RF Filters Design, Performance, and Implementation

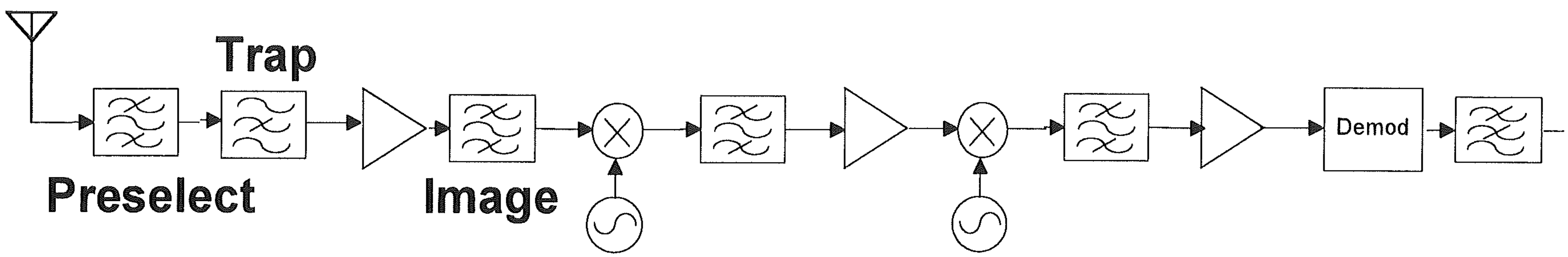
Presented by: Dr. William B. Kuhn,
~~Assistant~~ Professor at Kansas State University

w.kuhn@ieee.org

Outline

- Roles of RF Filters in Transceivers
- Filter Performance Characteristics
- Designing for Off-Chip Filters
- Design of On-Chip Filters
- Future Directions

Roles of Filters in Receivers

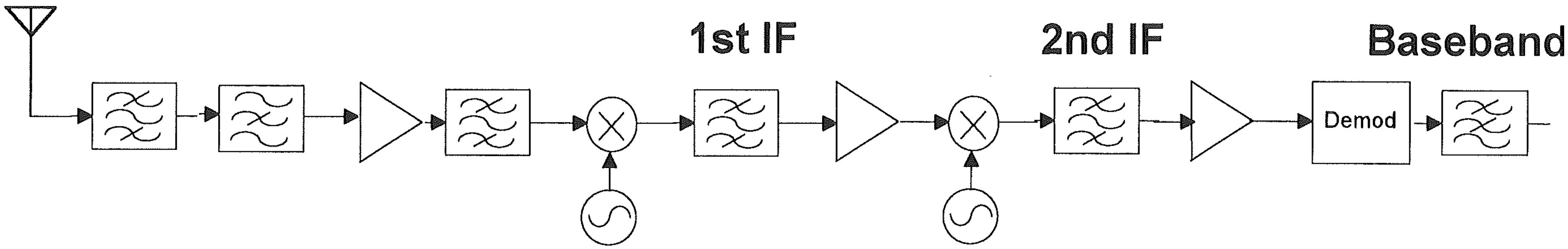


Preselect: Passes desired service band and attenuates out-of-band interferrers. (sometimes called "roofing filter")

Trap: Optional bandstop filter used if strong interferrence at certain frequencies is expected. (also called "notch" or "bandreject")

Image: Attenuates noise at image frequency to improve receiver noise figure. Also improves rejection of signal at image frequency. May be eliminated if image-reject mixer is used, although at expense of additional power consumption.

Roles of Filters in Receivers

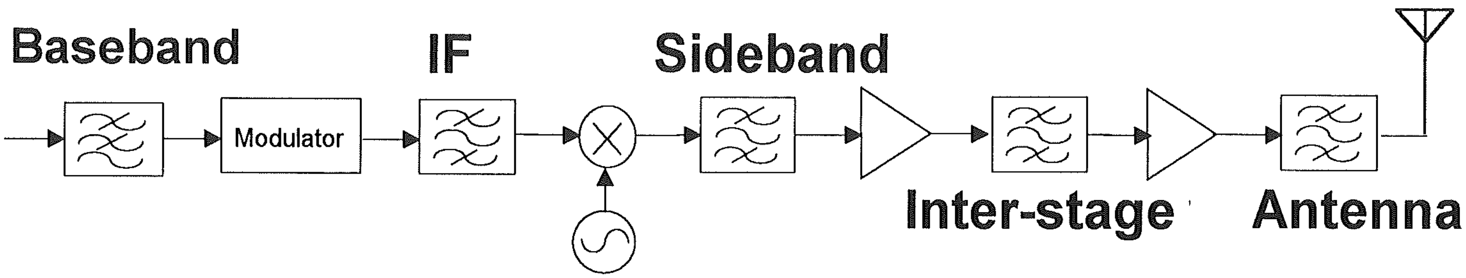


1st IF: Narrow bandwidth to one or a few channels. Also prevents "image' (spurious) responses in second downconversion and rejects other mixer sideband and additional mixer output frequencies.

2nd IF: Narrow bandwidth to one channel (usually). Together with 1st IF filter (and possibly post-detection lowpass filters), it determines receiver selectivity and noise bandwidth.

Baseband: Assist in or implement final IF channel selection.

Roles of Filters in Transmitters



Baseband: Shape data waveform to control spectral width. (Often implemented by waveform synthesis or in DSP)

IF: Control spectral width, and/or remove spurious modulator outputs.

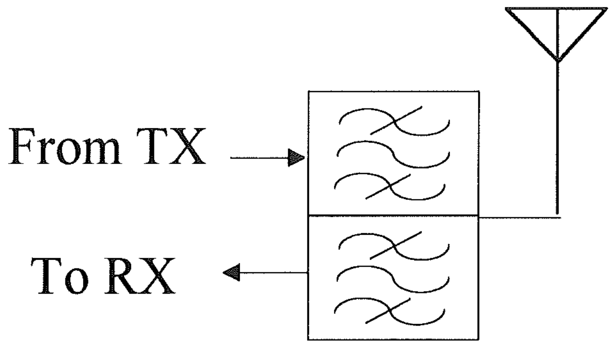
Sideband: Select desired up-conversion frequency out of mixer.

Inter-stage: Attenuate harmonics and out-of-band noise (often part of impedance matching function)

Antenna: Suppress harmonics generated in PA. Also, attenuate out-of-band noise and spurious emissions.

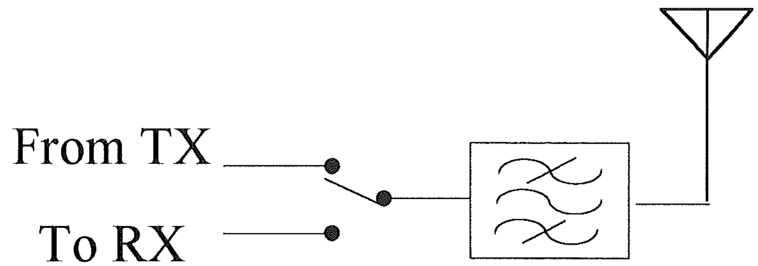
Dual Use in Transceivers

Frequency Division Duplex



Duplex filter doubles as receiver preselect filter and transmitter output/harmonic filter.

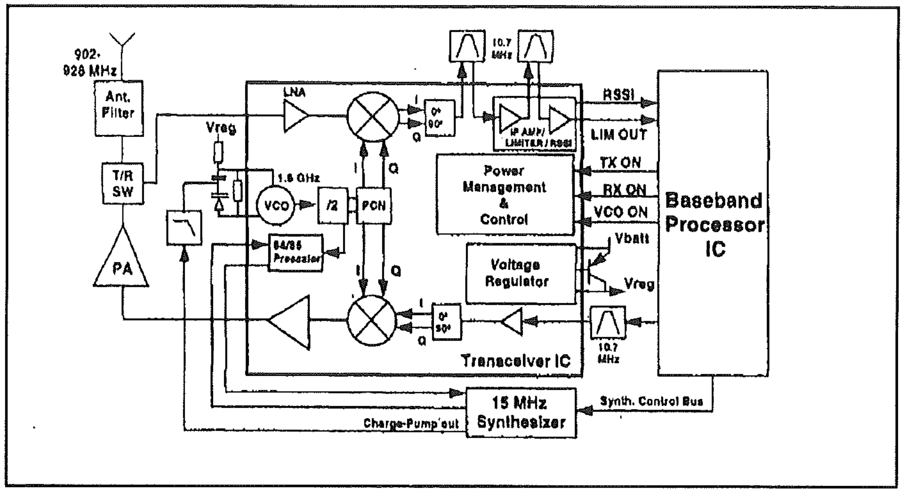
Time Division Duplex



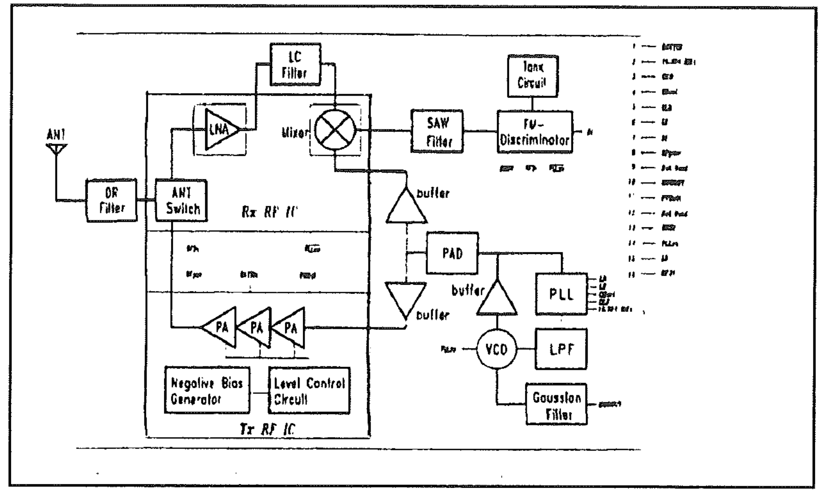
Filter serves role of both preselect and transmitter output/harmonic filter.

NOTE: These filters must handle transmit power levels and should be low-loss.

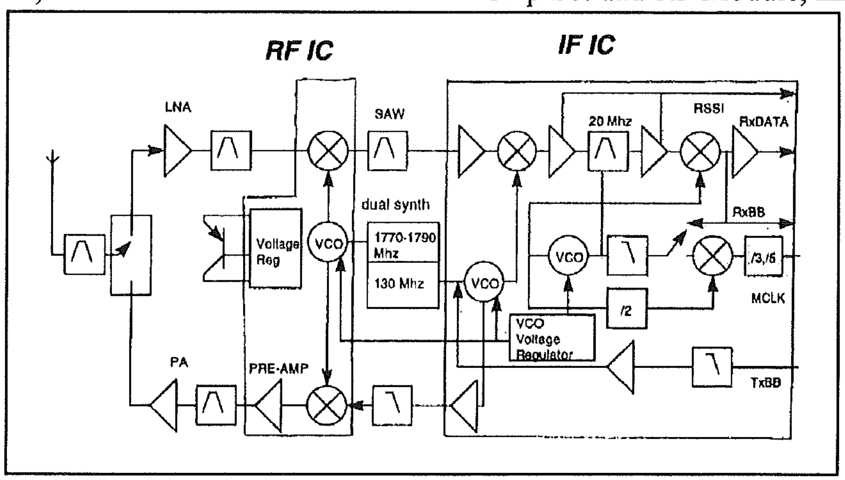
Highly Integrated RFICs



P. Katzin, et.al., "A 900 MHz Image-Reject Transceiver Si Bipolar IC," IEEE RFIC Symp., pp.97-100, 1998.



C.-K. Lee, et.al. "A 900 MHz ISM Band Transceiver RF IC Chip Set and RF Module, IEEE RFIC Symp, pp.245-249, 1998.



J. Strange and S. Atkinson, "A Highly Integrated Radio Trnaceiver Chipset for DECT," IEEE RFIC Symp, pp.131-134, 1997.

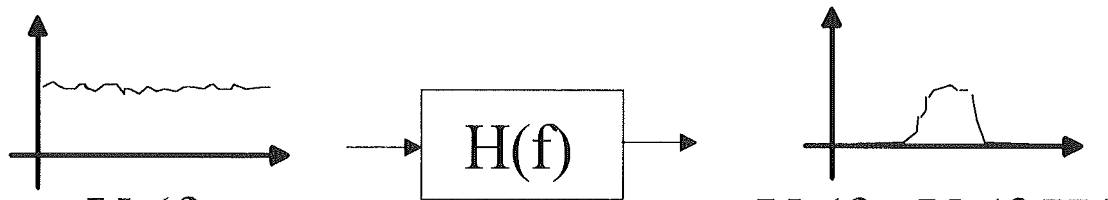
Important Observations

- Little integration of filtering functions in current transceiver designs.
- Image-reject mixers are beginning to be used to eliminate some bandpass filters.
- Transceiver architecture selection depends strongly on filter performance.
- Choice of architecture can make or break a project schedule !

