Radio Design 401 Episode 1 – Low-power Receivers in Crowded Spectrum Environments (a White Paper)

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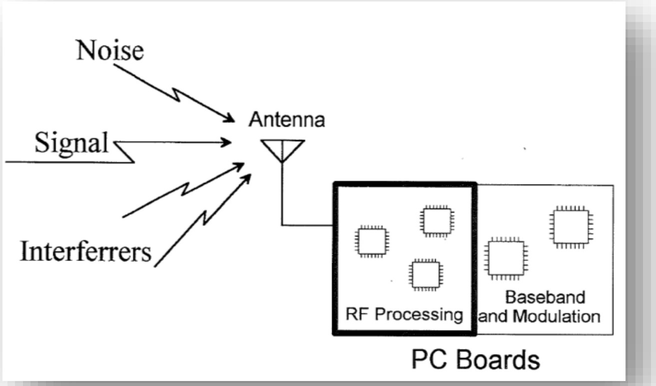
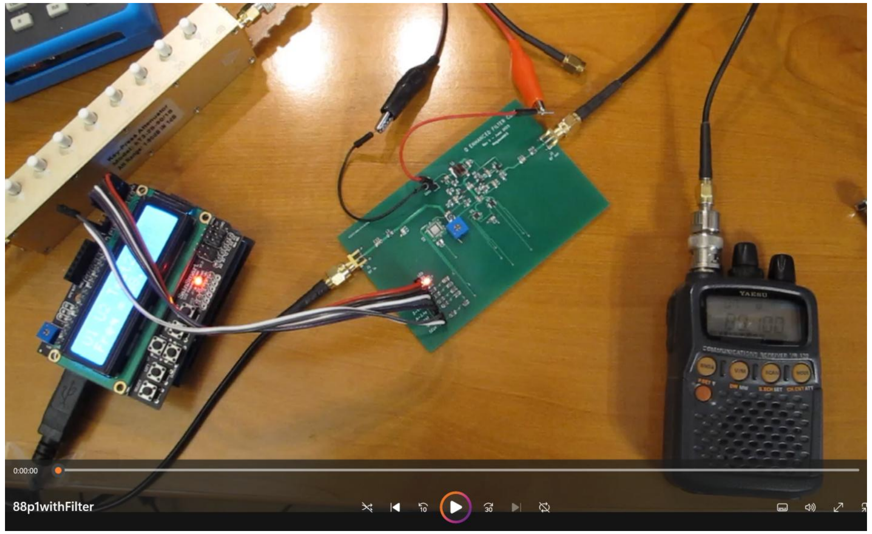
This is the first episode in our follow-on to the Radio Design 101 series. In RD401, we will be covering more advanced topics including fundamental research into how to improve the performance of receivers in dense spectrum environments. In keeping with RD101 series, we will be using the FM broadcast band for our demonstrations - but the material and circuit technologies are applicable to all radio receivers.





