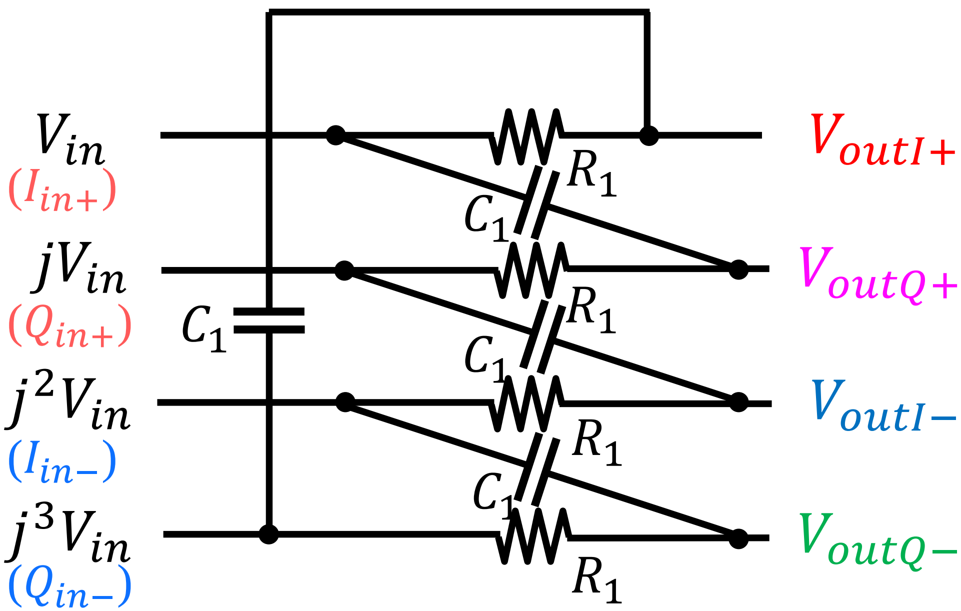
$$V_{outI+} = \frac{1}{1+j\omega CR} V_{in} + \frac{j\omega CR}{1+j\omega CR} j^3 V_{in}$$

$$V_{outQ+} = \frac{1}{1+j\omega CR} jV_{in} + \frac{j\omega CR}{1+j\omega CR} V_{in}$$

$$V_{outI-} = \frac{1}{1+j\omega CR} j^2 V_{in} + \frac{j\omega CR}{1+j\omega CR} jV_{in}$$

$$V_{outQ-} = \frac{1}{1+j\omega CR} j^3 V_{in} + \frac{j\omega CR}{1+j\omega CR} j^2 V_{in}$$

RC Polyphase Filter I/O relationship



Hilbert filter phase characteristics

Frequency at zero $\omega = \dfrac{1}{RC}$

$$V_{outI+} = \frac{1}{1+j\omega CR} V_{in} + \frac{j\omega CR}{1+j\omega CR} j^3 V_{in}$$

$$V_{outQ+} = \frac{1}{1+j\omega CR} jV_{in} + \frac{j\omega CR}{1+j\omega CR} V_{in}$$

$$V_{outI-} = \frac{1}{1+j\omega CR} j^2 V_{in} + \frac{j\omega CR}{1+j\omega CR} jV_{in}$$

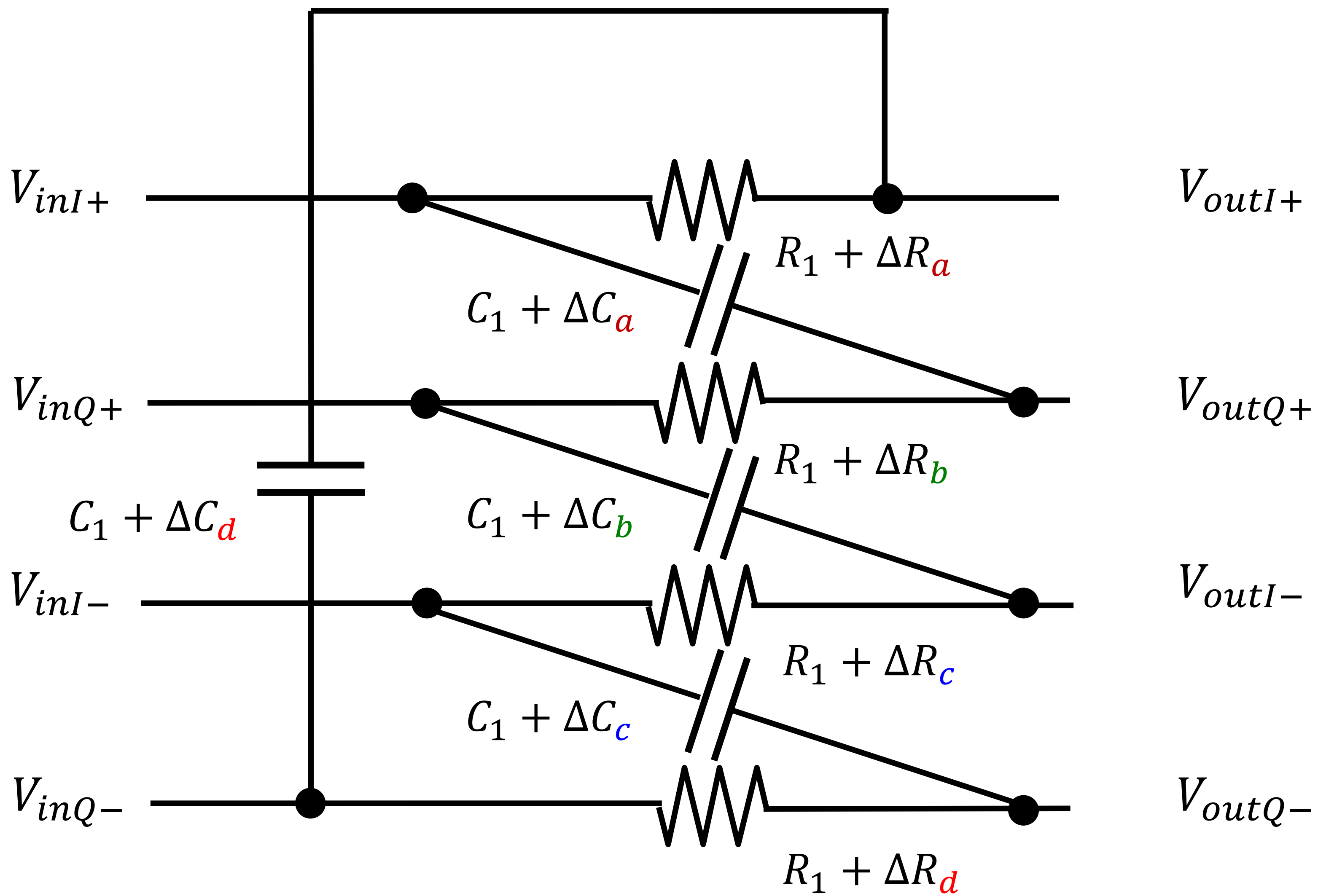
$$V_{outQ-} = \frac{1}{1+j\omega CR} j^3 V_{in} + \frac{j\omega CR}{1+j\omega CR} j^2 V_{in}$$

