An RF Tunable LC Bandpass Filter with small Passband Ripple and transformer emulator

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Outline

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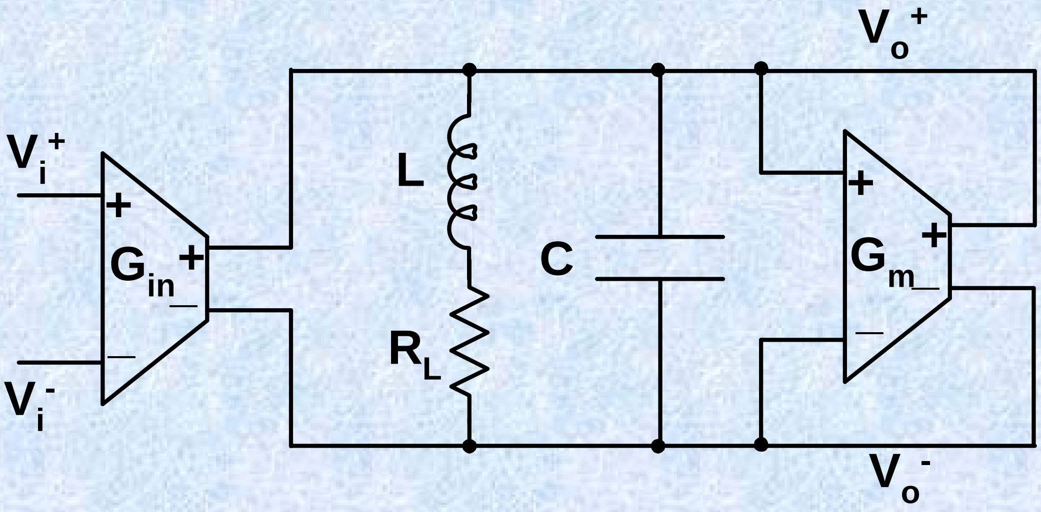
- ❑ High-Order filters
- ❑ Dual resonator bandpass filter
- ❑ Design Considerations
- ❑ Measurement Results
- ❑ Conclusions

Introduction



$$\omega_0 \cong \frac{1}{\sqrt{LC}} \sqrt{1 - \frac{1}{Q_0^2}}$$

$$Q \cong \frac{Q_0}{1 - (G_m / G_{loss})} \sqrt{1 - \frac{1}{Q_0^2}}$$

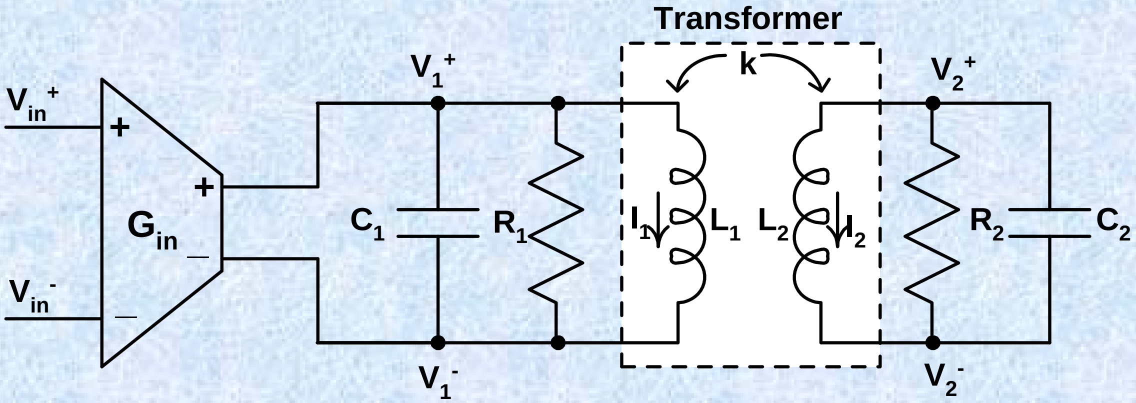
$$G_{loss} \cong R_L (\omega_o C)^2$$

- ☺ Replace off-chip filters
- ☺ Eliminate need of impedance matching
- ☺ Reduce power, area, and cost
- ☹ Integrated spiral inductors are lossy
- ☹ Positive feedback is needed for Q-enhancement

High-Order Filters

- Needed to provide acceptable IR
- Classic LC filter synthesis techniques can be used with Q-enhancement
- No guarantee that the filter frequency response will be preserved
- To avoid large element value spread, especially for narrow band, coupled filters are used
- Consists of reactive tank circuits coupled by capacitors, inductors, or magnetically

Dual Resonator Bandpass Filter



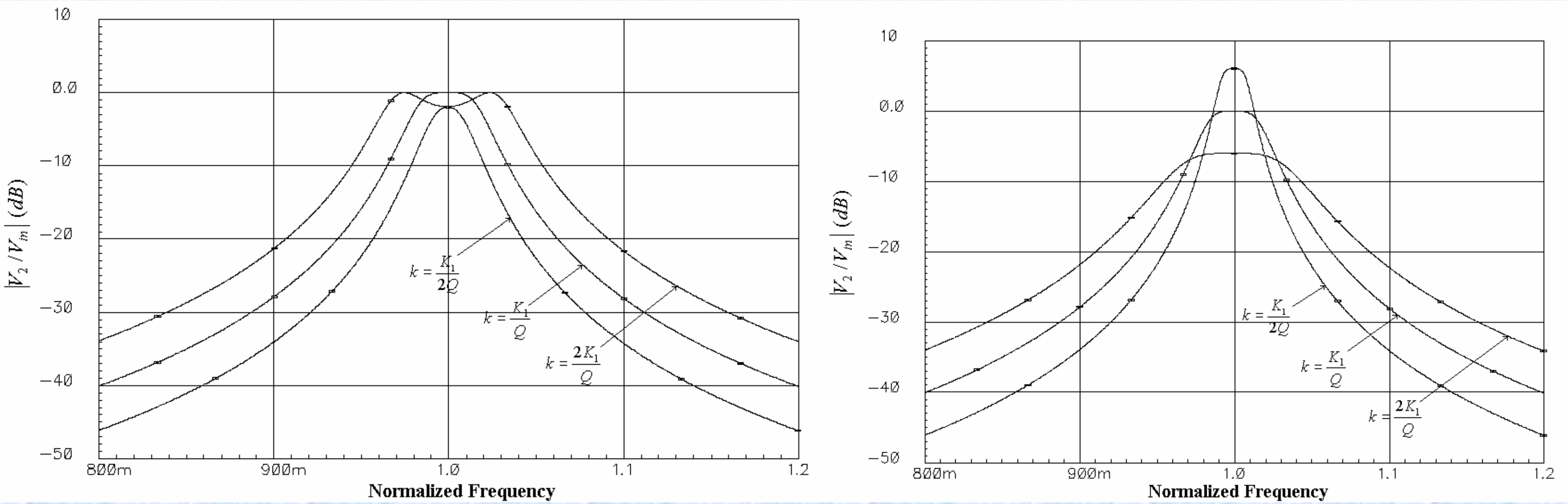
$$R = R_1 = R_2 = K_2 Q\sqrt{L/C}$$

- ❑ Two magnetically coupled resonators
- ❑ 4th order filter
- ❑ ω_0 is fixed by the LC product
- ❑ Coupling coefficient k is used to tune Q