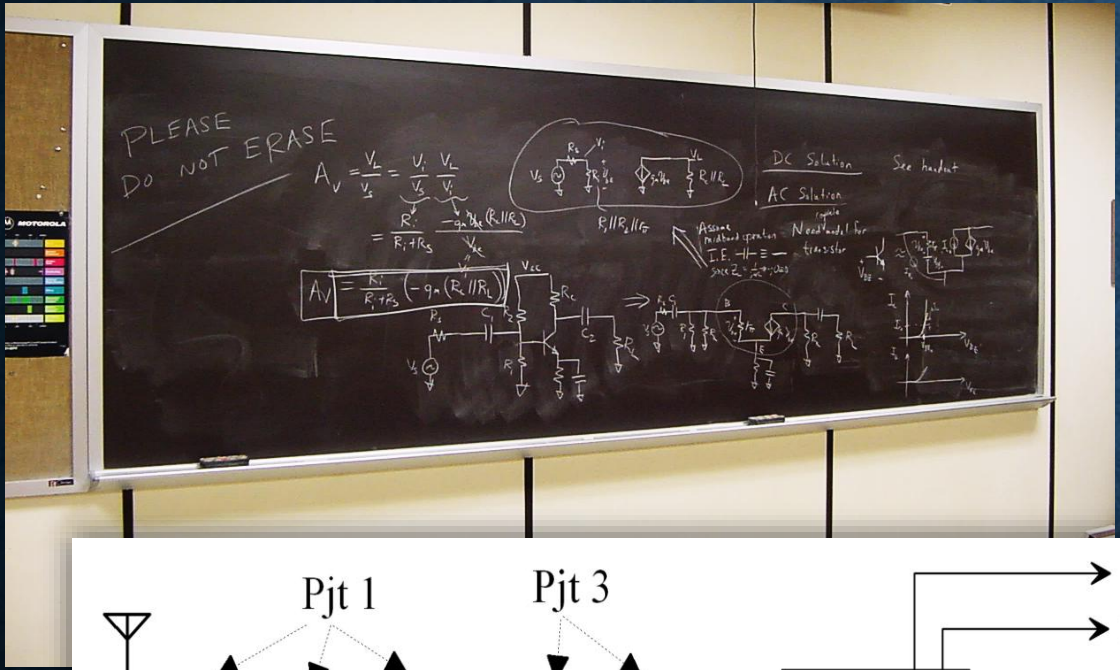
Radio Design 401

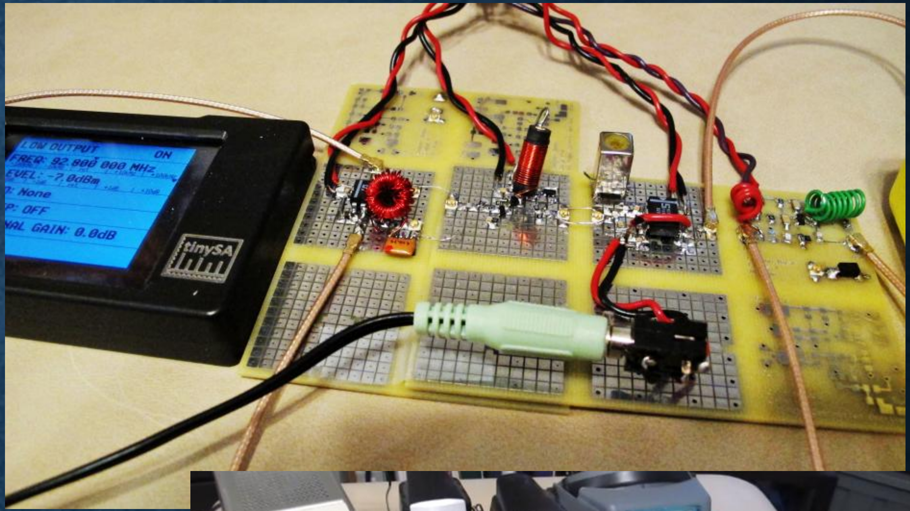
Episode 1

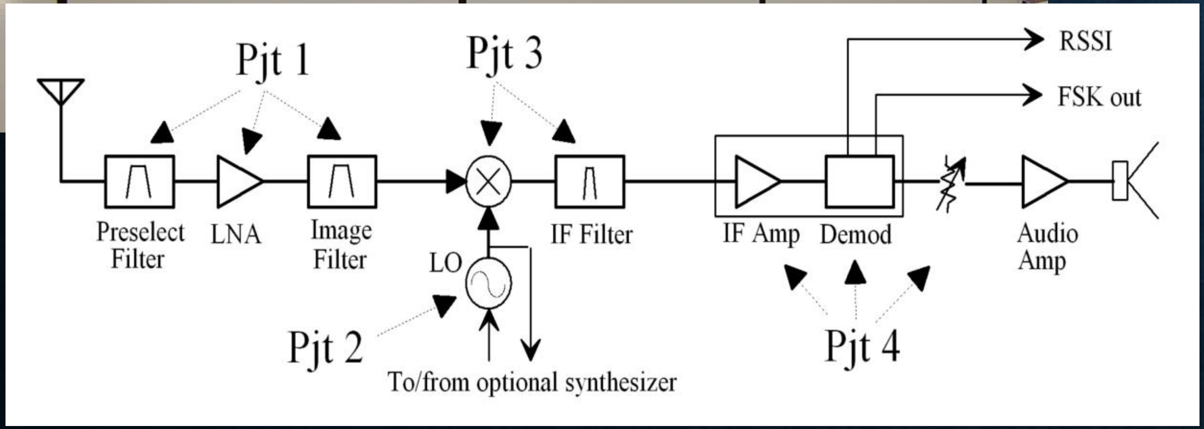
Low-power Receivers in Crowded Spectrum Environments

(An Advanced "Course" & "White Paper")

