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計測制御工学 第6回講義

複素アナログフィルタの基礎

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下記から講義使用 pdfファイルをダウンロードしてください。

出席・講義感想もここから入力してください。

<https://kobaweb.ei.st.gunma-u.ac.jp/lecture/lecture.html> 1

欧州のアナログ集積回路 研究教育事情

群馬大学 小林春夫

Disclaimer:

15年前に訪問した時の情報もあり、
一部は最新情報ではない

欧州地図



意外な欧州

- 日本は面積も人口も少ない？
➔ 欧州で面積 & 人口が日本より大の国なし
- 欧州は人口少ない、大都市少ない
アジアは多い
「アジアは米、欧州は小麦が主食のため」の説
米は何年も備蓄可、小麦は不可
- 「イギリス(ブリテン島)と欧州大陸は別」
の意識が双方にあり(?)

米国と欧州は異なる

- 技術、産業に対する考え方、システムは異なる。
- 「欧米」という表現には注意が必要
- 欧州内でも、国によってエレクトロニクスの技術、産業、大学教育は全く異なる。
- 欧州のエレクトロニクス(半導体)メーカー
Philips (NXP)、STマイクロ、Infineonの3社


欧州 2000年以上の西洋科学の伝統の底力

● 欧州のエレクトロニクス技術者への形容詞

「こつこつやる」、「マイペース」、「しつこい」

● ある日本の大手半導体メーカー技術者:

80年代にパワーエレクトロニクス(のある分野)で欧州を技術的・産業的に完全に負かした
とっていた。

2-3年後に欧州から先端研究発表があちこちからでてくる。  底力を実感した。

オランダ

3つの工科大学: Philips社と連携

Delft: 町の半分が大学. Prof. Huijing

Eindhoven: Philips社の都. Prof. Roermund

Twente: Prof. Nauta

産学ともエレクトロニクスのレベル高し。

アナログ回路、半導体プロセス・デバイスで強み。

オペアンプ、センサ、ADC/DAC等。

Dutch と呼ばれる謹厳な民族。

町中のほとんどの人が英語を話せる。

ベルギー(大学)

2つの民族(オランダ系、フランス系)

駅名: 英語、オランダ語、フランス語の3つで表示

Katholieke Universiteit Leuven (オランダ系)

戦後、貴族が土地を提供して充実

アナログで世界トップレベル

Prof. Sansen, Prof. Steyaert 幅広い分野

Catholic University Leuven (フランス系)

高温エレクトロニクス回路

ただし、ベルギー国内にはエレクトロニクス産業はそれほど盛んではない。

ベルギー（研究所）

IMEC（独立系研究機関）

エレクトロニクスで世界最高の研究機関の一つ
日本企業（ソニー、松下、日立等）からもアクセス多し。
半導体製造装置技術等、注目すべき技術多し
もともとは米国留学組、KULの卒業生の受け皿で、
フランダース系政府がサポート。
現在は世界中から研究者が集まってきている。

日本でもIMECをモデルにすべきとの考えの人多し。

イタリア

Pavia 大学（電池の発明者ボルタが教鞭）

ミラノ市の南 電車で1時間程度

STマイクロ社と連携

Prof. Castello, Maloberti, Malcovati

アナログで世界トップレベル

シシリア島のカターニア大学

STマイクロ社が支援

イギリス、アイルランド

イギリス: 海外では **UK** を使う

England, Scotland, Wales, Northern Ireland の
連合王国 **United Kingdom**
サッカー ワールドカップにも独立4チーム出場

NPL (National Physical Lab)

広帯域オシロスコープ校正技術
スコットランドのアルバ・プロジェクト



アイルランド: **ケルトの奇跡**

法人税を安くした。

アナログデバイスズ、インテル、デルコンピュータ等のハ
イテク企業が進出。

「何十年もアナログ関係に従事」という技術者

Limerick 大学: 周りにハイテク企業

ドイツ

Ruhr 大学 (ボッヘム市)

デュッセルドルフ市から電車で1時間
高速バイポーラトランジスタ回路、SiGe HBT
 f_T 近辺では SPICEは不十分

➡ 独自のトランジスタモデルを開発

職人芸的高速高周波技術

Infenion, HP, IBM等と連携

スイス

- **スイス連邦工科大学 (ETH Zurich)**

ドイツ語圏、 3つの公用語(独、仏、伊)

Prof. Q. Huang: RF CMOS, ADC

東芝と共同研究

Technology CAD Group

ISE社

半導体デバイスシミュレータでベンチャー企業

- **時計用エレクトロニクス**



低消費電力CMOS アナログ技術


Prof. Vittoz

北欧

- デンマーク工科大学
オーディオ用D級アンプ 日本メーカーと連携
- ヘルシンキ工科大学
Nokia 社等との連携
ADC, RF回路分野等で活発な研究

ロシア

半導体メーカ技術者より

- モスクワ近郊にLSIデザイン・ハウス多数。
能力の高い技術者がいる。
- 少し前の世代の設備でIC製造も行っている。
- 時計用IC等で中国市場にロシア製出回る。
- モスクワ・メインストリートに
サムソンの看板多数、日本メーカーの看板なし
 サムソンの営業力を感じる。
- 「台湾、韓国、中国、インドの次はロシアが出てくる」(談)

ポルトガル、イスラエル

● ポルトガル

リスボン工科大学

アナログで高いレベル

エレクトロニクス産業は自国には少ない

設計ベンチャー Chip Idea 社

エンリケ航海王子の時代に

船舶・航海の技術、貿易の技術で世界を制する。

その後オランダへ覇権が移る。

● イスラエル

半導体設計分野の産業は強い。

英語が最もよく通じる国の一つ。

スペイン バルセロナ市 雑景



サグラダファミリア(Sagrada Familia)
聖家族 贖罪教会

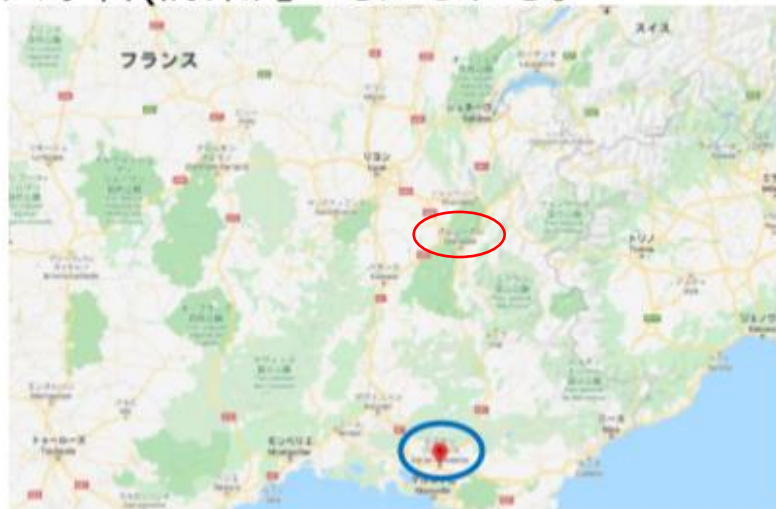
フランス

ルネッサンスの予言者 ペストから町を救う

ノストラダムスは医師、占星術師。
「大予言(詩集)」でも知られる。



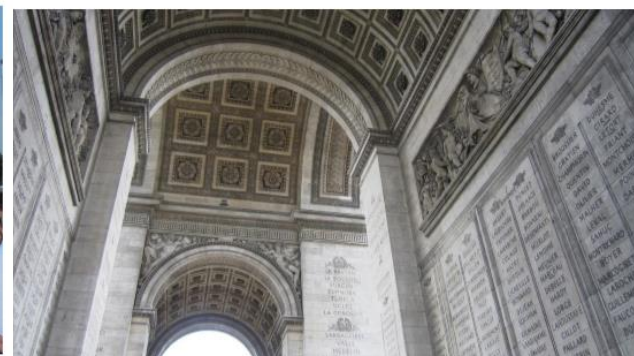
ミシェル・ノストラダムス
1503-1566



南仏の都市エクサン・プロヴァンスをペストから救う。
(近くの半導体関係の会社を20年以上前に訪問)

- **グルノーブル(Grenoble)**: フランスのシリコンバレー

フランス パリ 雑景



パリ第6大学

セーヌ川 エッフェル塔

凱旋門

日本企業への売り込み

- 欧州は大使館がビジネスを積極的に援助
東京のベルギー大使館がIMEC紹介主催、
懇親会には大使がでてくる。
- 米国は州知事が日本に来て
企業誘致を行うこともあり。

関係ファイル

https://kobaweb.ei.st.gunma-u.ac.jp/news/pdf/2019/oldrepo_NapoliUniv.pdf

https://kobaweb.ei.st.gunma-u.ac.jp/news/pdf/2019/oldrepo_Europe.pdf

<https://kobaweb.ei.st.gunma-u.ac.jp/warehouse/20160722am9IMSTW.pdf>

<https://kobaweb.ei.st.gunma-u.ac.jp/warehouse/IMSTW20150703.pdf>

Keynote Lecture 03

May 8, 2019

IPS04 Analog and Power

Complex Signal Processing in Analog / Mixed-Signal Circuits

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Minh Tri Tran, Koji Asami

Anna Kuwana, Hao San

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Gunma University



Outline

- Motivation for Complex Signal Processing Research
- RC Polyphase Filter: Transfer Function
- RC Polyphase Filter: Flat Passband Gain Algorithm
- RC Polyphase Filter and Hilbert Filter
- Active Complex Bandpass Filters
- Conclusion

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Why My Research for Complex Signal Processing ?



About 15 years ago

at IEEE International Solid-State Circuits Conference
San Francisco, CA

The most prestigious conference in IC design

Katholieke Universiteit Leuven (KU Leuven), Belgium

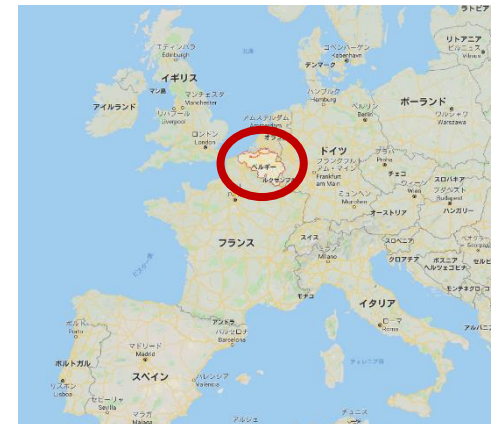
World top research group in analog IC design

presentation



Some simple circuit
with curious characteristics

However,
I could not understand its principle



Basics of Complex Signal

2 real signals: I, Q

$$V_{\text{signal}} = I + jQ \quad \text{Complex Signal}$$

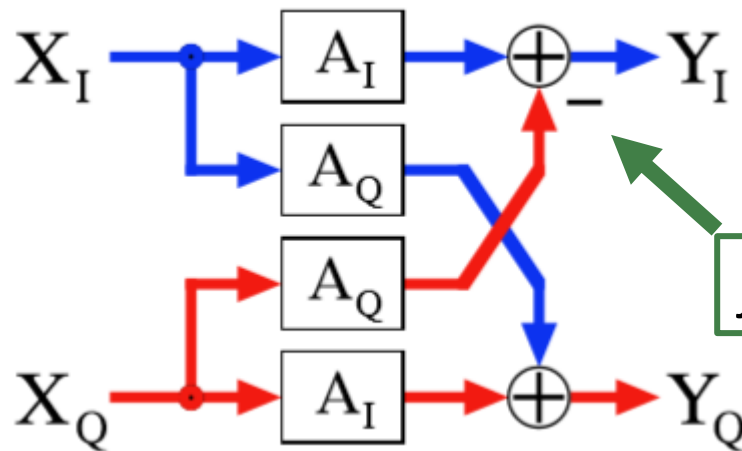
$$V_{\text{image}} = I - jQ \quad \text{Image}$$



$$I = [V_{\text{signal}} + V_{\text{image}}]/2$$

$$Q = [V_{\text{signal}} - V_{\text{image}}]/(2j)$$

Basic complex signal processing blocks



$$\dot{Y} = \dot{A} \cdot \dot{X}$$

$$Y_I + jY_Q = (A_I + jA_Q) \cdot (X_I + jX_Q)$$

$$= (A_I \cdot X_I - A_Q \cdot X_Q)$$

$$+ j \cdot (A_I \cdot X_Q + A_Q \cdot X_I)$$

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- Motivation for Complex Signal Processing Research
- **RC Polyphase Filter: Transfer Function**
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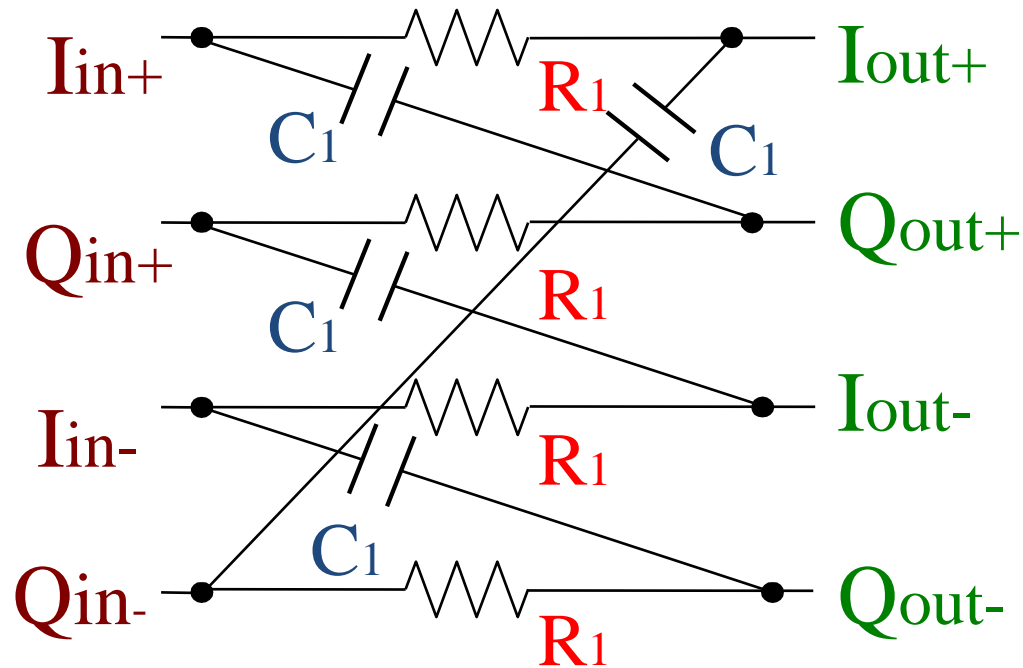
Research Goal of First Research

- To establish systematic design and analysis methods of RC polyphase filters.
- As its first step,
to derive explicit transfer functions of the 1st-, 2nd- and 3rd-order RC polyphase filters.

Features of RC Polyphase Filter

- Its input and output are **complex** signal.
- **Passive** RC analog filter
- One of key components in wireless transceiver analog front-end
 - **I, Q signal generation**
 - **Image rejection**
- Its explicit transfer function has not been derived yet.

First-order RC Polyphase Filter



I: In-Phase, Q: Quadrature-Phase

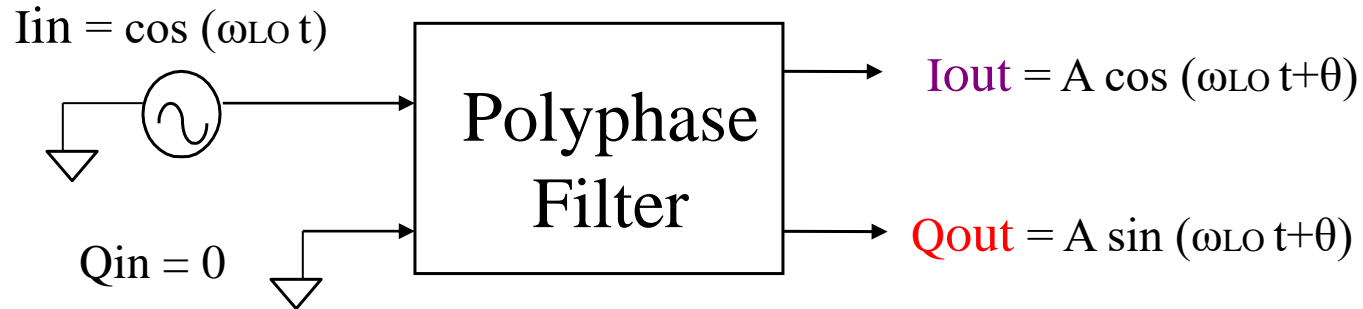
Differential Complex Input: $V_{in} = I_{in} + j Q_{in}$