$$\frac{V_{outI+}}{V_{outQ+}} = -j$$

90°

$$\frac{V_{outI-}}{V_{outQ-}} = j$$

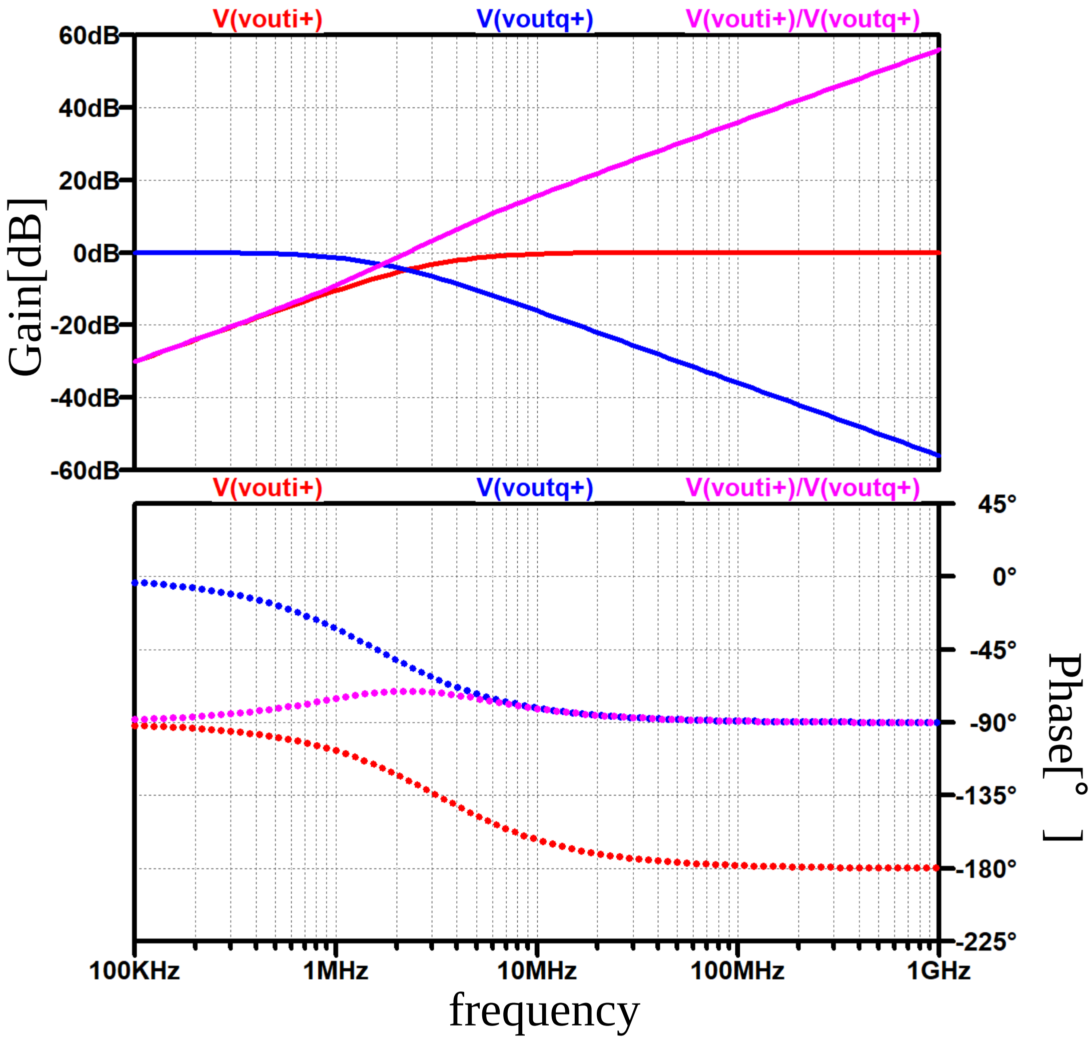
R, C Component Mismatch

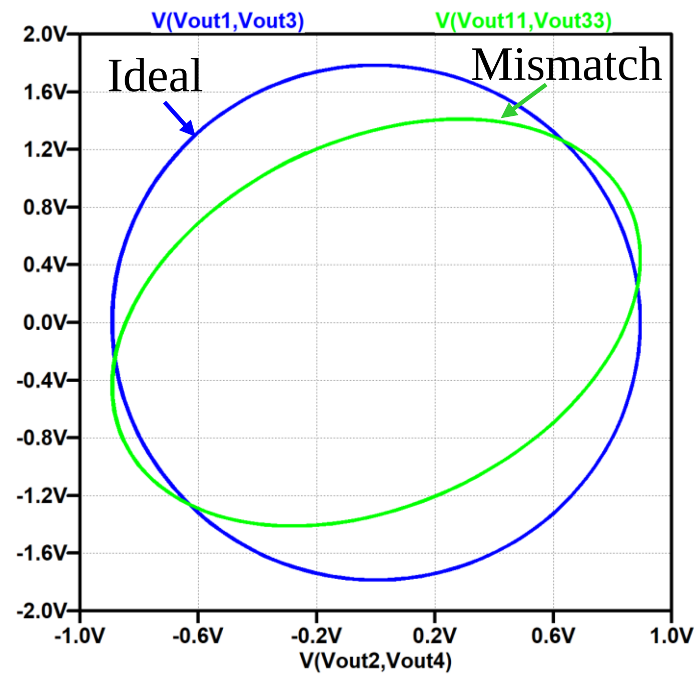


I, Q Imbalance

90° imperfection
in quadrature demodulator

I / Q channels
Phase difference ≠ 90°
Amplitudes are not the same





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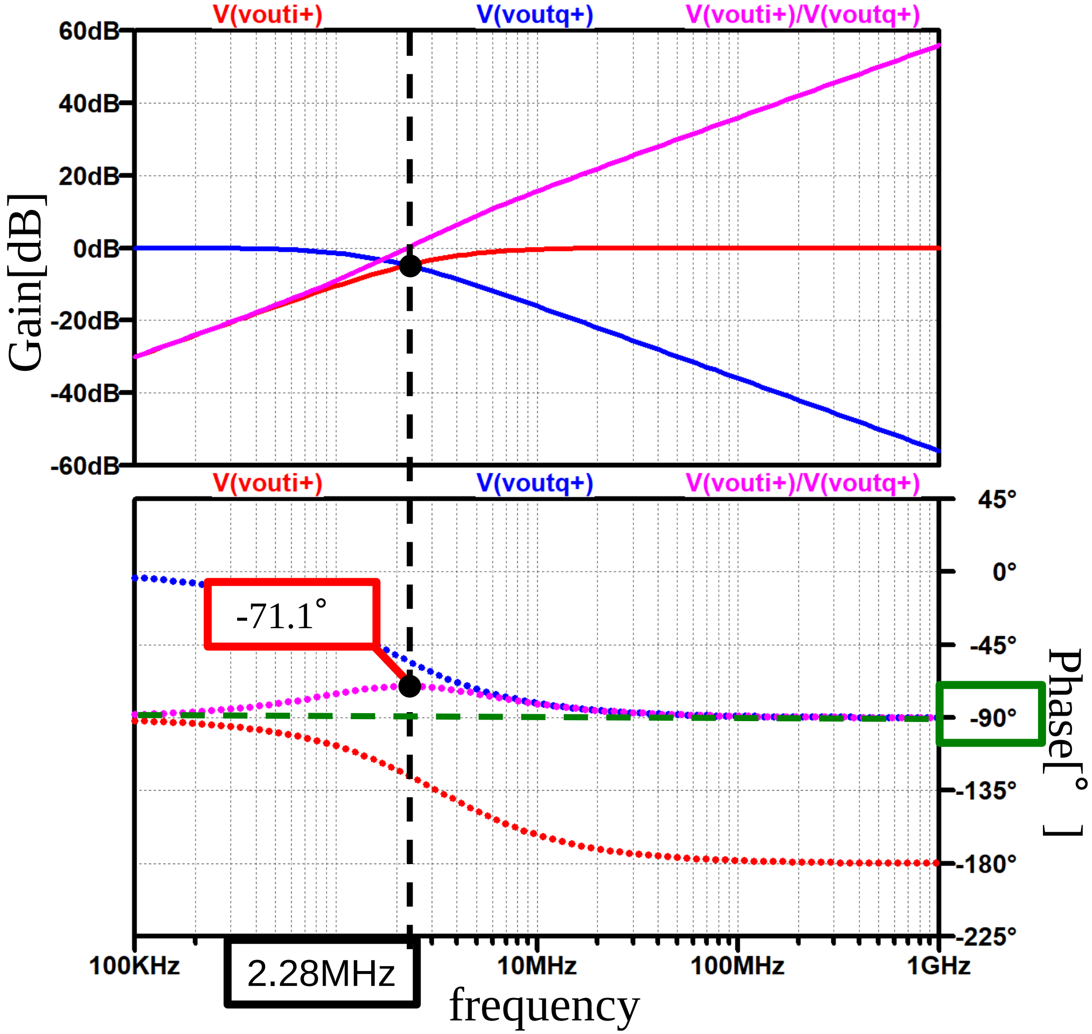

I / Q channels
Phase difference ≠ 90°
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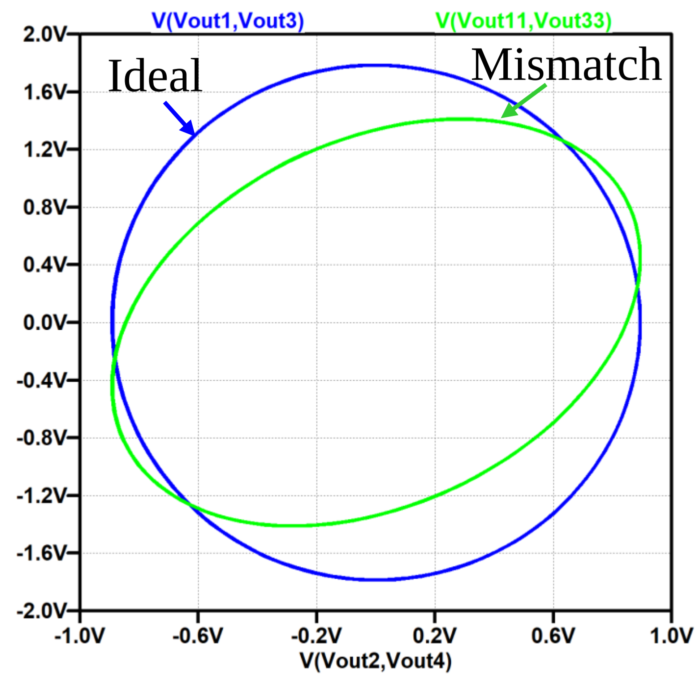

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  - RCPF orthogonal mismatch model
  - Orthogonal mismatch measurement method
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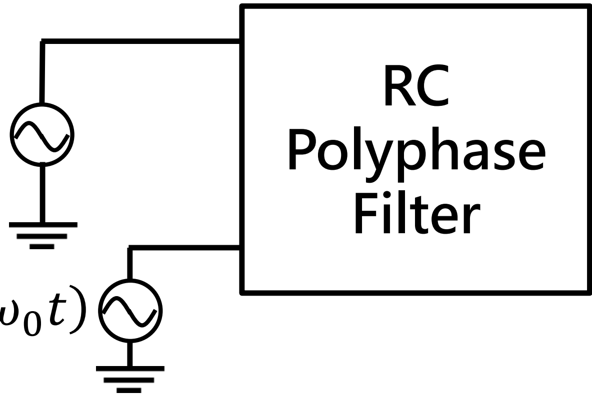
No Mismatch Case: RCPF Orthogonal