“Prereq”: Radio Design 101 ☺







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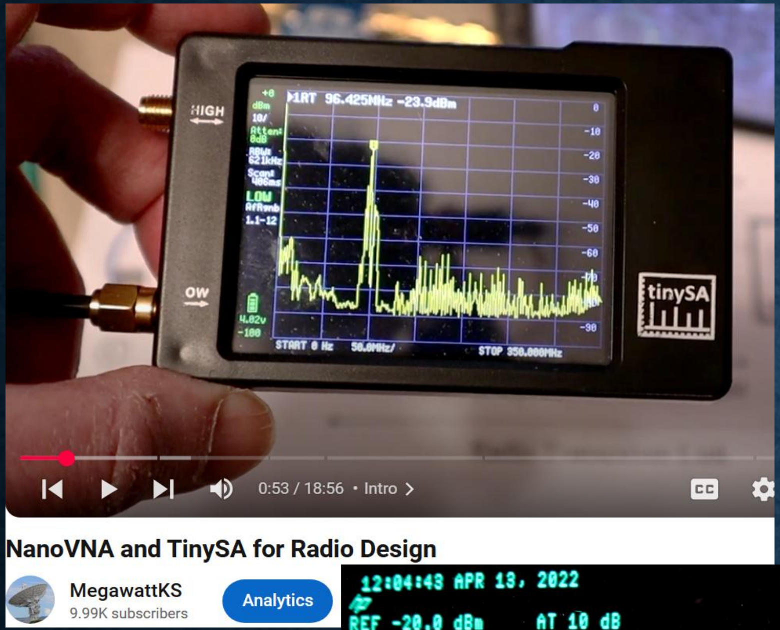
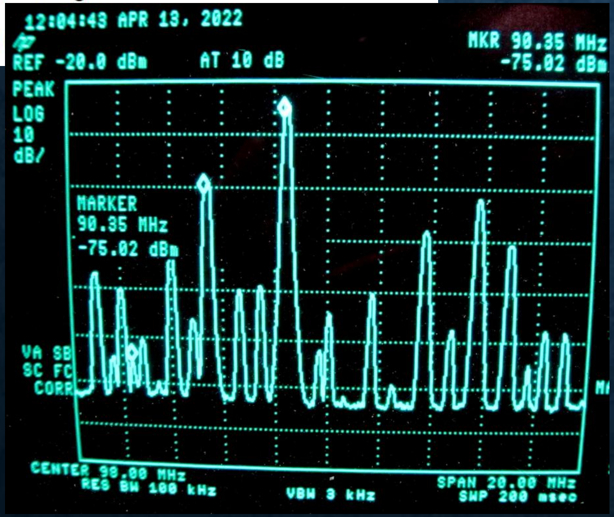
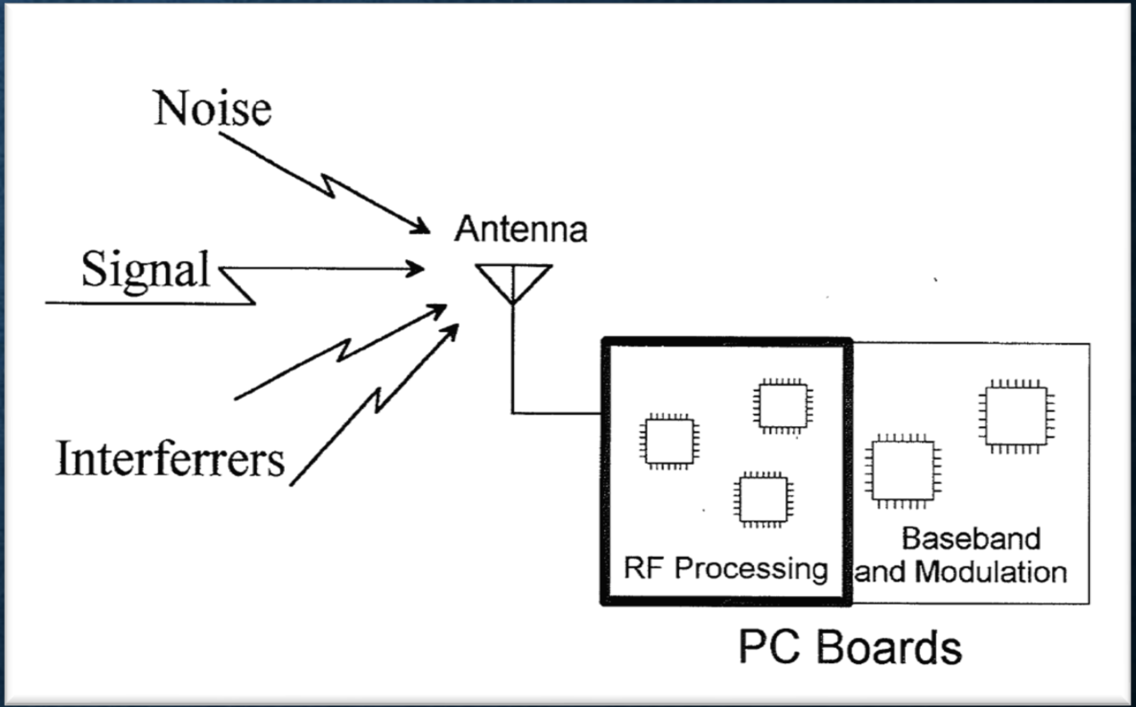
AI Overview