Filter Theory Review

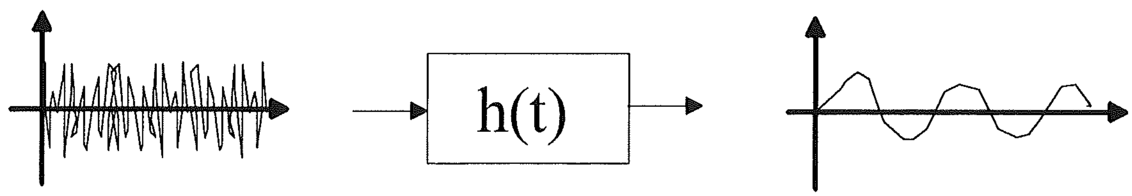
Filter Response Characteristics

Frequency Domain:



$V_i(f)$ $V_o(f)=V_i(f)H(f)$

Time Domain:



$v_i(t)$ $v_o(t)=v_i(t)*h(t)$

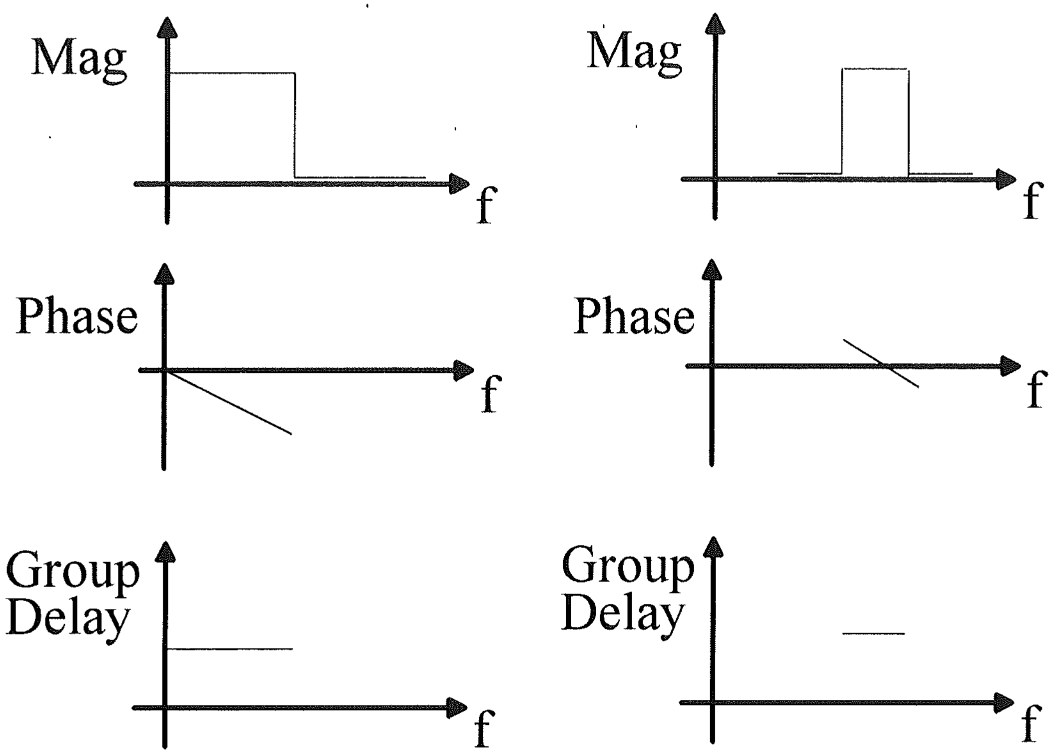
Recall $h(t) = \mathcal{F}^{-1}\{H(f)\}$

Ideal Filter Responses

"Brick Wall" Filters

Lowpass

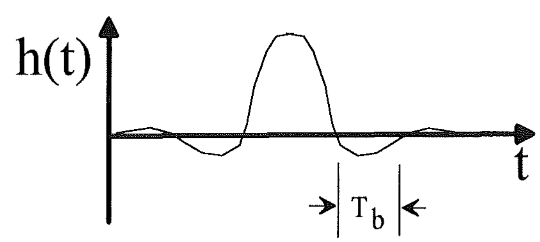
Bandpass



Matched Filters

$$H(f) = S^*(f)$$

Nyquist Filters



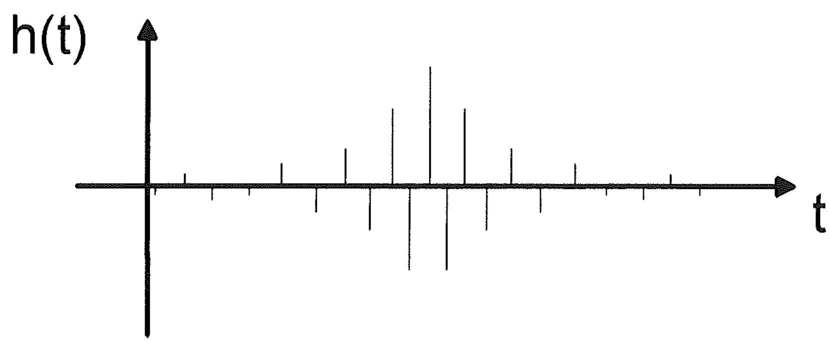
Practical Filters

Implementation Approaches

1) Approximate desired H(f): ("recursive" or "IIR" filter)

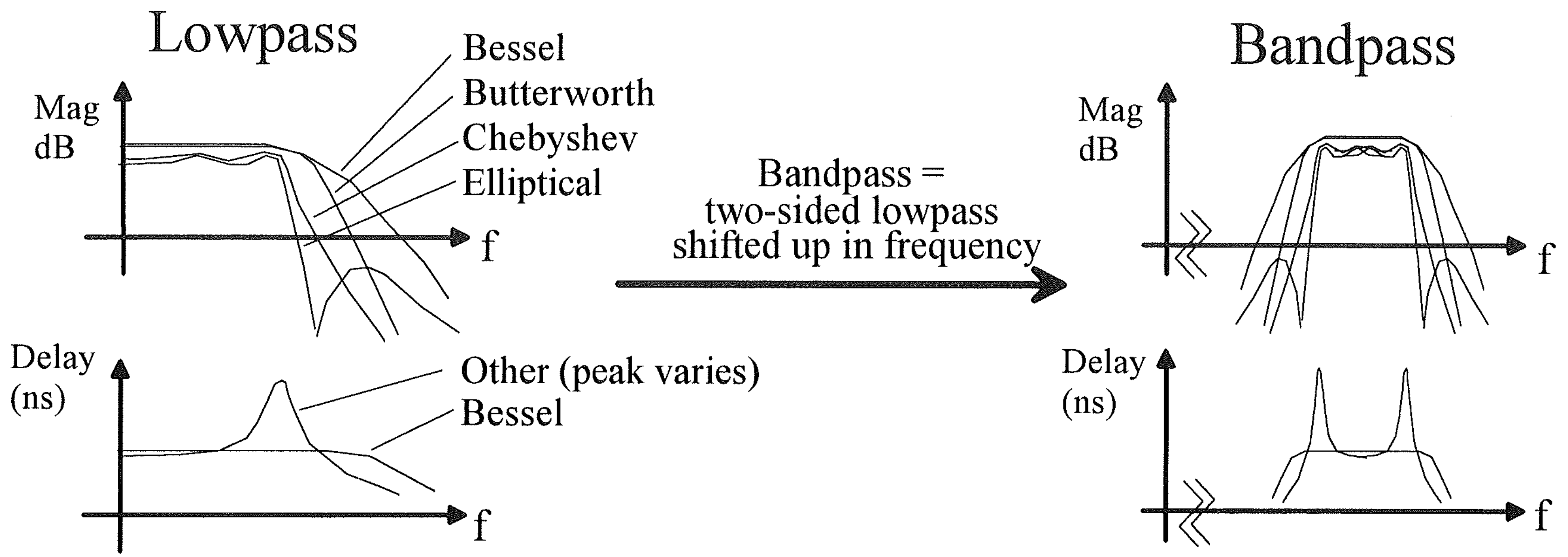
$$\text{e.g.}\quad H(s) = \frac{k(s-\omega_{z1})(s-\omega_{z2})}{s^4+a_3s^3+a_2s^2+a_1s+a_0}$$

2) Approximate desired h(t): ("transversal" or "FIR" filter)



Practical Filter Responses

Recursive / IIR Filters



Attenuation in "stop-band" depends on number of poles N in filter.

An "N-pole" bandpass is actually of order 2N.

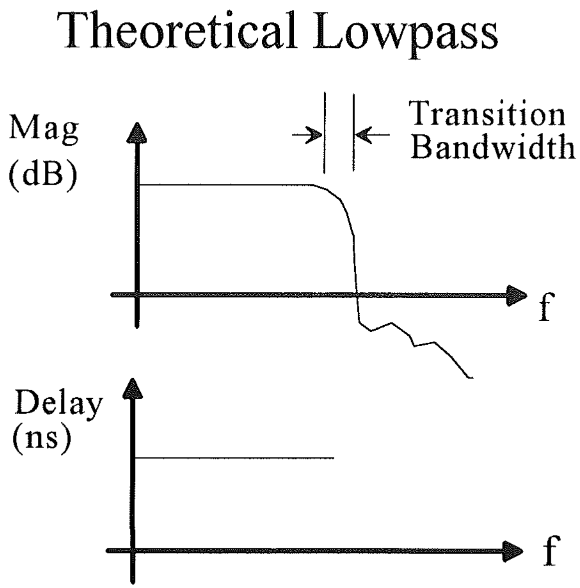
Stopband attenuation for Butterworth lowpass is: $A \approx 20N\log\left|\frac{f}{f_c}\right|$ (6NdB/octave)

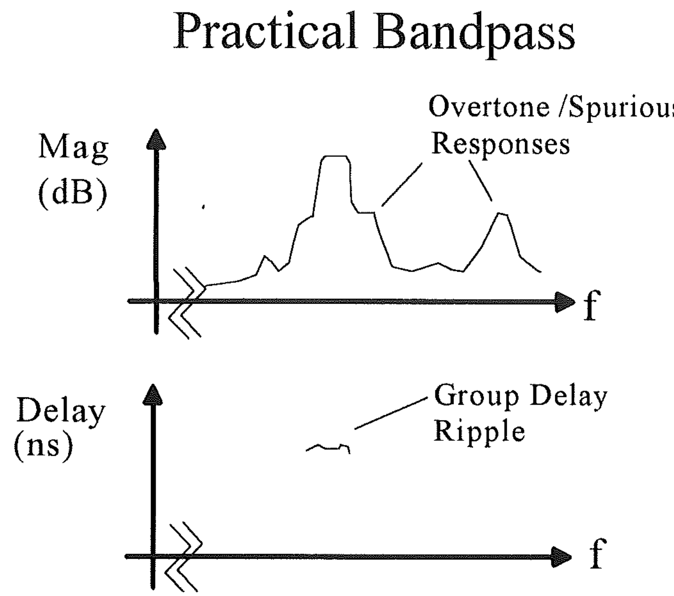
For bandpass, $A \approx 20N\log\left|\frac{f-f_o}{B/2}\right|$

N = 1 to 3 is relatively easy/inexpensive. N>6 may be best done by cascading.

Practical Filter Responses

Transversal / FIR





Transition bandwidth typically ¼ to 1/20 of bandwidth.

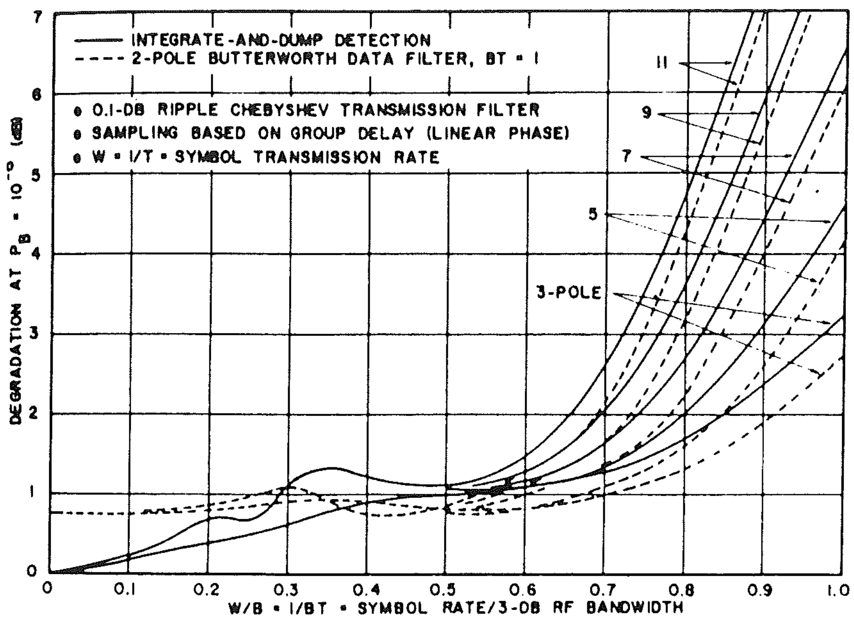
Bandpass can be implemented with Surface Acoustic Wave (SAW) technology.

Watch out for Spurious Responses ! (Not unique to these filters.)

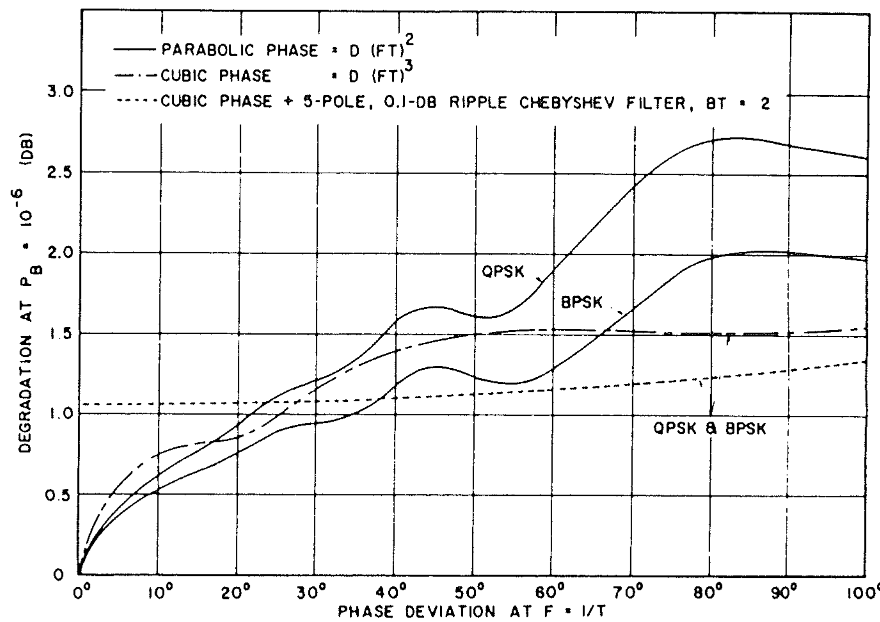
Effects of Non-Ideal Responses

Effects of channel-select filters on demodulation / link performance

Bandwidth-Limiting Degradation of QPSK and BPSK Signals



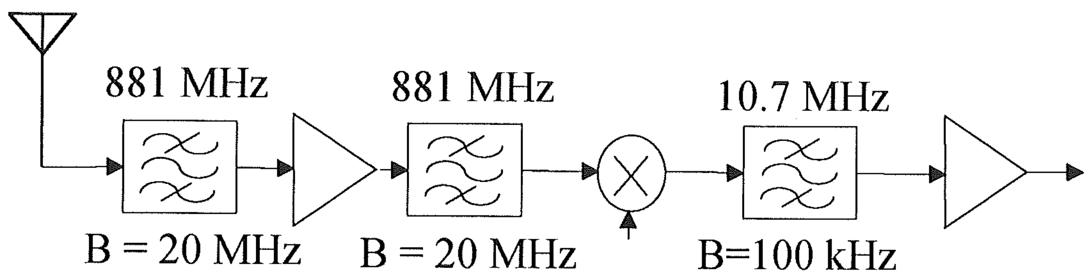
Effect of pure phase distortion with integrate-and-dump detection



From: The Handbook of Digital Communications, Microwave Systems News, Vol. 9, No. 11, pp. 91, Oct 1979.