Differential Complex Output: $V_{out} = I_{out} + j Q_{out}$

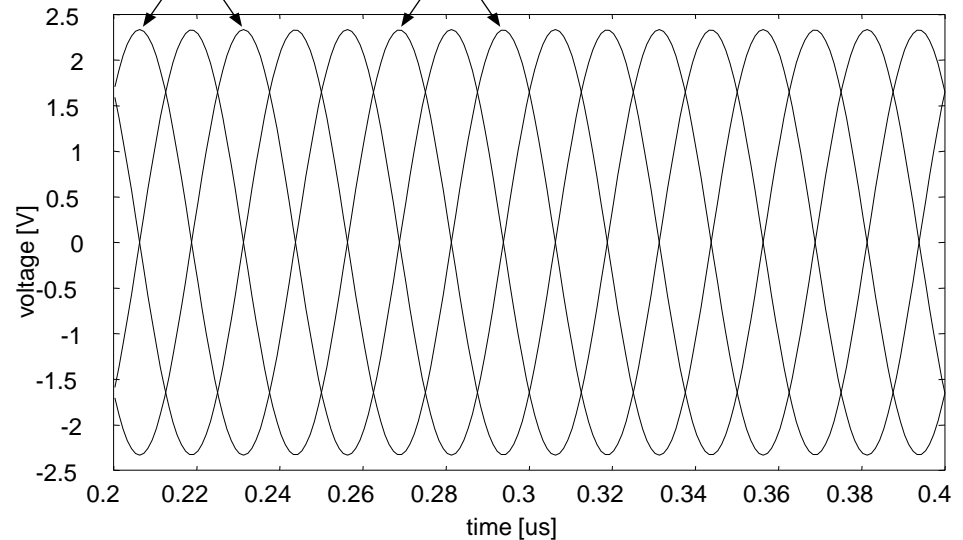
I, Q Signal Generation

Single cosine

Cosine, Sine signals

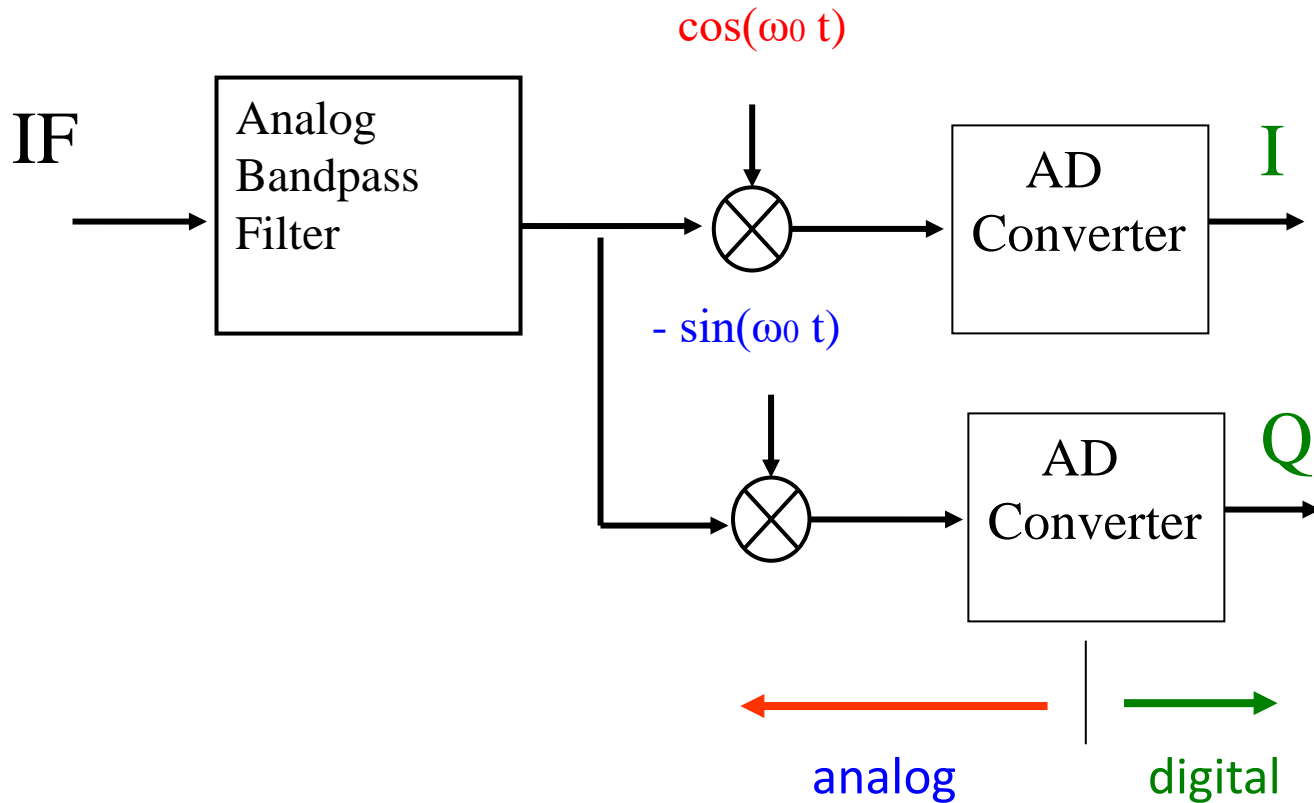


I_{out} Q_{out}



$$\omega_{LO} = \frac{1}{R_1 C_1}$$

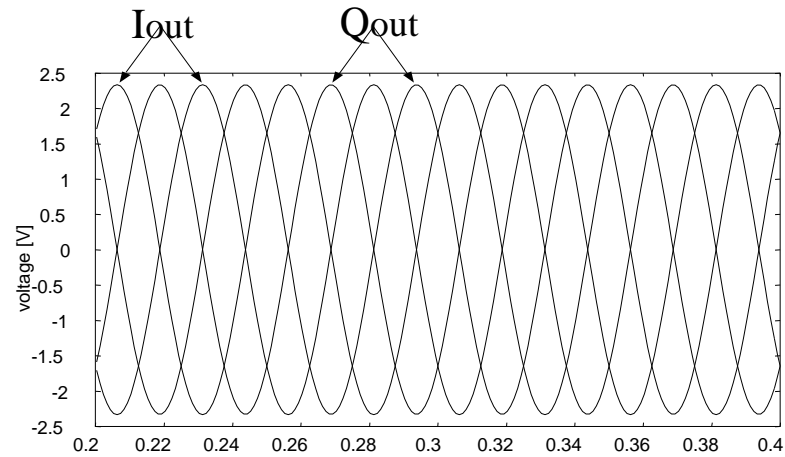
Cosine, Sine Signals in Receiver



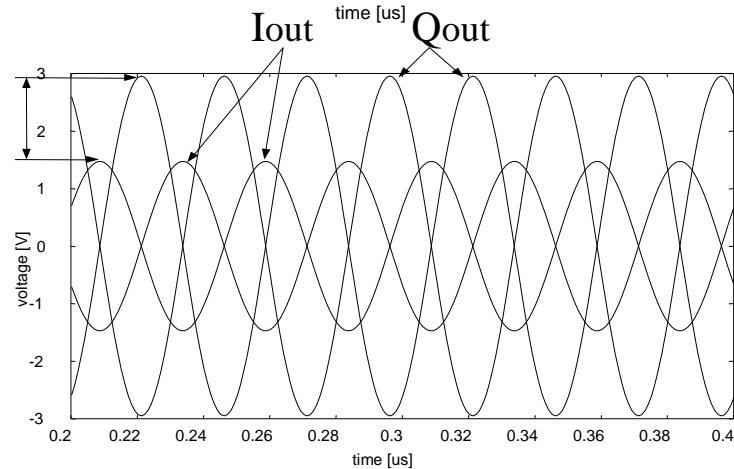
They are used for down conversion

Problem when $\omega_{LO} \neq 1/R_1C_1$

$$\omega_{LO} = \frac{1}{R_1C_1}$$



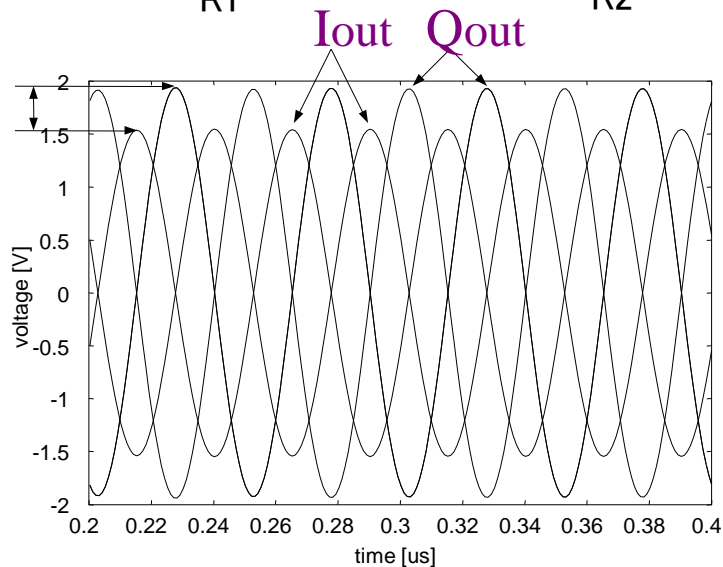
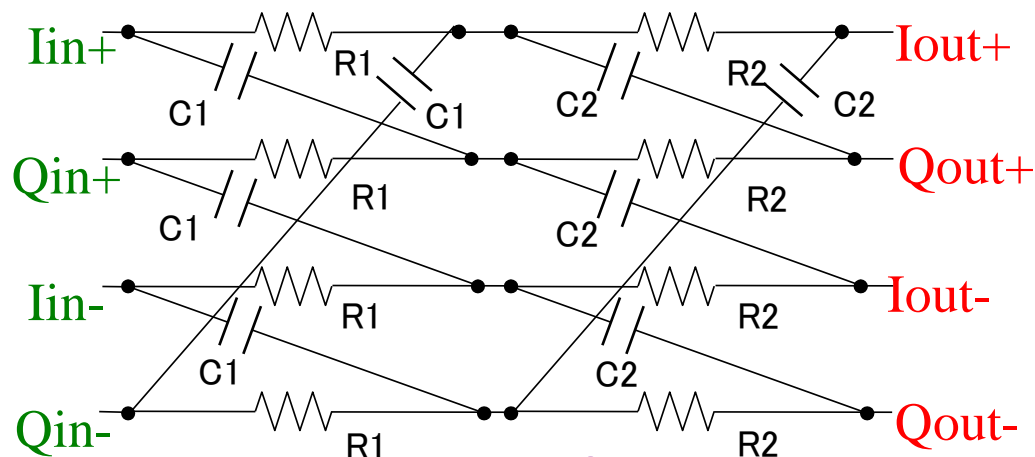
$$\omega_{LO} = \frac{2}{R_1C_1}$$



2nd-order RC Polyphase Filter

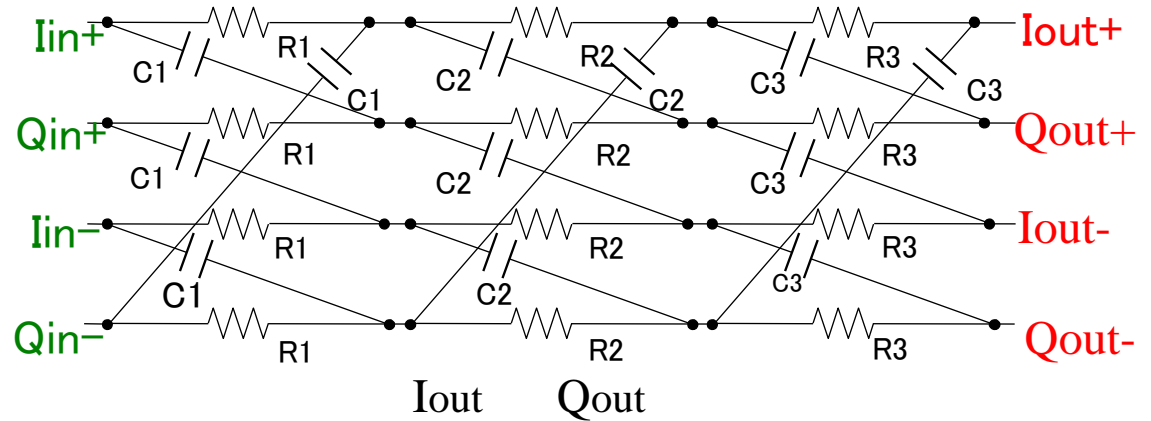
The problem of large difference between I_{out} , Q_{out} amplitudes can be alleviated

$$\omega_{LO} = \frac{2}{R_1 C_1}$$

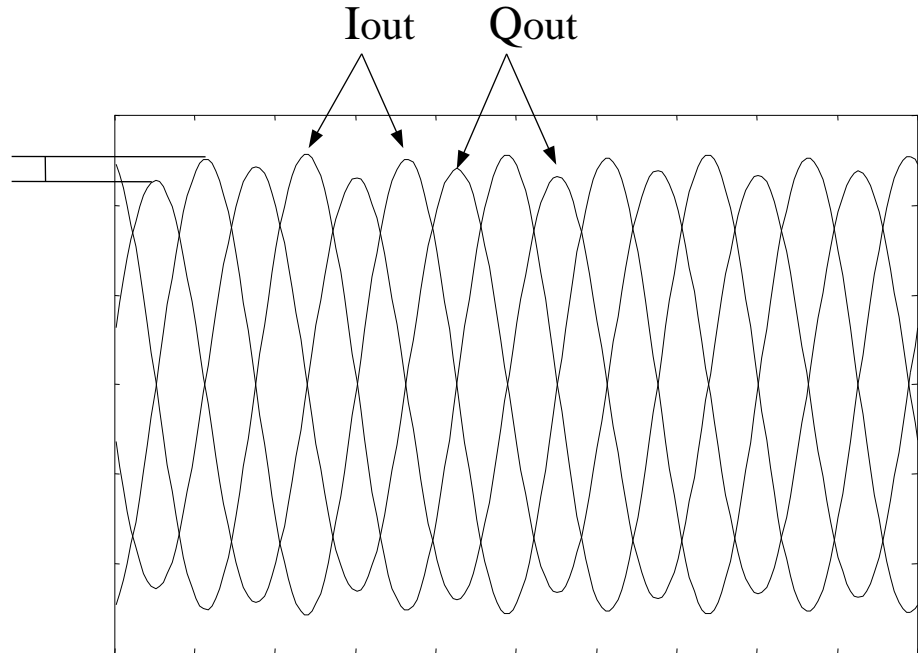


3rd-order RC Polyphase Filter

The amplitude difference problem is further alleviated.

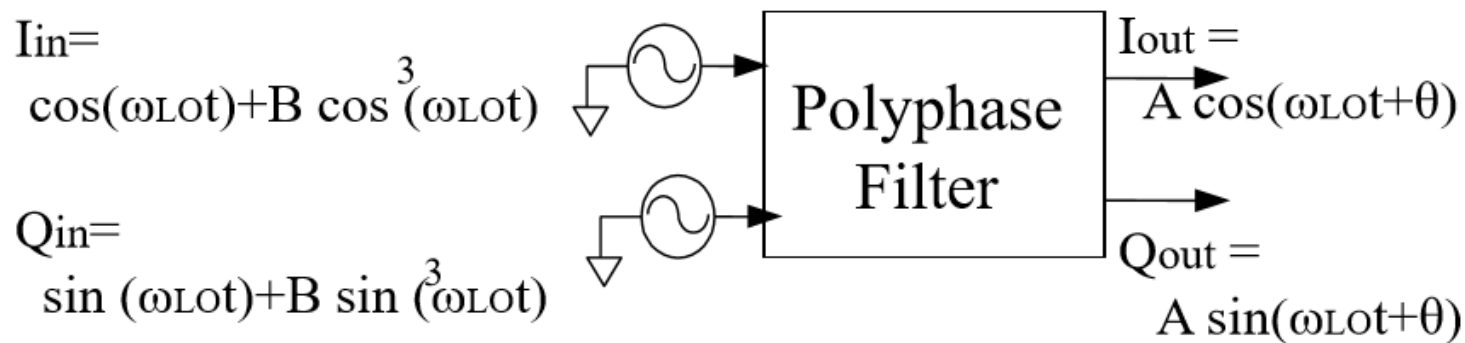


$$\omega_{LO} = \frac{2}{R_1 C_1}$$



Pure I, Q Signal Generation

3rd-order harmonics rejection



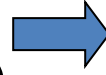
With
3rd-order harmonics.

Without
3rd-order harmonics.

Simulation of 3rd-order Harmonics Rejection

$$I_{in}(t) = \cos(\omega_{LO}t) + a \cos^3(\omega_{LO}t)$$

$$Q_{in}(t) = \sin(\omega_{LO}t) + a \sin^3(\omega_{LO}t)$$



$$3\omega_{LO} = \frac{1}{R_1 C_1}$$

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

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

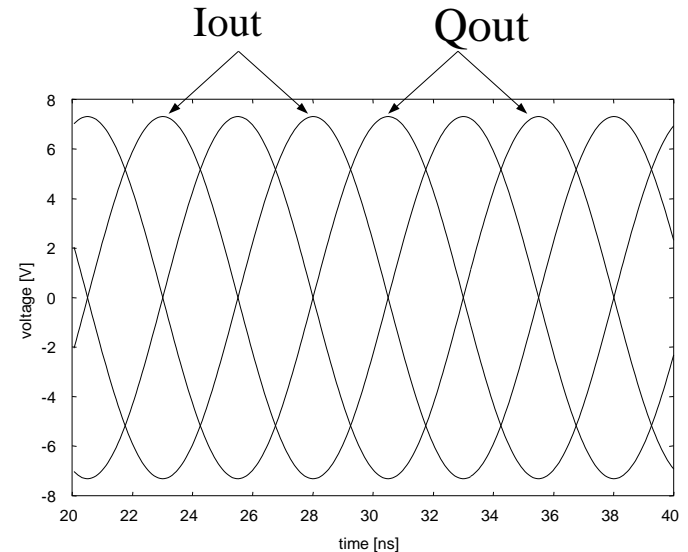
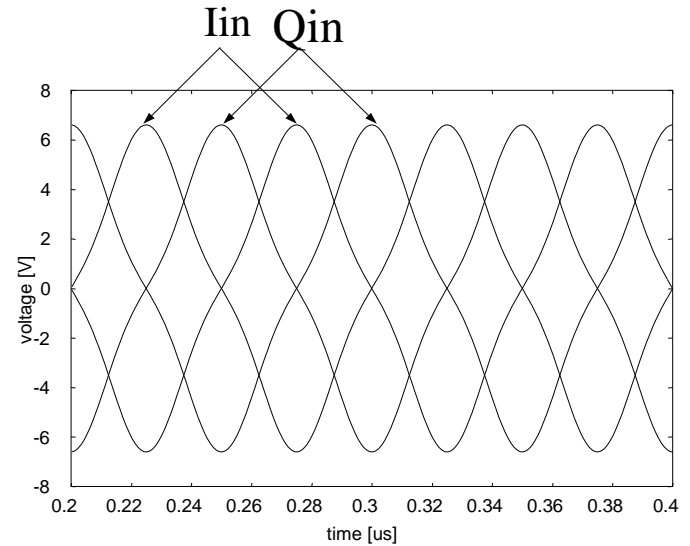
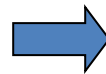
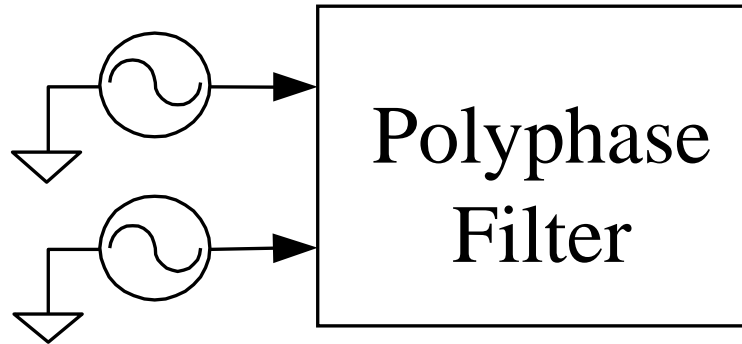


Image Rejection Filter

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

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



$$I_{out} = A \cos(\omega t)$$

$$Q_{out} = A \sin(\omega t)$$

$$Ae^{j\omega t} + Be^{-j\omega t}$$

signal

image

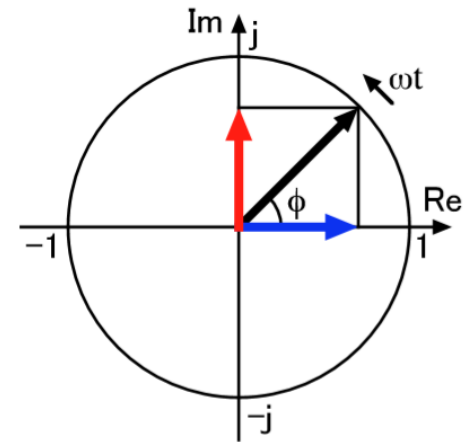


$$Ae^{j\omega t}$$

Approach (1)

Complex Signal Processing

There is NO physical complex signal.
It is only defined mathematically.



Complex Input: $V_{in} = I_{in} + j Q_{in}$

Complex Output: $V_{out} = I_{out} + j Q_{out}$

Gauss plane



Complex Signal Processing is NOT Complex.

Complex Transfer Function

- Complex Signal Theory

- Complex input
- Complex output

$$V_{in}(j\omega) = I_{in} + j \cdot Q_{in}$$

$$V_{out}(j\omega) = I_{out} + j \cdot Q_{out}$$

- Complex
Transfer Function

$$G(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)}$$

Signals in RC Polyphase Filter

Differential signal

$$I_{in}(t) = I_{in+}(t) - I_{in-}(t)$$

$$Q_{in}(t) = Q_{in+}(t) - Q_{in-}(t)$$

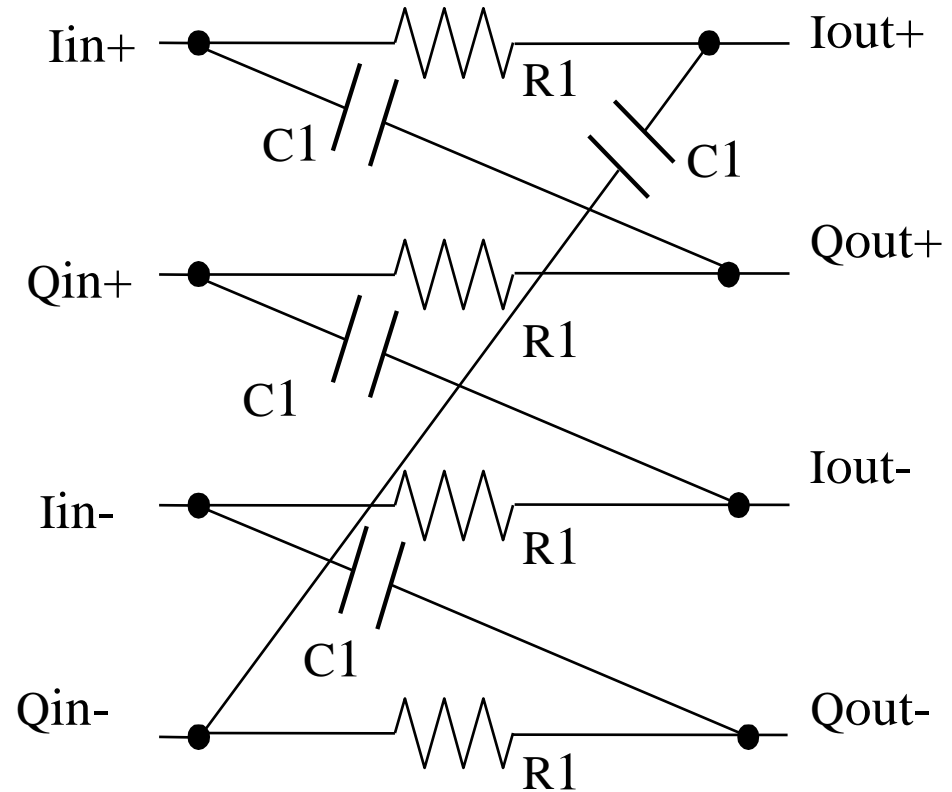
$$I_{out}(t) = I_{out+}(t) - I_{out-}(t)$$

$$Q_{out}(t) = Q_{out+}(t) - Q_{out-}(t)$$

Complex signal

$$V_{in}(t) = I_{in}(t) + jQ_{in}(t)$$

$$V_{out}(t) = I_{out}(t) + jQ_{out}(t)$$



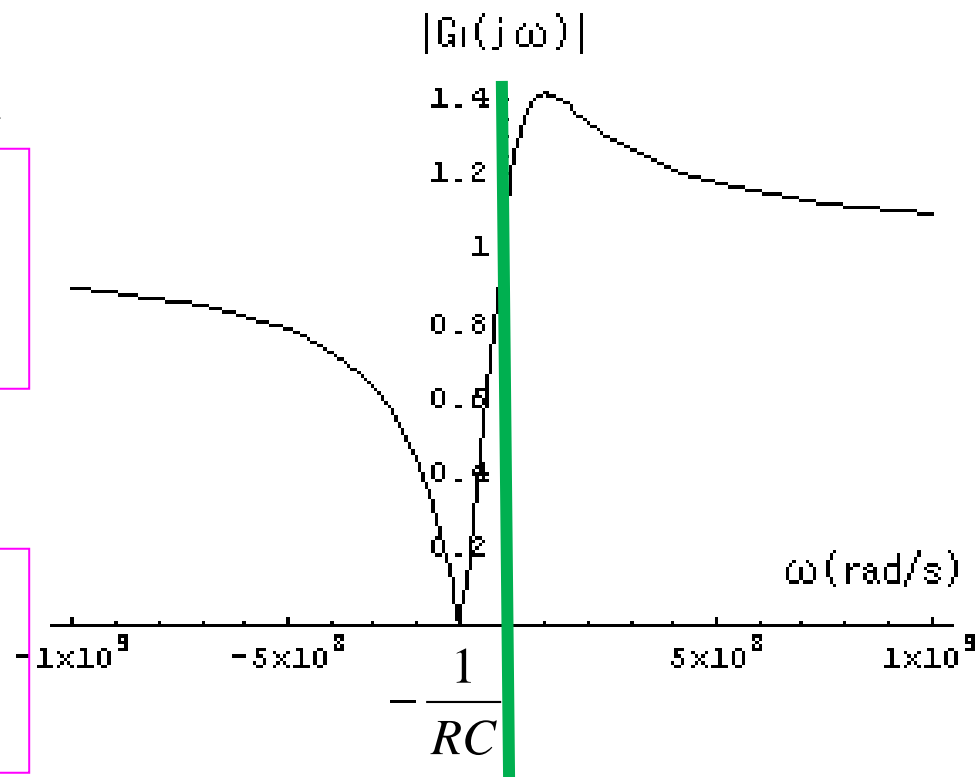
Transfer Function of RC Polyphase Filter