$$LC = (1/\omega_0^2)$$

$$k = K_1/Q$$

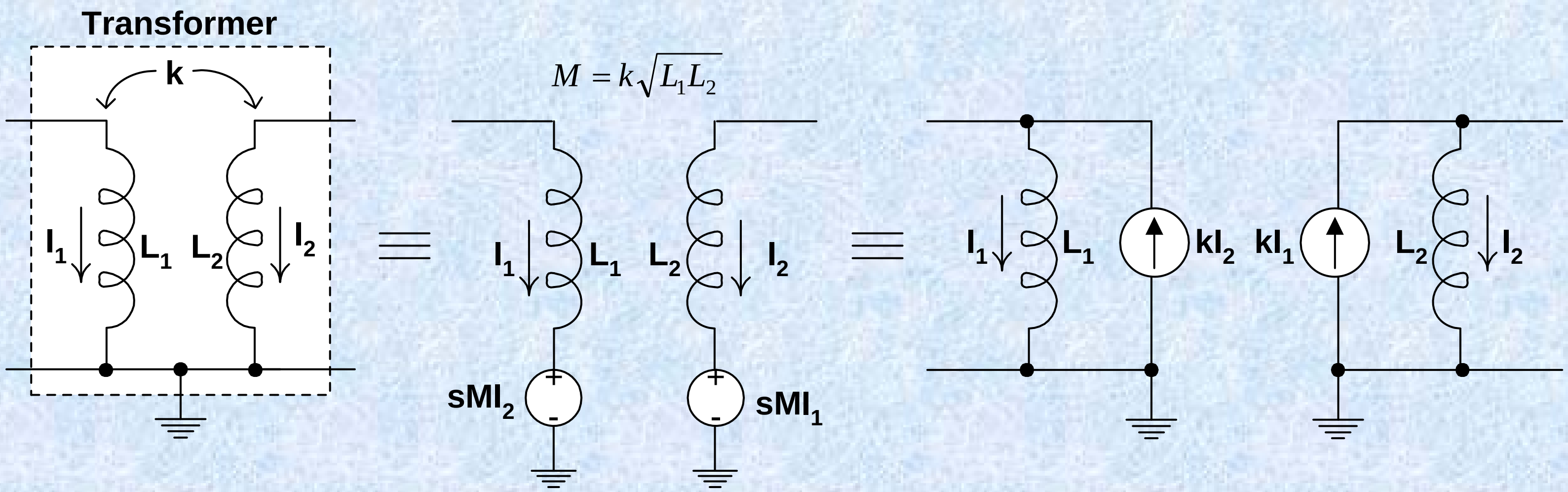
Effect of tuning k



$K=\{K_1/2Q, K_1/Q, 2K_1/Q\}$

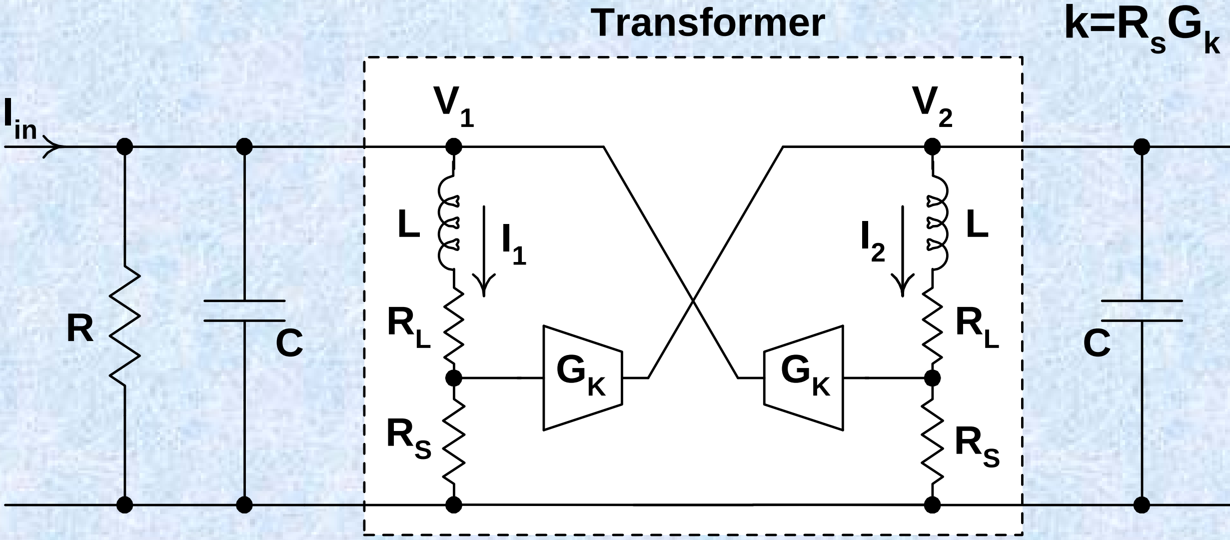
- Minimum passband ripple at critical coupling
- Tuning k and R simultaneously to keep k×R constant

Transformer Models



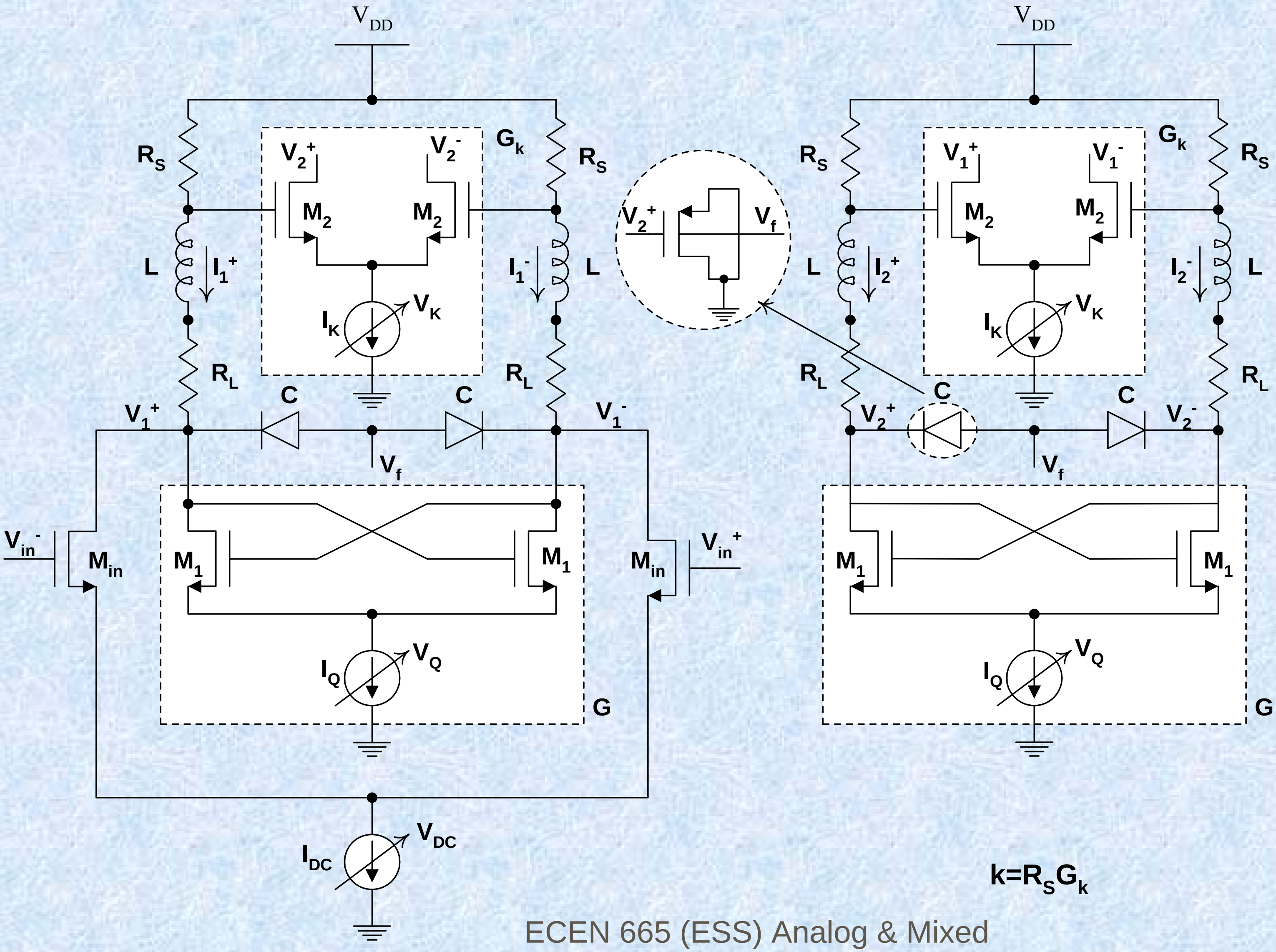
- ☐ Transformer can be replaced by induced currents
- ☐ Due to losses, induced currents are not in phase
- ☐ Severe passband ripples
- ☐ Coupling neutralization to maintain a flatband response
- ☐ Emulate the transformer action by electric coupling