$I_{in} = (A + B)\cos(\omega_0 t)$

$Q_{in} = (A - B)\sin(\omega_0 t)$

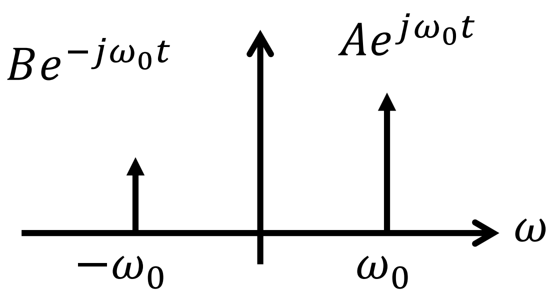


$I_{out} = A\cos(\omega_0 t + \theta)$

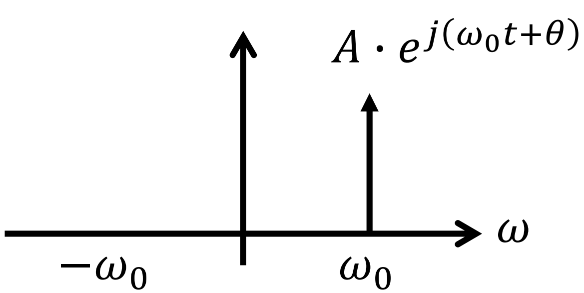
$Q_{out} = A\sin(\omega_0 t + \theta)$

$(G = 1)$

$I_{in} + jQ_{in}$

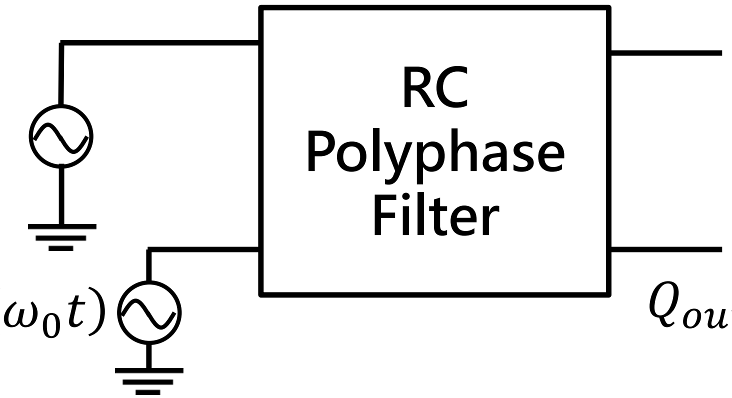


$I_{out} + jQ_{out}$



Mismatch Case :RCPF Orthogonal error

$I_{in} = (A + B)\cos(\omega_0 t)$



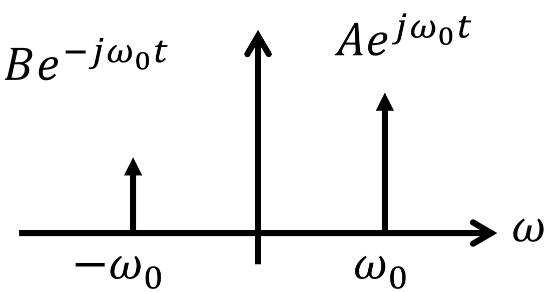
$I_{out} = A\cos(\omega_0 t + \theta)$

$Q_{in} = (A - B)\sin(\omega_0 t)$

$Q_{out} = (1 + \Delta G) \cdot A\sin(\omega_0 t + \theta_{err})$

(Gain mismatch, Phase mismatch)

$I_{in} + jQ_{in}$



$I_{out} + jQ_{out}$

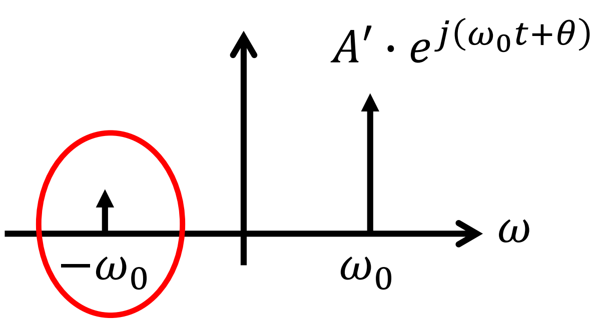
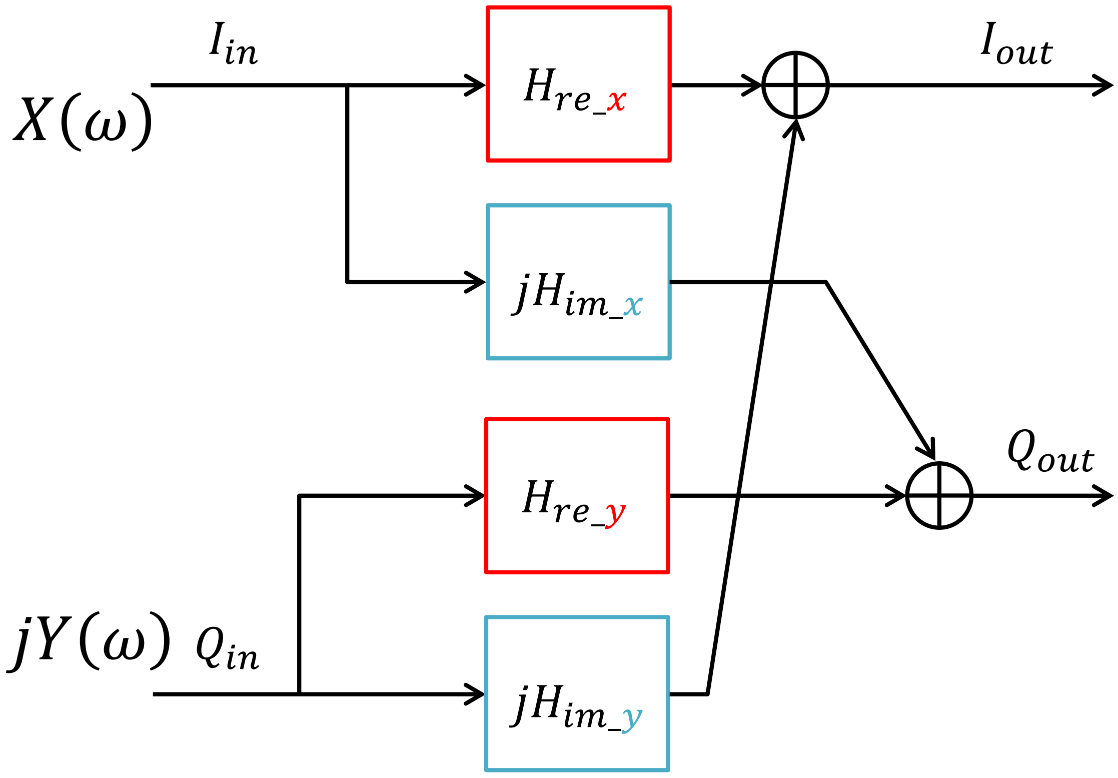
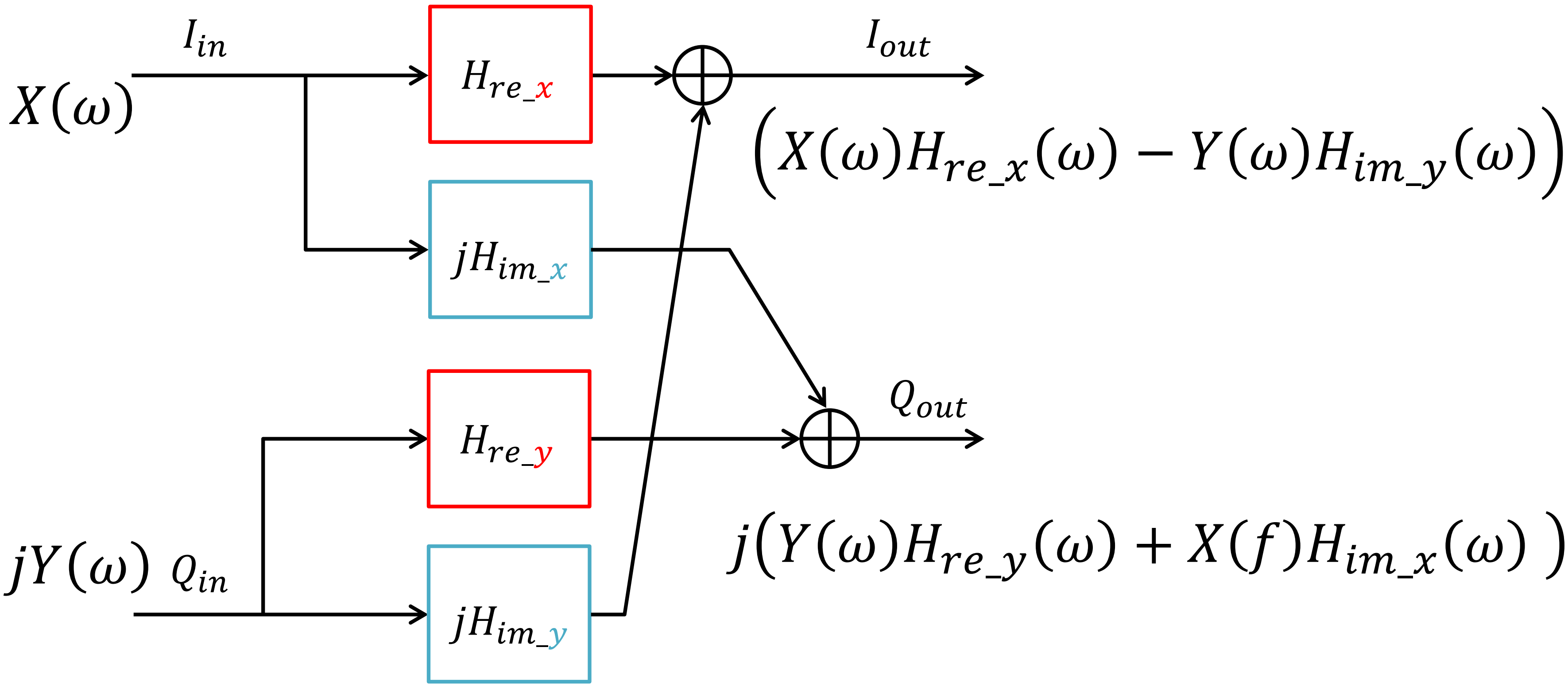


Image signal remains

RCPF Orthogonal Mismatch Model



RCPF Orthogonal Mismatch Model



Orthogonal:

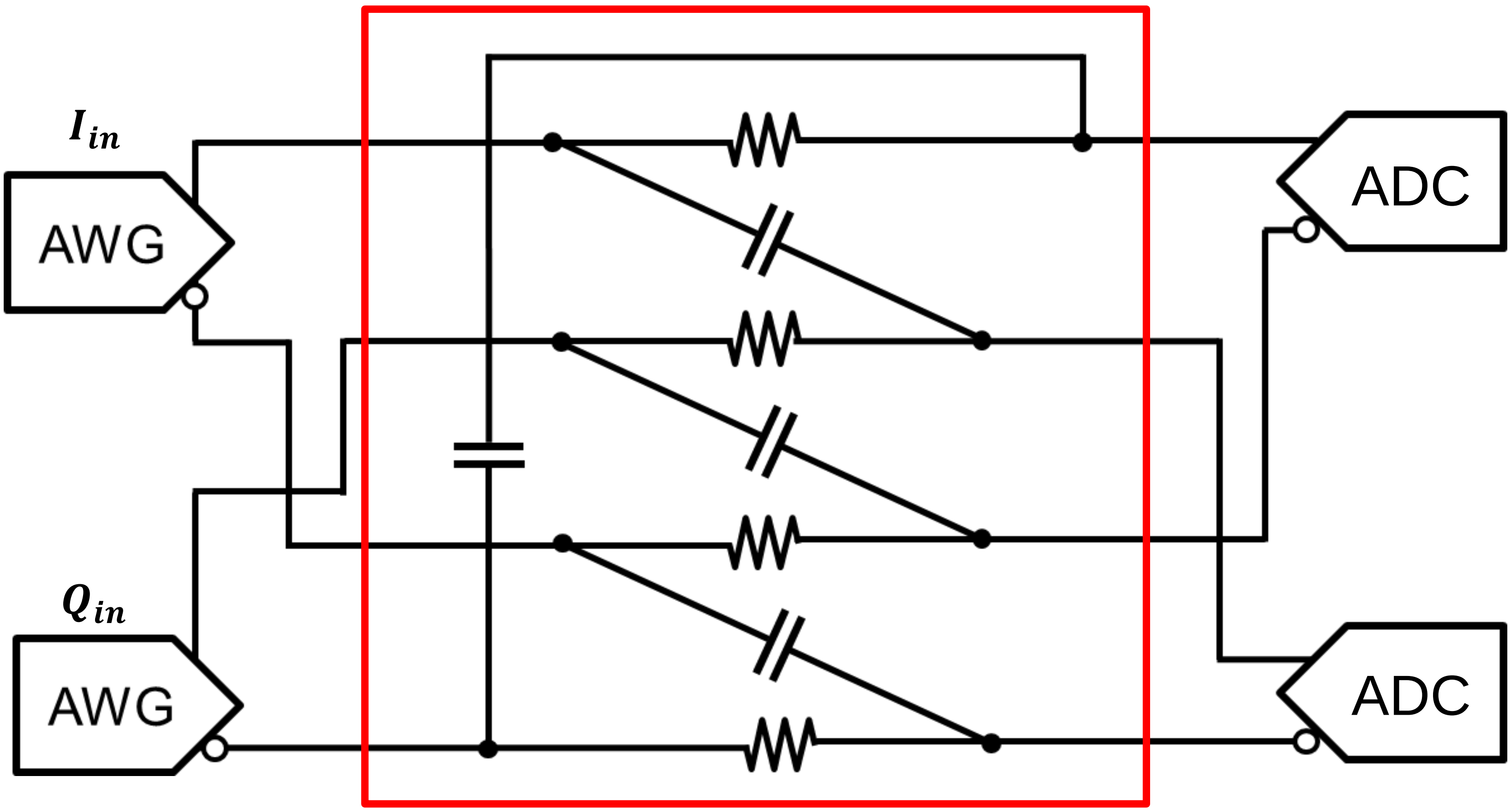
$$H_{im}(\omega)/H_{re}(\omega) = -j \ \ (\omega > 0)$$

Orthogonal mismatch:

$$H_{im}(\omega)/H_{re}(\omega) \neq -j \ \ (\omega > 0)$$

OUTLINE

Mismatch Measuring Method

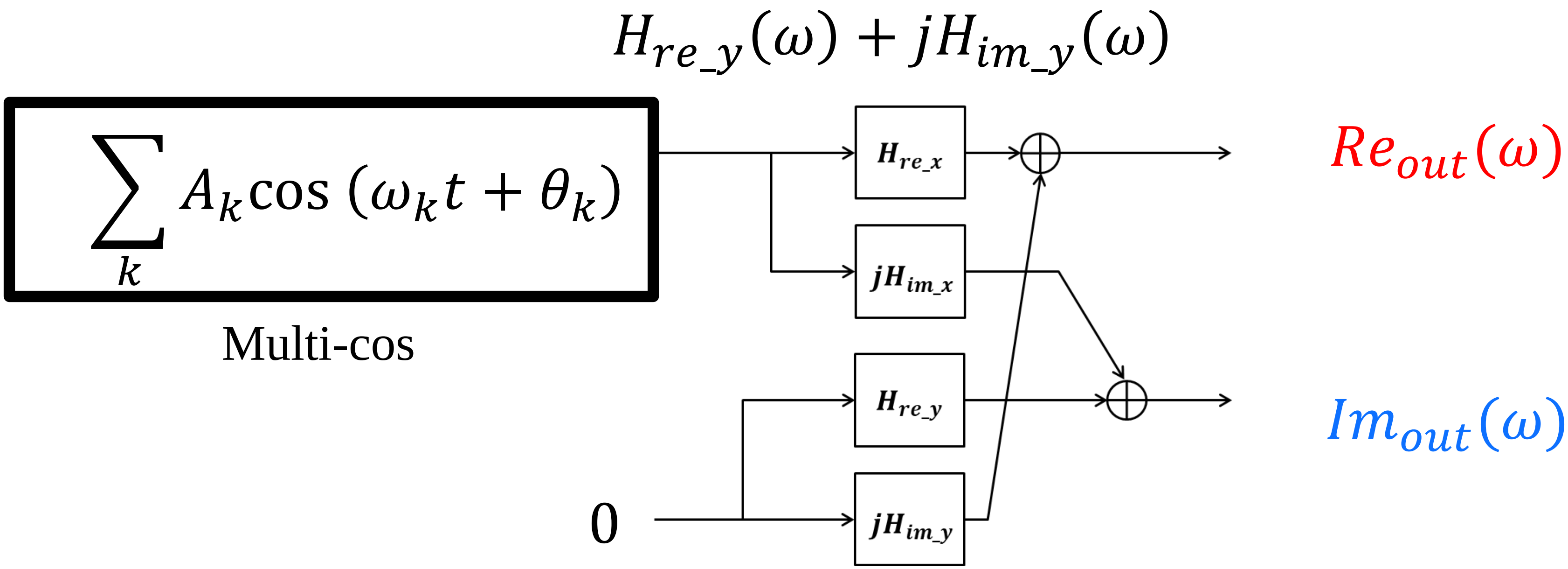


RCPF

AWG : Arbitrary waveform generator

ADC : AD conversion

Real-Path Measurement Method



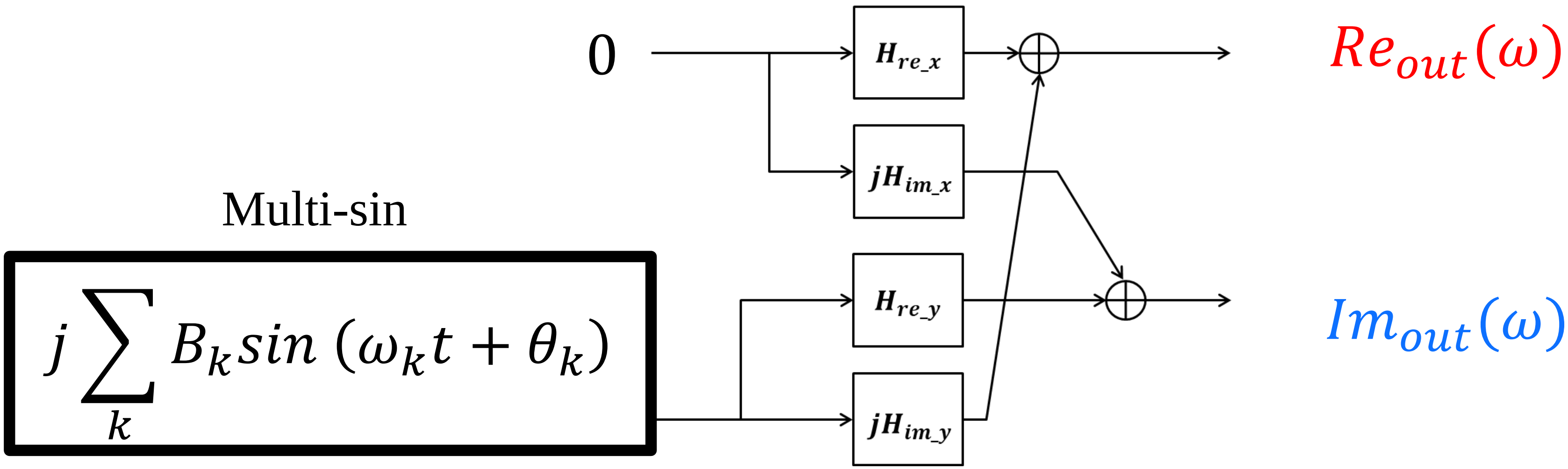
$$ReOut(\omega) = \frac{1}{2}\sum_k A_k\left(H_{re\_x}(\omega_k)e^{j(\omega_k t+\theta_k)} + H_{re\_x}(-\omega_k)e^{-j(\omega_k t+\theta_k)}\right)$$

$$ImOut(\omega) = \frac{j}{2}\sum_k A_k\left(H_{im\_x}(\omega_k)e^{j(\omega_k t+\theta_k)} + H_{im\_x}(-\omega_k)e^{-j(\omega_k t+\theta_k)}\right)$$

$$Imbalance(\omega) = \frac{ImOut(\omega)}{ReOut(\omega)} = \frac{jH_{im\_x}(\omega)}{H_{re\_x}(\omega)}$$