Effects of Non-ideal Responses

An impractical receiver design:

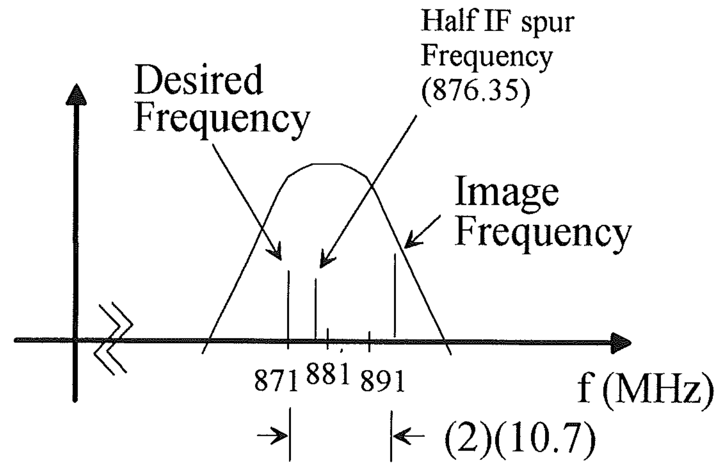


Problems:

Preselect filter not sharp enough.

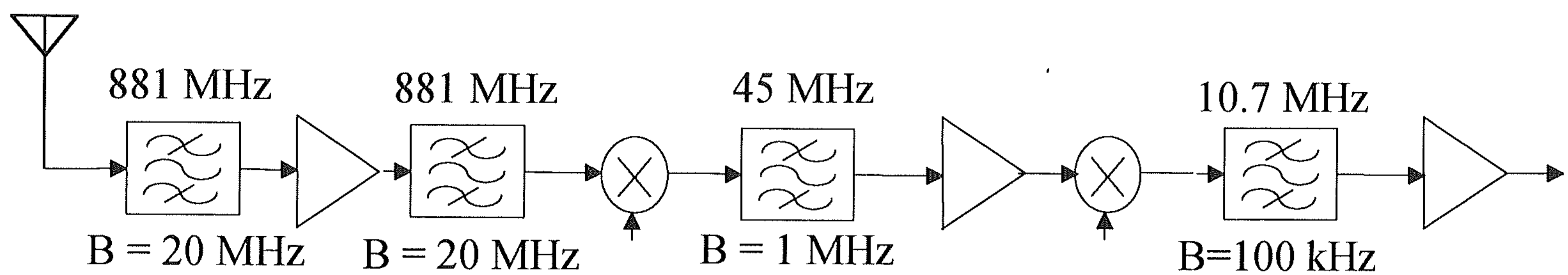
Insufficient attenuation of image.

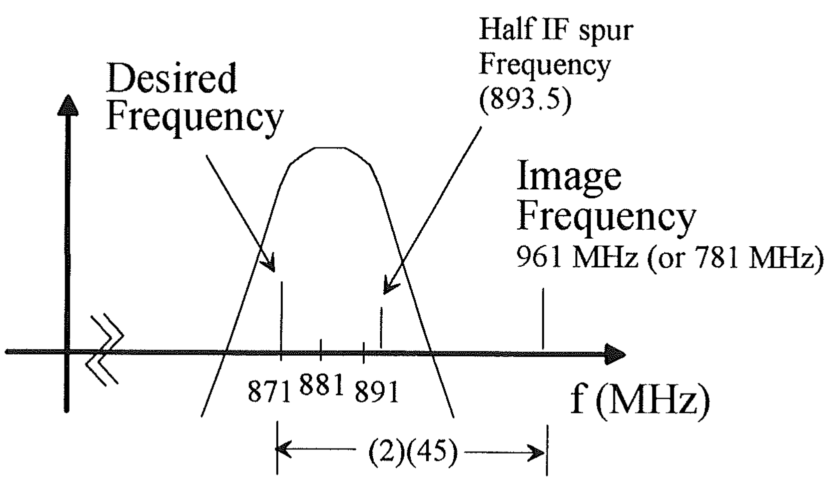
No attenuation of "half-IF" spur.



Effects of Non-ideal Responses

A practical dual conversion receiver design:





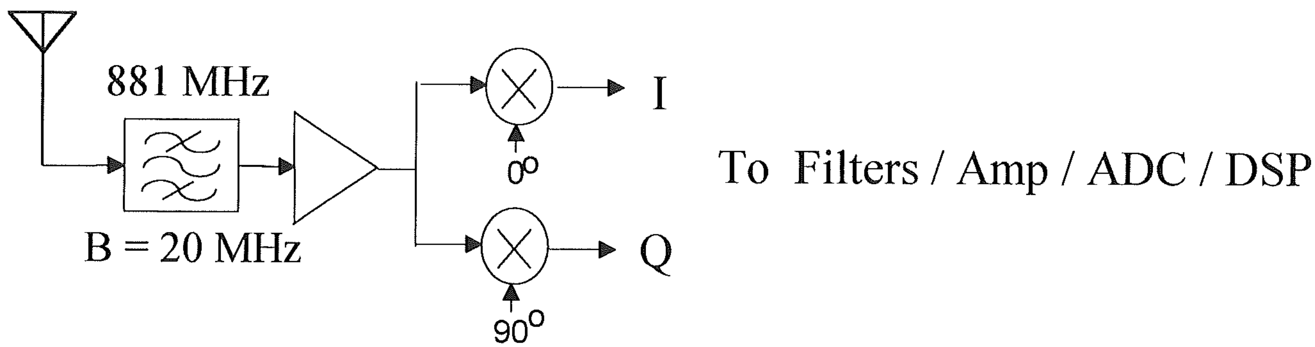
CAUTION:

Check same considerations in second downconversion.

Also, watch out for spurious responses and mixer non-idealities.

The Zero-IF Option

A practical highly-integrated design ???:



Some of the things to consider:

Preselect filter is needed for protection from out-of-band interferrers, and to attenuate signals at harmonics of desired frequency.

Several practical problems exist: DC offsets in mixer, radiation, need for high gain and dynamic range in baseband circuits, area consumption of filters ...

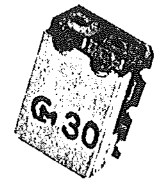
Superhet with RF/IF filters may be safer and cheaper !

Designing for Off-Chip Filters

- Off-Chip Filter Technologies
- Performance Characteristics
- Examples

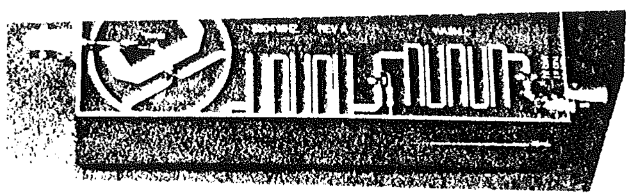
Off-Chip Filter Technologies

LC

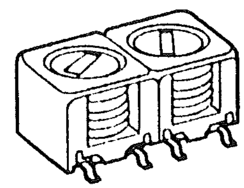


Dielectric Resonator

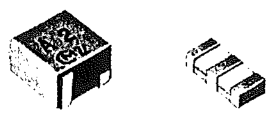
SAW



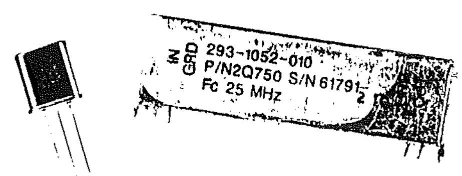
Microstrip



Heilical Resonator



Ceramic (MCF)



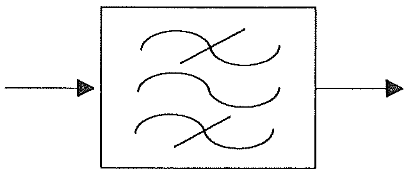
Crystal

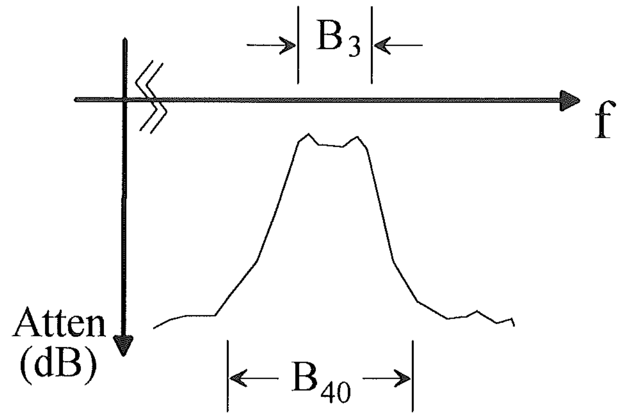
Off-Chip Filter Technologies

Technology	*Typical Frequency Range*	*Relative Cost*
LC	10 MHz - 2 GHz	Low
Dielectric Resonator	500 MHz - 2+ GHz	Medium
Surface Acoustic Wave (SAW)	70 MHz - 2 GHz	Med-High
Microstrip	1 GHz - 30 GHz	Low
Heilical Resonators	100 MHz - 1 GHz	Med-High
Crystal	5 MHz - 50 MHz	High
Ceramic (MCF)	250 kHz - 10.7 MHz	Low

Others: Mechanical, Bulk-Acoustic Wave, Cavity Resonator, ...

Performance Characteristics



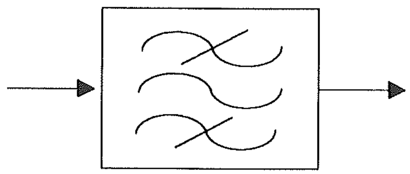


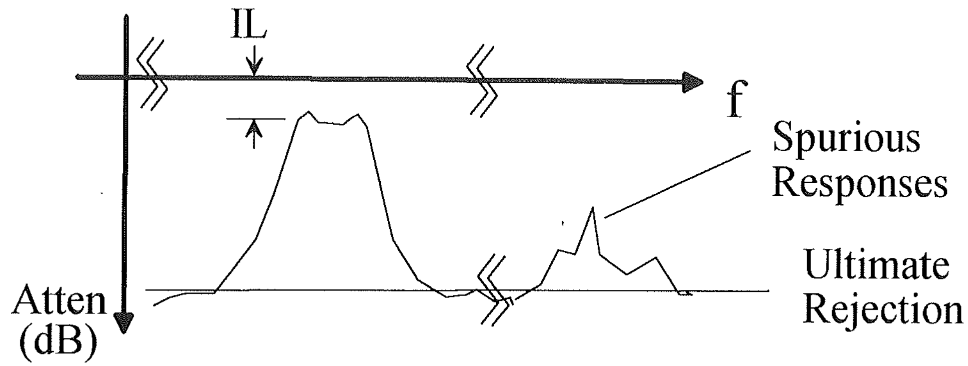
Bandwidth: Typically quoted at -3dB point relative to maximum response.

Fractional Bandwidth: Ratio of bandwidth to center frequency. Small fractional bandwidths (e.g. < 0.01) are difficult to achieve in some technologie

Selectivity: Usually quoted as amount of attenuation at some specified offset from center frequency. May be quoted as bandwidth at specified attenuation.

Performance Characteristics



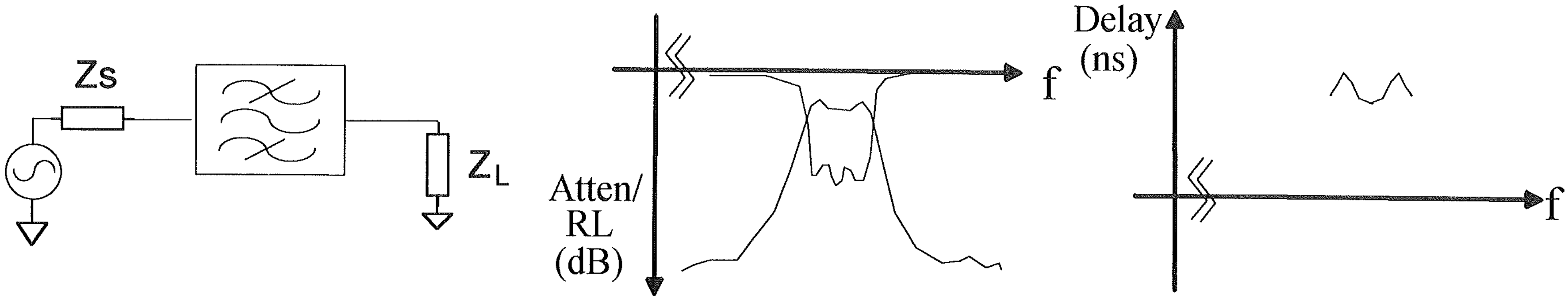


Insertion Loss Power loss through filter at maximum response. 2dB is good, and 6 dB is OK, but can be as high as 20 dB for some filters.

Ultimate Rejection Maximum attenuation (on average) of filter. Only achieved in practice with careful PC board layout and IC pinout planning !

Spurious Responses Frequencies outside passband where response rises above ultimate rejection value significantly. Some filters have strong spurious responses at overtones of the center frequency (especially 3f, 5f, ...). Others have non-harmonic spurious.

Performance Characteristics

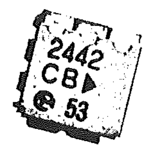


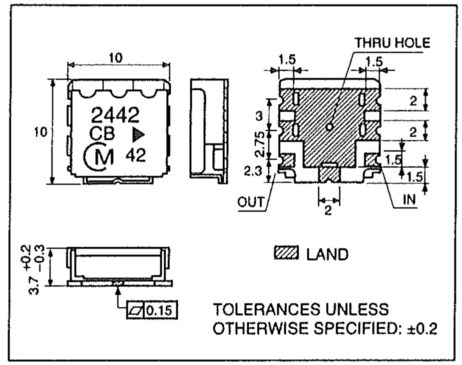
Terminating Impedance	Source and load Z required to achieve specified performance. Typically 50 Ohms for DR filters. Other filters vary from 50 to 1K depending on technology and frequency.
Return Loss	In 50 Ohm system filters (e.g. DR type), a measure of how well filter is matched to 50 Ohms. See text on S-parameter design.
Gain and Delay Flatness	Variation in gain and group delay across passband. Especially important in IF channel-select filters to achieve good BER or fidelity.