Emulation of Magnetic Coupling



- $k = G_k R_s (\cong 0.01)$
- Provide possibility of BW tuning while maintain flatband
- Placing inductors apart to diminish magnetic coupling

Circuit Implementation



$k=R_SG_k$

Design Considerations

- Noise Analysis

Inductor loss

Negative G_m

Input G_{in}

Q_0 ↑ G_{loss} ↓ v_{noise} ↓

$$v_{noise}^2 = \frac{1}{A_v^2}\left(\frac{KT}{C}\right)\left[\frac{Q}{Q_0} + \zeta\frac{Q}{Q_0} + \zeta A_v\right] = \frac{1}{A_v^2}\left(\frac{KT}{C}\right)\left(\frac{Q}{Q_0}\right)\left[1 + \zeta + \zeta\frac{G_{in}}{G_{loss}}\right]$$

ζ is a noise factor that depends on the implementation

- For low peak gain $A_v<(Q/Q_0)$, contribution of the input transconductance can be neglected

Design Considerations

- Nonlinearity Analysis
  - To isolate nonlinear effects, each nonlinear element is considered separately

$$V_{1-dB,in}^2 = V_{1-dB}^2\Big|_{G_{in}}$$

$$V_{1-dB}\Big|_{G_{in}} = \boxed{1.077\times(V_{GS}-V_T)} = 1.077\times\sqrt{\frac{2I_{SS}}{K_n(W/L)_{in}}}$$

A differential pair based OTA

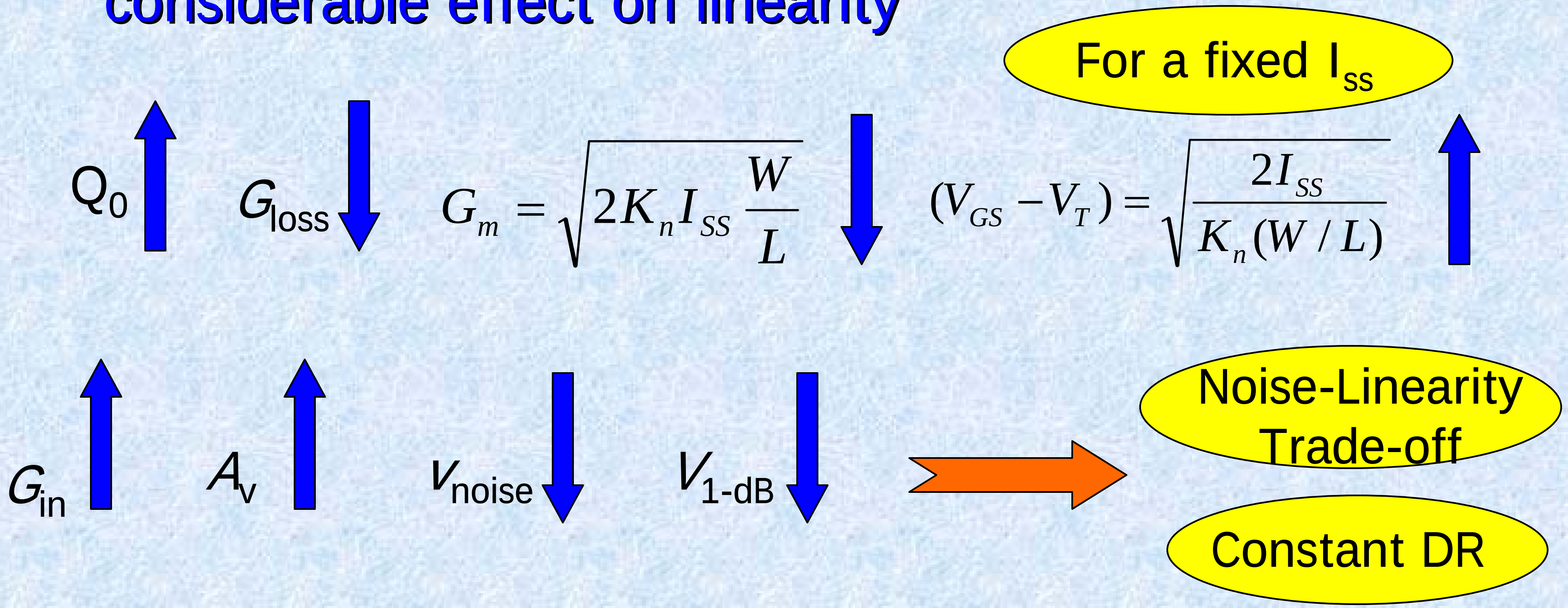
$$V_{1-dB,Gm}^2 = \frac{V_{1-dB}^2\Big|_{Gm}}{A_v^2}\cdot\frac{Q_0}{Q}$$

- For high Q narrowband or high gain applications, the negative OTA dominates linearity performance

Design Considerations

☐ Nonlinearity Analysis

- Starting inductor's quality factor Q_0 has a considerable effect on linearity



For a fixed I_{ss}

Q_0 ↑ G_{loss} ↓ $G_m = \sqrt{2K_n I_{SS}\frac{W}{L}}$ ↓ $(V_{GS} - V_T) = \sqrt{\frac{2I_{SS}}{K_n(W/L)}}$ ↑