Imaginary-Path Measurement Method

$$H_{re\_y}(\omega) + jH_{im\_y}(\omega)$$



$$ReOut(\omega) = \frac{j}{2}\sum_k B_k\left(H_{im\_y}(\omega_k)e^{j(\omega_k t+\theta_k)} - H_{im\_y}(-\omega_k)e^{-j(\omega_k t+\theta_k)}\right)$$

$$ImOut(\omega) = \frac{1}{2}\sum_k B_k\left(H_{re\_y}(\omega_k)e^{j(\omega_k t+\theta_k)} - H_{re\_y}(-\omega_k)e^{-j(\omega_k t+\theta_k)}\right)$$

$$Imbalance(\omega) = \frac{ReOut(\omega)}{ImOut(\omega)} = \frac{jH_{im\_y}(\omega)}{H_{re\_y}(\omega)}$$

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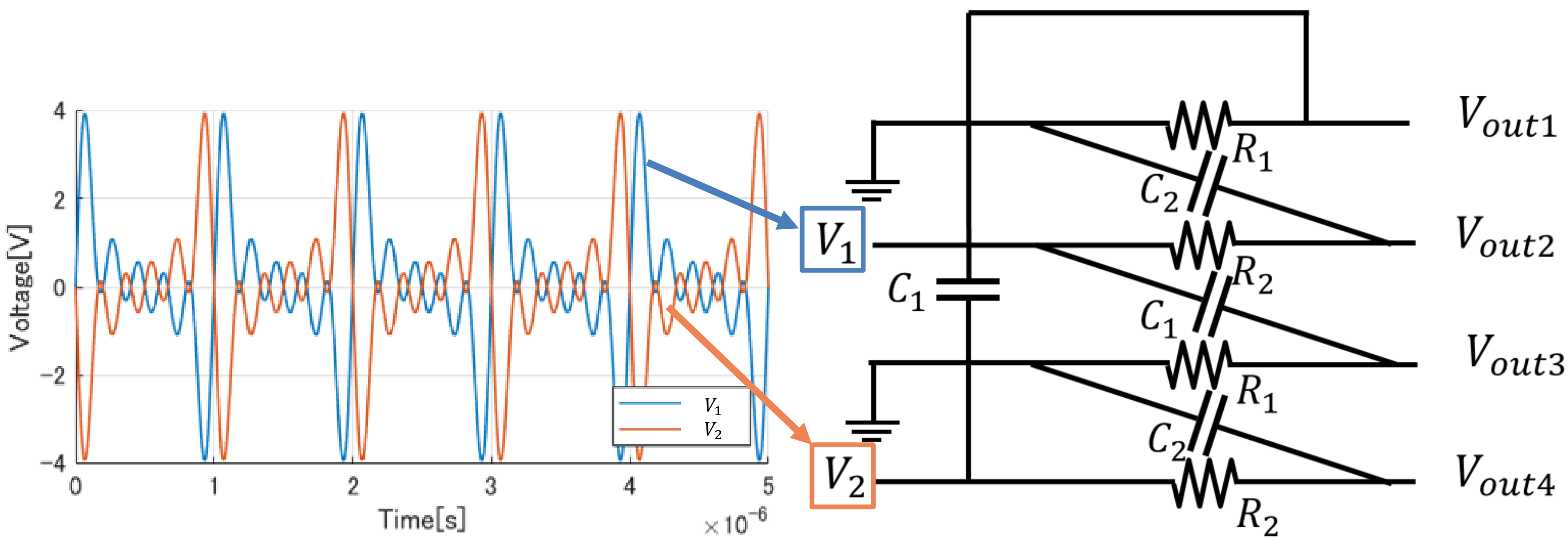
Simulation model

LT spice simulation

Gain characteristics

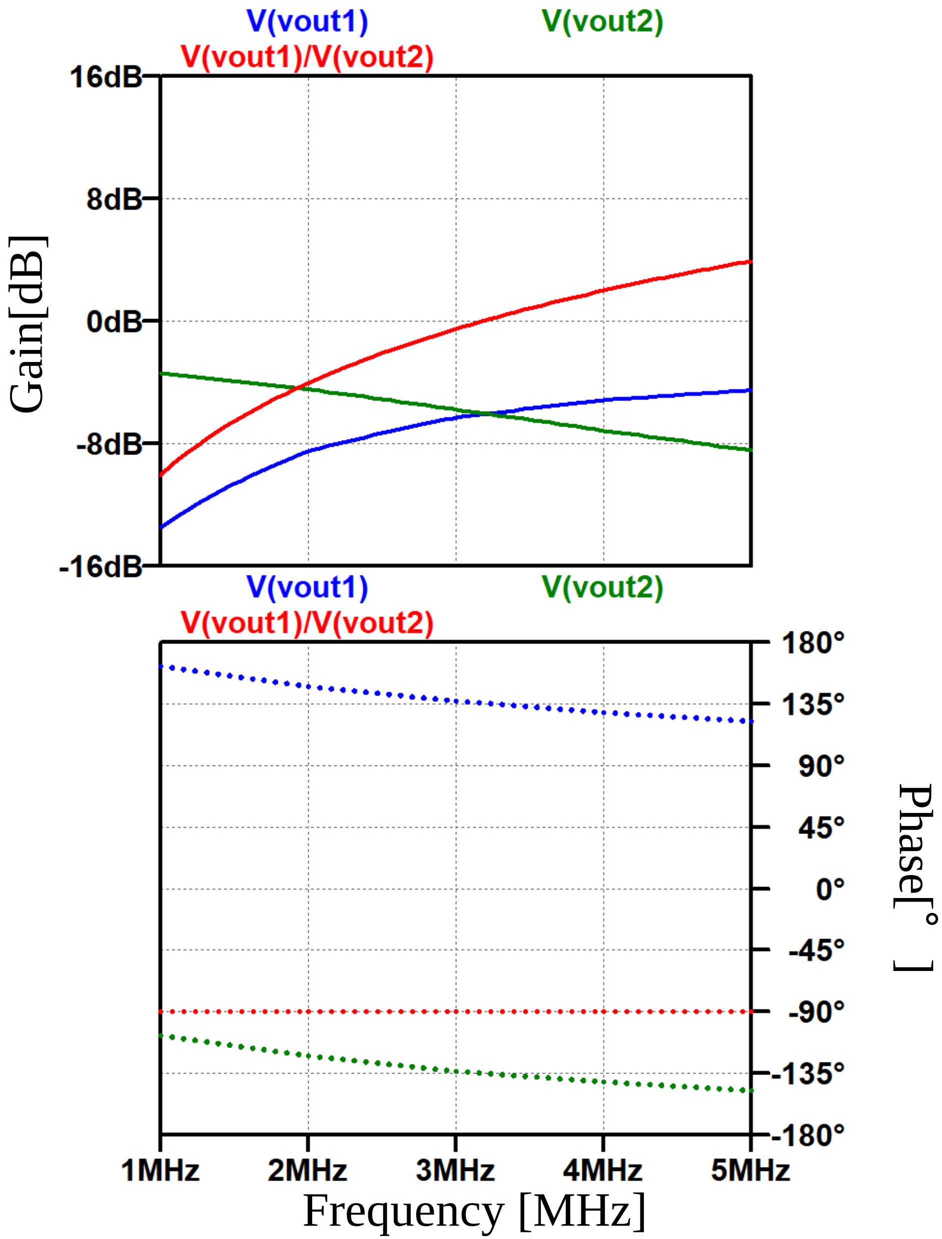
$R_1C_1 = R_2C_2$

3.18MHz、20log（Vout 1 / Vout 2）= 0dB

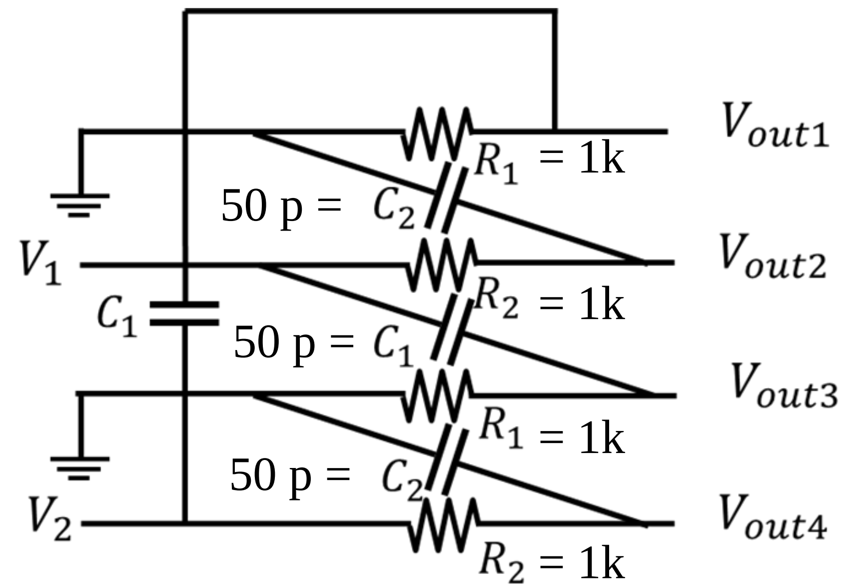


Input waveforms

Simulation result [No mismatch]