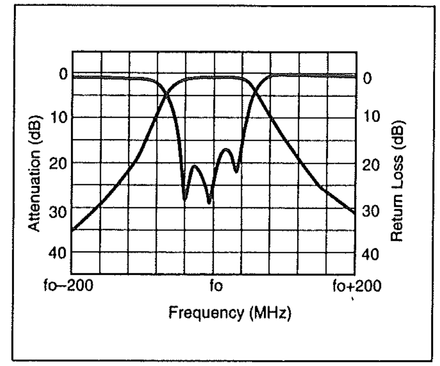
Example RF Filters

DR Filter

(From muRata Catalog)





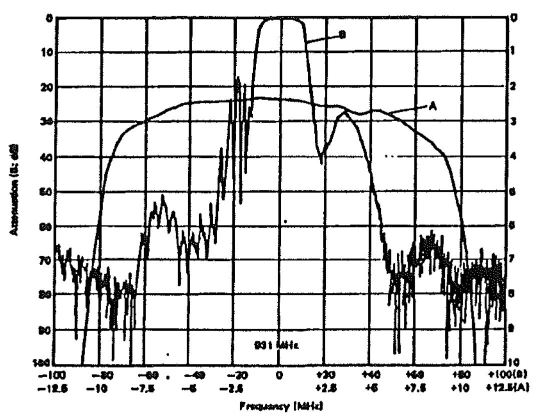


SPECIFICATIONS

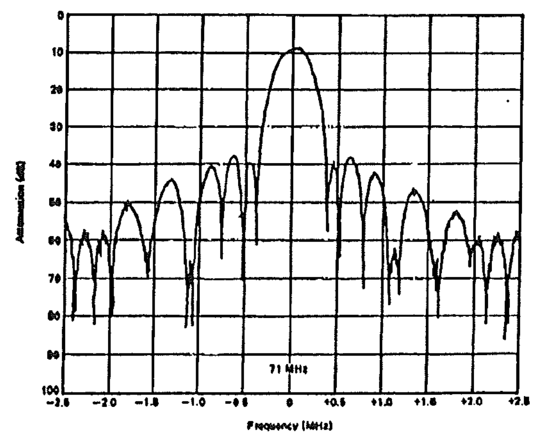
Part Number	Center Frequency fo (MHz)	Bandwidth (MHz)	Insertion Loss in BW (dB)	Ripple in BW (dB)	V.S.W.R. in BW max.	Attenuation (dB) (MHz)
DFC32R44P084BHD	2442.0	fo ± 42.0	2.0 (0 ~ +85°C) 2.4 (−30 ~ 85°C)	1.0	2.0	6 (fo ± 80)

SAW Filter

(From Toyocom Catalog)



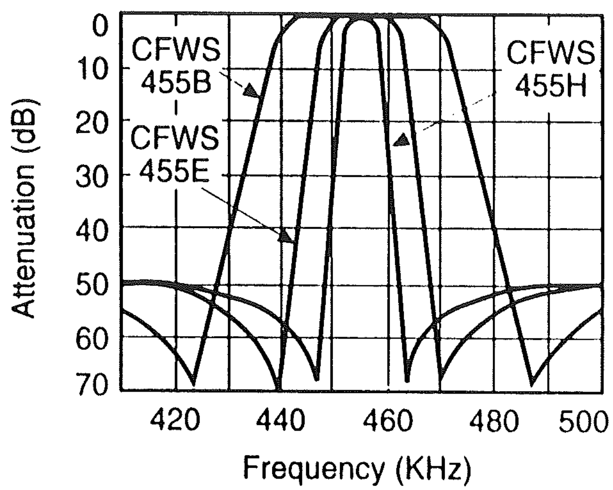
TQS-705 Frequency characteristics

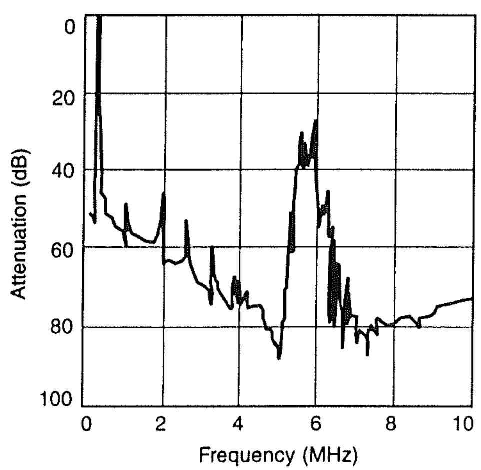


TQS-422 Frequency characteristics

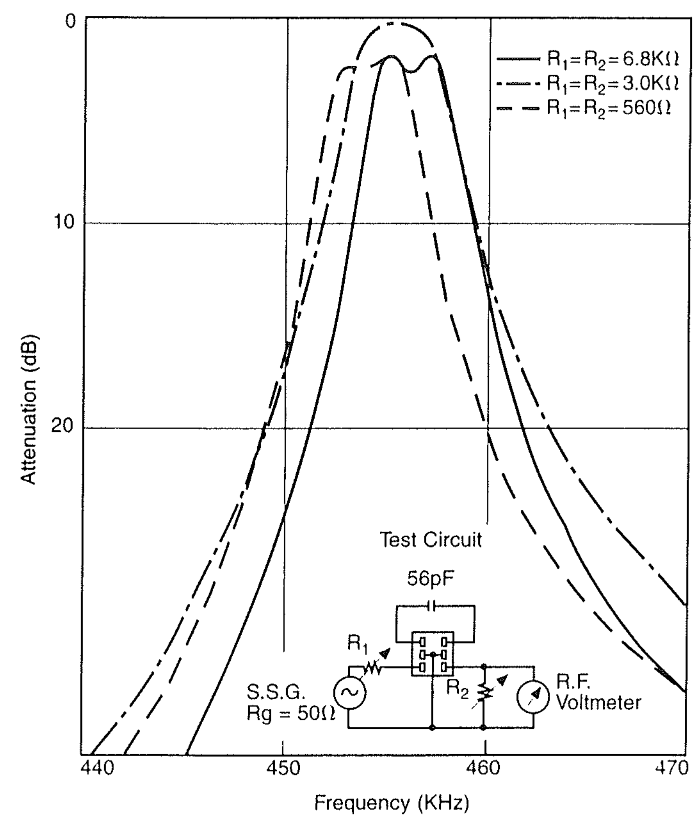
Example IF Filters

455 kHz Ceramic Filter



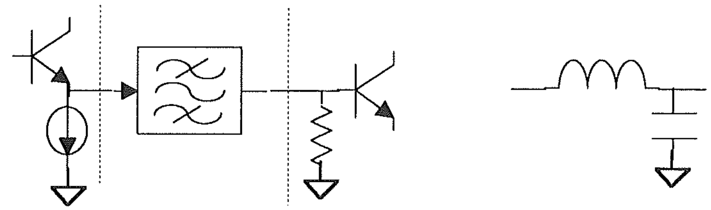


Effects of impedance mismatch (From muRata catalog)

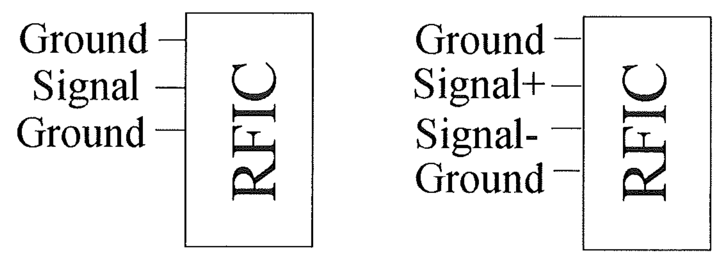


A Few Hints and Tips

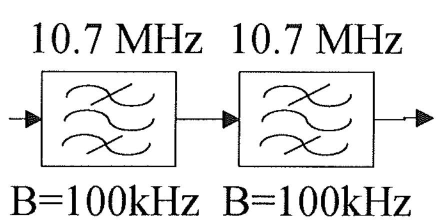
Consider on-chip impedance matching (but watch noise and dynamic range).



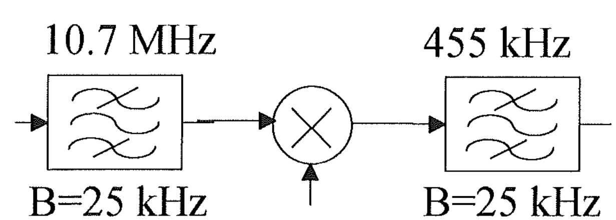
To achieve good performance (esp. in RF filters), design pinout carefully and watch pad/bond-wire parasitics.



Achieving good selectivity with low-cost filters:



Simple cascade (watch IL and bandwidth!)

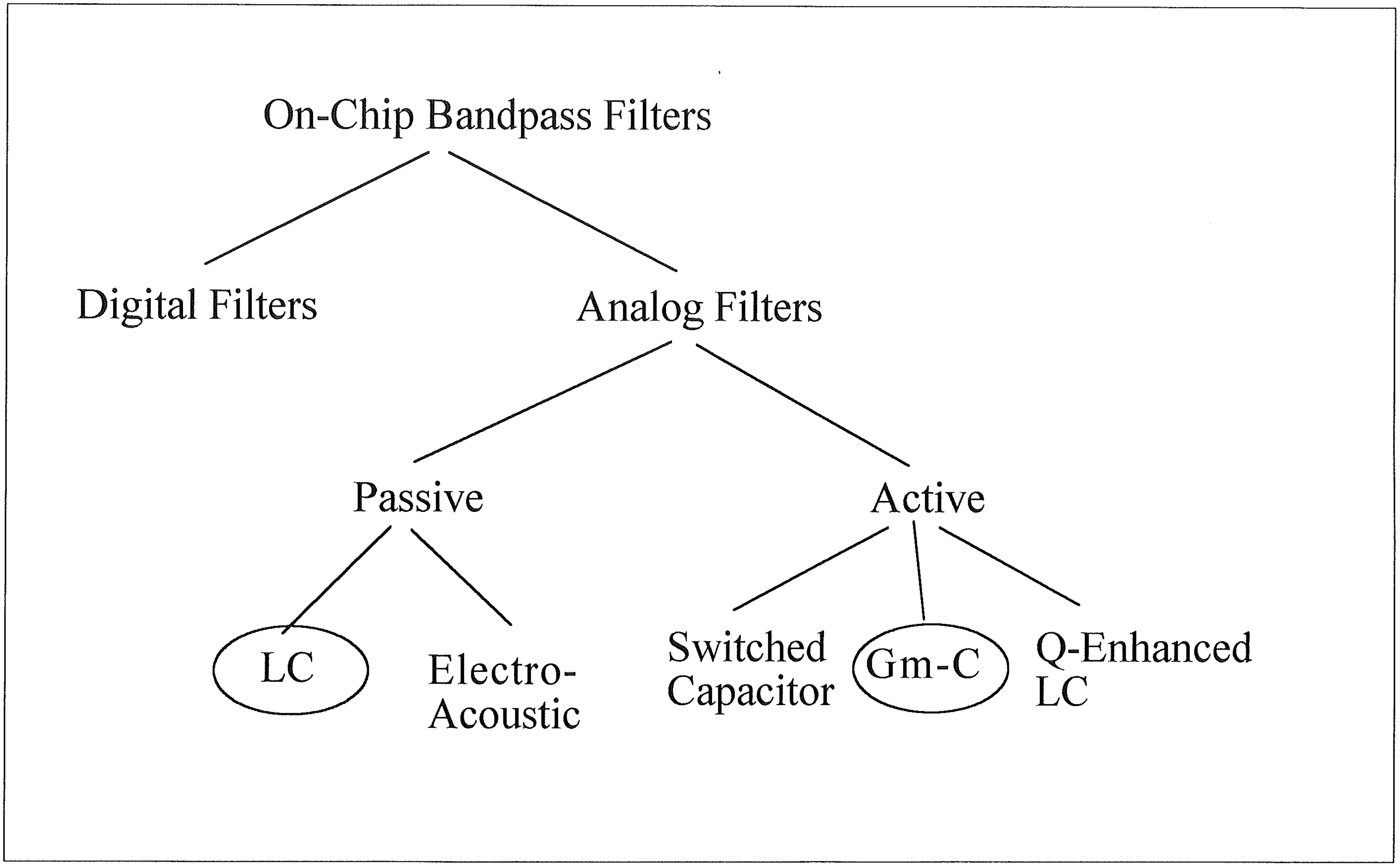


Dual conversion

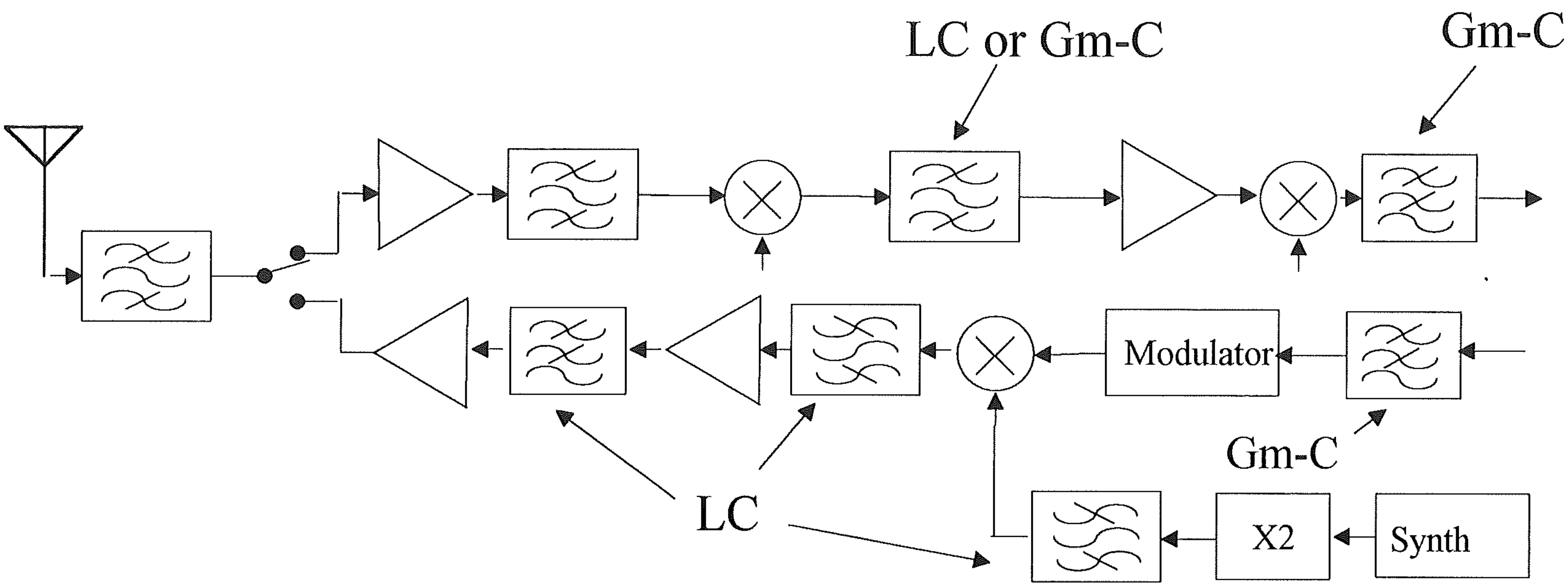
Designing On-Chip Filters

- Applications of On-Chip Filtering
- Lowpass LC and Gm-C Filters
- Bandpass LC and Gm-C Filters
- Future Possibilities