- Transfer Function

$$G_1(j\omega) = \frac{1 + \omega RC}{1 + j\omega RC}$$

- Gain

$$|G_1(j\omega)| = \frac{|1 + \omega RC|}{\sqrt{1 + (\omega RC)^2}}$$



Asymmetric

Explanation of I, Q Signal Generation by $G_1(j\omega)$

$$Q_{in}(t) \equiv 0, \quad I_{in}(t) = \cos(\omega t)$$

$$V_{in}(t) = I_{in}(t) + j Q_{in}(t) = \cos(\omega t) = \frac{1}{2} [e^{j\omega t} + e^{-j\omega t}]$$



$$V_{out}(t) = \frac{1}{2} [|G_1(j\omega)| e^{j(\omega t + \angle G_1(j\omega))} + |G_1(-j\omega)| e^{j(-\omega t + \angle G_1(-j\omega))}]$$
$$= \frac{\sqrt{2}}{2} \cos\left(\omega t - \frac{\pi}{4}\right) + \frac{j\sqrt{2}}{2} \sin\left(\omega t - \frac{\pi}{4}\right)$$

$$|G_1(-j\omega)| e^{j(-\omega t + \angle G_1(-j\omega))} = 0$$

Here

$$|G_1(j\omega)|_{\omega=\frac{1}{RC}} = 0, \quad |G_1(j\omega)|_{\omega=\frac{1}{RC}} = \sqrt{2}, \quad \angle G_1(j\omega) = -\frac{\pi}{4}$$

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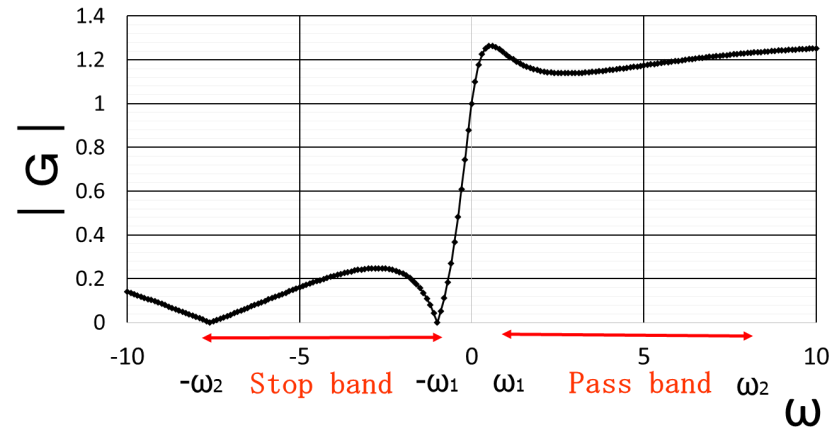
Transfer Function of 2nd-order RC Polyphase Filter

Transfer Function

$$G_2(j\omega) = \frac{(1 + \omega R_1 C_1)(1 + \omega R_2 C_2)}{1 - \omega^2 R_1 C_1 R_2 C_2 + j\omega(C_1 R_1 + C_2 R_2 + 2R_1 C_2)}$$

Derivation is very complicated, so we used "Mathematica."

Gain $|G_2(j\omega)|$
characteristics



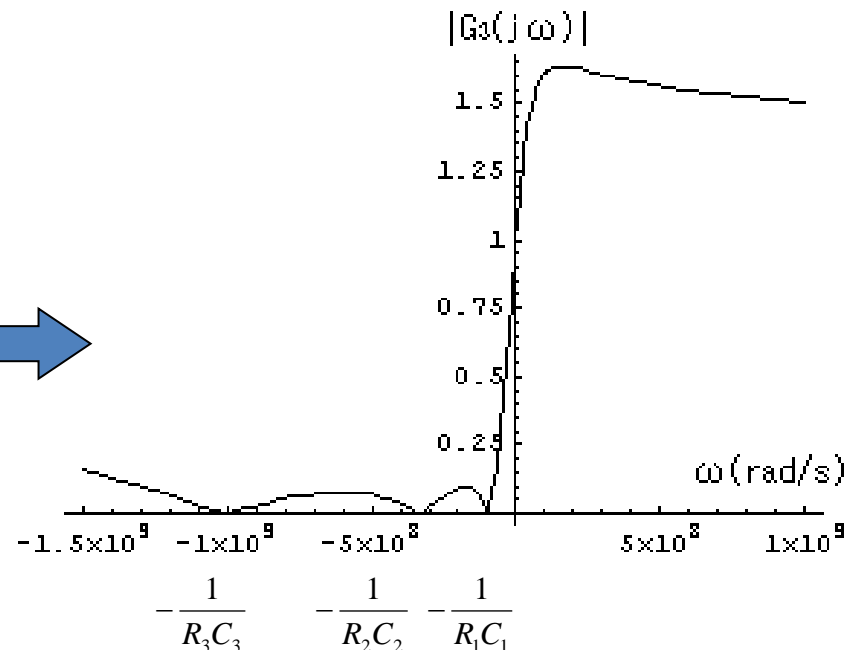
Gain of 3rd-order RC Polyphase Filter

Gain: $|G_3(j\omega)| = \frac{|N_3(j\omega)|}{\sqrt{D_{3R}(j\omega)^2 + D_{3I}(j\omega)^2}}$

Phase: $\tan(\angle G_3(j\omega)) = -\frac{D_{3I}(j\omega)}{D_{3R}(j\omega)}$

$$N_3(j\omega) = (1 + \omega R_1 C_1)(1 + \omega R_2 C_2)(1 + \omega R_3 C_3)$$

Gain characteristics



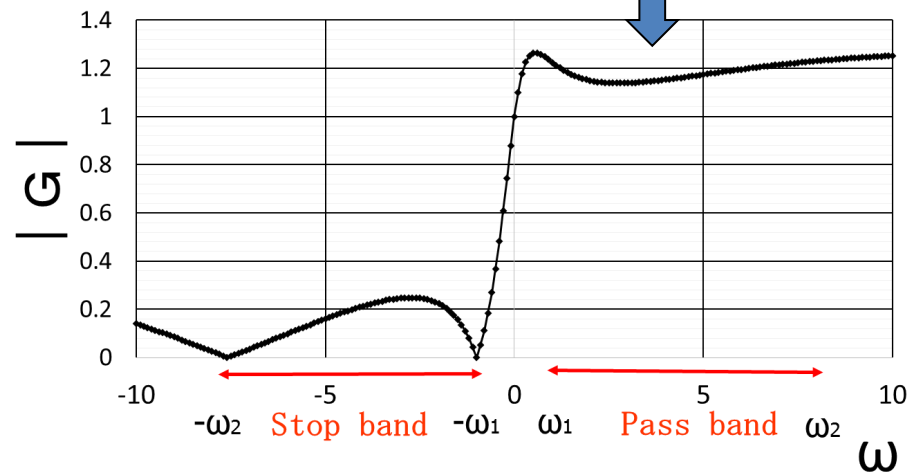
Need for Flat Passband Gain Algorithm

Transfer Function

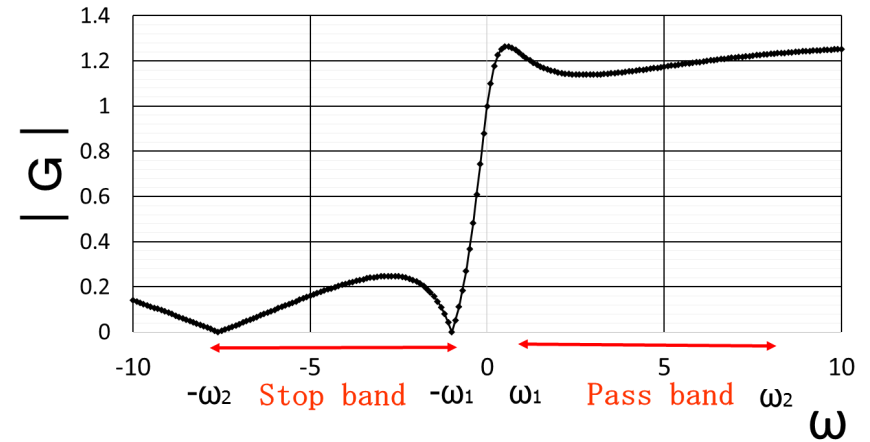
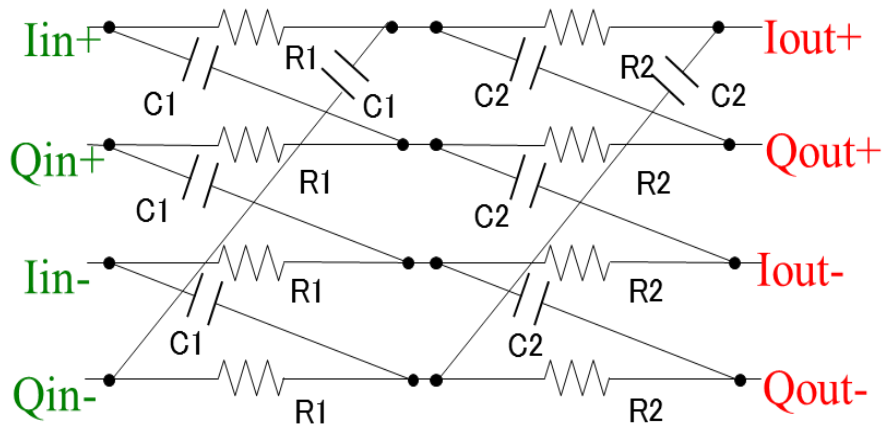
$$G_2(j\omega) = \frac{(1 + \omega R_1 C_1)(1 + \omega R_2 C_2)}{1 - \omega^2 R_1 C_1 R_2 C_2 + j\omega(C_1 R_1 + C_2 R_2 + 2R_1 C_2)}$$

We need flat passband gain

Gain $|G_2(j\omega)|$
characteristics



Four Design Parameters

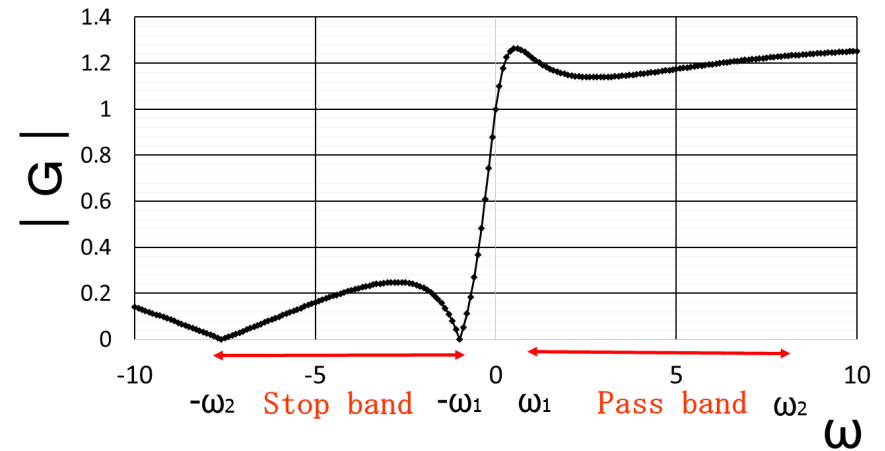
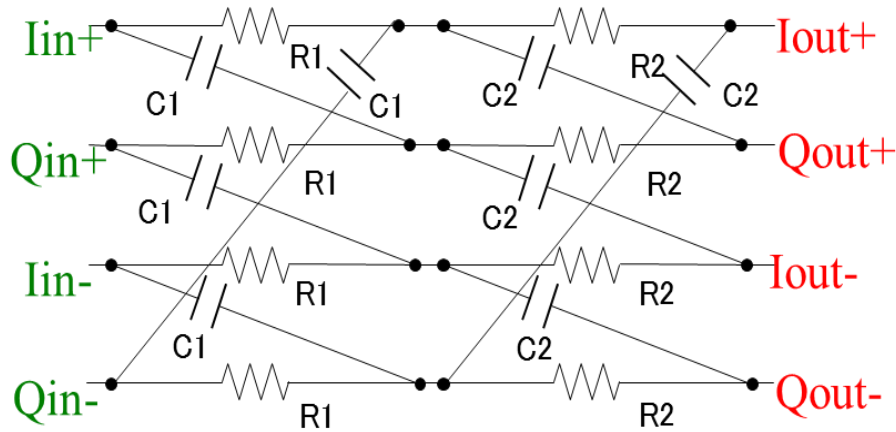


4 parameters : R_1, R_2, C_1, C_2

$$\omega_1 = \frac{1}{R_1 C_1}, \omega_2 = \frac{1}{R_2 C_2}, X = \frac{1}{R_2 C_1}, Y = \frac{1}{R_1 C_2}$$

4 constraints

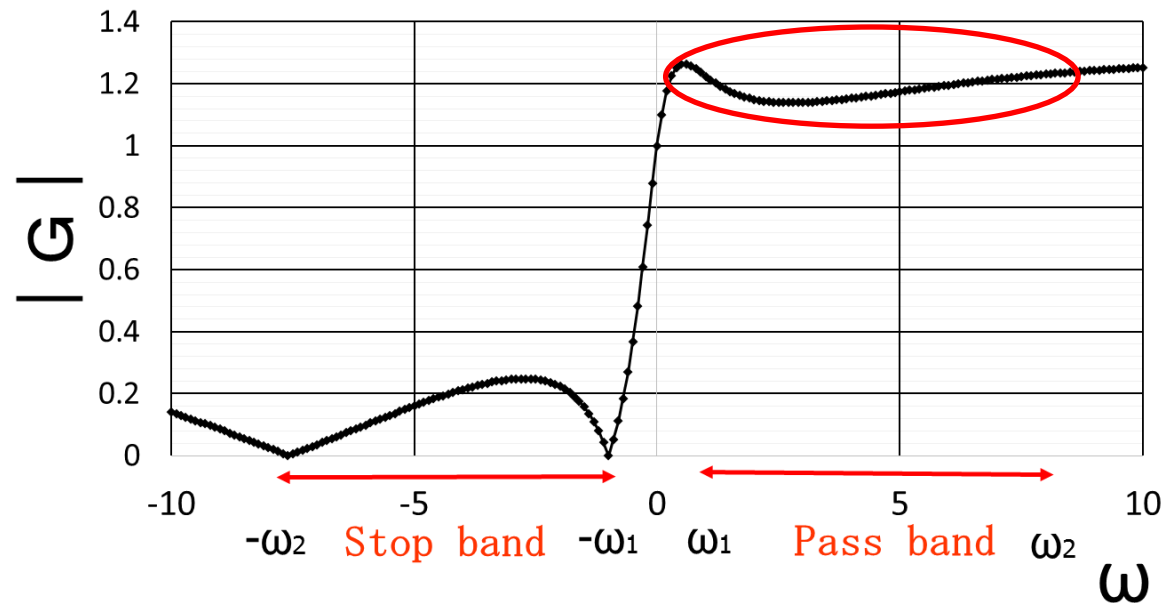
Two Constraints from Filter Spec.



● 2 zeros : $-\omega_1 = \frac{-1}{R_1 C_1}$, $-\omega_2 = \frac{-1}{R_2 C_2}$

are given from the filter specification.

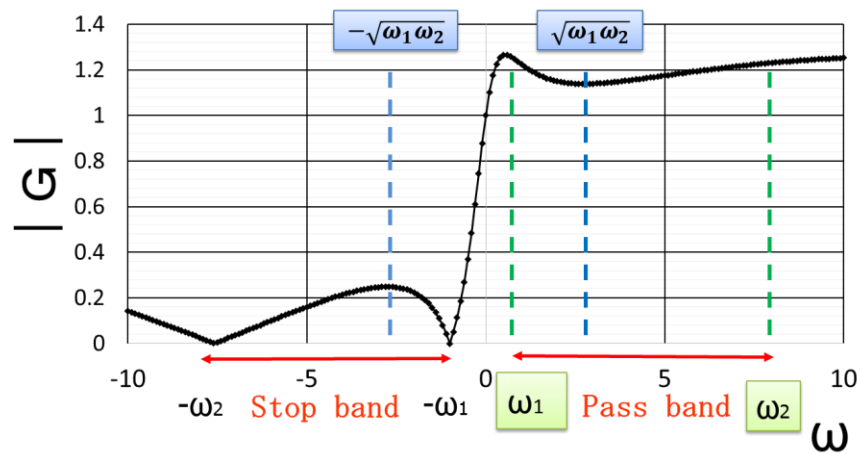
Proposed Algorithm Uses Third Constraint



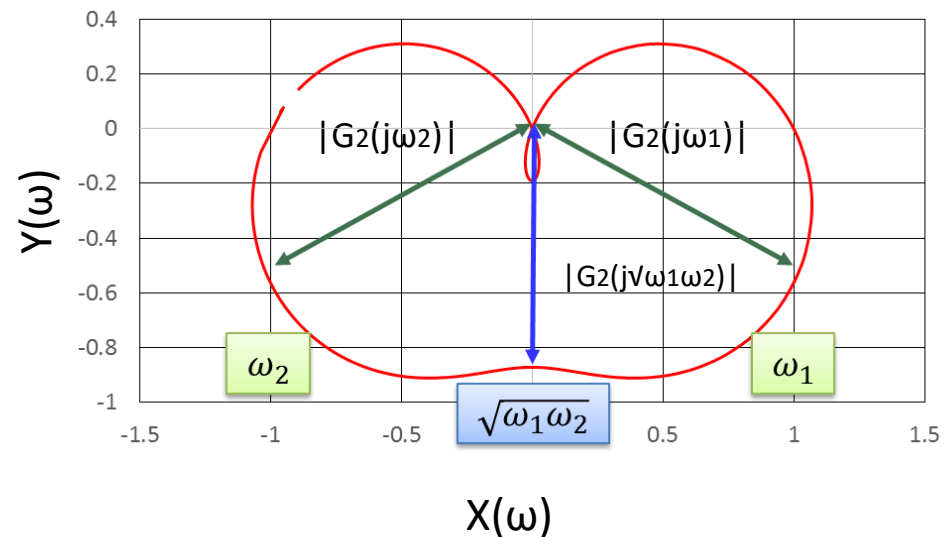
- We use the third constraint $X = \frac{1}{R_2 C_1}$ for passband gain flattening.
- The fourth constraint is left for ease of IC realization.