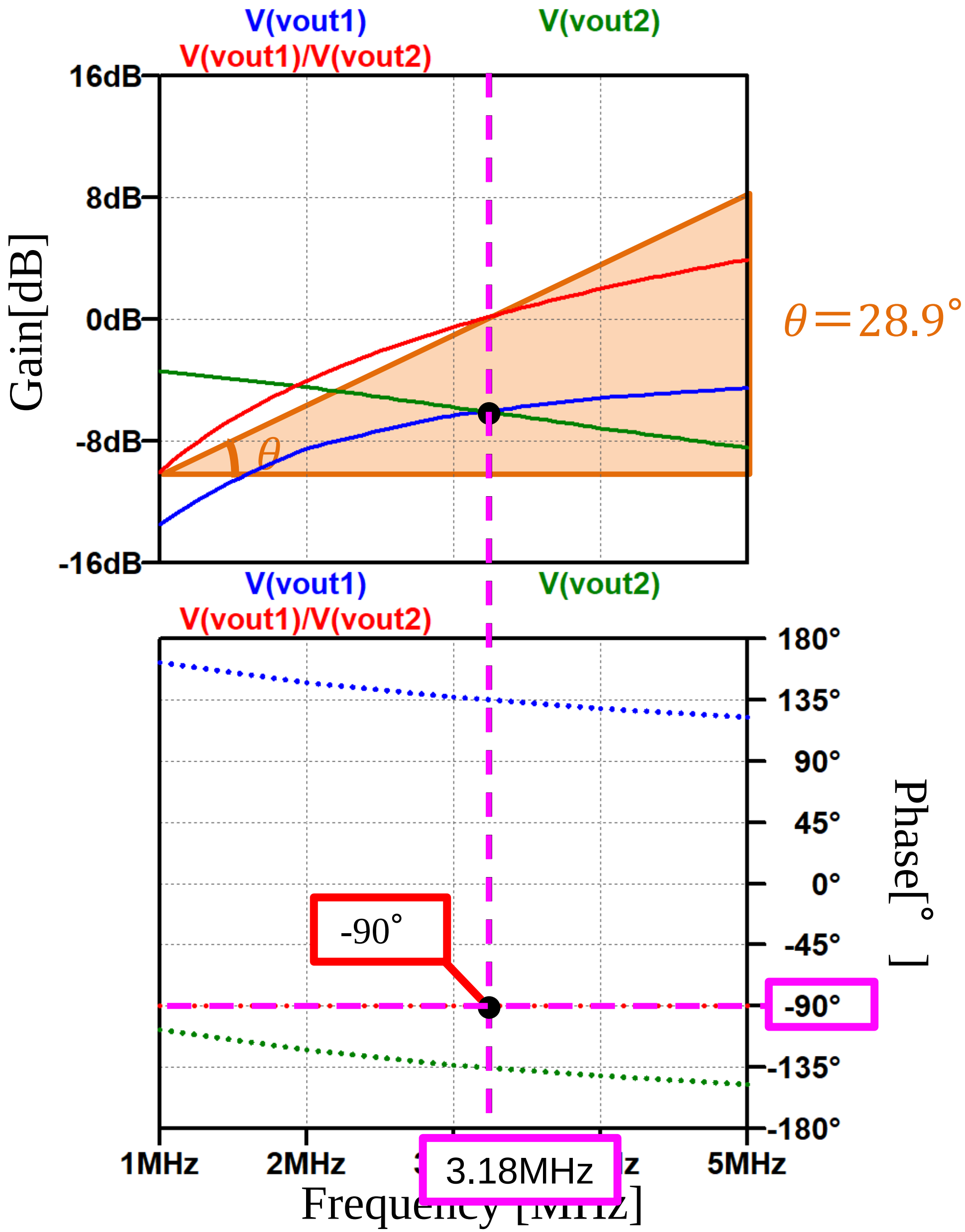


$$R_1 = R_2$$
$$C_1 = C_2$$
$$\frac{Imout}{Reout} = j$$



1/ (2πR1C1) = 3.18MHz
1/ (2πR2C2) = 3.18MHz

Simulation result [No mismatch]



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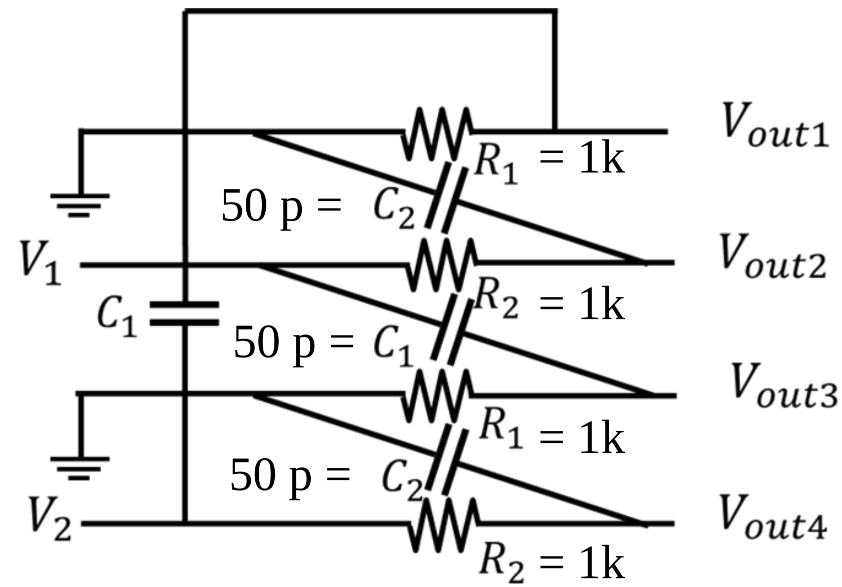
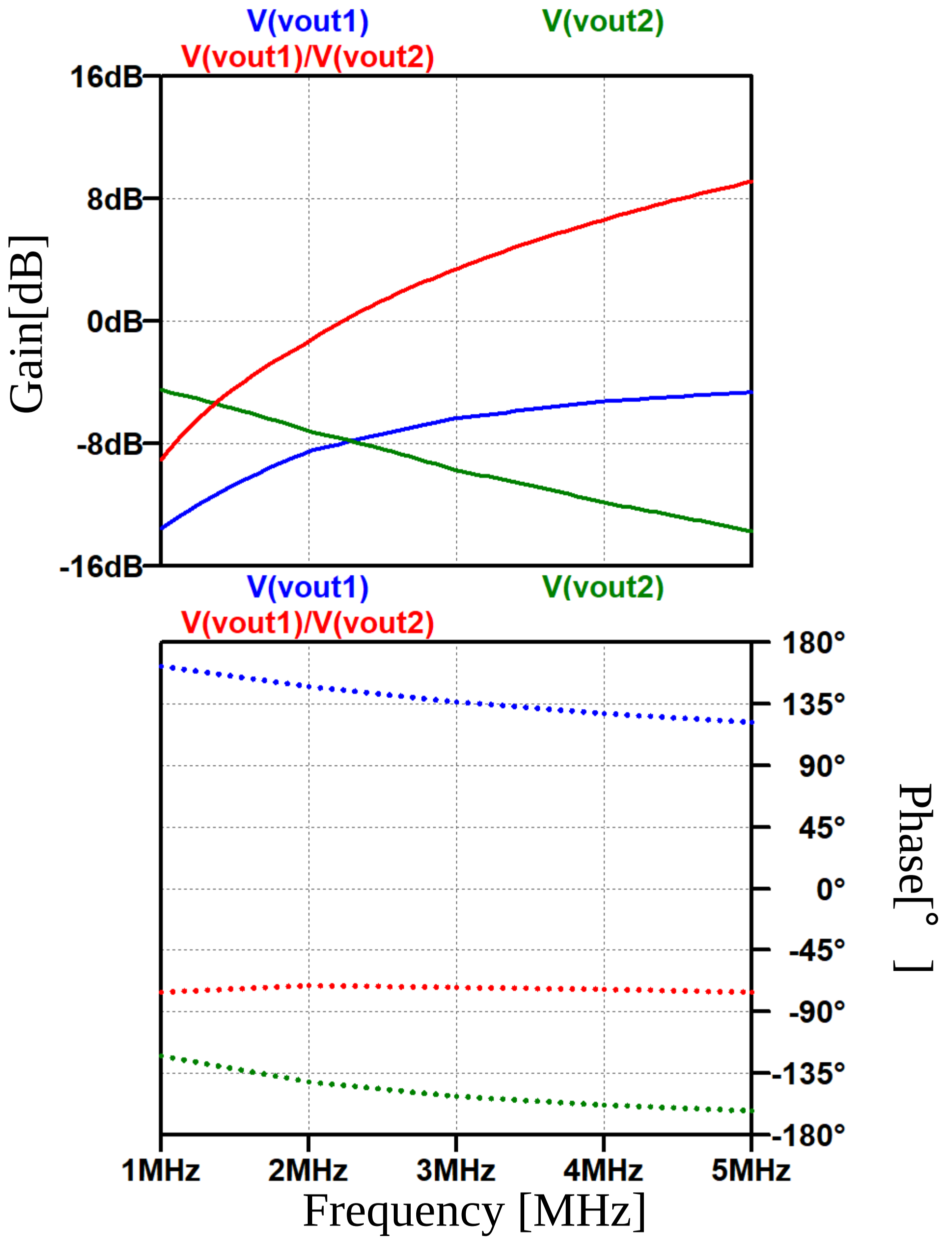
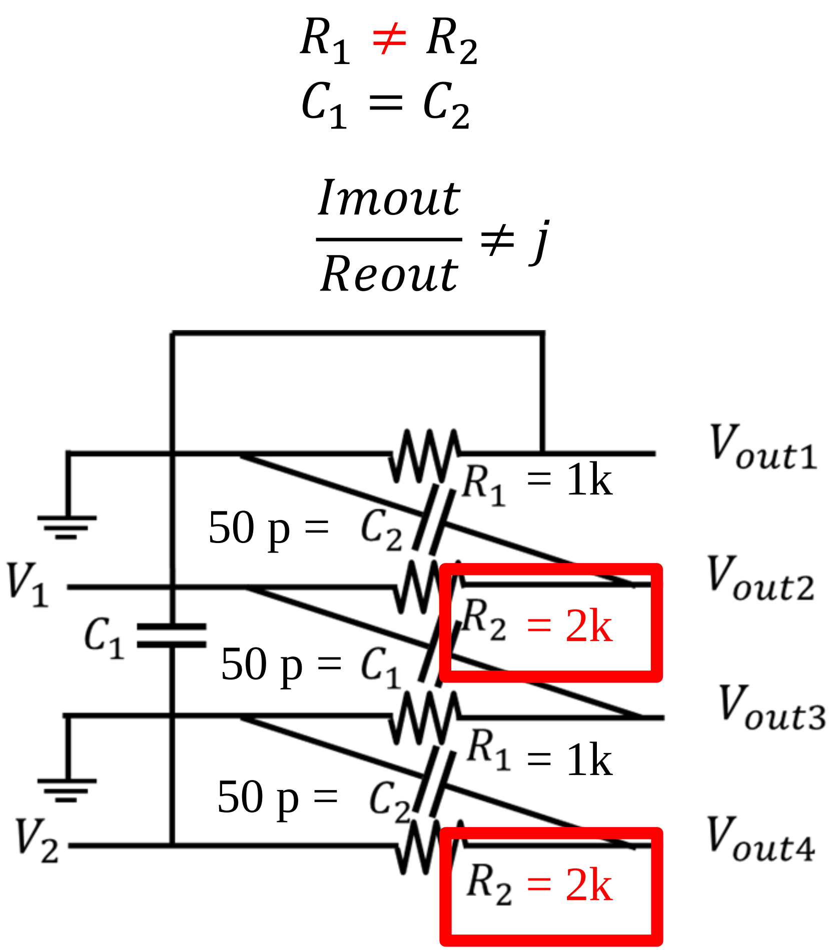