G_{in} ↑ A_v ↑ v_{noise} ↓ $V_{1\text{-}dB}$ ↓ →

Noise-Linearity Trade-off

Constant DR

Design Considerations

- Dynamic range

Factor of Q^2_0 improvement over OTA-C counterpart

$$DR = \frac{V_{1-dB}^2}{v_{noise}^2} = \frac{V_{1-dB}^2\big|_{G_m}}{KT\left(1+\zeta+\zeta\frac{G_{in}}{G_{loss}}\right)} C\left(\frac{Q_0}{Q}\right)^2$$

Selectivity-DR trade-off

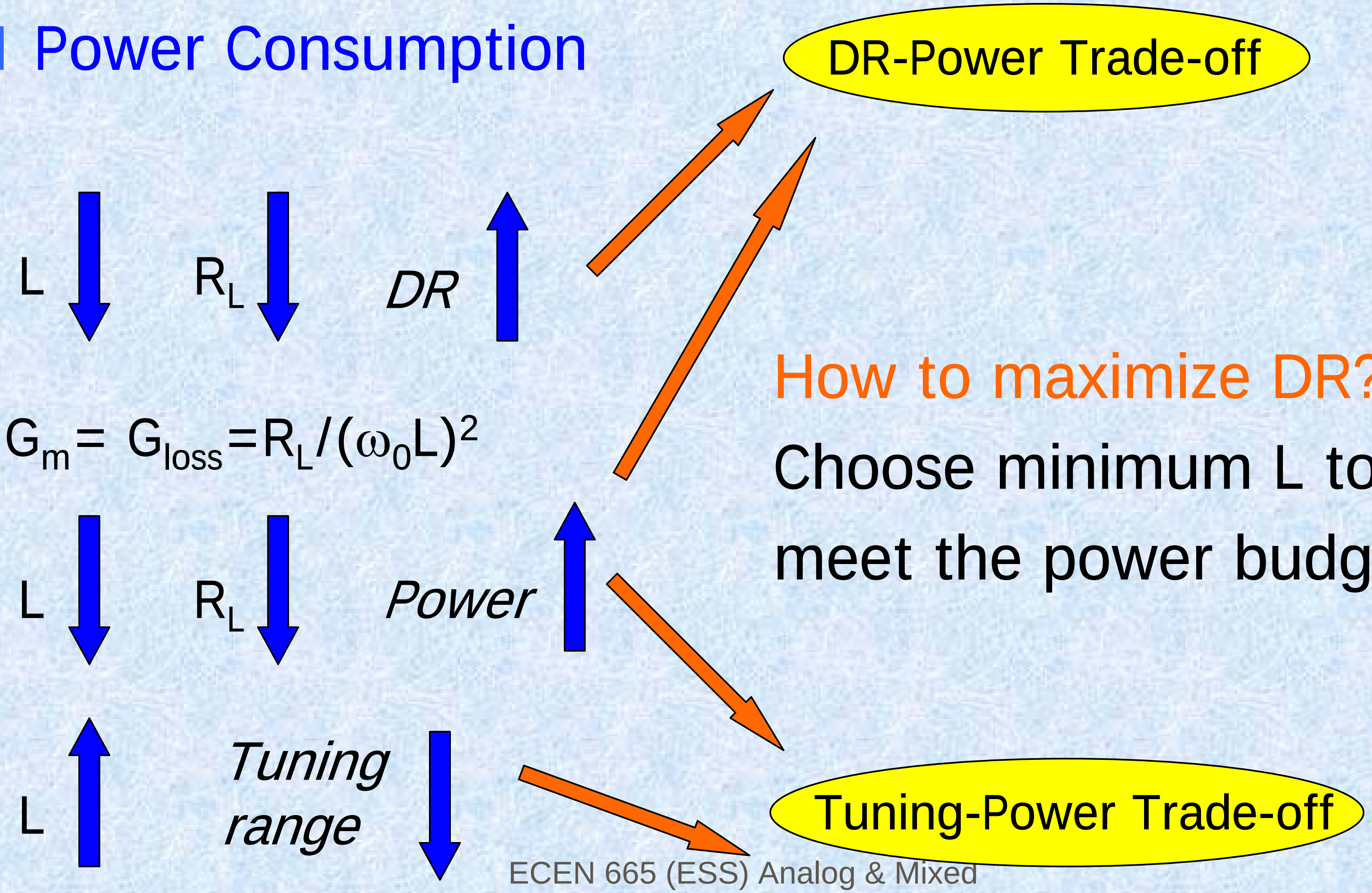
$CQ^2_0=L/R^2_L \uparrow \quad DR \uparrow$

L and R_L scale proportionally

- DR is maximized by minimizing the losses of the inductor
- Technology issue TSMC 0.13μm Q>10 @5GHz

Design Considerations

- ☐ Power Consumption



L ↓ R_L ↓ *DR* ↑

$G_m = G_{loss} = R_L/(\omega_0 L)^2$

L ↓ R_L ↓ *Power* ↑

L ↑ *Tuning range* ↓

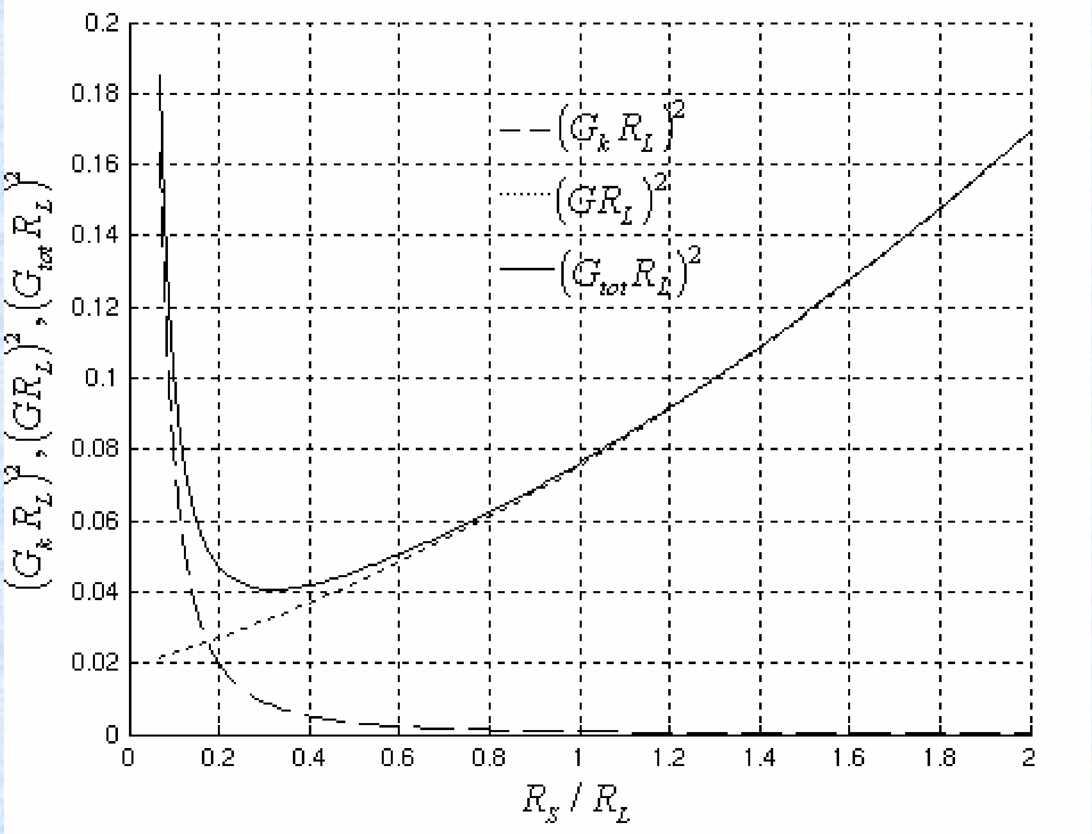
DR-Power Trade-off

Tuning-Power Trade-off

How to maximize DR?