Nyquist Chart of $G_2(j\omega)$

Gain characteristics $|G_2(j\omega)|$



Nyquist chart of $G_2(j\omega) = X(\omega) + jY(\omega)$



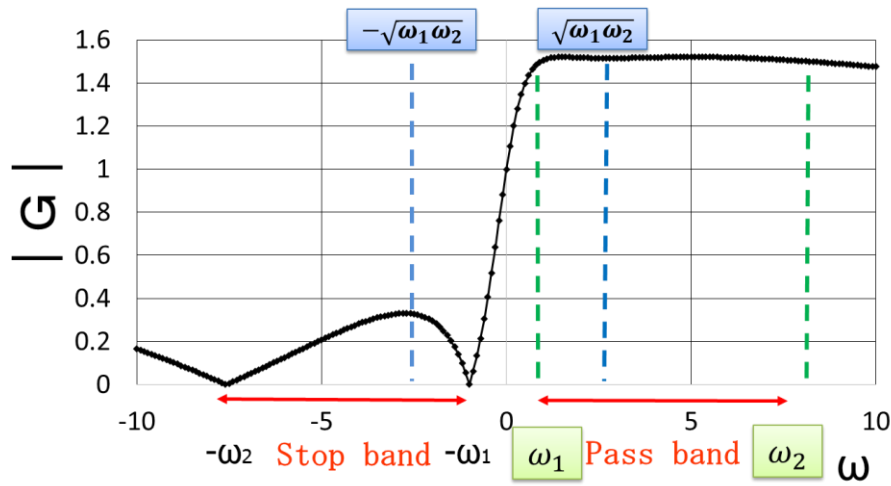
$$|G_2(j\omega_1)| = |G_2(j\omega_2)|$$

But in general

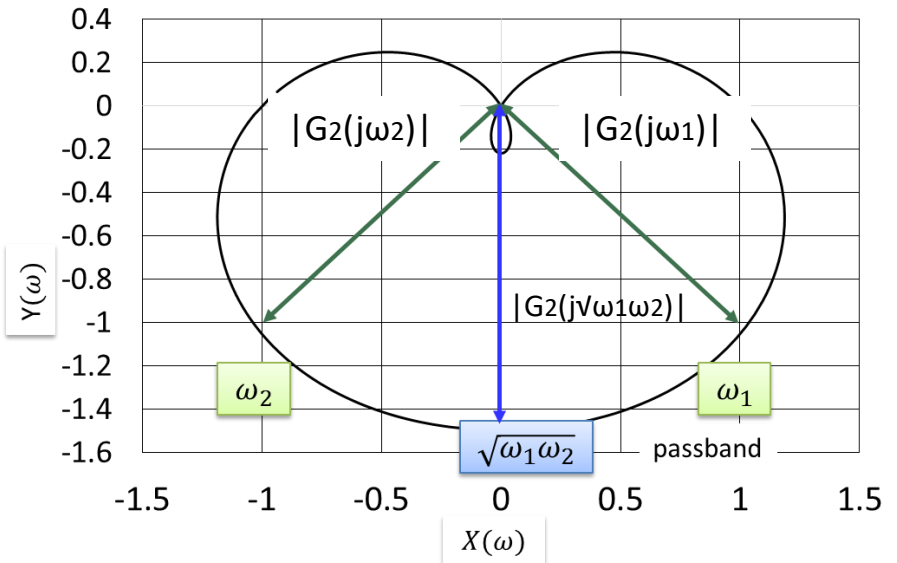
$$|G_2(j\omega_1)| = |G_2(j\omega_2)| = \cancel{|G_2(j\sqrt{\omega_1\omega_2})|}$$

Our Idea for Flat Passband Gain Algorithm

Gain characteristics $|G_2(j\omega)|$



Nyquist chart of $G_2(j\omega)=X(\omega)+j Y(\omega)$

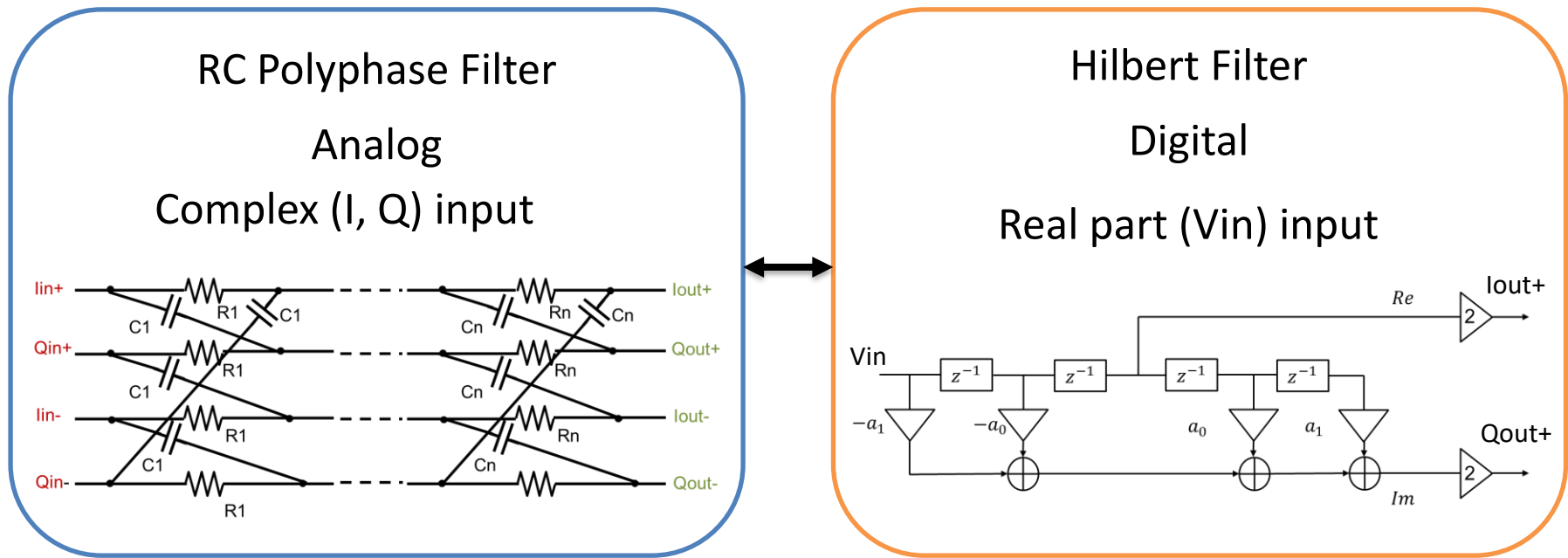


If we make $|G_2(j\omega_1)| = |G_2(j\omega_2)| = |G_2(j\sqrt{\omega_1\omega_2})|$,
Passband gain becomes flat from ω_1 to ω_2 .

Outline

- Motivation for Complex Signal Processing Research
- RC Polyphase Filter: Transfer Function
- RC Polyphase Filter: Flat Passband Gain Algorithm
- **RC Polyphase Filter and Hilbert Filter**
- Active Complex Bandpass Filters
- Conclusion

Research Objective



Analyze RC polyphase filter

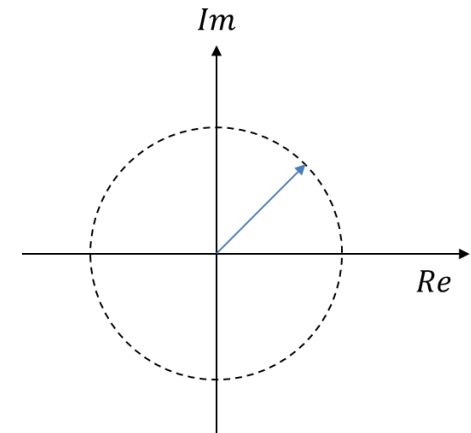
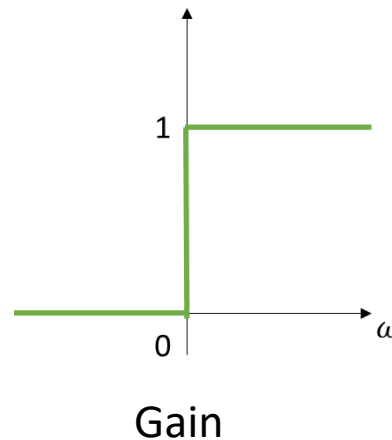
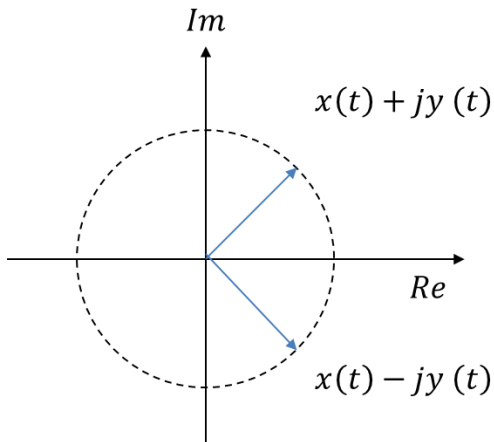
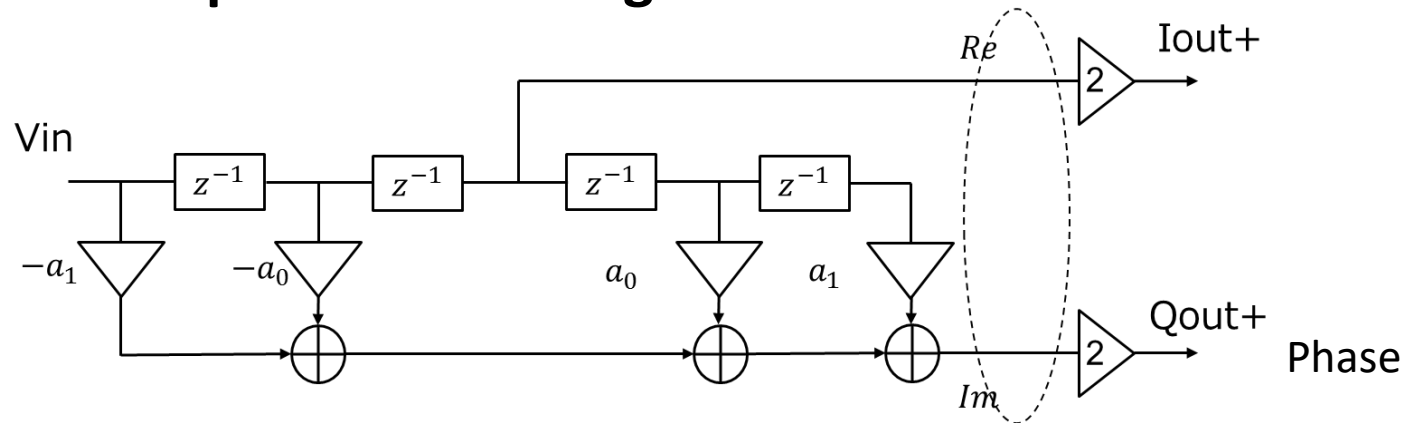


**We found that relevance between
RC polyphase filter and Hilbert filter**

Hilbert Filter

■ Characteristics

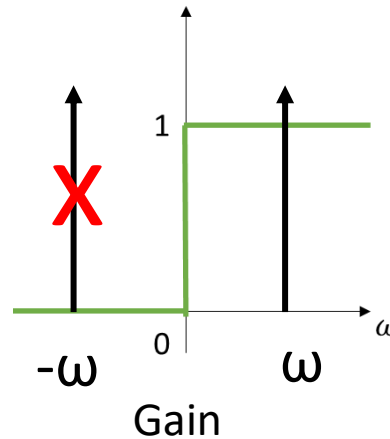
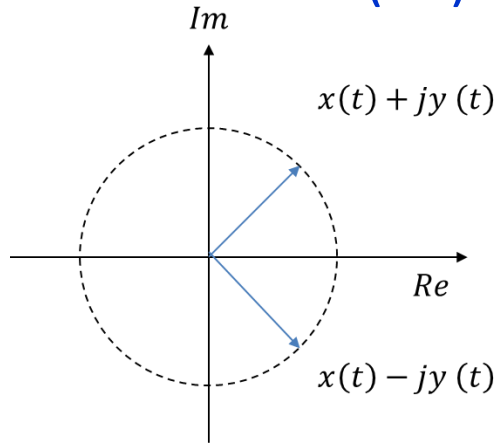
- Hilbert transform
- 1 input and 2 outputs
- It is often implemented in digital filter



Cosine, Sine Generation with Hilbert Filter

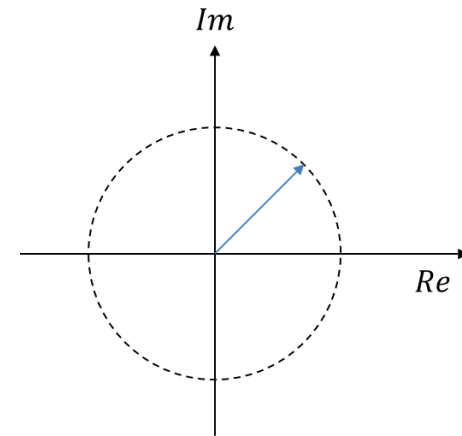
ω component

$$\cos(\omega t) + j\sin(\omega t)$$



ω component

$$\cos(\omega t) + j\sin(\omega t)$$



$$\cos(\omega t) - j\sin(\omega t)$$

$-\omega$ component

Hilbert filter

$$\cos(\omega t)$$

$$\sin(\omega t)$$

$$2 \cos(\omega t)$$

Hilbert Transform

Complex signal from real signal $x(t)$

$$x(t) \rightarrow x(t) + jy(t)$$

Hilbert transform

$$y(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau = x(t) * \frac{1}{\pi t}$$

Impulse response Fourier Transform

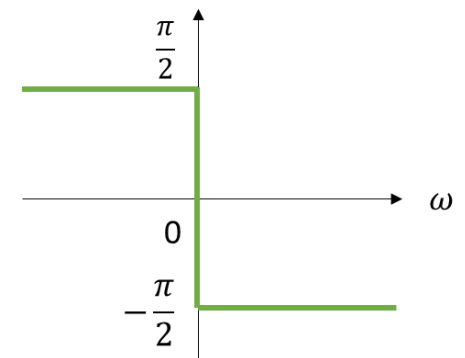
$$h(t) = \frac{1}{\pi t} \begin{array}{c} \longleftrightarrow \\ \text{Fourier} \end{array} H(\omega) = \begin{cases} -j & (\omega \geq 0) \\ j & (\omega < 0) \end{cases}$$

Frequency characteristic $H(\omega)$

$$Y(\omega) = H(\omega)X(\omega) = \begin{cases} -jX(\omega) & (\omega \geq 0) \\ jX(\omega) & (\omega < 0) \end{cases}$$



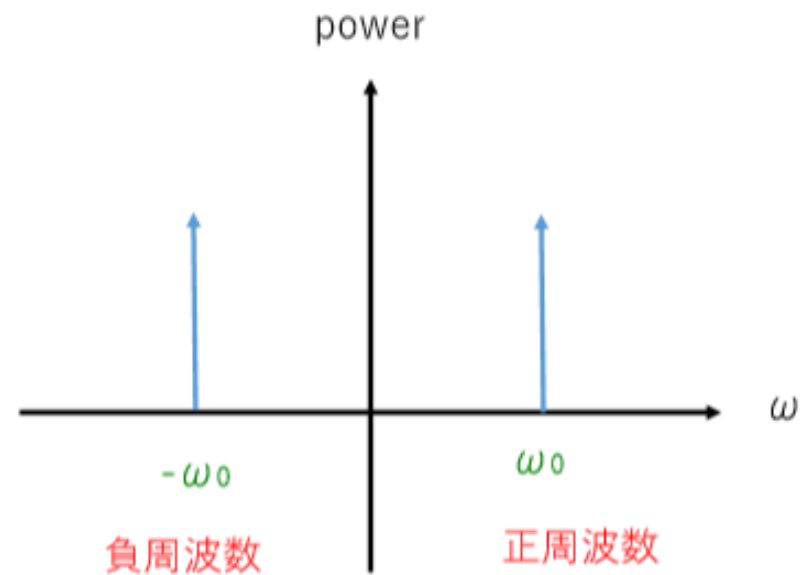
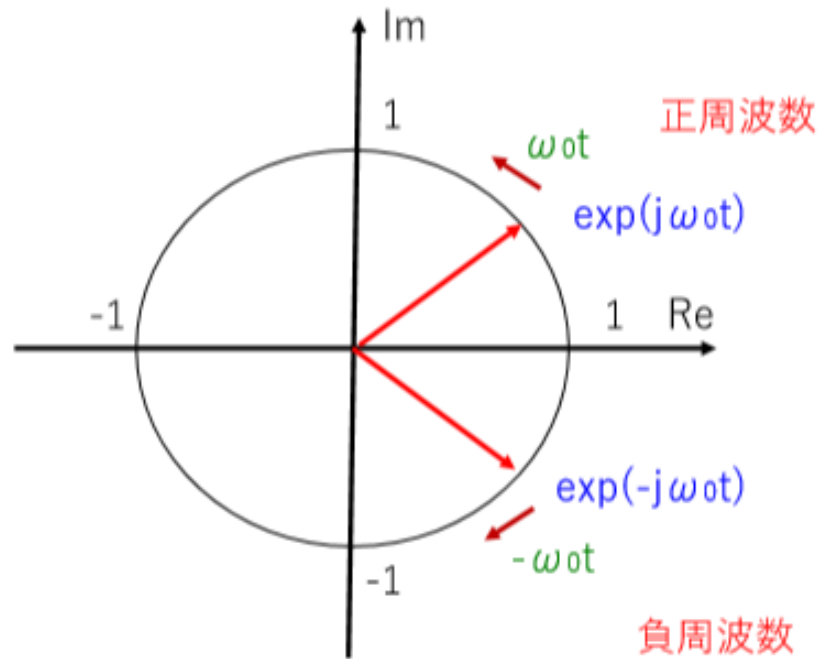
David Hilbert
1862-1943



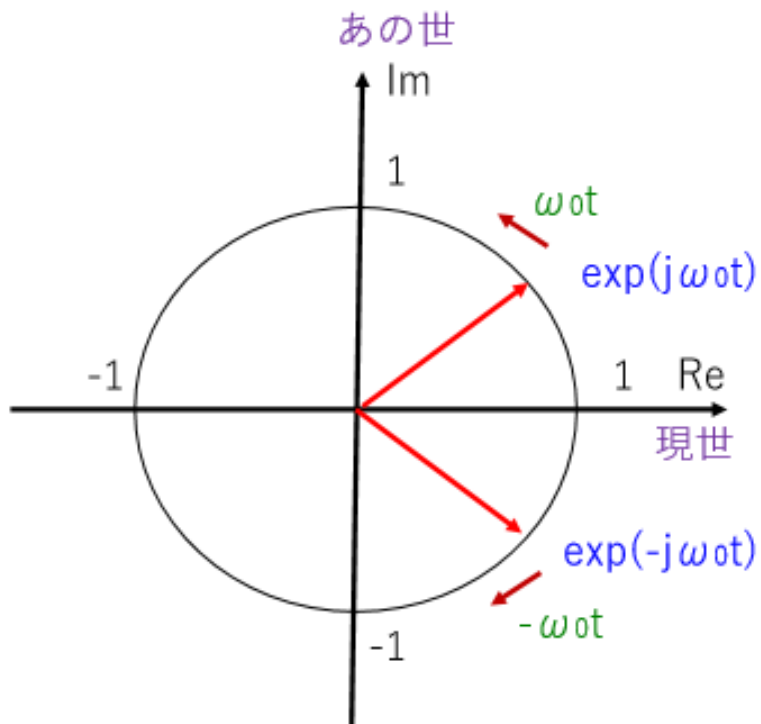
Phase

余弦波の複素平面での解釈

$$\exp(j\omega t) + \exp(-j\omega t) = 2 \cos(\omega t)$$



「現世」と「あの世」



$$\exp(j\omega t) = \overset{\text{現世}}{\downarrow} \cos(\omega t) + j \overset{\text{あの世}}{\downarrow} \sin(\omega t)$$

$$+) \exp(-j\omega t) = \cos(\omega t) - j \sin(\omega t)$$

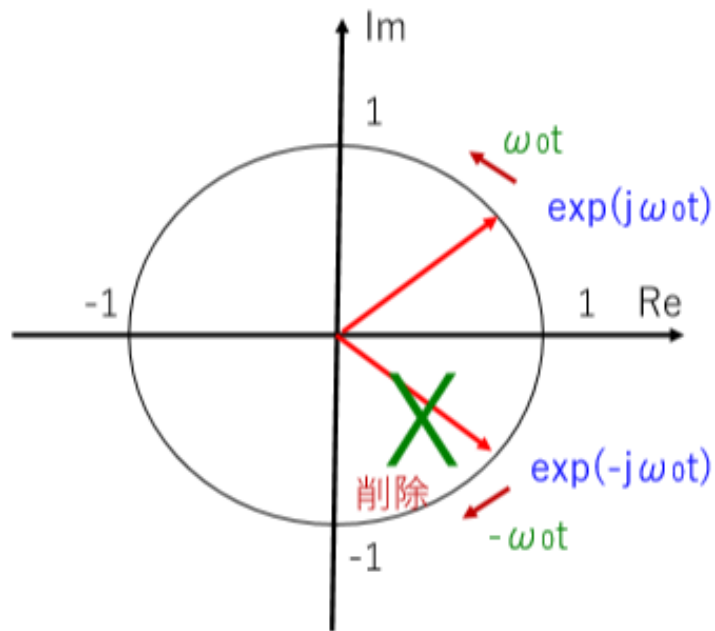
$$\exp(j\omega t) + \exp(-j\omega t) = 2 \cos(\omega t)$$

↑
実信号

↑
現世

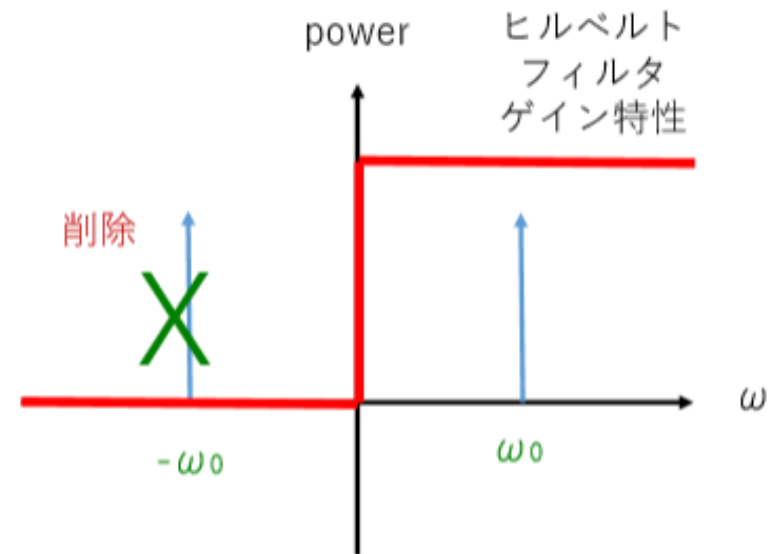
「実信号」で見えるのは「現世」のみ

ヒルベルトフィルタで負周波数成分のカット



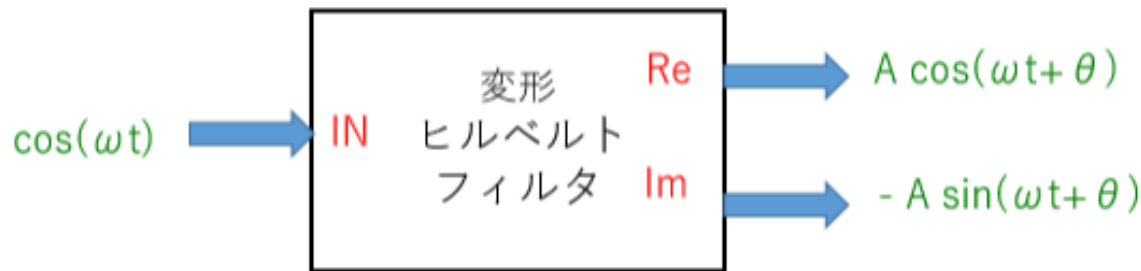
現世 あの世
↓ ↓

$$\exp(j\omega t) = \cos(\omega t) + j \sin(\omega t)$$

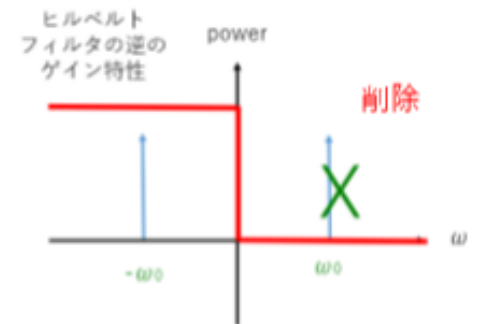
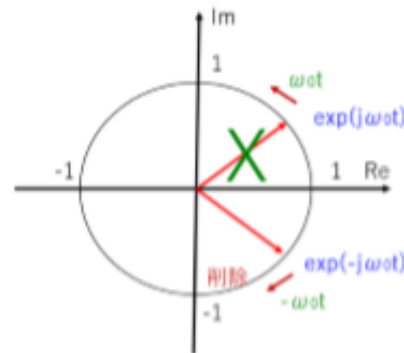