1/ (2πR1C1) = 3.18MHz
1/ (2πR2C2) = 3.18MHz

Simulation result [R mismatch]

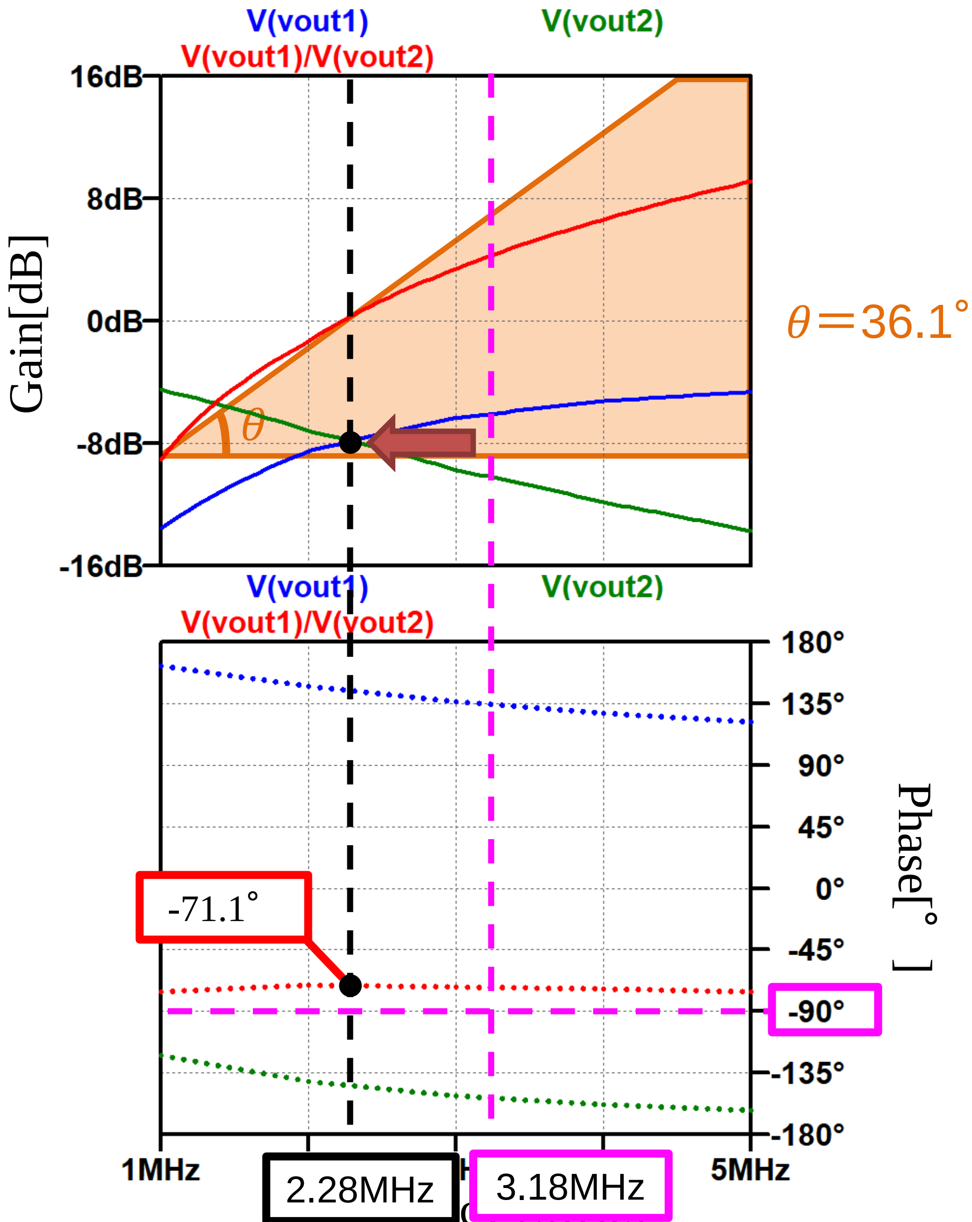




1/ (2πR1C1) =3.18MHz

1/ (2πR2C2) =1.59MHz

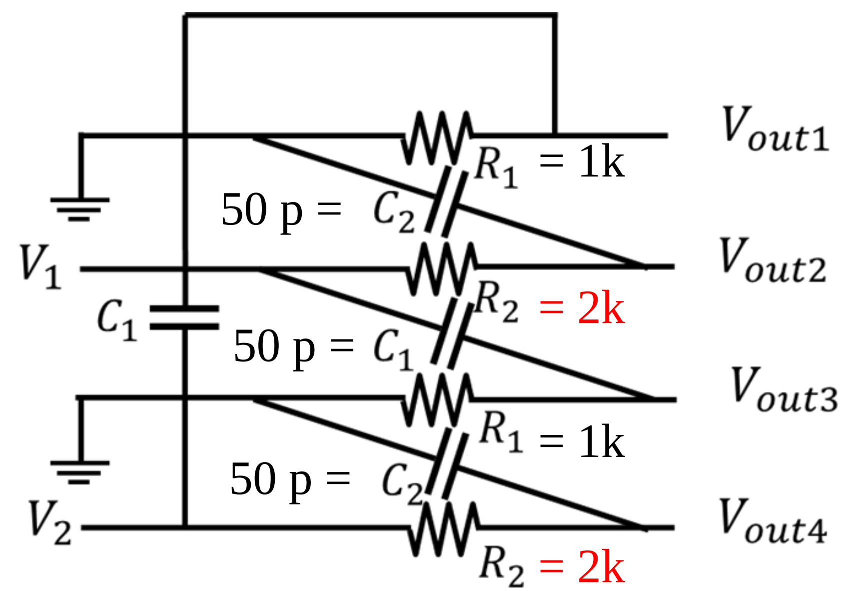
Simulation result [R mismatch]