Choose minimum L to meet the power budget

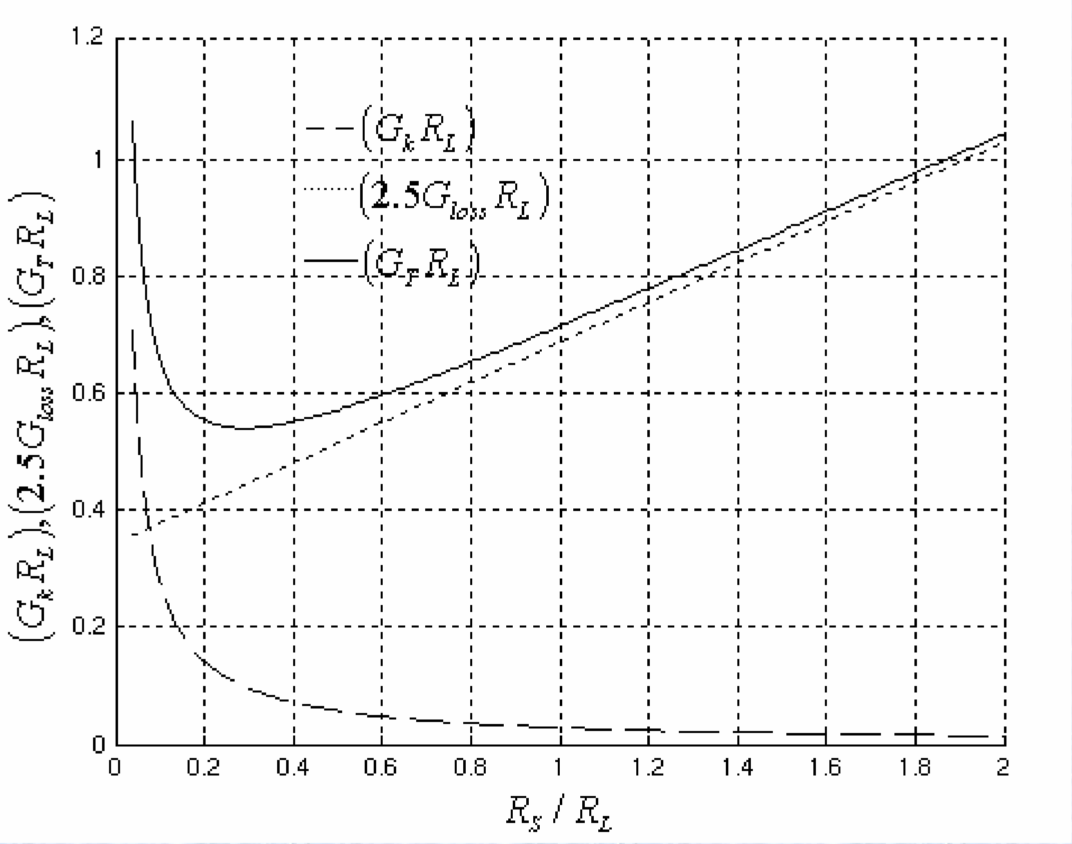
Effect of R_S on filter power consumption



R_S ↑ G ↑ For a fixed R_L

R_S ↓ G_k ↑ For a fixed k

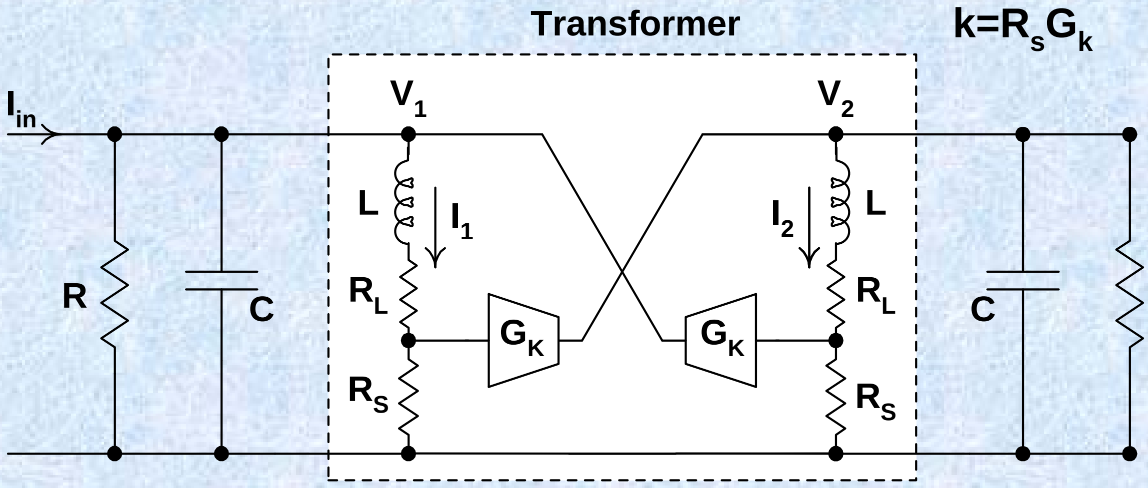
Effect of R_S on filter noise performance