On-Chip Filtering Alternatives



Some Possible Applications



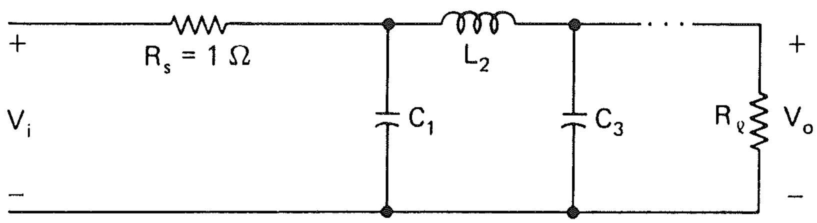
Limitations:

Imprecise cutoff / center frequencies (e.g. +- 15%)
Large fractional bandwidths (e.g. 20%)
Relatively high insertion loss in LC in Silicon processes
Dynamic range concerns
Area consumption concerns

Filter Design

Lowpass Filters:

1) Look up normalized prototype filter in handbook



(c) $R_\ell = R_s$

n	C_1	L_2	C_3	L_4	C_5	L_6	C_7	L_8	C_9
1	2.0000								
2	1.4142	1.4142							
3	1.0000	2.0000	1.0000						
4	0.7654	1.8478	1.8478	0.7654					
5	0.6180	1.6180	2.0000	1.6180	0.6180				
6	0.5176	1.4142	1.9319	1.9319	1.4142	0.5176			
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450		
8	0.3902	1.1111	1.6629	1.9616	1.9616	1.6629	1.1111	0.3902	
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473

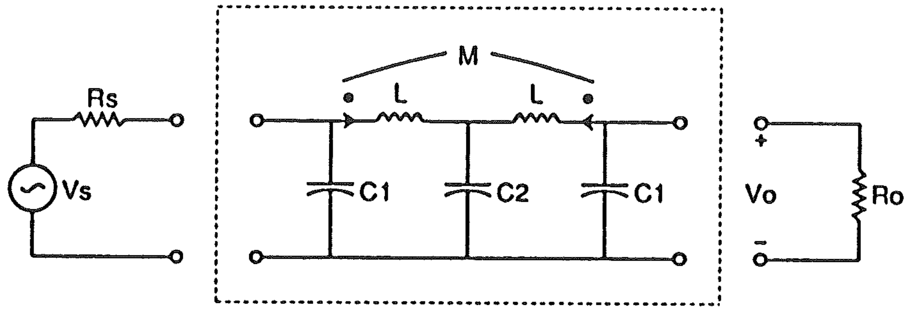
(From H. Y.-F. Lam, *Analog and Digital Filters*, Prentice Hall, 1979.)

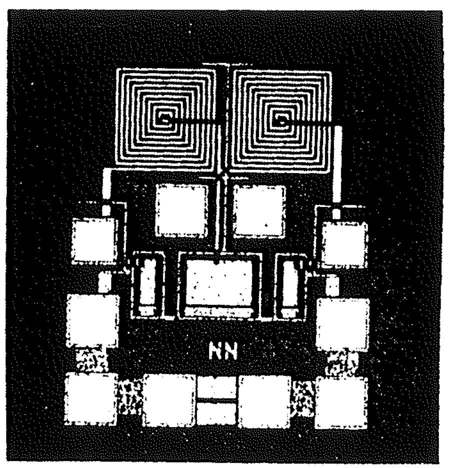
2) Scale to desired frequency: $C \rightarrow \frac{C}{2\pi f_c}$ $\quad L \rightarrow \frac{L}{2\pi f_c}$

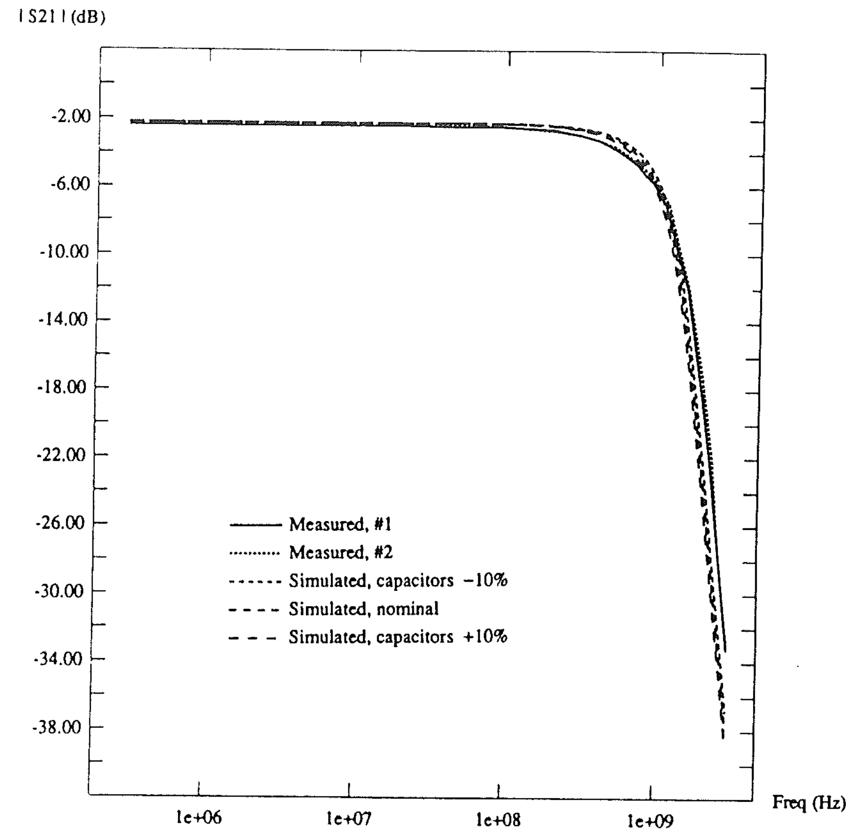
3) Scale to desired impedance: $C \rightarrow \frac{C}{R}$ $\quad L \rightarrow L(R)$ $\quad R_s \rightarrow R_s(R)$ $\quad R_L \rightarrow R_L(R)$

4) Implement directly (if inductors not too big), or with transconductors and C.

Integrated LC Lowpass Filter





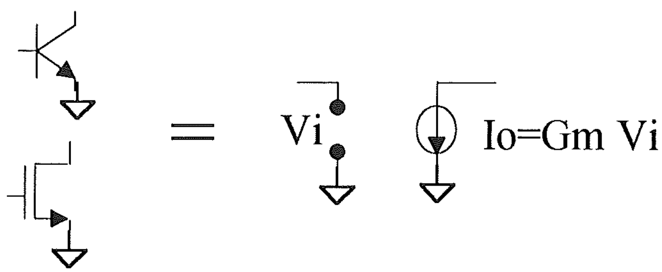


From N. M. Nguygen and R. G. Meyer, "Si IC-Compatible Inductors and LC Passive Filters," IEEE J. Solid-State Circuits, pp. 1028-1031, Aug. 1990.

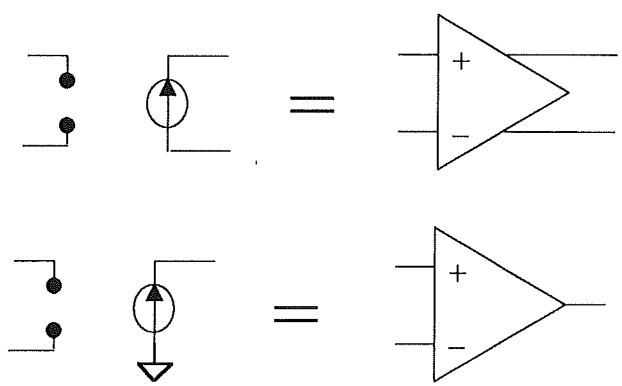
Active Gm-C Lowpass Filters

Transconductor Symbols

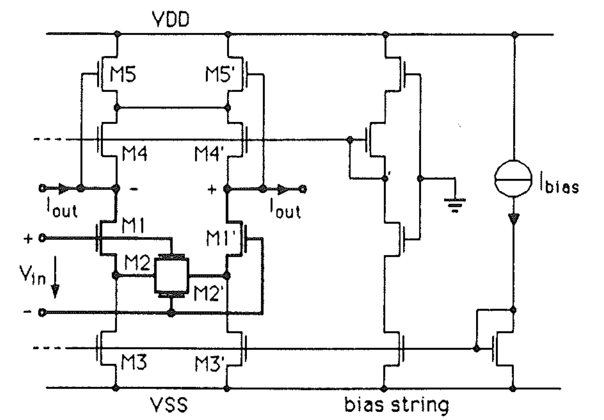
Single-Ended



Differential



Practical Transconductor



From: F. Krummenacher and N. Joehl, "A 4-MHz CMOS Continuoius-Time Filter with On-Chip Tuning," IEEE JSSC, pp. 750-758, June 1988.

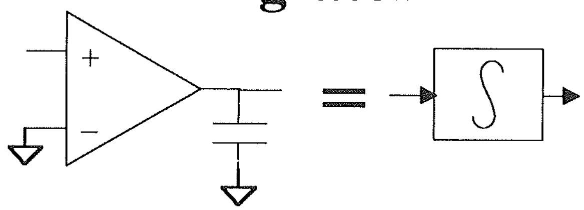
Important Design Considerations:

- Transconductor linearity
- Common-mode voltage control
- Output impedance
- Tuning