ヒルベルトフィルタで負周波数が見える

「負の周波数などあるのか、あるなら見せてみる」に対する回答

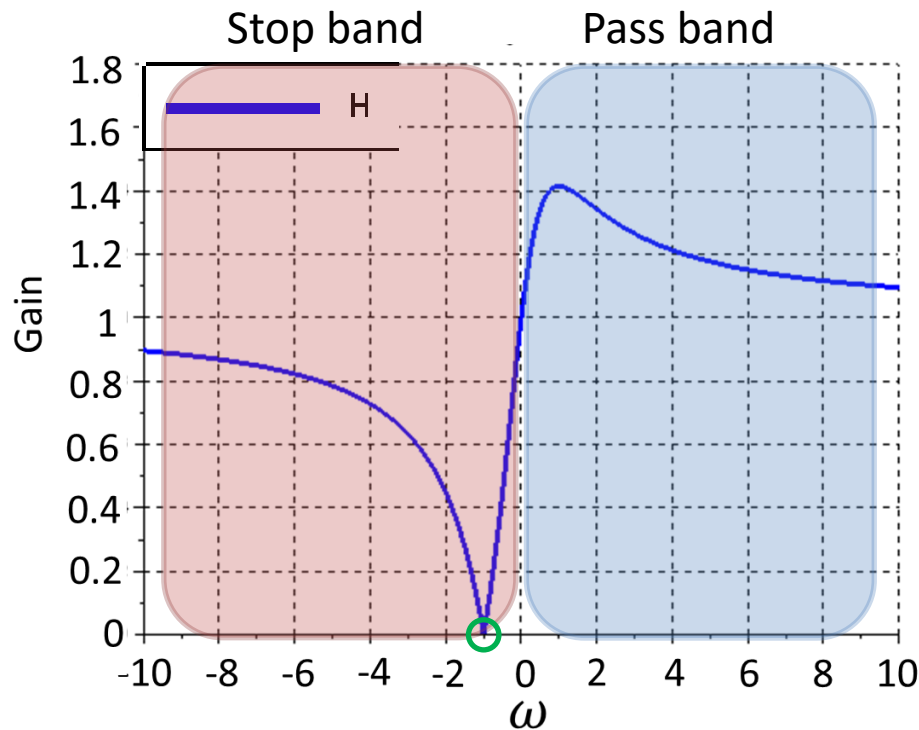


$$\exp(-j\omega t) = \cos(\omega t) - j \sin(\omega t)$$

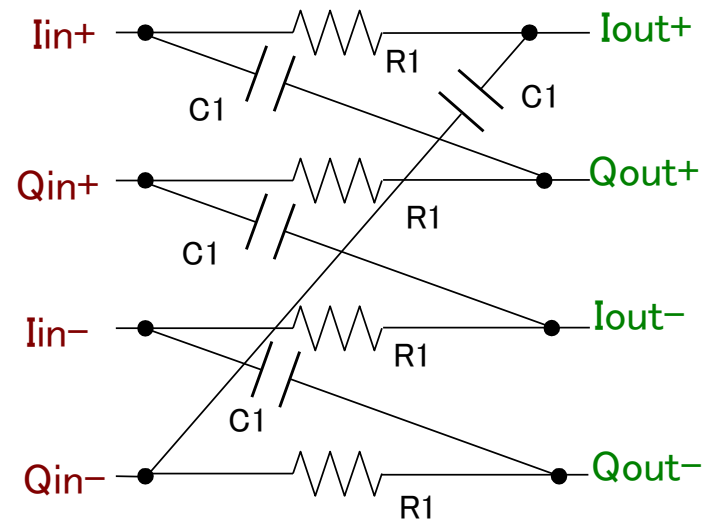


1st order RC Polyphase Filter: Analysis

$$H_1(j\omega) = \frac{1 + \omega R_1 C_1}{1 + j\omega R_1 C_1} \quad : \text{Transfer function}$$



Zero: $\omega_k = \frac{1}{R_k C_k}$



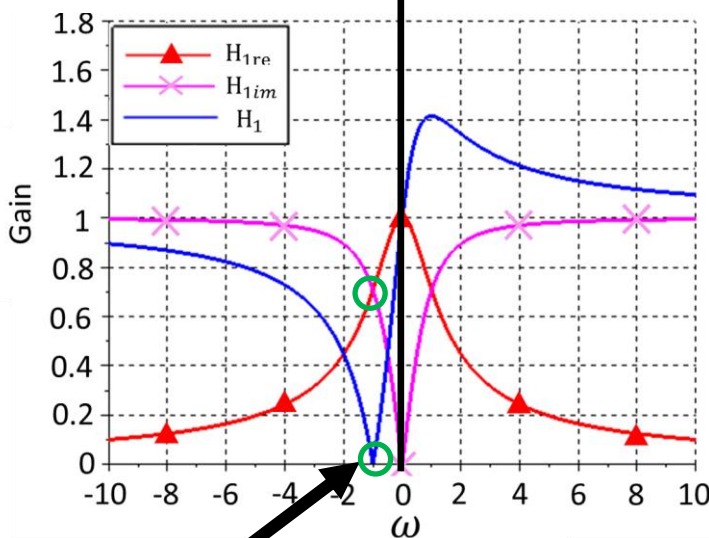
1st order RC Polyphase Filter : Gain and Phase

$$H_1(j\omega) = H_{1re}(j\omega) + jH_{1im}(j\omega)$$

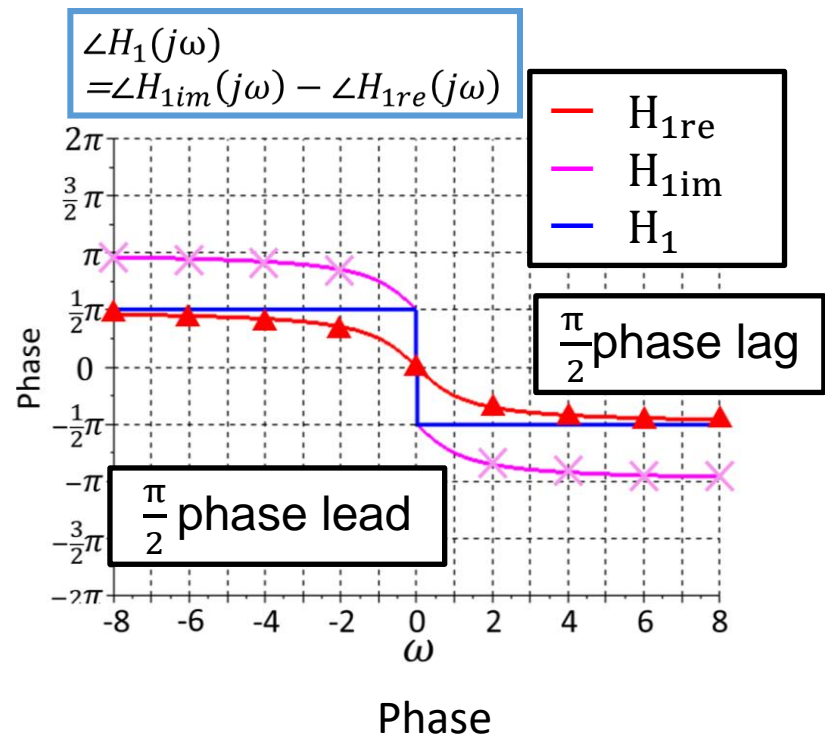
$$H_{1re}(j\omega) = \frac{H_1(j\omega) + H_1^*(-j\omega)}{2} = \frac{1}{1 + j\omega R_1 C_1}$$

$$H_{1im}(j\omega) = \frac{H_1(j\omega) - H_1^*(-j\omega)}{2} = -j \frac{\omega R_1 C_1}{1 + j\omega R_1 C_1}$$

$$||H_{1re}| - |H_{1im}|| \quad \leftarrow \quad \rightarrow \quad |H_{1re}| + |H_{1im}|$$



$$|H_{1re}| = |H_{1im}| \quad \text{Gain}$$

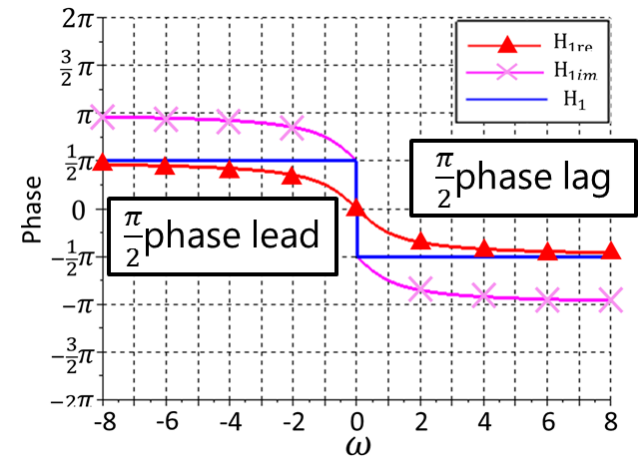
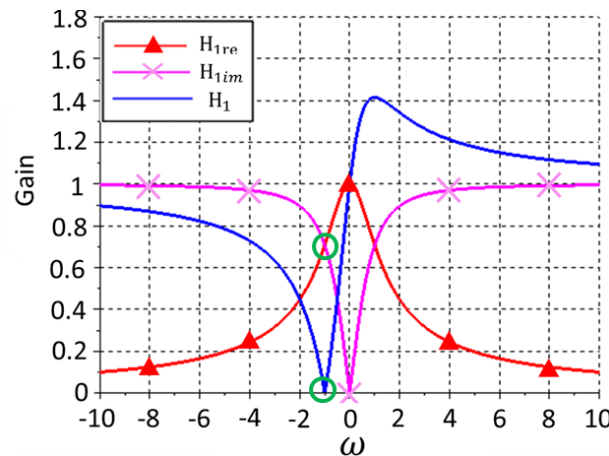


1st order case Analysis Results

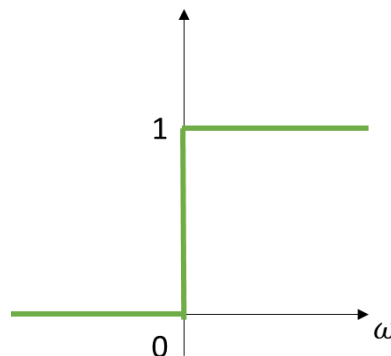
Gain : Hilbert filter only at zero

Phase : Completely Hilbert filter

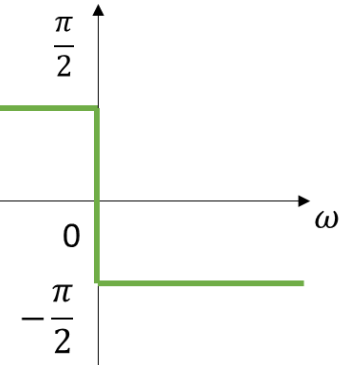
RC Polyphase Filter



Hilbert filter

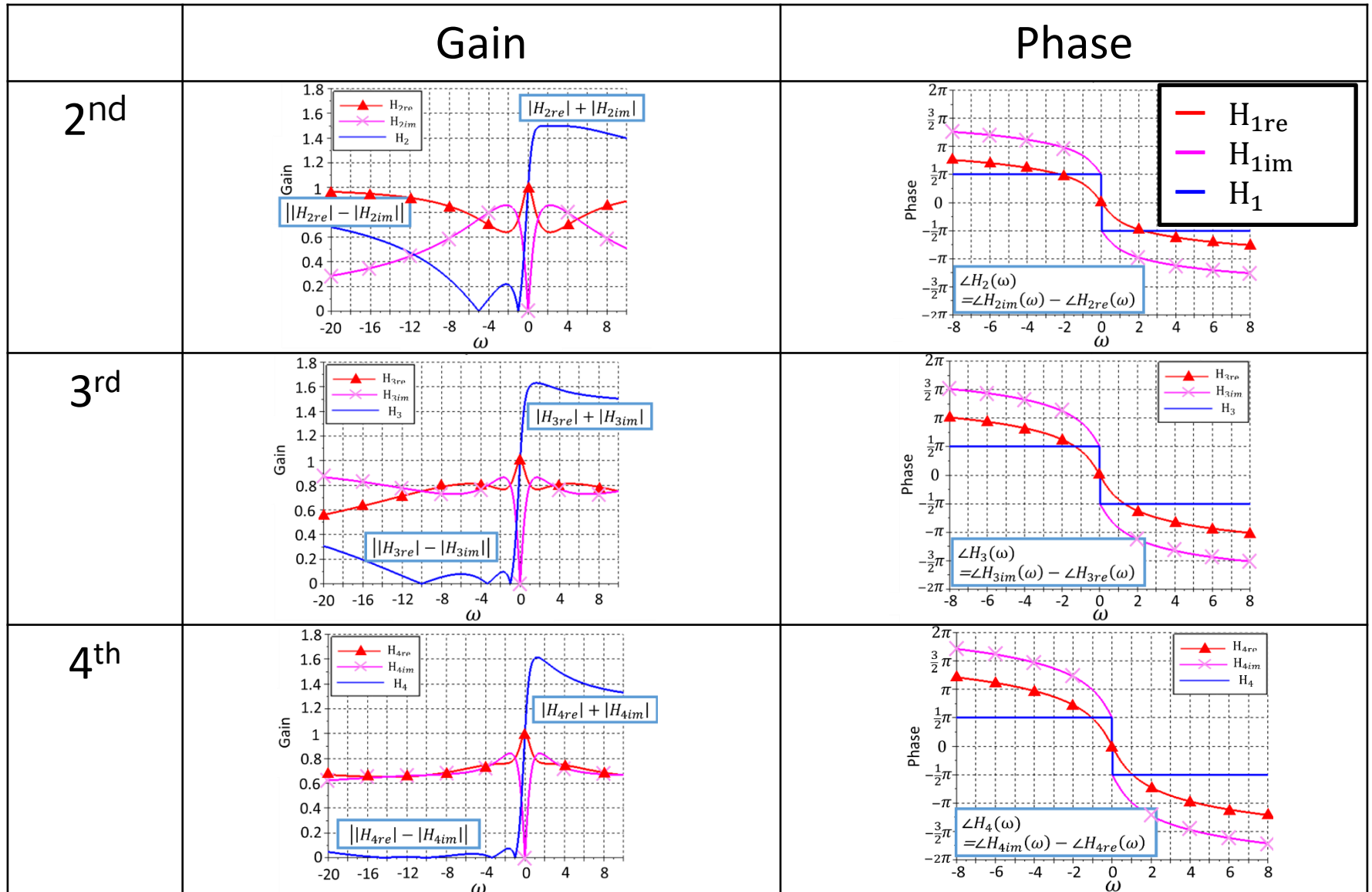


Gain



Phase

Results: 2nd to 4th RC Polyphase Filter



Analysis Results and Consideration

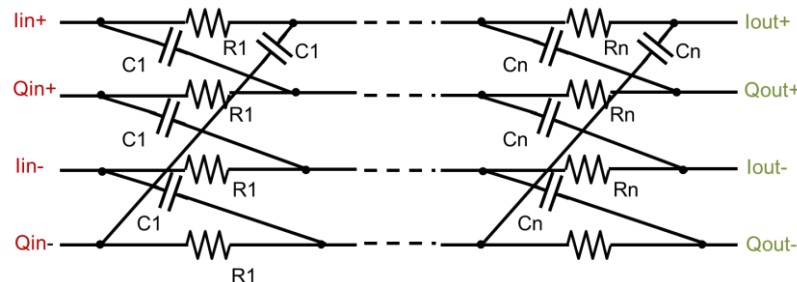
1st to 4th order RC Polyphase Filter Analysis results

Gain : Hilbert filter only at zero

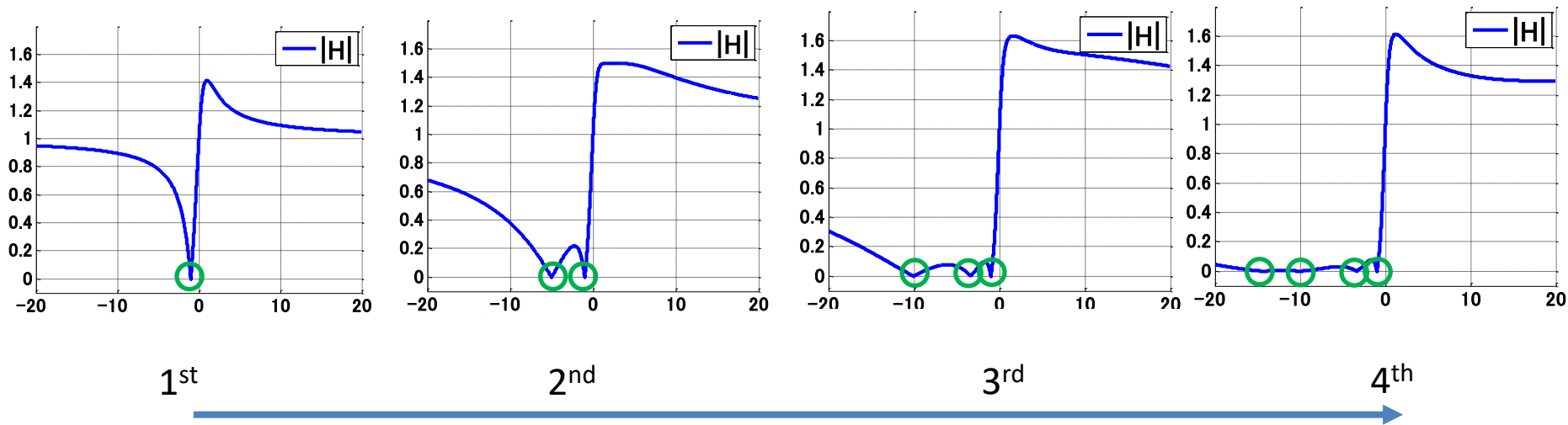
Phase : Completely Hilbert filter



Prove for general n-th order case
($n = 1, 2, 3, 4, 5, \dots$)



Order and Gain

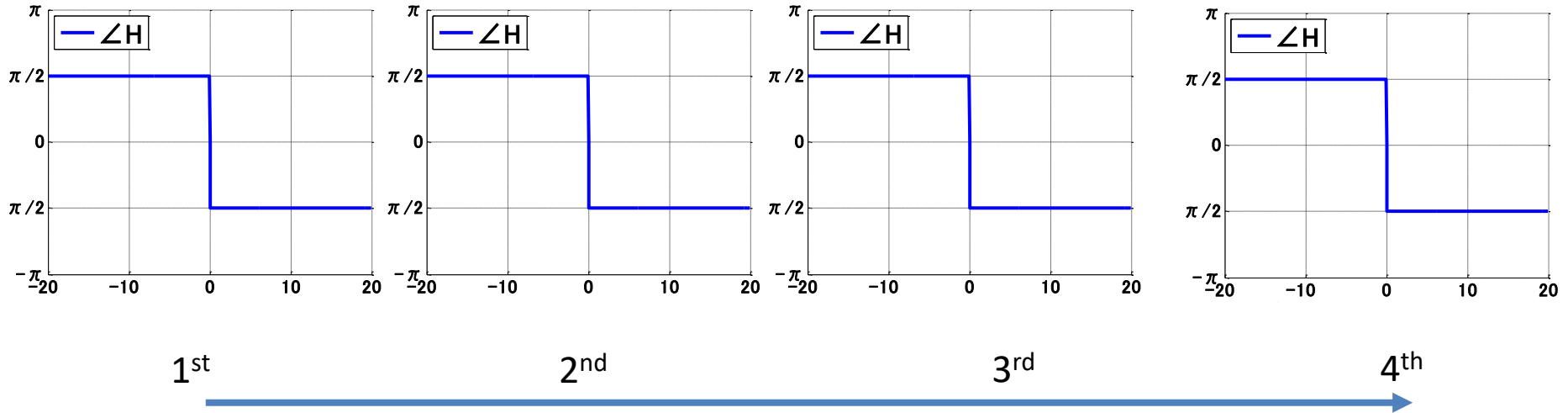


The higher orders,
Increase number of zeros
 $|H_{re}|$ and $|H_{im}|$ becomes close in wide range