R_S ↑ G_{loss} ↑ For a fixed R_L

R_S ↓ G_k ↑ For a fixed k

Power and Noise optimization



Q_0=3, Q=100

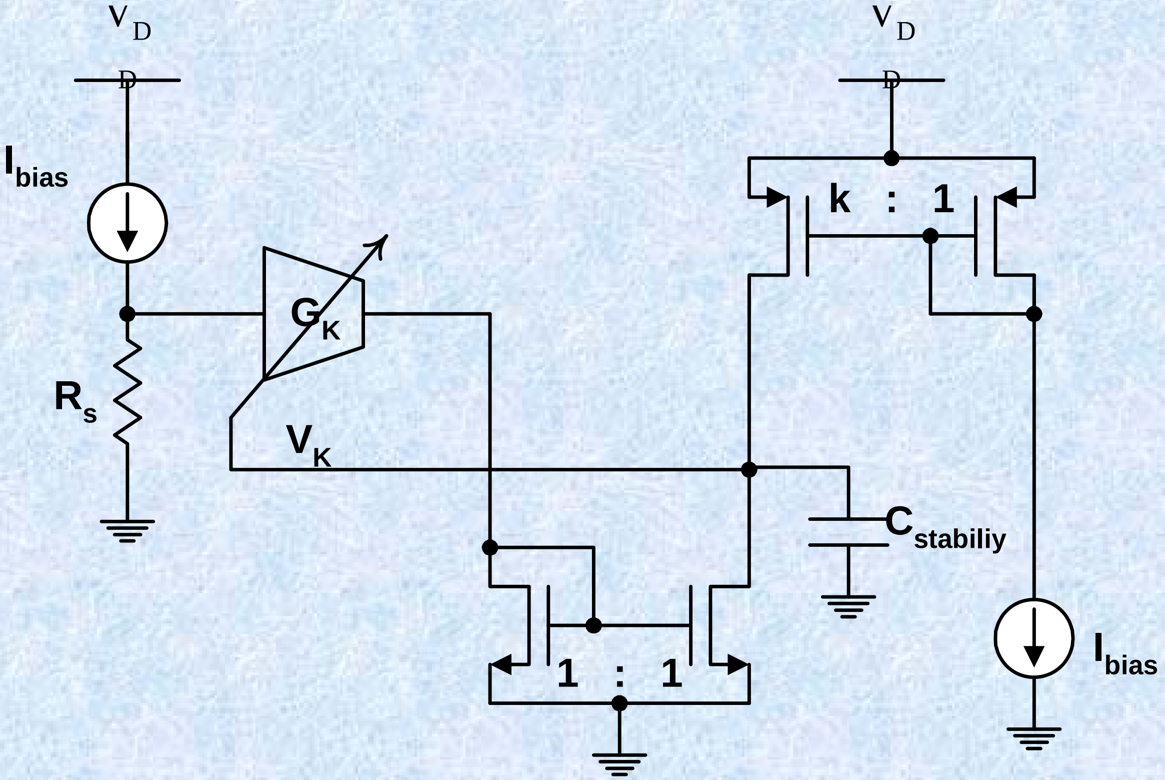
$$R_S \cong R_L\left(\frac{Q_0^2}{2.5\sqrt{2Q}}\right)^{1/2}$$