A "white paper" is an informative document, often used in business, that presents a detailed analysis of a specific topic, problem, or solution, usually with the intent to educate the reader and persuade them to support a particular view-point or product, often by providing facts and evidence in a professional and authoritative tone; the term originated from

First Day Review

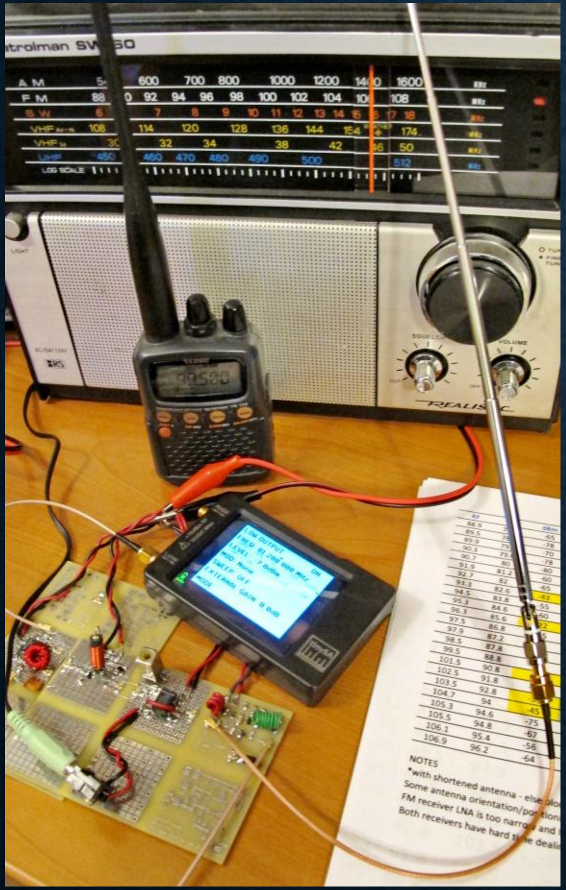


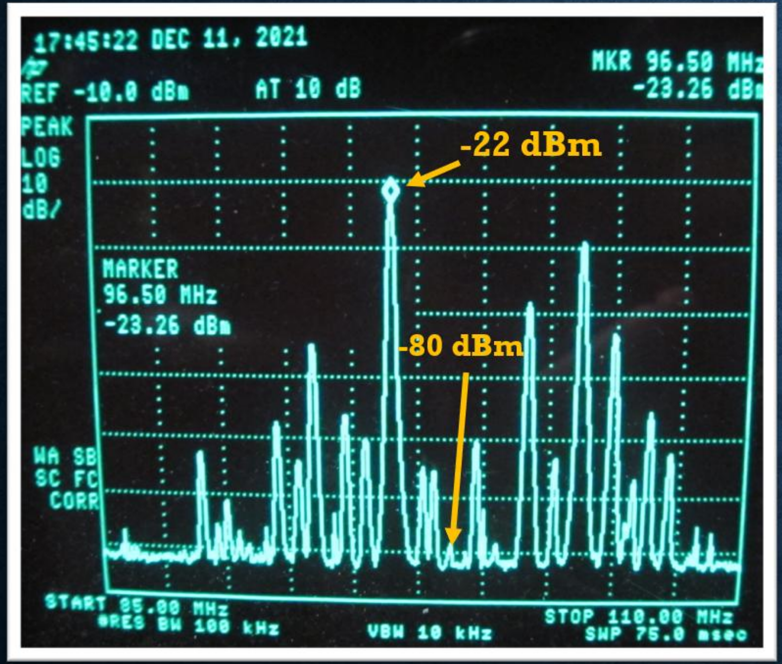




Radio Performance Testing

(From Radio Design 101 – Epilogue 1)