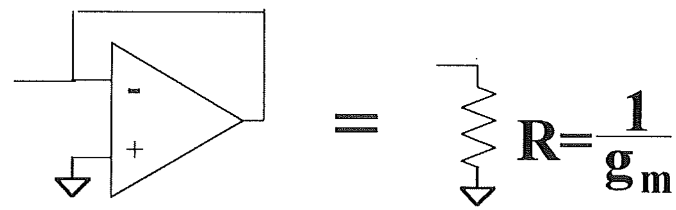
Active Gm-C Lowpass Filters

Basic Building Blocks

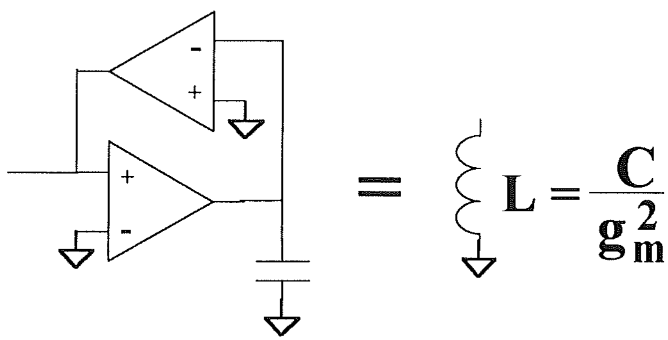
Integrator



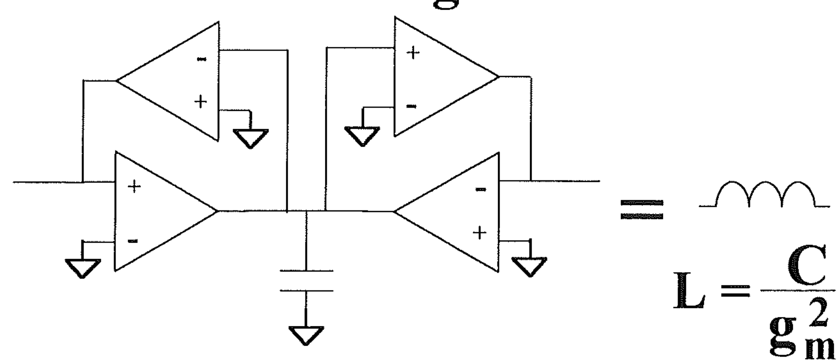
Resistor



Inductor

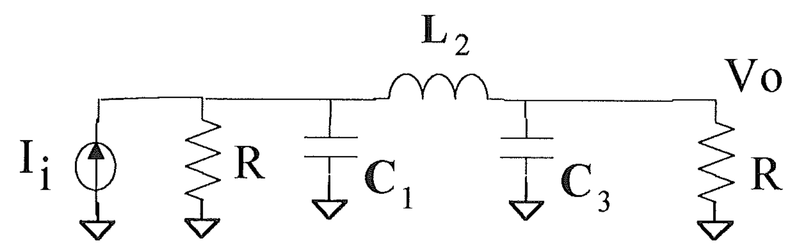


Floating Inductor



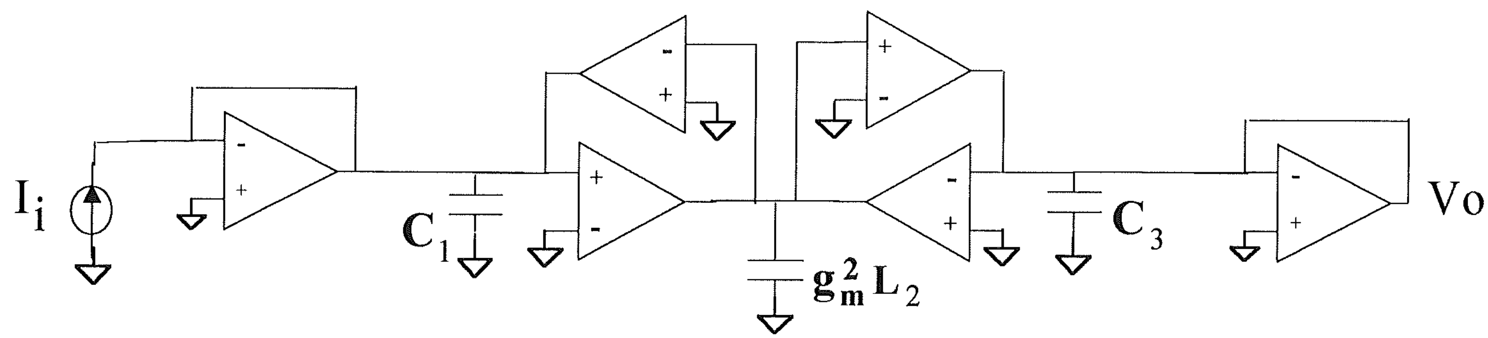
Active Gm-C Lowpass Filters

Direct Replacement Method



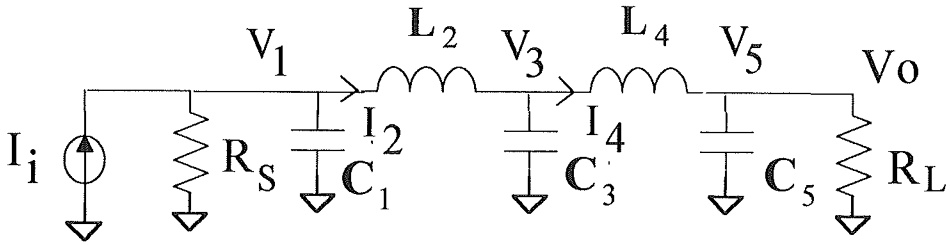
=

$g_m = 1/R$



Active Gm-C Lowpass Filters

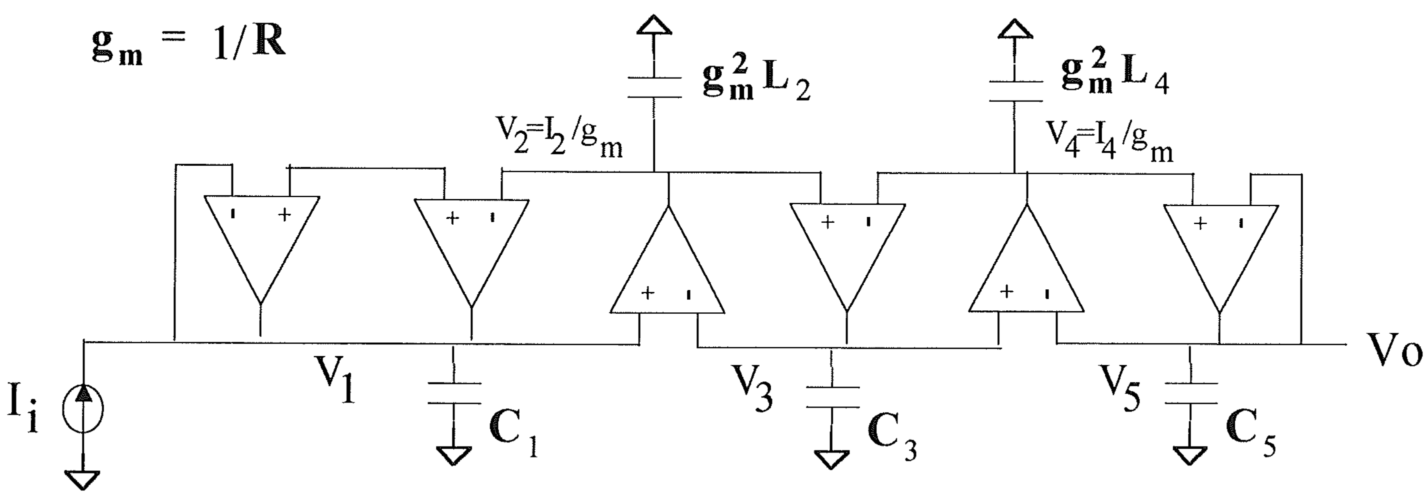
"Leap Frog" Method



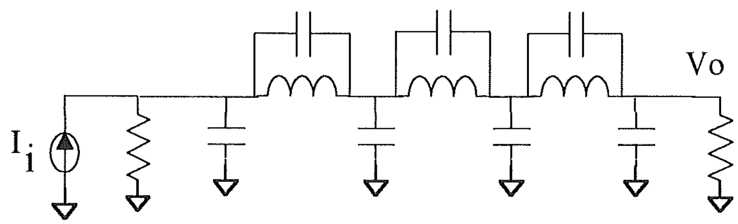
$$V_1 = (I_i - I_{R_s} - I_2)\frac{1}{sC_1} \quad I_R = \frac{V_1}{R_s}$$
$$I_2 = (V_1 - V_3)\frac{1}{sL_2}$$
$$V_3 = (I_2 - I_4)\frac{1}{sC_3}$$
$$I_4 = (V_3 - V_5)\frac{1}{sL_4}$$
$$V_5 = (I_4 - I_{R_L})\frac{1}{sC_5} \quad I_{R_L} = \frac{V_5}{R_L}$$

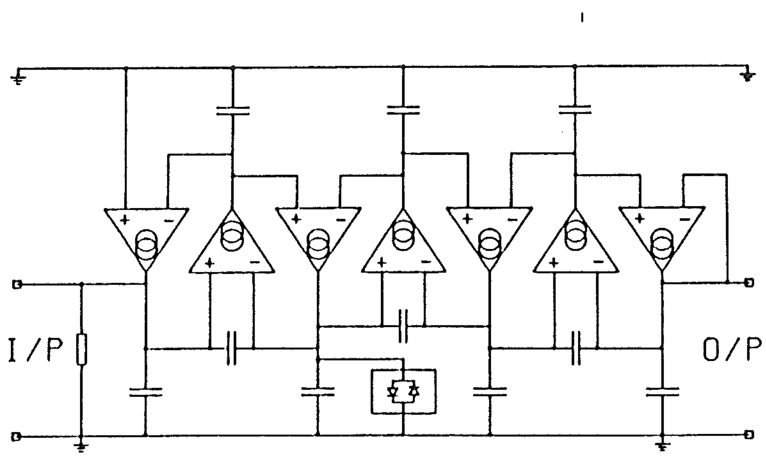
=

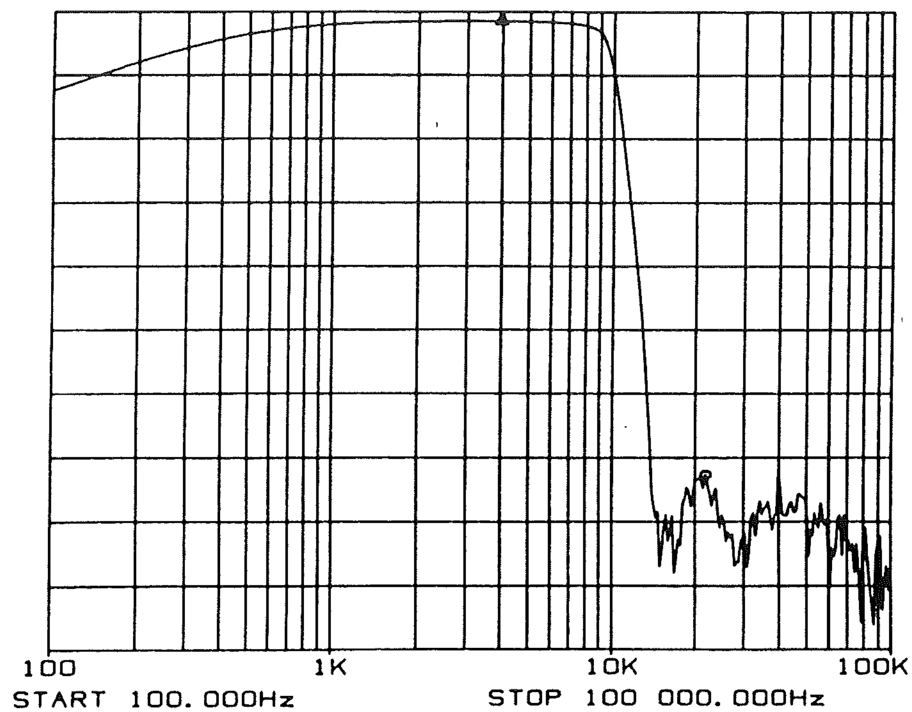
$g_m = 1/R$



Example Elliptical Filter







From: J. F. Wilson, R. Youell, T.H. Richards, G. Luff, and R. Pilaski, "A Single-Chip VHF and UHF Receiver for Radio Paging," IEEE JSSC, pp. 1944-1950, Dec. 1991.

Practical Considerations

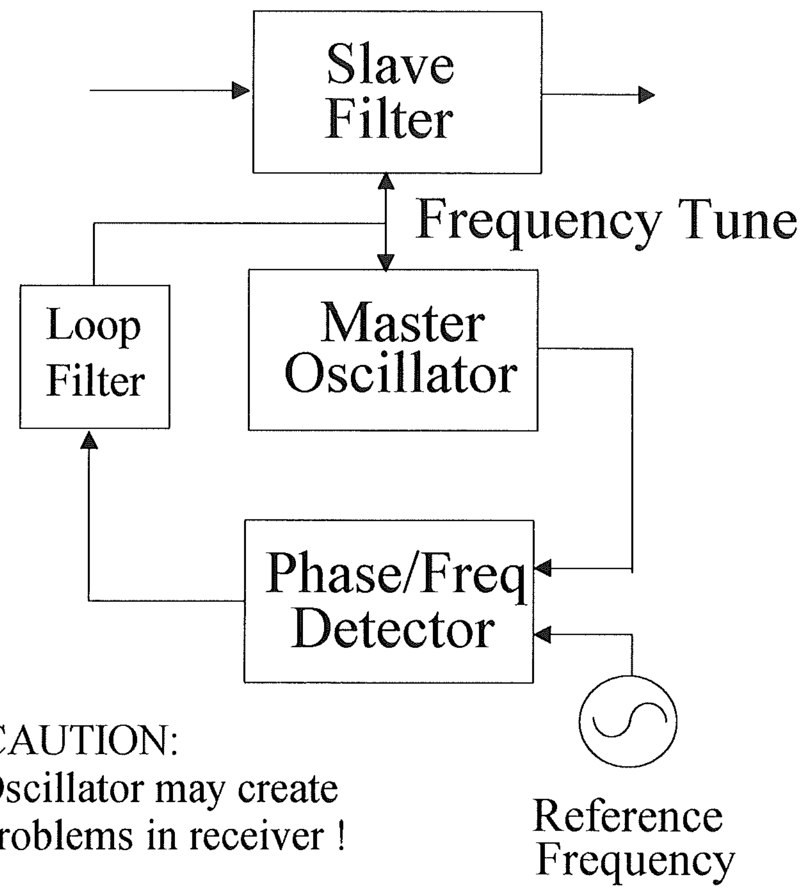
Cutoff frequency depends on C and g_m (e.g. $f \propto \frac{g_m}{C}$), and may vary by 15% or more without tuning.

C and g_m do not track with temperature.

Q accuracy depends (primarily) on ratios of like components and can be maintained well for low Q circuits.

Real-time tuning can be implemented with "Master-Slave" and other methods.

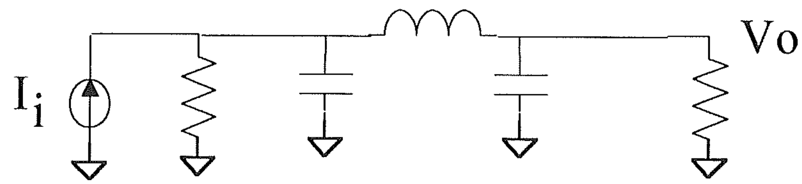
Master-Slave Frequency Tuning



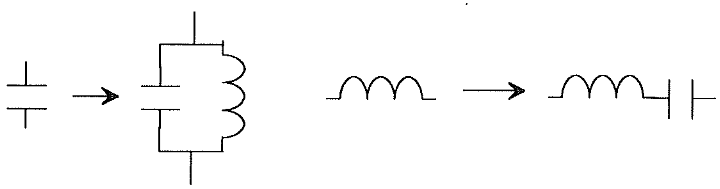
CAUTION:
Oscillator may create problems in receiver !

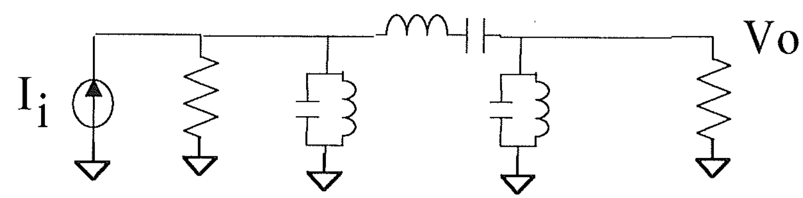
Bandpass Filter Design

1) Begin with lowpass prototype

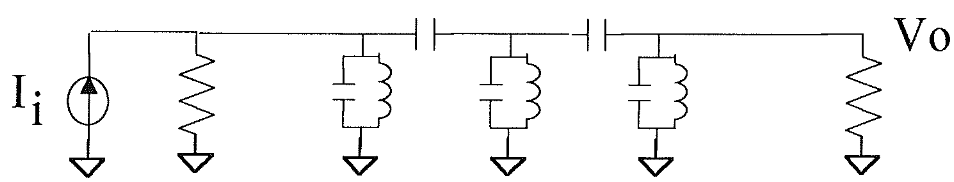


2) Apply transformations

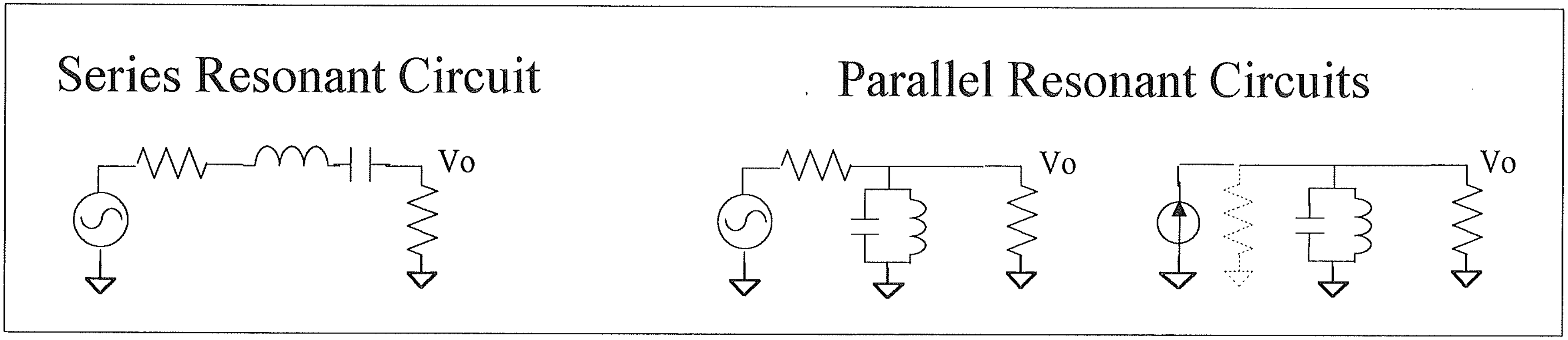




3) Convert to "Coupled-Resonator" topology if desired (See Hagen)



Simple 1-Pole BPFs



At resonance: $X_L = -X_C$

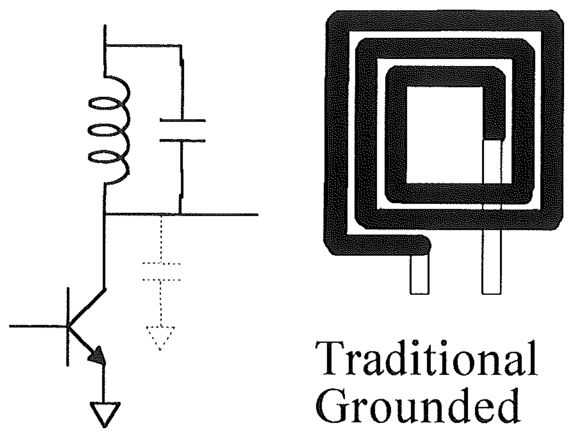
For series circuit, LC becomes short circuit.
For parallel circuit, LC becomes open circuit.