→ Optimize Noise — NF+1.76dB

$$R_S \cong R_L\left(\frac{Q_0^4}{2Q^2}\right)^{1/3}$$

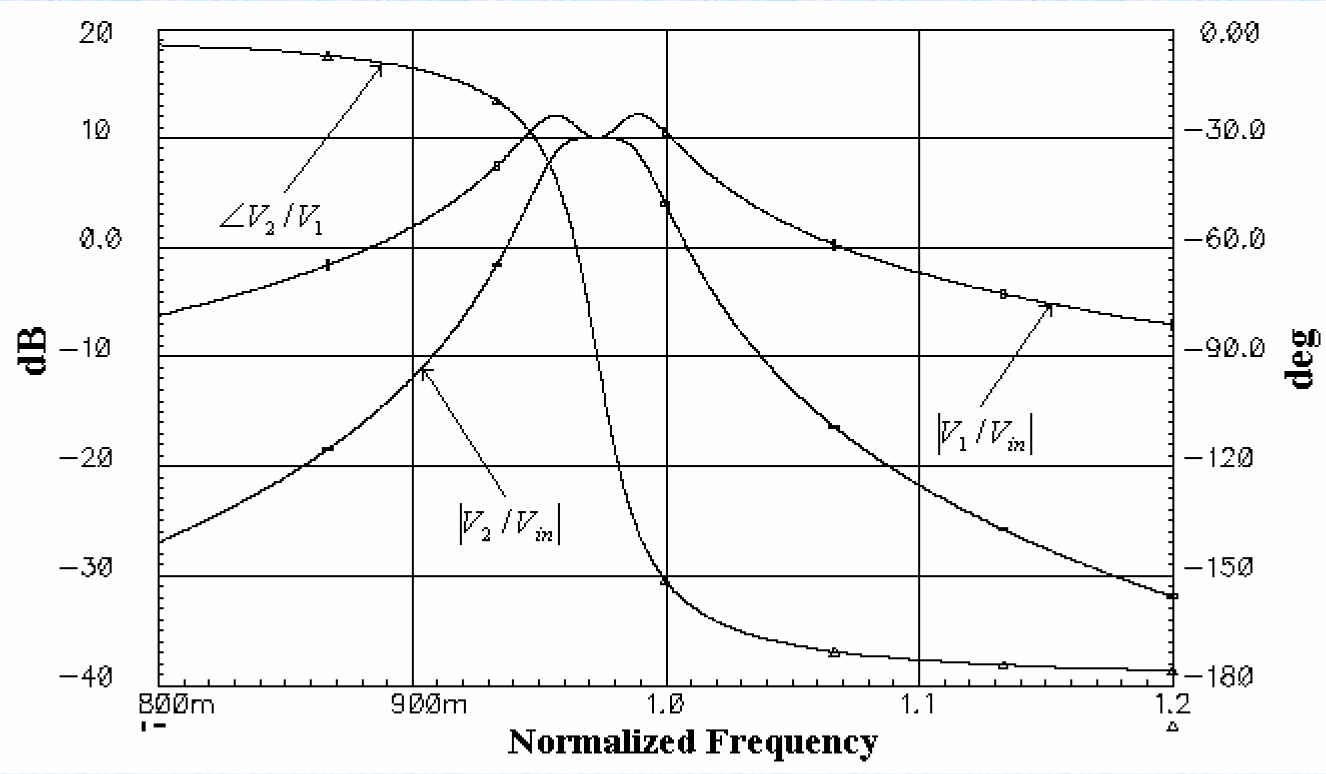
→ Optimize Power — P*1.15

Filter Tuning



Tuning the coupling coefficient

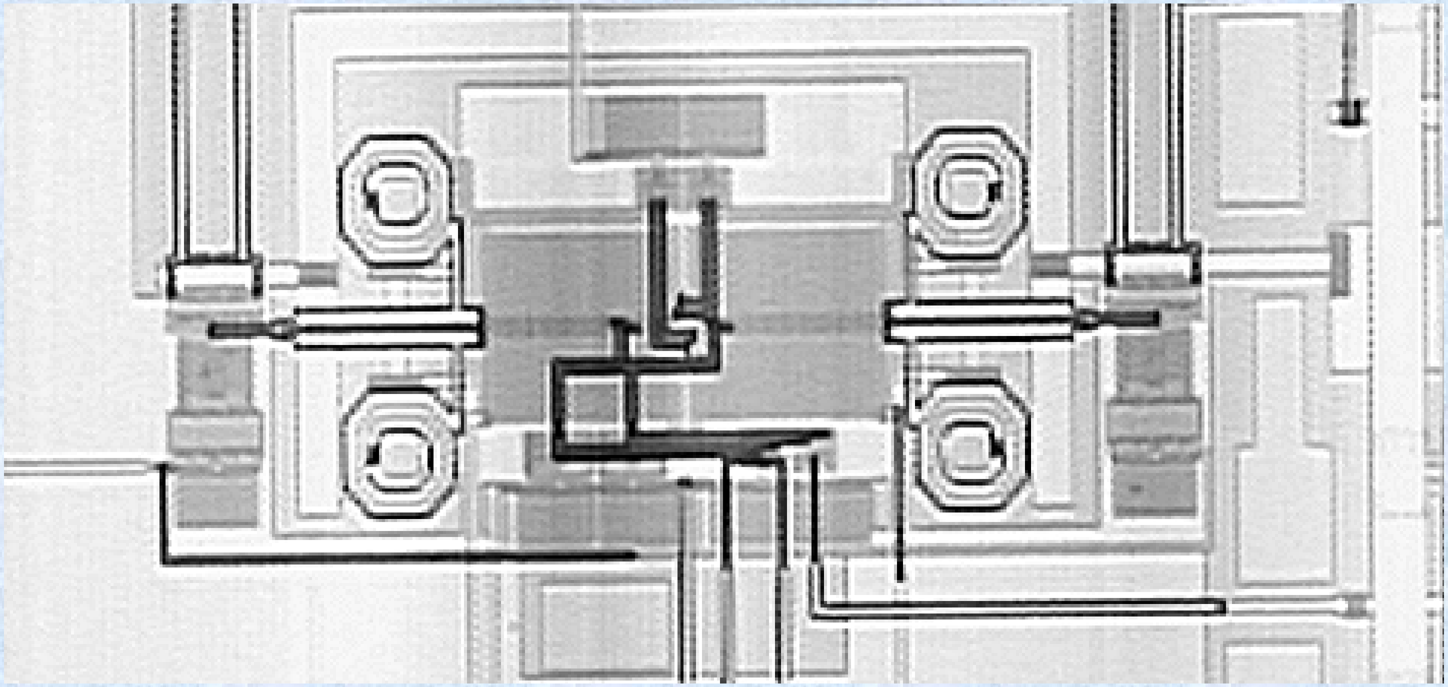
Filter Tuning



$$\frac{V_2}{V_1}(j\omega_0) = j\frac{1}{\sqrt{1-(1/Q_0^2)}} \cong j$$

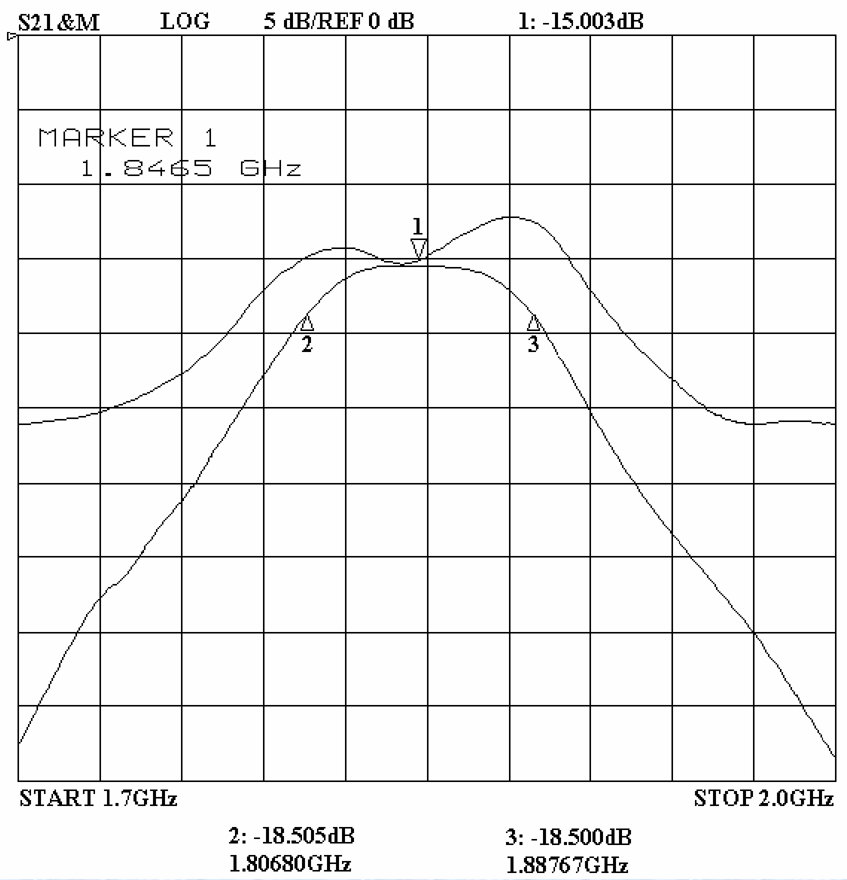
Frequency and Q tuning

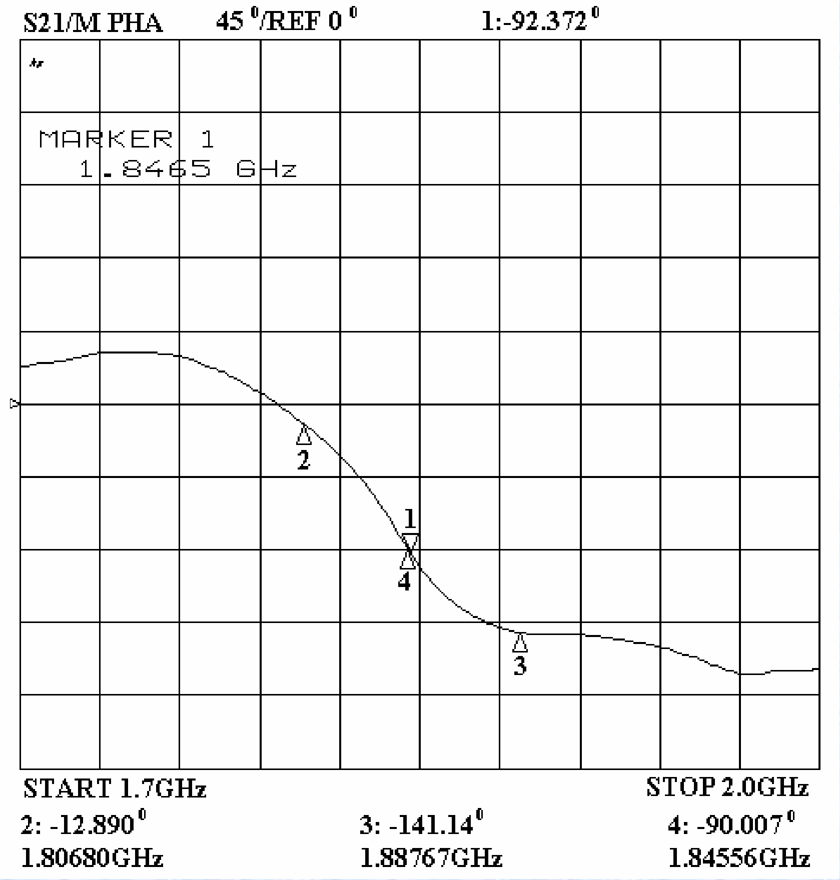
Chip Micrograph



X=500μm, Y= 300μm

Measurement Results





Upper trace $|V_1/V_{in}|$ (dB)

Lower trace $|V_2/V_{in}|$ (dB)