Close to ideal Hilbert transform

Order and Phase



Phase characteristic is not changed

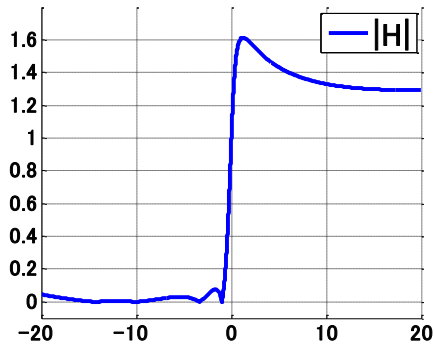
There is always 90° phase

Fulfill Hilbert transform in full range

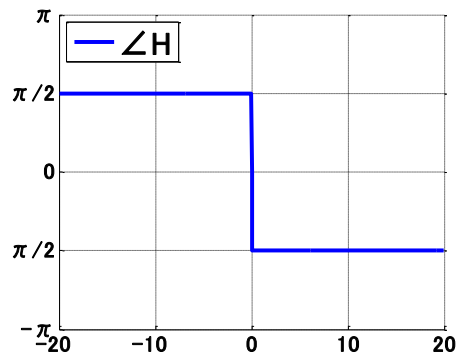
Conclusion

RC Polyphase Filter

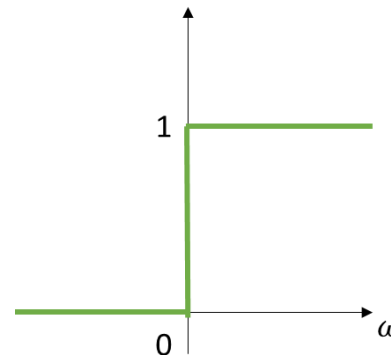
Hilbert Filter



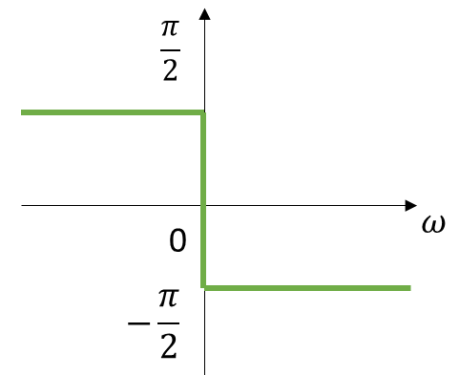
Gain



Phase



Gain



Phase

RC polyphase filter is approximation of ideal Hilbert filter for complex input signal

Outline

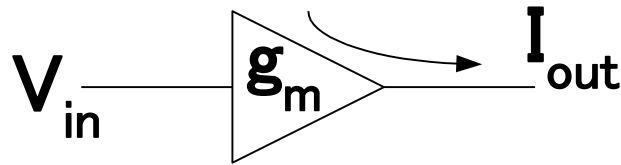
- Motivation for Complex Signal Processing Research
- RC Polyphase Filter: Transfer Function
- RC Polyphase Filter: Flat Passband Gain Algorithm
- RC Polyphase Filter and Hilbert Filter
- **Active Complex Bandpass Filters**
- Conclusion

Gm : Transconductance

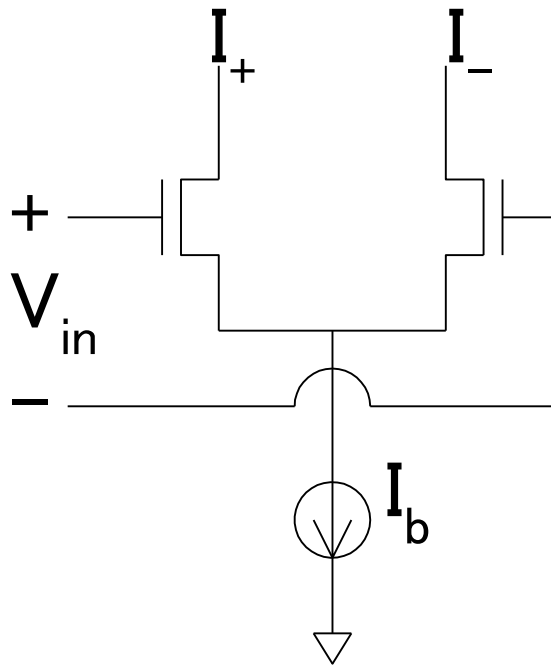
Input voltage: V_{in}

Output current : I_{out}

$$I_{out} = g_m V_{in}$$

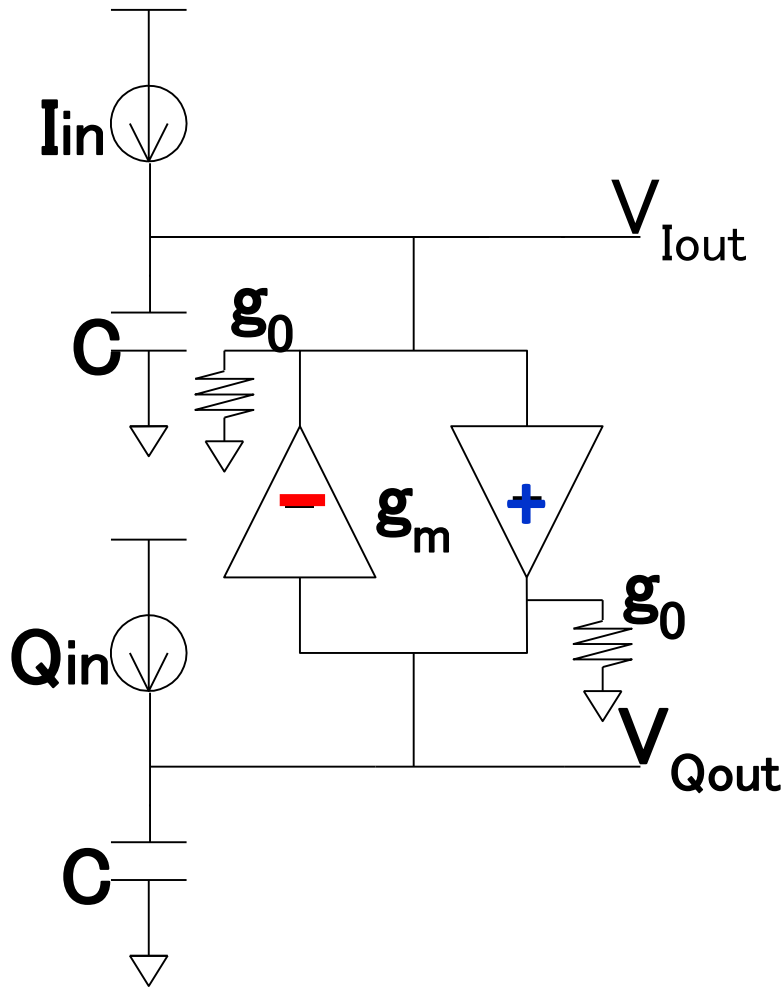


dimension of $g_m \Rightarrow \frac{1}{R}$



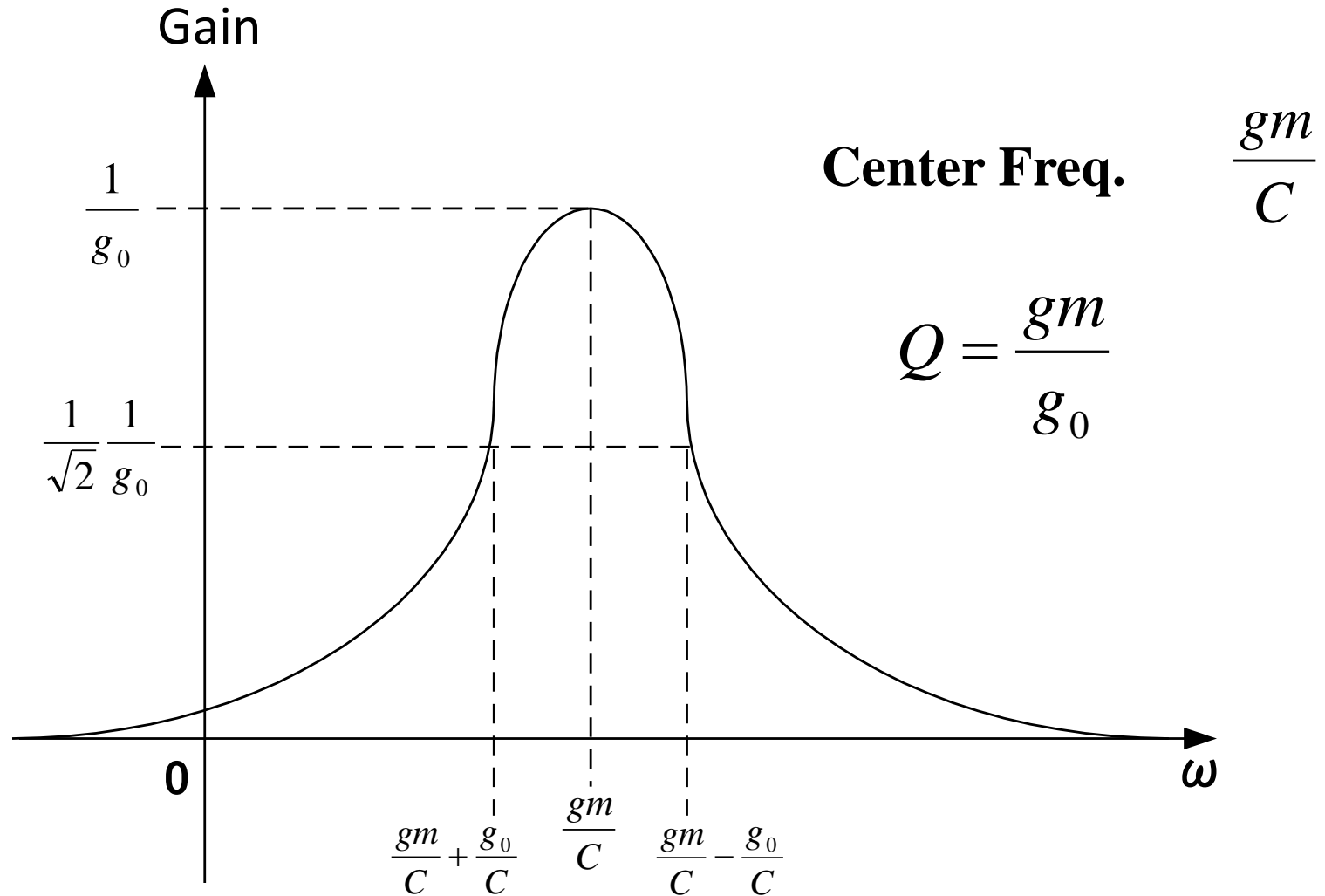
$$I_{out} = I_+ - I_-$$
$$= g_m V_{in}$$

Complex Bandpass Gm-C Filter

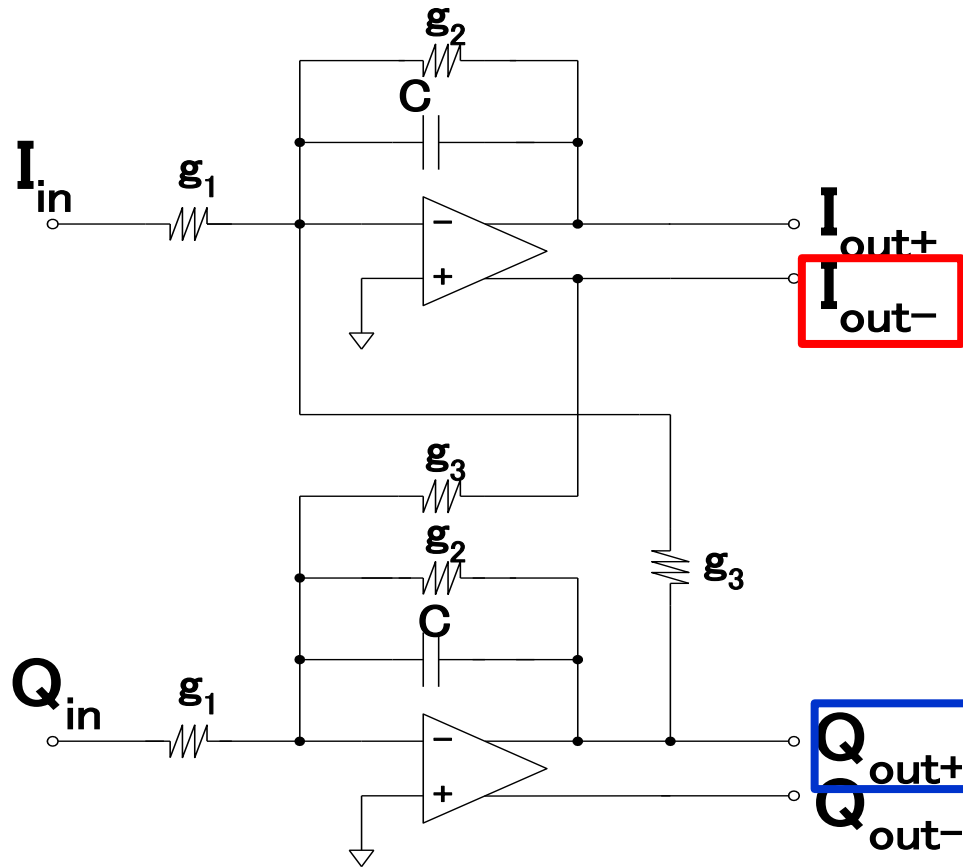


$$\frac{V_{Iout} + jV_{Qout}}{I_{in} + jQ_{in}} = \frac{g_0 + sC - jg_m}{g_0^2 + g_m^2 + s^2C^2 + 2g_0sC}$$

Gain of Complex Bandpass Gm-C Filter



Complex Bandpass Active RC Filter



$$H(j\omega) = \frac{-g_1}{g_2 + j(-g_3 + \omega C)}$$

Center freq. $\omega_0 = \frac{g_3}{C}$

$Q = \frac{g_3}{2g_2}$

Gain $|H(j\omega)| = \frac{g_1}{g_2}$

Our Investigation Results

- Transfer functions of complex bandpass Gm-C and active RC filters are the same.
- Both complex bandpass filters are NOT close to Hilbert filter
Phase characteristics are far from Hilbert.
- RC polyphase filter is close to Hilbert filter.

Outline

- Motivation for Complex Signal Processing Research
- RC Polyphase Filter: Transfer Function
- RC Polyphase Filter: Flat Passband Gain Algorithm
- RC Polyphase Filter and Hilbert Filter
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- **Conclusion**

Conclusion

RC polyphase filter is simple, but very interesting



Even somewhat mysterious !



To understand its principle, we use
its complex transfer function and
Hilbert transfer form.



These are useful for filter design as well as analysis

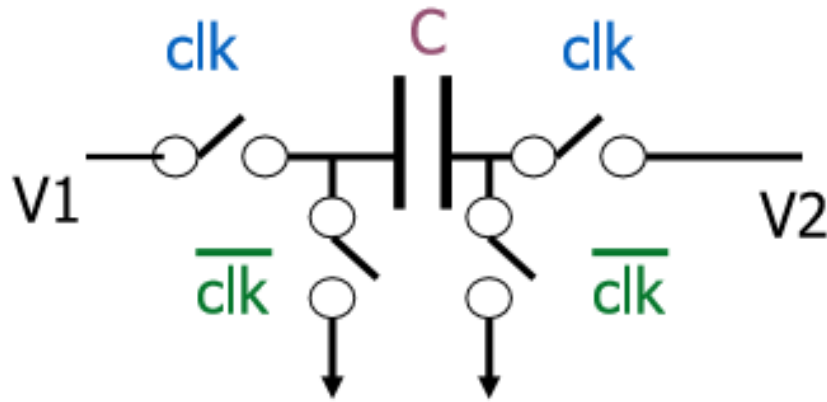
Final Statement

Our World is in **Complex** Domain.

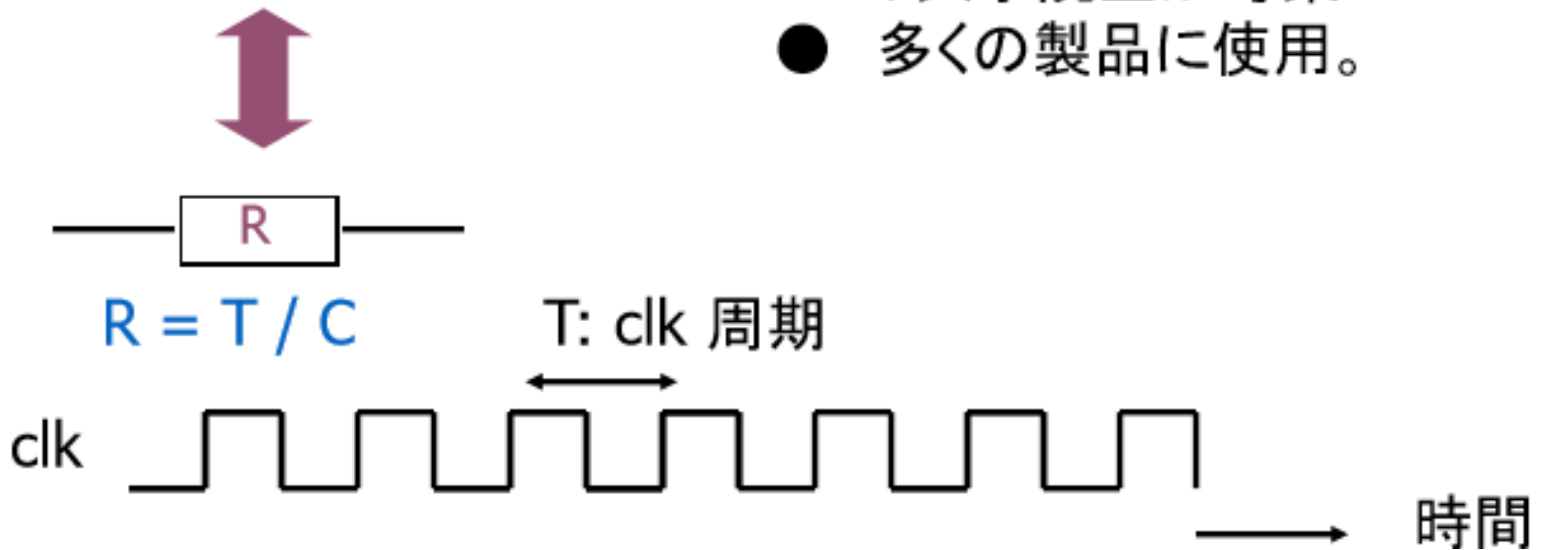
Real **Imaginary**

Complex Signal Processing is NOT Complex.
Quadrature Signals: Complex, But Not Complicated.

付録： スイッチトキャパシタ回路

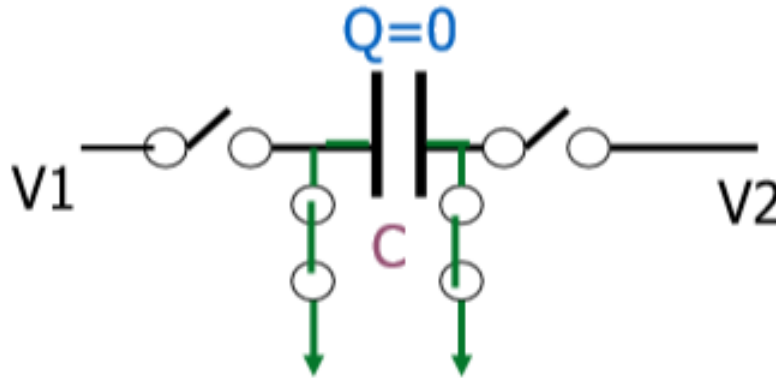


- 容量 C とスイッチで等価的に抵抗 R を実現
- MOSスイッチ使用
- 米国カルフォルニア大学の大学院生が考案
- 多くの製品に使用。



スイッチトキャパシタ回路の動作原理

clk=low
のとき

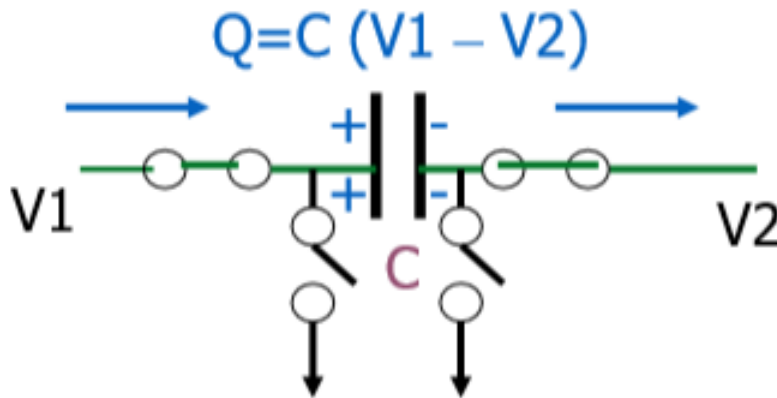


時間Tに電荷
 $Q=C(V1 - V2)$
が流れる。



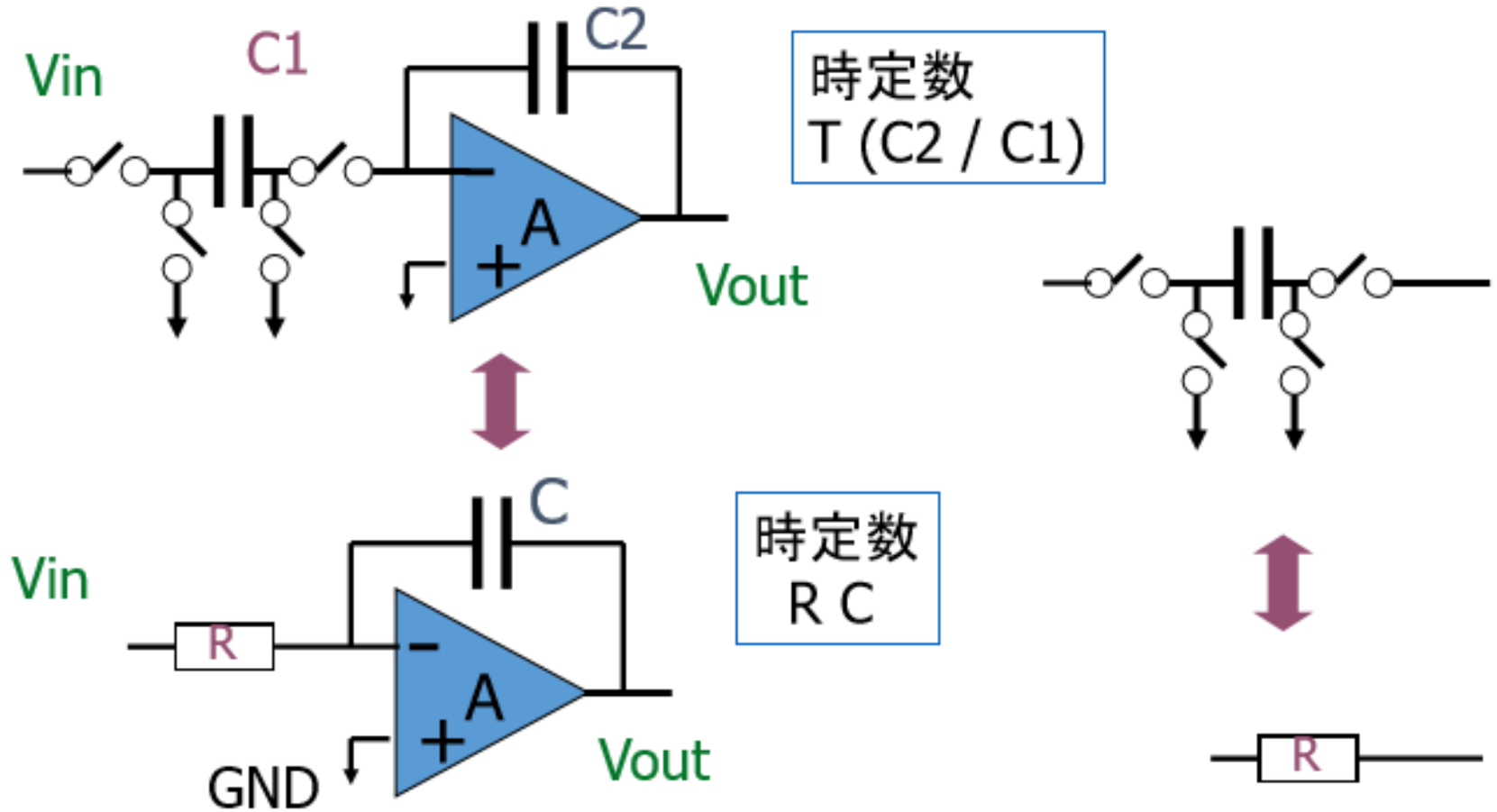
$$I = \frac{C}{T}(V1 - V2)$$
$$= \frac{1}{R}(V1 - V2)$$

clk=high
のとき



$$\therefore R = \frac{T}{C}$$

スイッチト・キャパシタ積分回路



A Multibit Complex Bandpass $\Delta\Sigma$ AD Modulator with I,Q Dynamic Matching and DWA Algorithm