Occurs at frequency: $$f_o = \frac{1}{2\pi\sqrt{LC}}$$

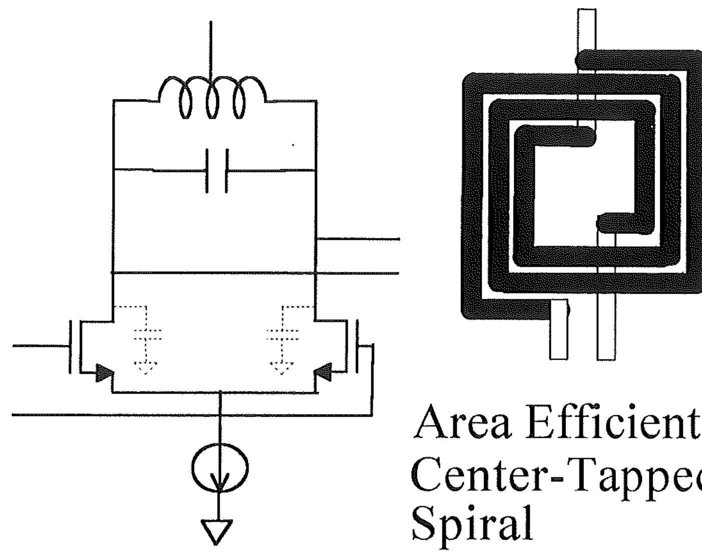
Bandwidth is found from: $$B = \frac{f_o}{Q}$$

Where for series circuit, $Q = \frac{X}{R}$, and for parallel circuit, $Q = \frac{R}{X}$
(with R = total series R or equivalent parallel R).

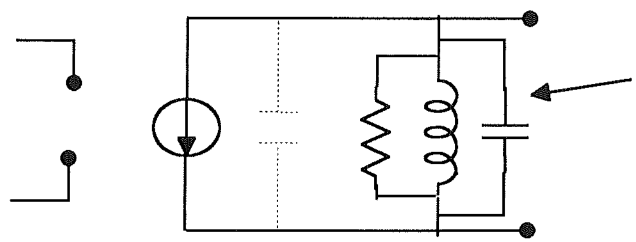
On-Chip Bandpass Filtering



Traditional
Grounded
Spiral



Area Efficient
Center-Tapped
Spiral

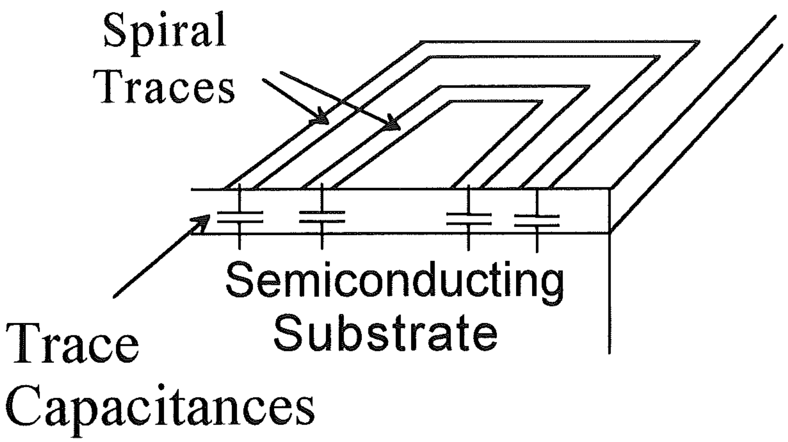


Approximate
Spiral inductor model

On-Chip Spiral Inductors

Performance Limitations

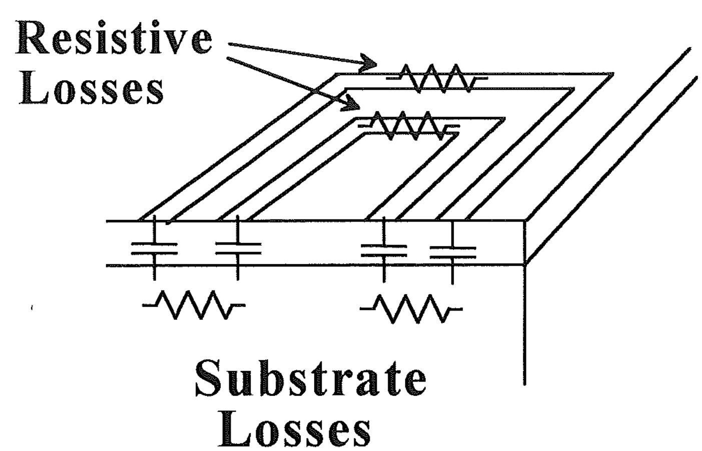
Low Self Resonant Frequency



Limits:

Max Reactance
Max Quality Factor

Low Quality Factor (Q)



Limits:

Circuit Performance
(Gain, Noise, Bandwidth)

Typical Performance

Simulated performance for grounded spirals in Silicon
(eddy current losses excluded)

Size (D)	*Turns (N)*	*L*	*SRF*	*Q @ 0.7 SRF*	*X_L @ 0.7 SRF*
330 um	4	3.5 nH	3.9 GHz	8	60
330 um	8	11 nH	2.3 GHz	5.5	110
330 um	16	39 nH	1.2 GHz	3	205
1,000 um	24	250 nH	150 MHz	1.5	165

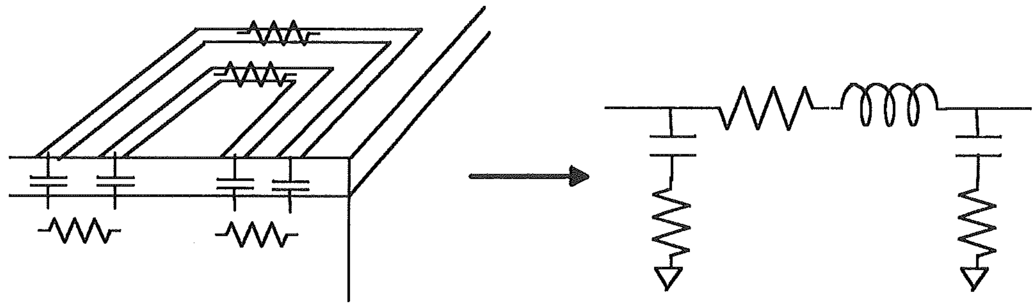
(Very) Rough estimate of L: $L \sim (850E-9)\ D\ N^{1.8}$

Series limit on Q: $Q < \frac{\omega L}{R_s}$ where $R_s \approx R_{sheet} \frac{TraceLength}{TraceWidth}$

CAUTION: ***Accurate modeling in target process is essential.***

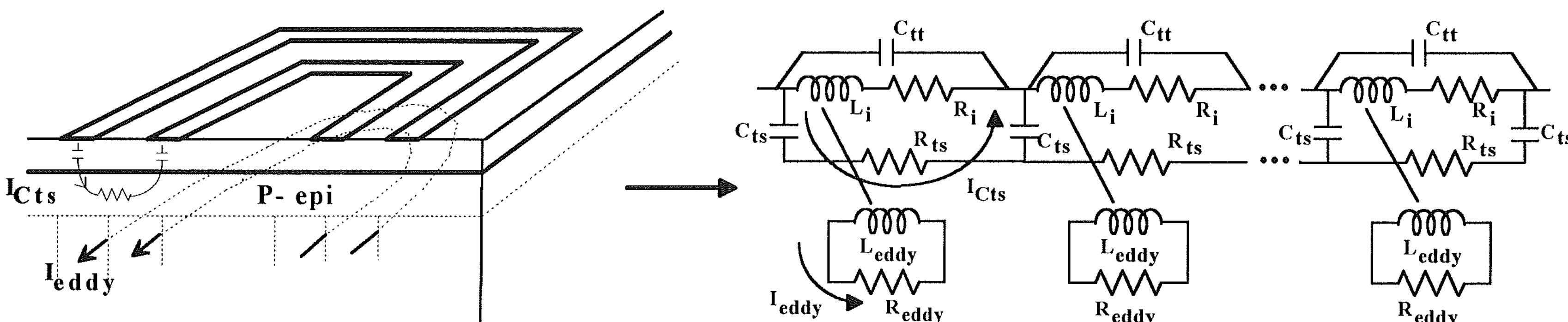
Spiral Inductor Models

Typical Empirical Model



NOTE: Component values must be found by fitting measured or EM simulated data.

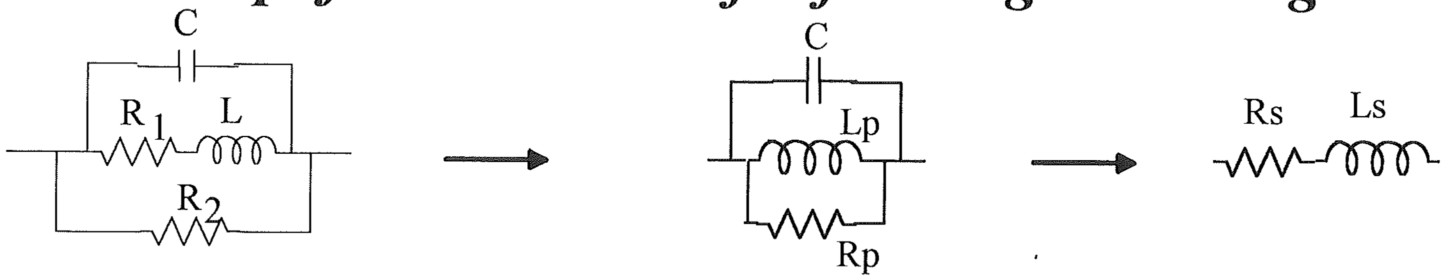
Approximate Physical model



NOTE: Turn-to-turn magnetic coupling not shown for simplicity. Connections of Rts depend on grounding scheme for substrate.

Simplified Models

Simplified models useful for rough cut design:



Useful to first resonance

Useful at single frequency

L: Estimate from measured data, or simulation. Must be low-frequency value.

C: Pick to match measured or simulated SRF.

R1: Estimate from series R of traces (include skin effect).

R2: Pick to give measured or simulated Q vs. frequency.

Convert R_1 in series with L to parallel circuit at desired frequency and combine with R_2.

Define $q = \frac{X_L|_{f_o}}{R_1}$

Then: $R_p = R_2 \| (1+q^2)R_1$

$$L_p = \left(\frac{1+q^2}{q^2}\right)L$$

Combine reactance of C and Lp into an equivalent value at desired frequency. Then convert parallel RL circuit to series form:

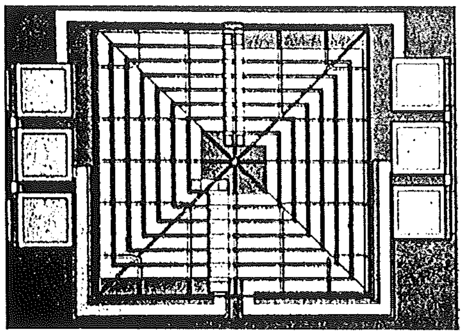
$$X_{eq} = X_{Lp} \| (-X_c)$$

$$q = \frac{Rp}{X_{eq}}$$

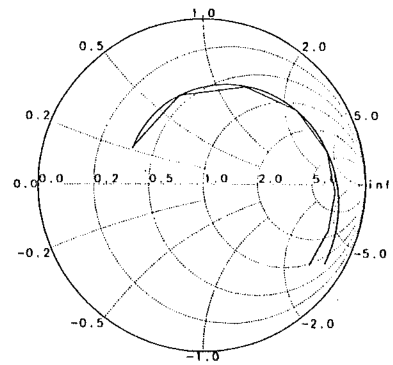
$$R_s = R_p \frac{1}{1+q^2}$$

$$L_s = \frac{1}{2\pi f_o} X_p \left(\frac{q^2}{1+q^2}\right)$$

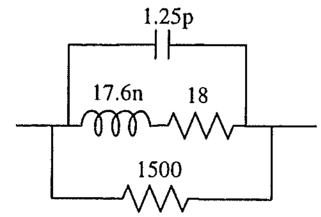
Example Rough-Cut Design



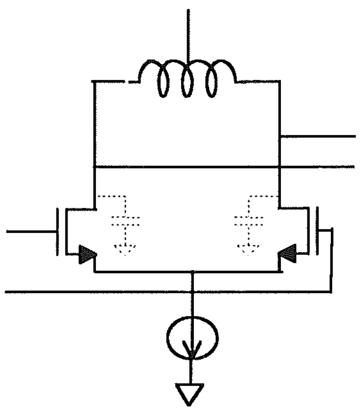
600 um Center-tapped Inductor
(Patent pending?)



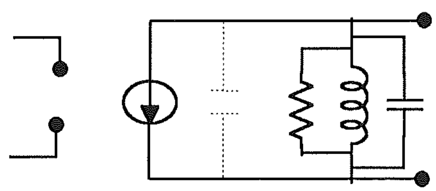
Measured and modeled differential impedance



Fitted Model



Amp/filter at 900 MHz.