Phase Response

Measurement Results

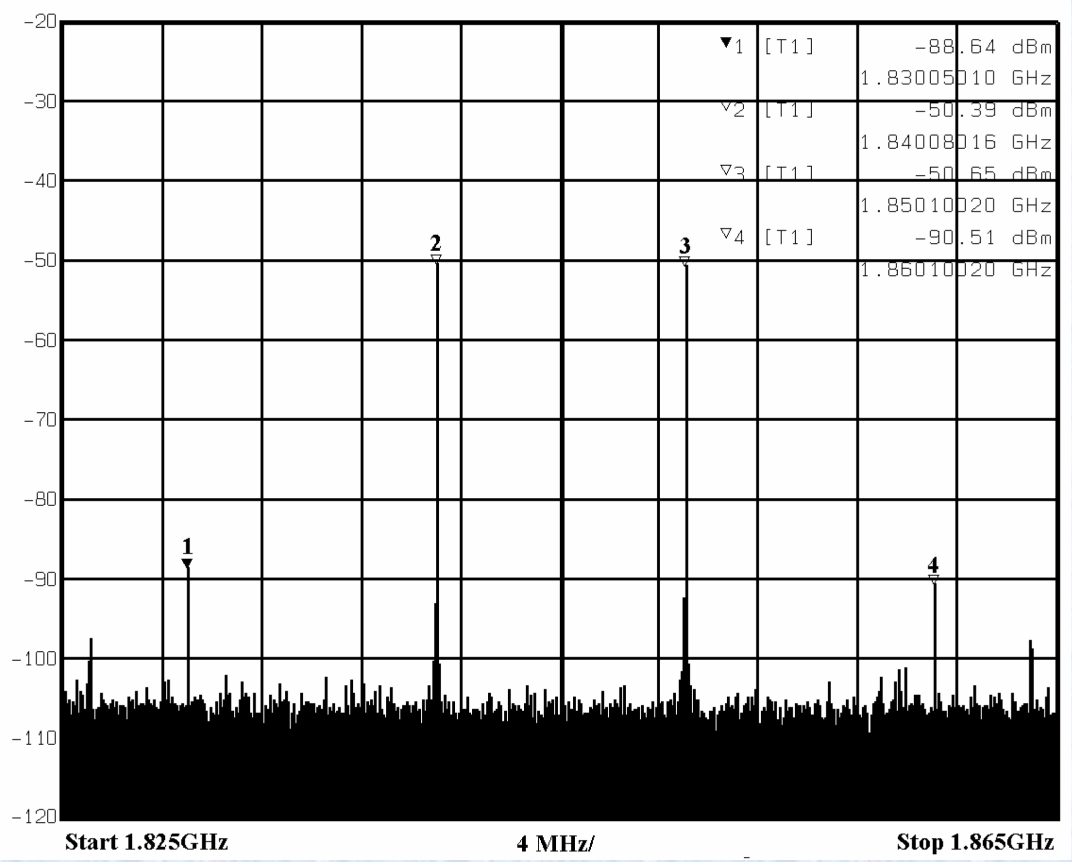
Frequency tuning

$f_0=\{1.77\text{GHz},1.86\text{GHz}\}$

Bandwidth tuning

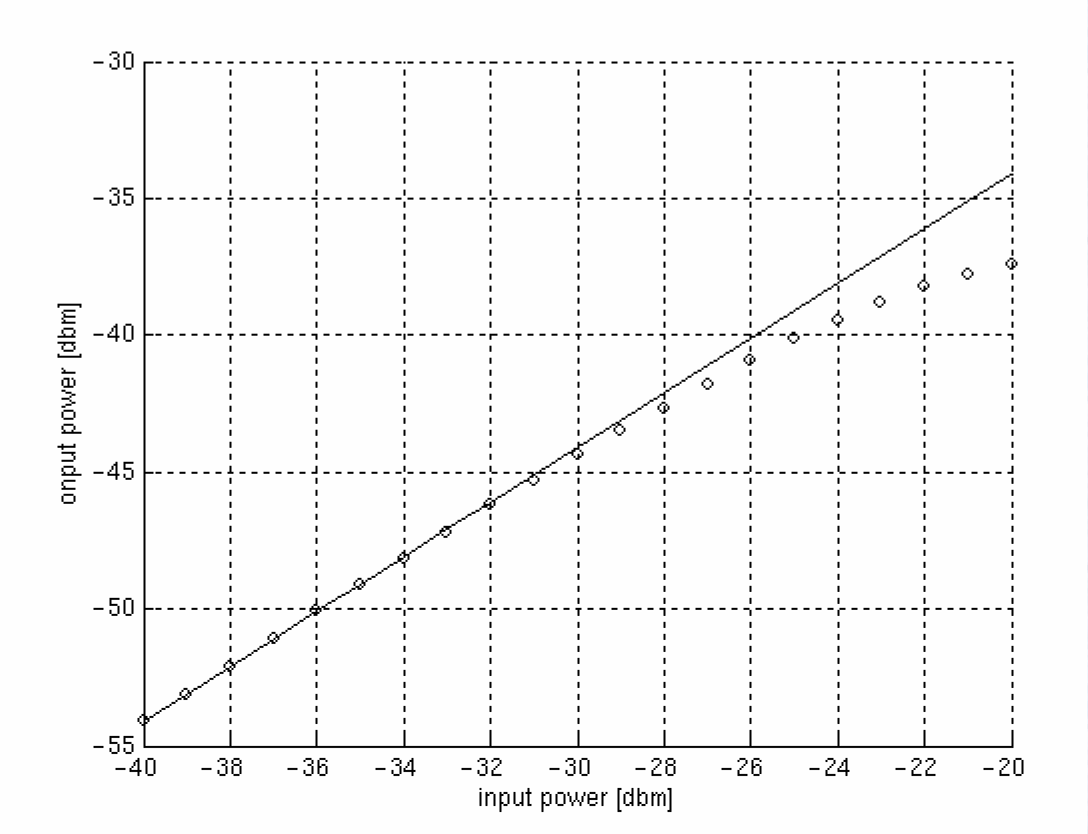
BW={70MHz,100MHz}

Measurement Results



Two Tone intermodulation distortion -34dBm each

Measurement Results



1 dB Compression Dynamic Range

Comparison with previously published work

	[4]	[5]	[6]*	This Work
Filter order	4	4	6	4
f_0 (GHz)	0.85	1.9	2.1	1.8
BW (MHz)	18	150	60	80
Passband gain (dB)	0	0	0	9
Ripple in passband (dB)	< ±1	+1.6	±0.35	< ±0.25
Q_{ind}	< 3	?	?	2.7
1dB compression DR	61	63	63	42
Current drain/pole (mA)	19.25	4.5	1.17+	4
Technology	0.8μm CMOS	0.25μm BiCMOS	0.25μm+ CMOS	0.5μm CMOS
Area/pole (mm^2)	0.5	0.25	0.585	0.0375
Supply voltage (V)	2.7	2.7	2.5	2.7

Remarks

- ❑ A 4th Order tunable LC filter is presented in 0.5μm CMOS process
- ❑ The architecture uses electric emulation of the magnetic coupling
- ❑ Electric coupling provide the capability of BW tuning with small passband ripple
- ❑ Design trade-offs have been demonstrated
- ❑ The filter achieves 42dB of DR with ±0.25dB passband ripple and consumes 16mA

Reference.-
Mohieldin, A.N.; Sanchez-Sinencio, E.; Silva-Martinez, J., "A 2.7-V 1.8-GHz fourth-order tunable LC bandpass filter based on emulation of magnetically coupled resonators," *IEEE Journal of Solid-State Circuits*, Volume :38 Issue:7, pp 1172-1181 July 2003