*H. San, Y. Jingu, H. Wada, H. Hagiwara,
A. Hayakawa, J. Kudoh², K. Yahagi²,
T. Matsuura², H. Nakane², H. Kobayashi,
M. Hotta³, T. Tsukada², K. Mashiko⁴, A. Wada⁵*

- 1) *Gunma University*
- 2) *Renesas Technology Corp.*
- 3) *Musashi Institute of Technology*
- 4) *STARC*
- 5) *Sanyo Electric Co., Ltd.*

Outline

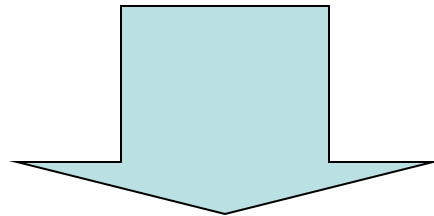
- **Motivation**
- **Complex Bandpass Delta-Sigma AD Modulator**
- **Proposed Architecture**
 - **I, Q Dynamic Matching**
 - **Complex DWA Algorithm**
- **Measured Results**
- **Conclusion**

Outline

- **Motivation**
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 - I, Q Dynamic Matching
 - Complex DWA Algorithm
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- **Conclusion**

Motivation

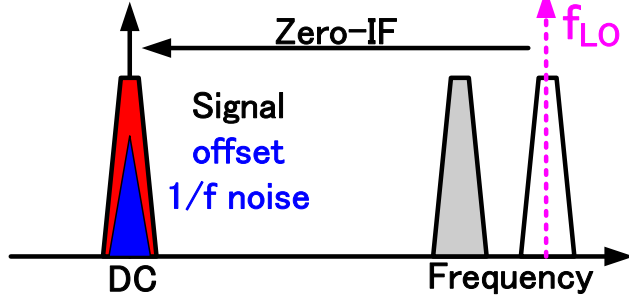
**Low power ADC in low-IF receiver
targeted for bluetooth, wireless LAN.**



**Complex bandpass delta-sigma
AD modulator**

Receiver Architecture Comparison

Direct conversion receiver



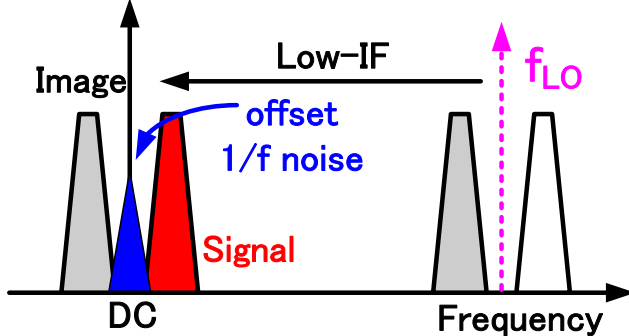
RF \rightarrow Baseband

Zero-IF

\Rightarrow No image

Problem of DC offset, flicker noise

Low-IF receiver Conventional



RF \rightarrow Low-IF

No problem of DC offset, flicker noise.

Image as well as signal are

AD converted \Rightarrow Power is wasted

Quadrature-IF

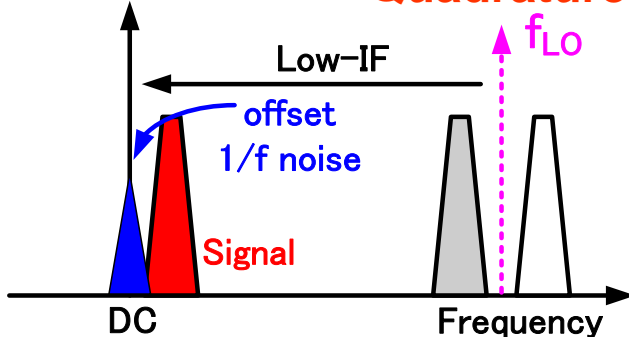
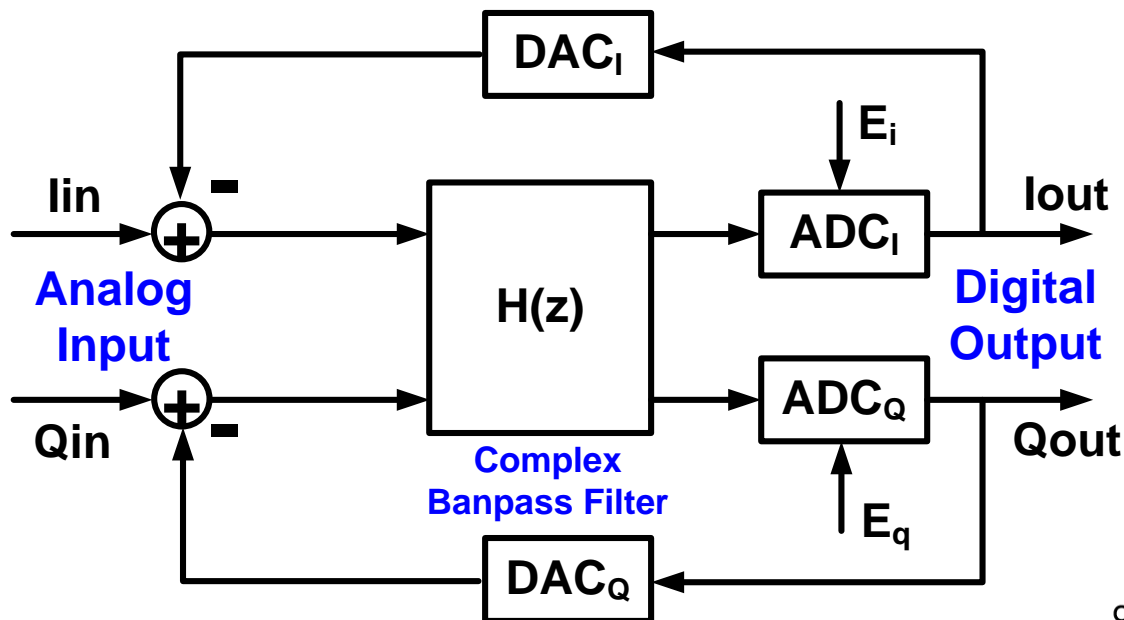


Image is not AD converted.

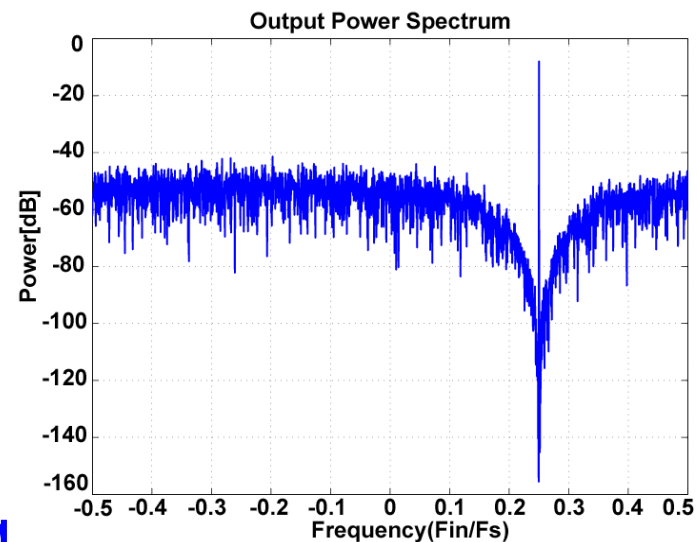
Outline

- Motivation
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Complex Bandpass Delta-Sigma Modulator



$$I_{out} + jQ_{out} = \frac{H}{1+H} (I_{in} + jQ_{in}) + \frac{1}{1+H} (E_i + jE_q)$$

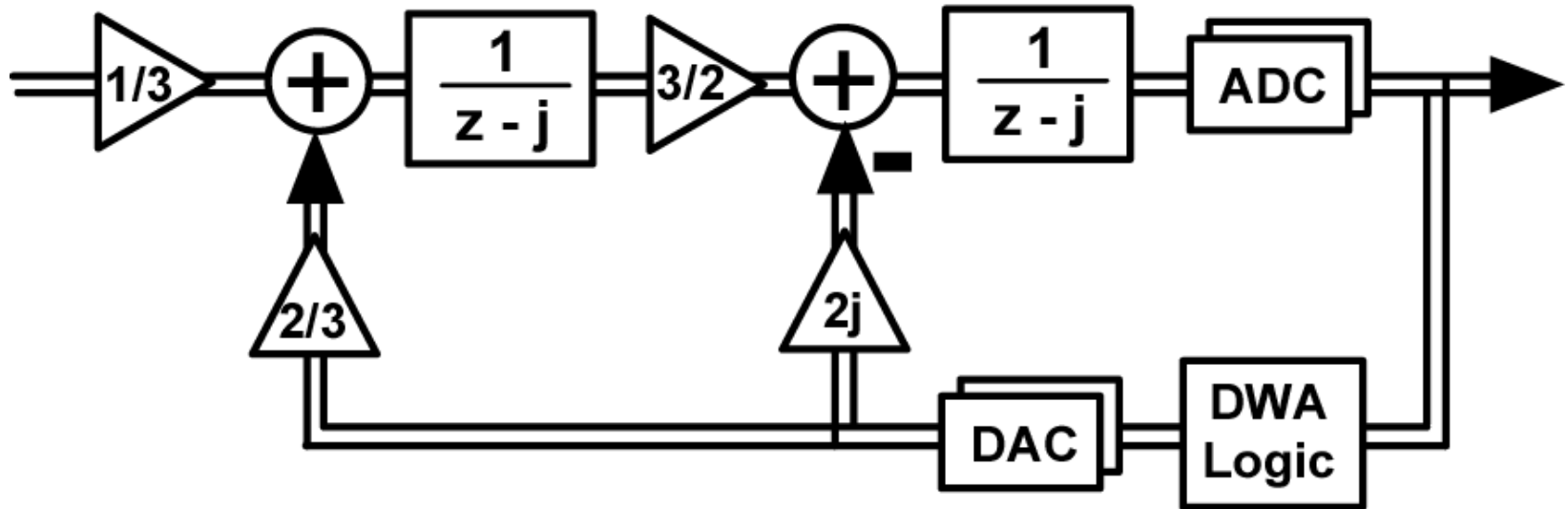


Complex bandpass noise-shaping

Outline

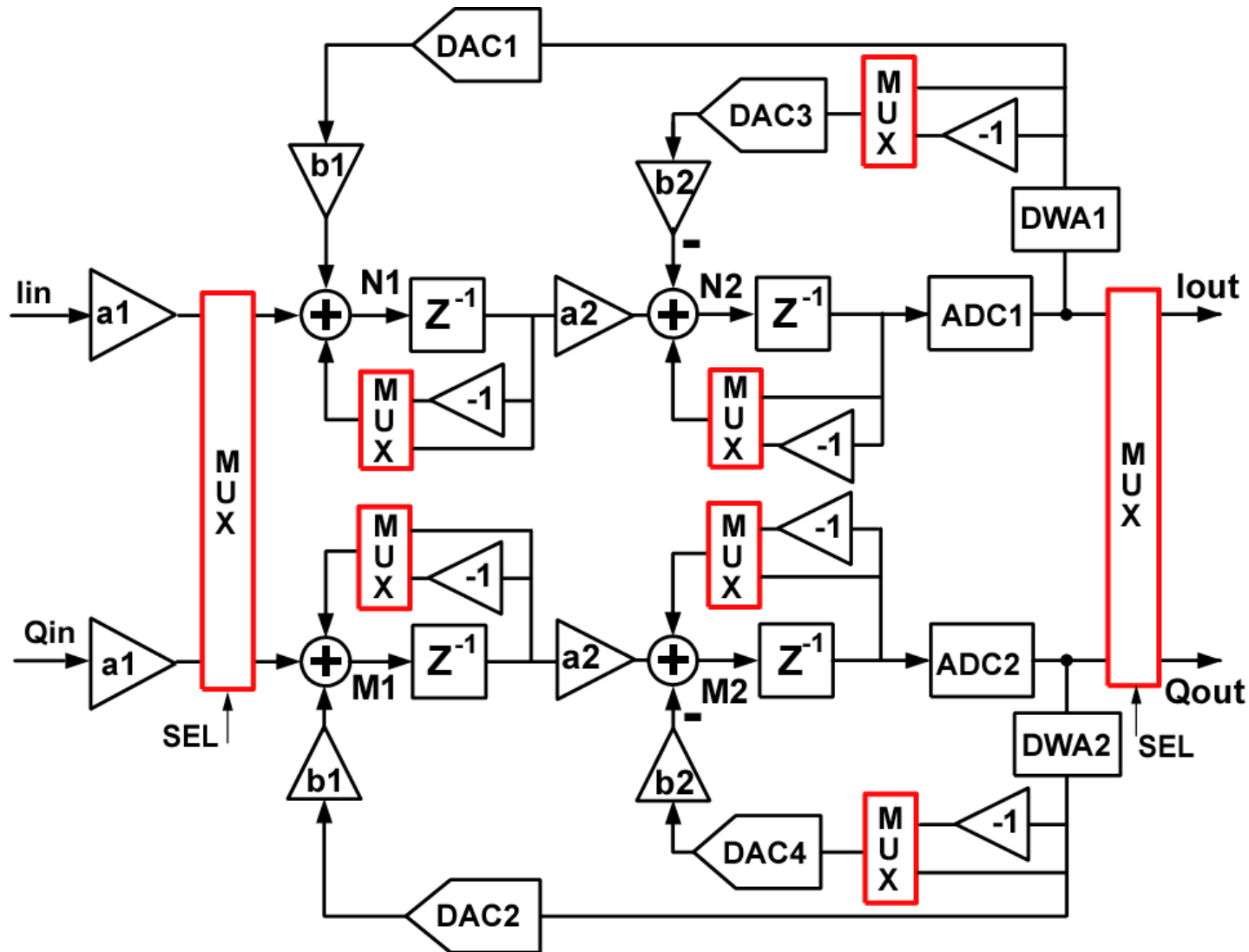
- Motivation
- Complex Bandpass Delta-Sigma AD Modulator
- **Proposed Architecture**
 - I,Q Dynamic Matching
 - Complex DWA Algorithm
- Measured Results
- Conclusion

Proposed Architecture

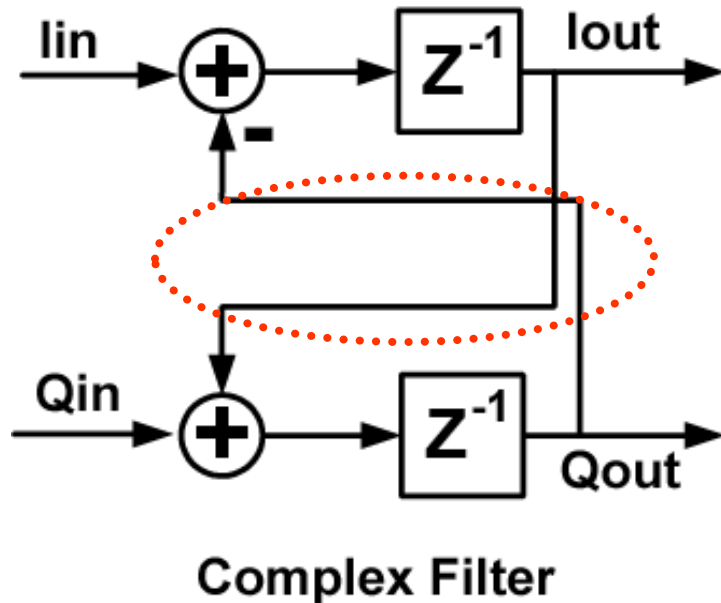


- **New complex bandpass filter**
- **Multi-bit ADCs/DACs**
- **Complex DWA algorithm**

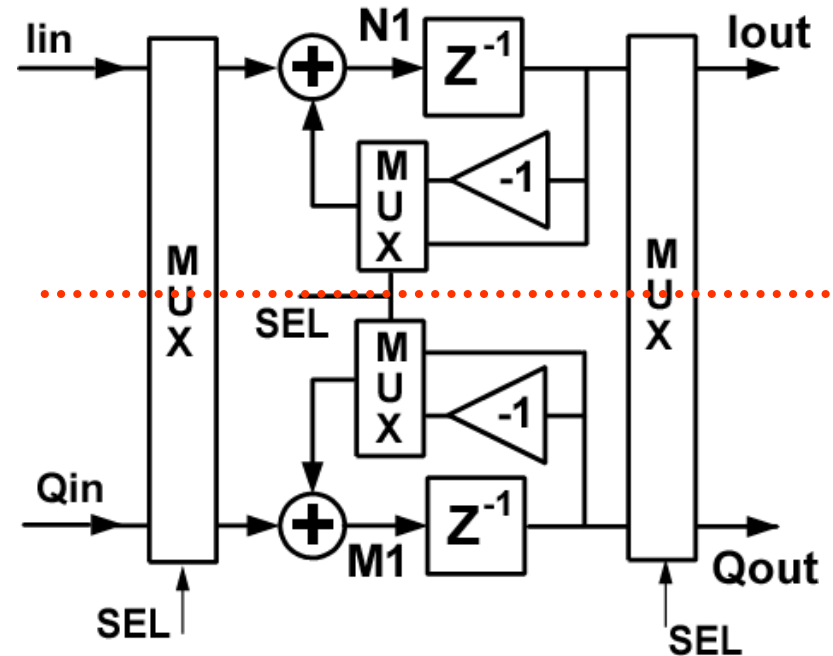
Proposed Structure



I,Q Dynamic Matching of Complex Filter



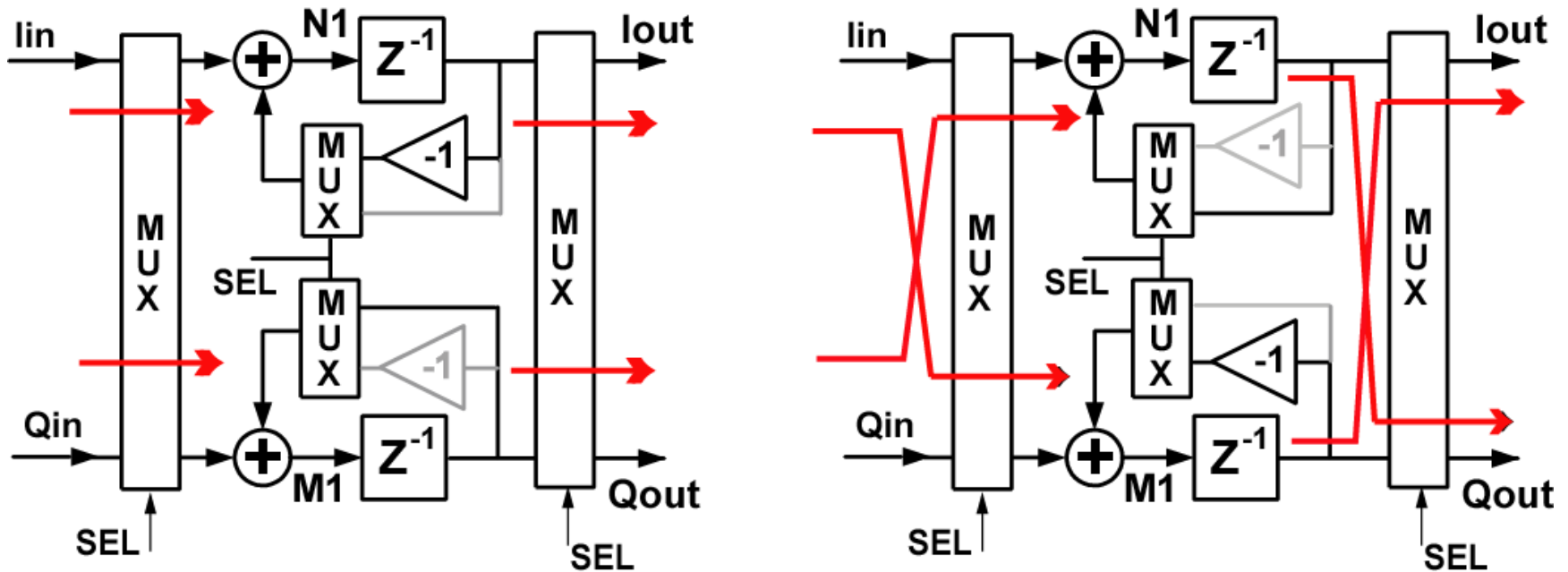
Conventional complex filter
I & Q crossing paths



Proposed complex filter
Upper, lower separated paths

- I,Q mismatch reduction.
- Layout simplification.