Model

$$A_V = g_m R_p$$

$$f_o = \frac{1}{2\pi\sqrt{L_p C_{total}}} = 900MHz$$

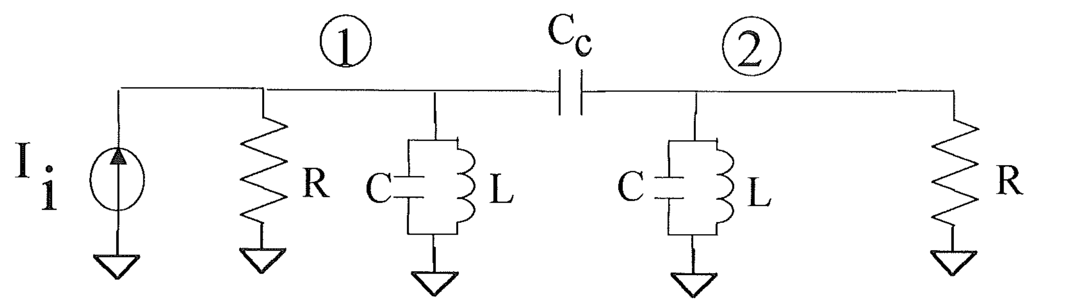
$$Q \leq \frac{R_p}{X_p} = 4$$

$$B = \frac{f_o}{Q} \geq 225MHz$$

Design Equations

Higher-Order Bandpass Filters

Simplified 2-Pole Coupled-Resonator Design



Design Equations

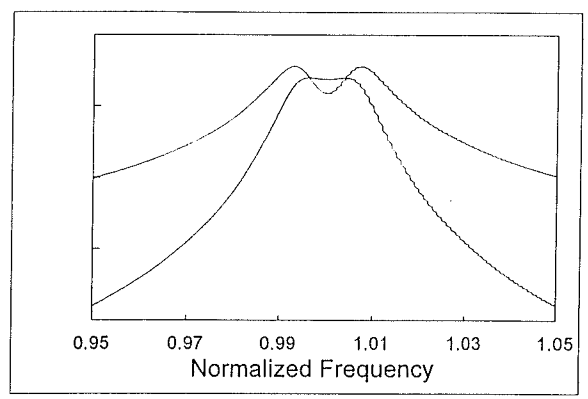
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

$$Q_{res} = \frac{R}{X|_{f_o}}$$

$$C_c \sim \frac{C}{Q}$$

$$B \sim \frac{f_o}{\sqrt{2}\,Q_{res}}$$

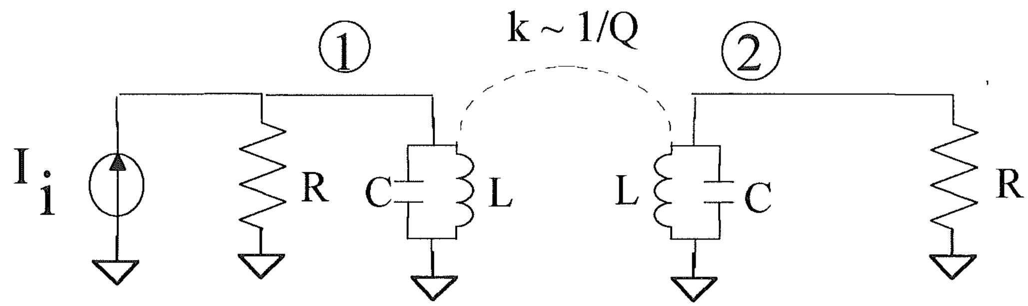
Response to Nodes 1 and 2



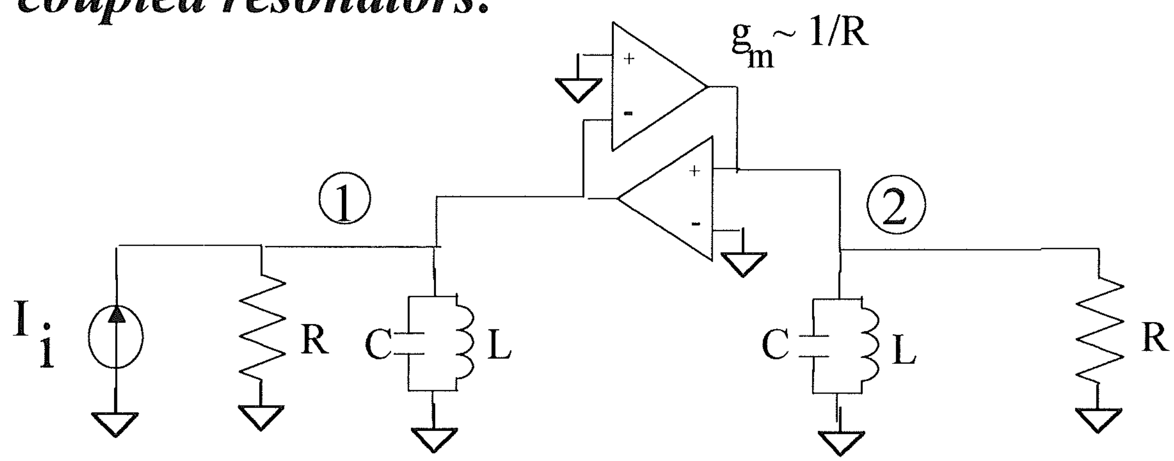
NOTE: Q of spiral may be too low for passive design

Alternative Coupling

Magnetically coupled resonators:

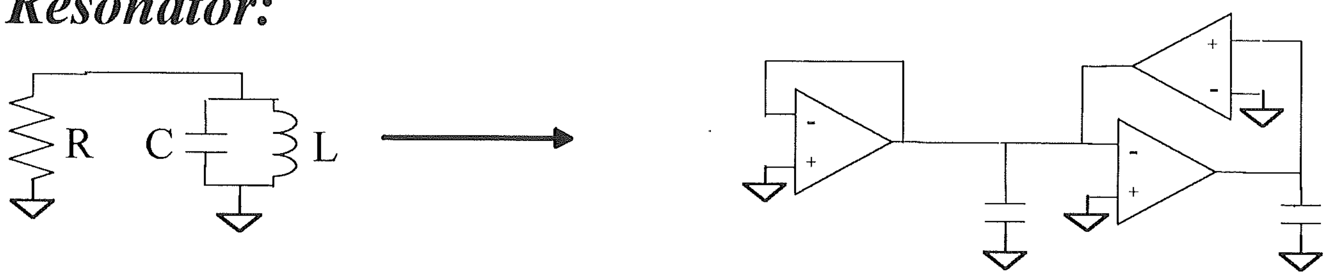


Actively coupled resonators:



Active LC Resonators

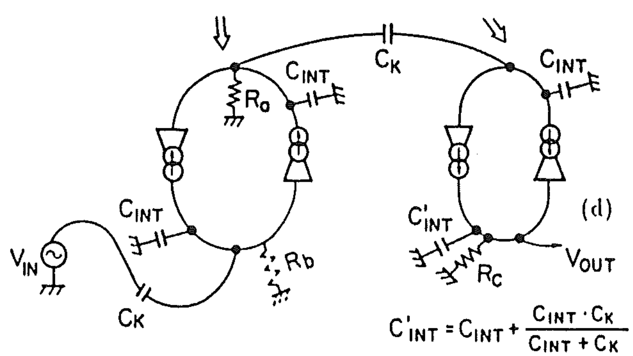
Single Resonator:

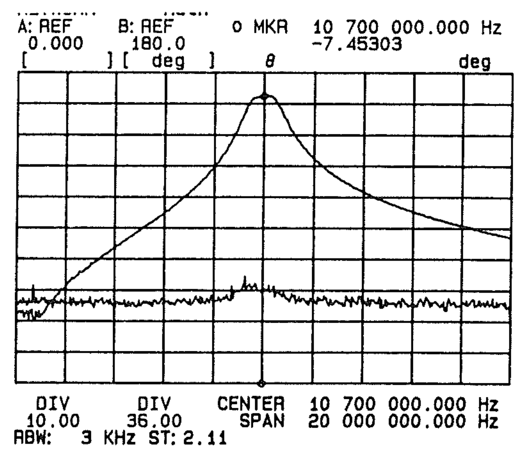


$R=1/g_m$ C $L=C/(g_m^2)$

Coupled Resonator Design

(From: M. Koyama, et.al., "A 10.7 MHz Continuous-Time Bandpass Filter Bipolar IC," Proc. Custom Integrated Circuits Conference, pp. 25.2.1 - 25.2.4, 1989.)





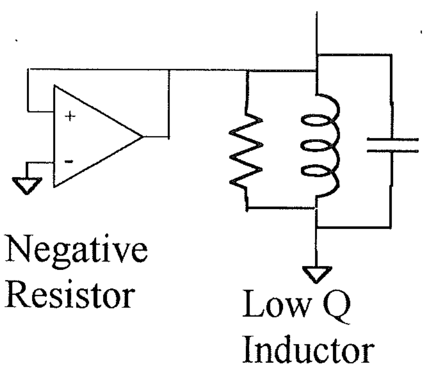
Problems and Concerns:

Freq accuracy, dynamic range, Q sensitivity => Use Q < 10 !!

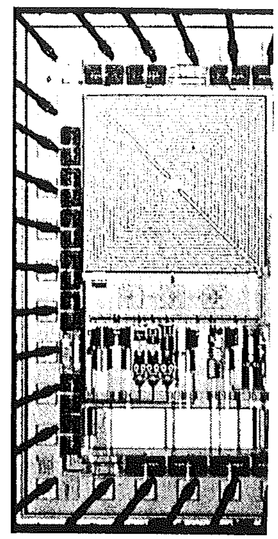
A Look Ahead

Experimental Single-Pole Q-Enhanced LC Bandpass Filter:

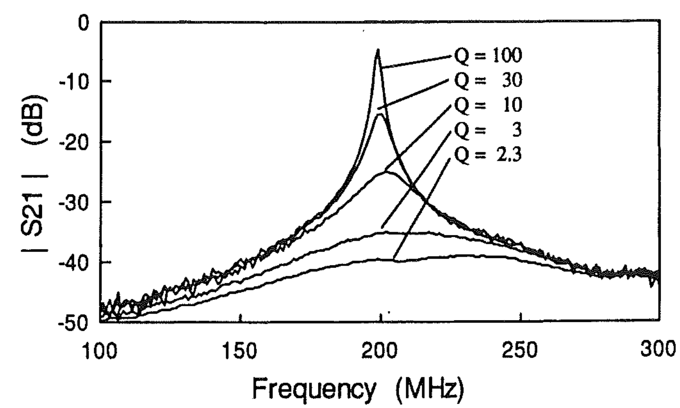
Q-enhanced Inductor:



Implementation:



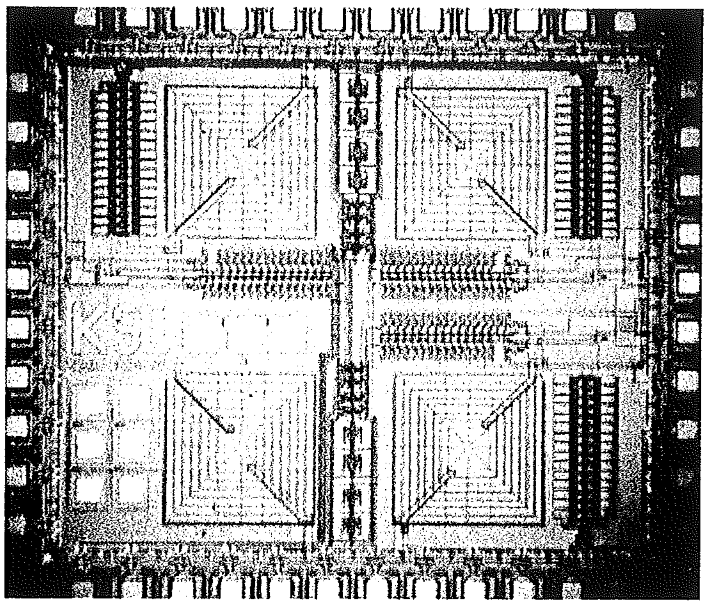
Measured Results:

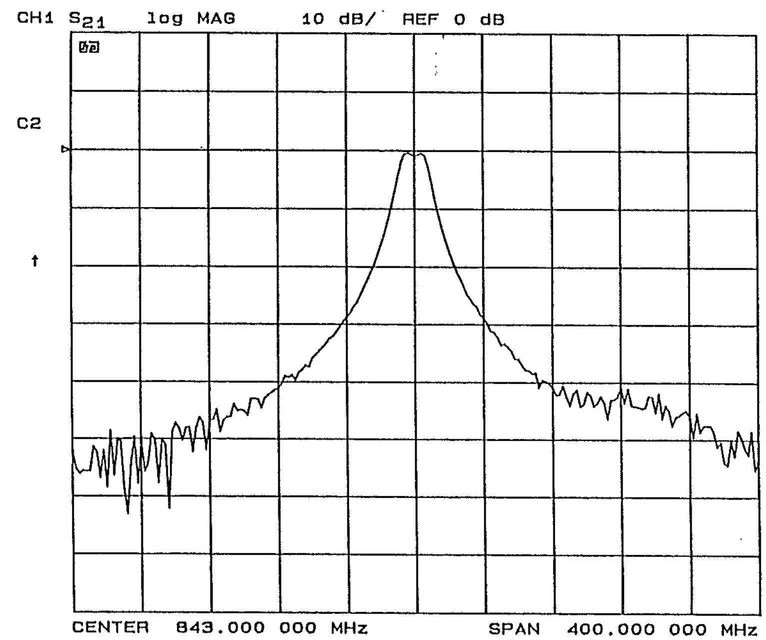


From: W.B. Kuhn, F.W. Stephenson, and A. Elshabini-Riad, "A 200 MHz CMOS Q-Enhanced LC Bandpass Filter," IEEE J. Solid-State Circuits, pp. 1112-1122, 1996.

A Look Ahead

Experimental Two-Pole Q-Enhanced LC Bandpass Filter:





From: W.B. Kuhn, N.K. Yanduru, and A.Wyszynski, "A High-Dynamic Range, Digitally Tuned, Q-Enhanced LC Bandpass Filter for Cellular/PCS Receivers," IEEE Radio Frequency Integrated Circuits Symposium, pp. 261 - 264, 1998.

For More Information ...

- T. E. Larson, "Integrated Circuit Technology Options for RFIC's - Present Status and Future Directions," IEEE Journal of Solid-State Circuits, pp. 387-399, March 1998.
- K. Hansen, "Wireless Communications Devices and Technology: Future Directions, IEEE RFIC Symp. pp. 1-5, 1998.
- J. Strange and S. Atkinson, "A Highly Integrated Radio Transceiver Chipset for DECT," IEEE RFIC Symp., pp.131-134, 1997.
- Y.P. Tsividis, "Integrated Continuous-Time Filter Design - An Overview," IEEE J. Solid-State Circuits, pp.166-176, Mar. 1994.
- Y.P. Tsividis and J.O. Voorman, Editors, *Integrated Continuous-Time Filters - Principles, Design, and Applications*, IEEE Press, 1993.
- J. E. Kardontchik, *Introduction to the Design of Transconductor - Capacitor Filters*, Norwell, MA: Kluwer Academic Publishers, 1992.

- C. P. Yue and S. S. Wong, "On-Chip Spiral Inductors with Patterned Ground Shields for Si-Based RF IC's," IEEE Journal of Solid-State Circuits, pp. 743-752, May 1998.
- J. R. Long, M. A. Copeland, ``The Modeling, Characterization, and Design of Monolithic Inductors for Silicon RF IC's," IEEE J. Solid-State Circuits, pp. 357-369, March 1997.
- W. B. Kuhn, A. Elshabini-Riad, and F. W. Stephenson, ``Centre-tapped Spiral Inductors for Monolithic Bandpass Filters," Electron. Lett., vol. 31, no. 8, pp. 625-626, 13 April 1995.
- D. Lovelace, N. Camilleri, and G. Kannell, ``Silicon MMIC Inductor Modeling for High Volume, Low Cost Applications," Microwave Journal, pp. 60-71, August 1994.
- J. Y.-C. Chang, A. A. Abidi, and M. Gaitan, ``Large Suspended Inductors on Silicon and Their Use in a 2-um CMOS RF Amplifier," IEEE Electron Device Letters, May 1993, pp. 246-248.
- N. M. Nguyen, and R. G. Meyer, ``Si IC-compatible inductors and LC passive filters," IEEE JSSC, August 1990, pp. 1028-1031.
- H. Y-F. Lam, *Analog and Digital Filters,* Prentice Hall, 1979.