$R_1 \neq R_2$

$C_1 = C_2$

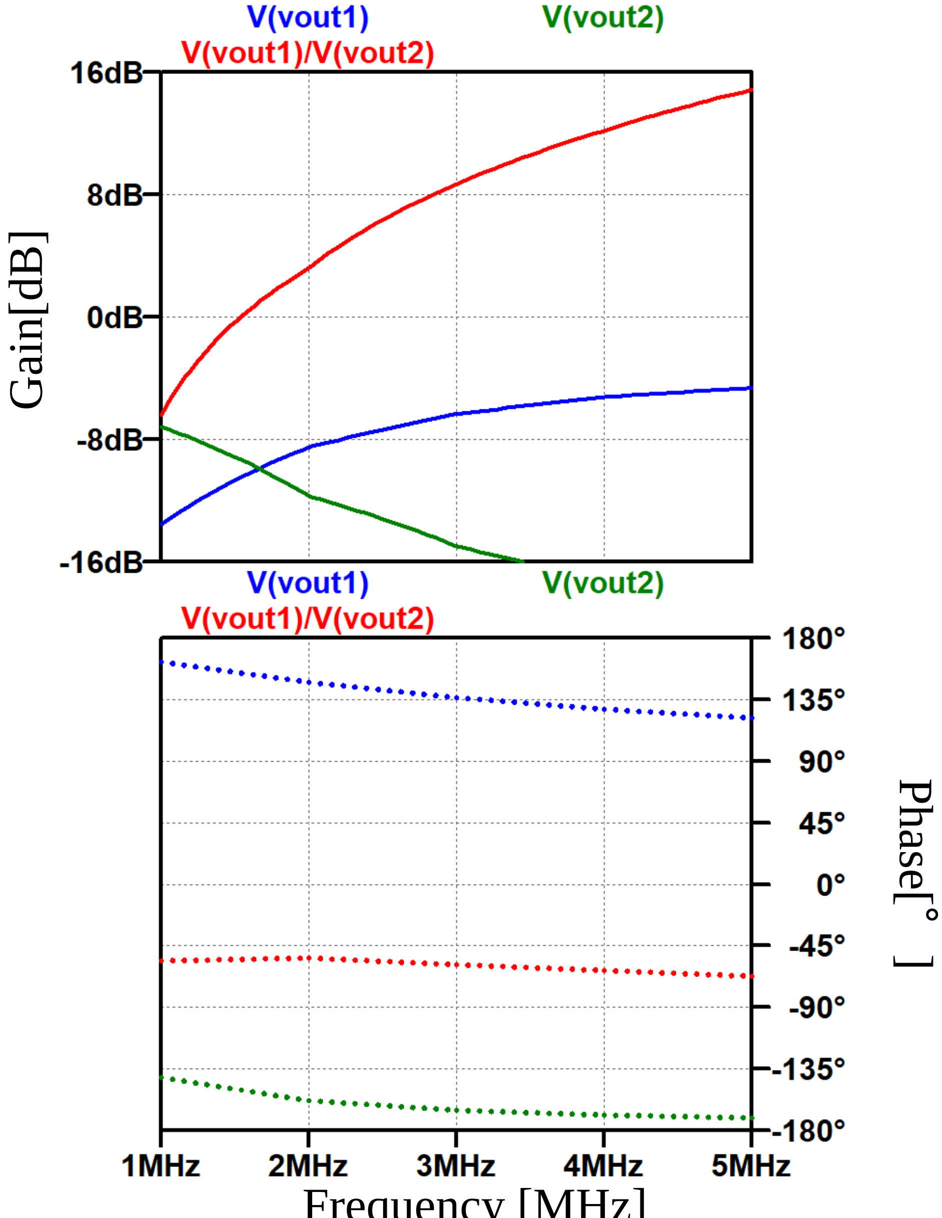
$$\frac{Imout}{Reout} \neq j$$



1/ (2πR1C1) =3.18MHz

1/ (2πR2C2) =1.59MHz

Simulation result [R&C mismatch]



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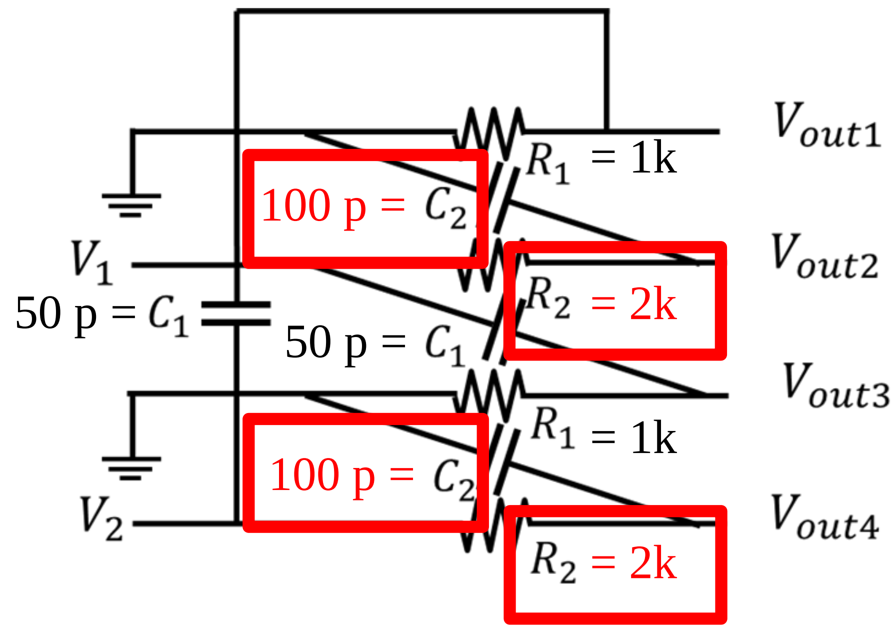

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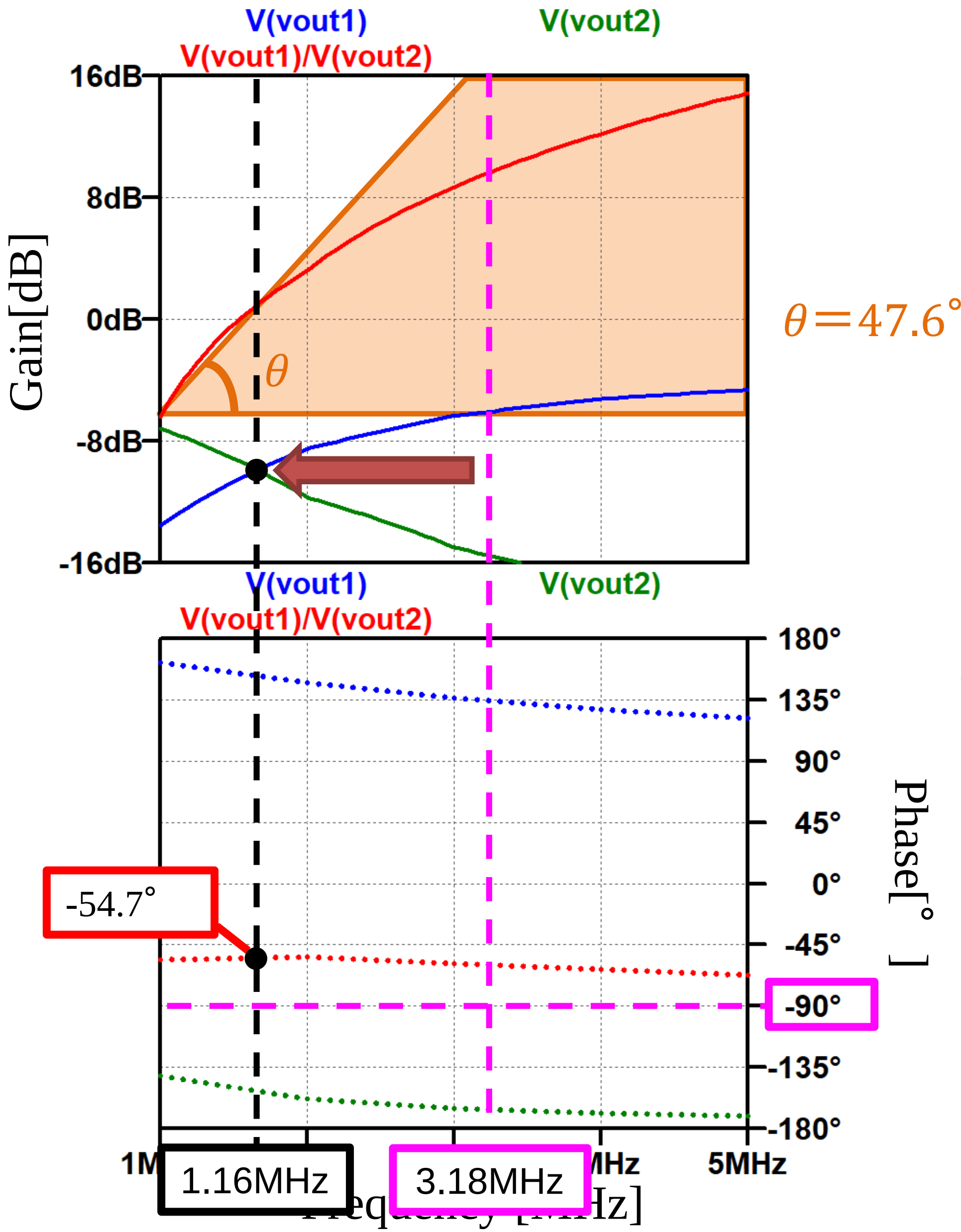

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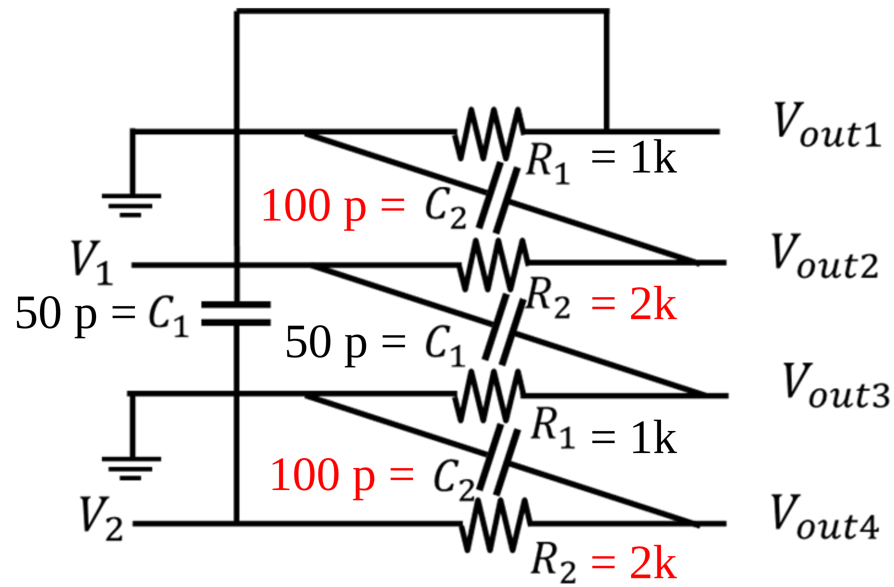

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Conclusion

- Measurement method proposal for RCPF orthogonal.

  - Derived by theoretical analysis

  - Verified with SPICE simulation

- Our Findings

  - In case : I, Q signals are orthogonal → I, Q channels
    Phase difference ＝ 90°

  - In case: I, Q signal are NOT orthogonal → I, Q channels
    Phase difference ≠ 90°

  Gain slope of 20log（Vout 1 / Vout 2）with respect to ω is steep.

- Our method can be applied to
  various kinds of analog complex filters