Operation of Proposed Complex Filter



$$lout(n) = lin(n-1) - Qout(n-1)$$
$$Qout(n) = Qin(n-1) + lout(n-1)$$

Complex BPDSM with Low-power

- **2nd order ---- low power**
- **9-level ADCs/DACs**
 - **Stability improvement**
 - **Low quantization error**
 - **Power reduction of amplifiers**

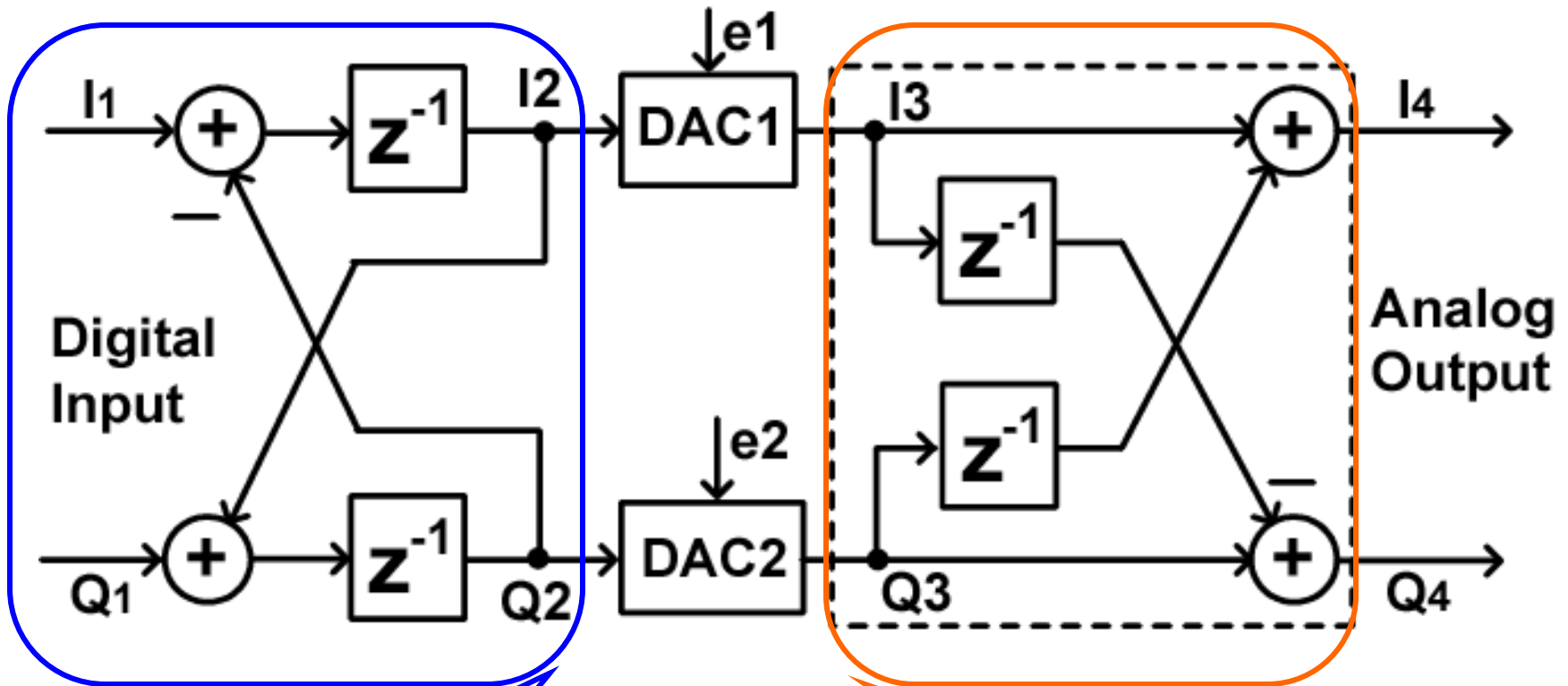
I,Q mismatch

- **Solved by dynamic matching**

Nonlinearities of multibit DAC

- **Solved by complex DWA**

Complex DWA (1)



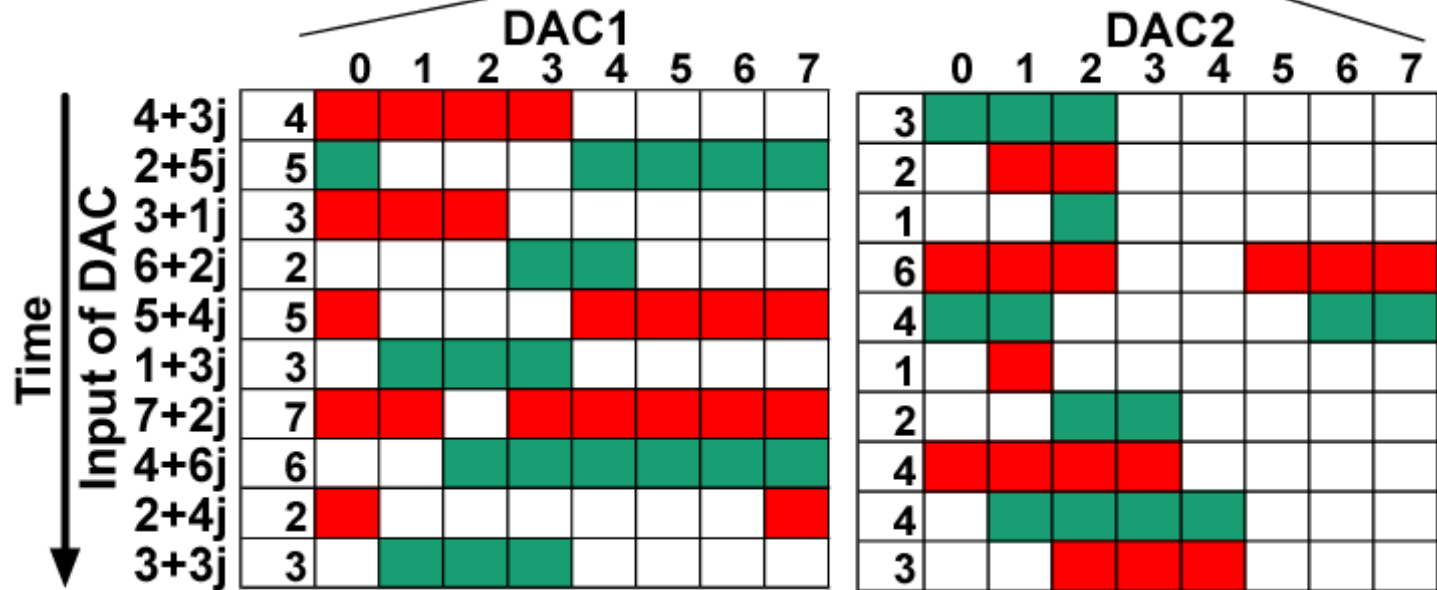
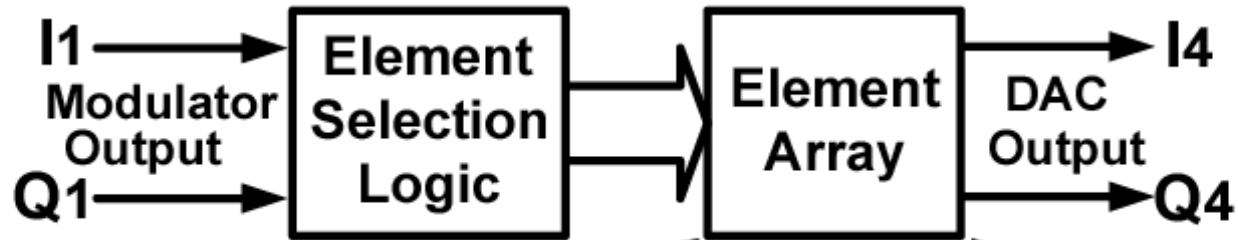
$$H_1(z) = \frac{1}{z - j}$$

Digital bandpass filter

$$H_2(z) = z - j$$

Analog band elimination filter

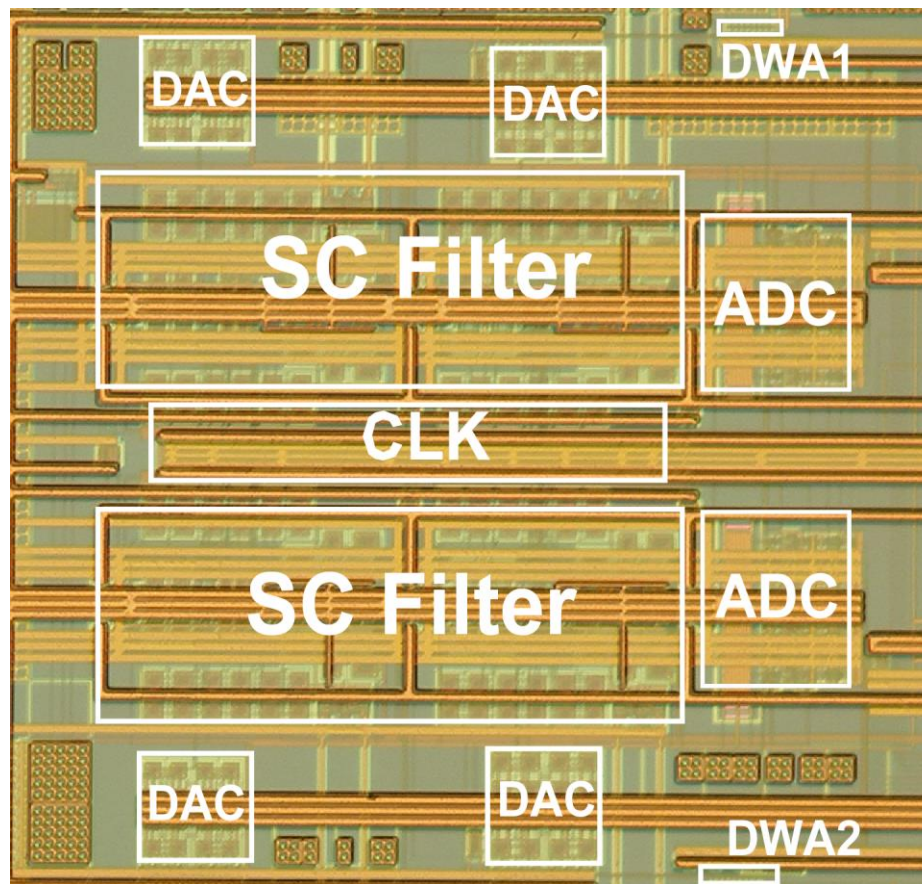
Complex DWA (2)



Outline

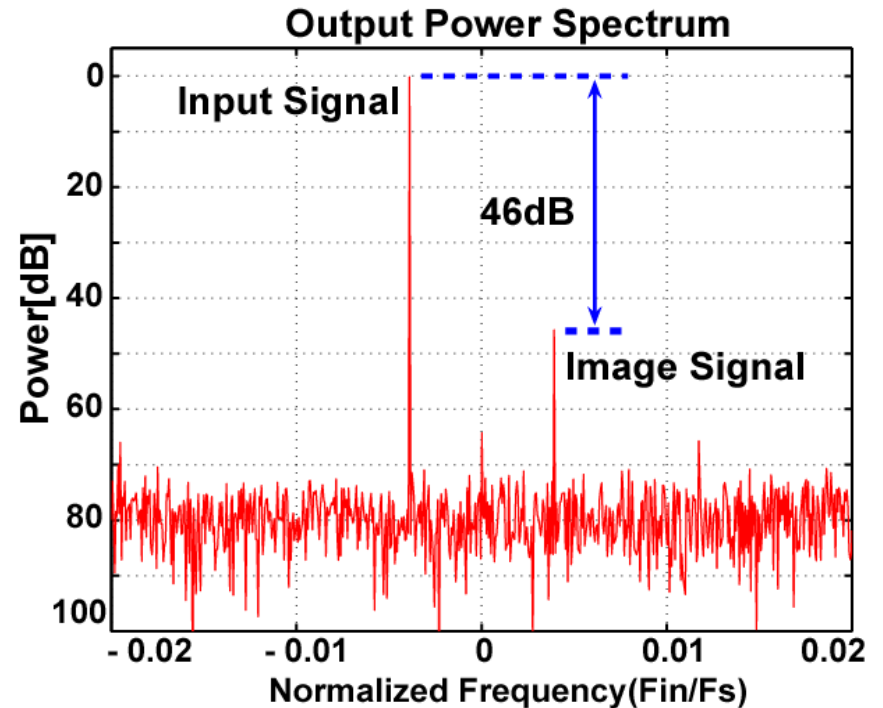
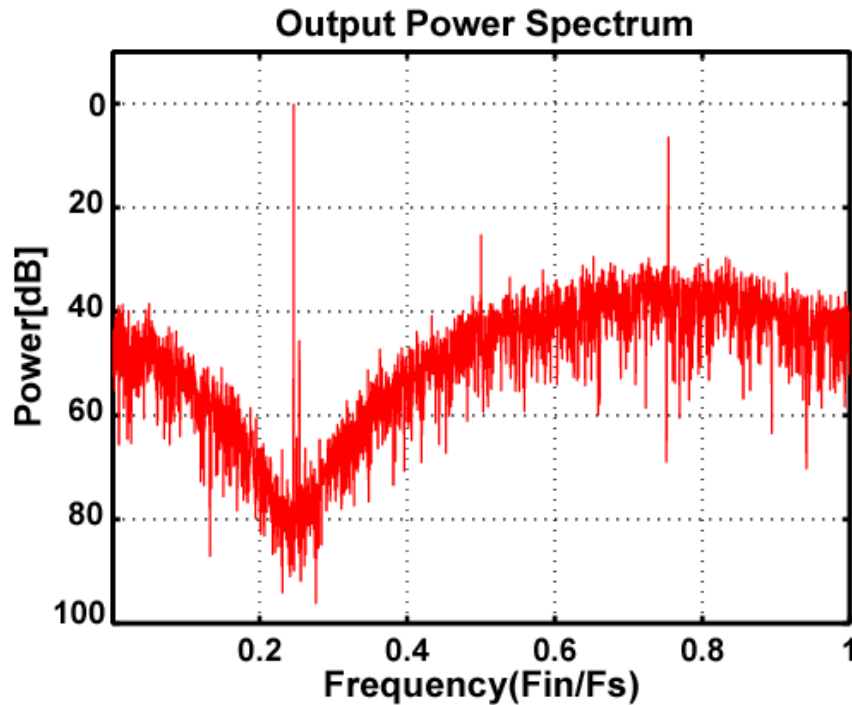
- Motivation
- Complex Bandpass Delta-Sigma AD Modulator
- Proposed Architecture
 - I,Q Dynamic Matching
 - Complex DWA Algorithm
- **Measured Results**
- Conclusion

Chip Implementation

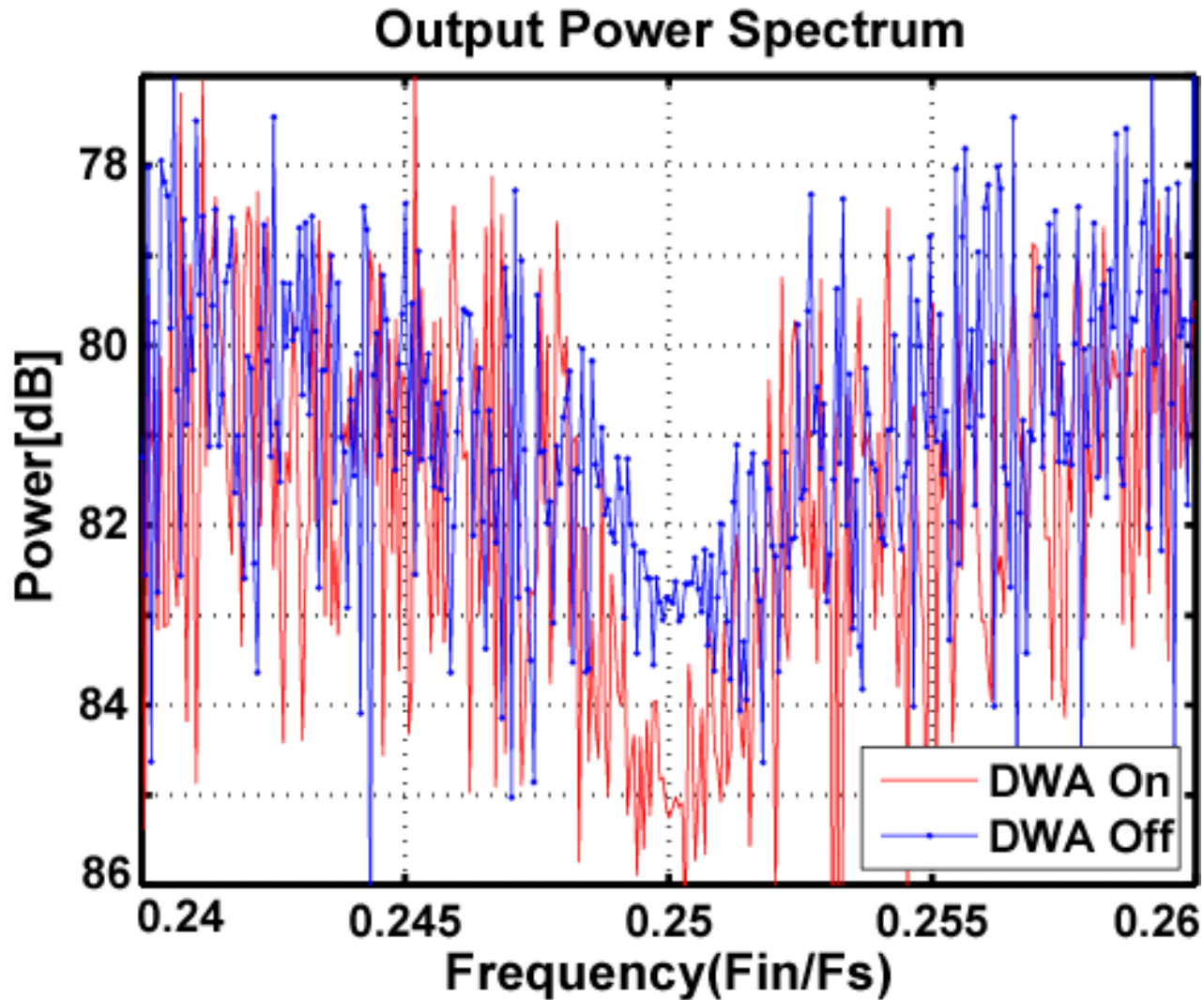


- **1P6M 0.18 μ m CMOS Process**
- **Core size 1.4 *1.3mm².**

Measured Output Power Spectrum



Effect of Complex DWA



Summary of Modulator Performance

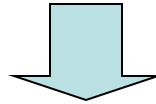
Technology	0.18-μm CMOS 1P6M
Supply voltage	2.8V
Sampling Frequency	20MHz
SNDR	64.5dB @ BW=78kHz
Power consumption	28.4mw
Active area	1.4mm*1.3mm

Outline

- Motivation
- Complex Bandpass Delta-Sigma AD Modulator
- Proposed Architecture
 - I,Q Dynamic Matching
 - Complex DWA Algorithm
- Measured Results
- Conclusion

Conclusion

- **A 2nd-order multi-bit complex bandpass delta-sigma modulator**



Low power

- **Complex filter with dynamic matching**
 - **I,Q mismatch reduction**
 - **Layout simplification**
- **Complex DWA**
 - **Suppression of multibit DACs nonlinearities**
- **Chip measurements demonstrated these**