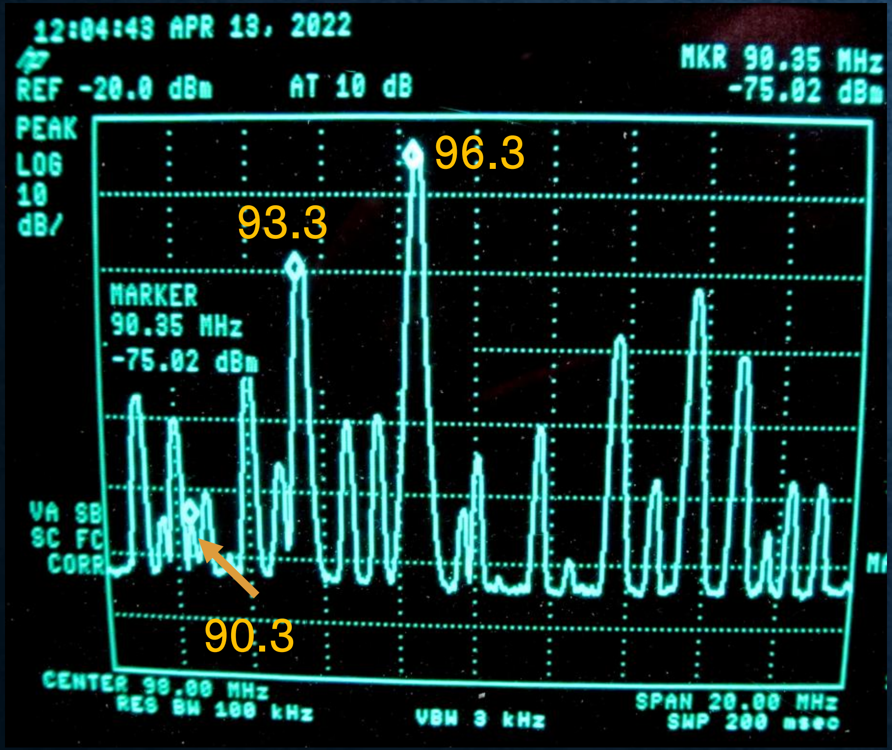




RF	LO	dBm	FMrx	FMrxFixed	VR120	VR120atten	Old Radio
88.9	78.2	-65				yes	yes
89.5	78.8	-78			yes		yes
89.9	79.2	-70	quiet	quiet	yes	yes	yes
90.3	79.6	-78		quiet		yes	yes
90.7	80	-80					yes
91.9	81.2	-60	quiet	good	yes	yes	yes
92.7	82	-65		good		yes	yes
93.3	82.6	-43	excellent	excellent	yes	yes	yes
94.5	83.8	-55	quiet	good	yes	yes	yes
95.3	84.6	-60	quiet	good	yes	yes	yes
96.3	85.6	-22	excellent	excellent	yes	yes	yes
97.5	86.8	-65		good		yes	yes
97.9	87.2	-67	quiet	quiet	yes	yes	yes
98.5	87.8	-80					?
99.5	88.8	-61	?	excellent*		yes	yes
101.5	90.8	-40	excellent	excellent	yes	yes	yes
102.5	91.8	-62					yes
103.5	92.8	-30	excellent	excellent	yes	yes	yes
104.7	94	-45	good	excellent	yes	yes	yes
105.3	94.6	-75					yes
105.5	94.8	-67			yes	yes	yes
106.1	95.4	-56		very quiet	yes	yes	yes
106.9	96.2	-64		yes	yes	yes

Today’s Topic – The Intermod Problem

Two strong signals at 96.3 and 93.3 MHz ‘mix’ and block weaker (-75 dBm) signal at 90.3 MHz



Result – Using New Technology

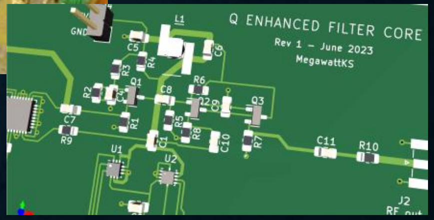
RD101 Radio Out-performed all 3 Commercial Ones !

(when using 200 kHz bandwidth Q-enhanced Front-End filter)

88.1 MHz

Station	dBm	ATS 25	VR-120	SW-60	RD-101*
88.1	-96				
88.9	-58				
89.5	-75				
89.9	-61				
90.3	-77				
90.5	-85				
90.7	-71				
91.3	-80				
91.9	-55				
92.5	-82				
92.7	-70				
93.3	-41				
94.5	-63				
95.3	-60				
96.3	[illegible]				
97.5	[illegible]				
97.9	[illegible]				

With Q-enhanced filter front-end added



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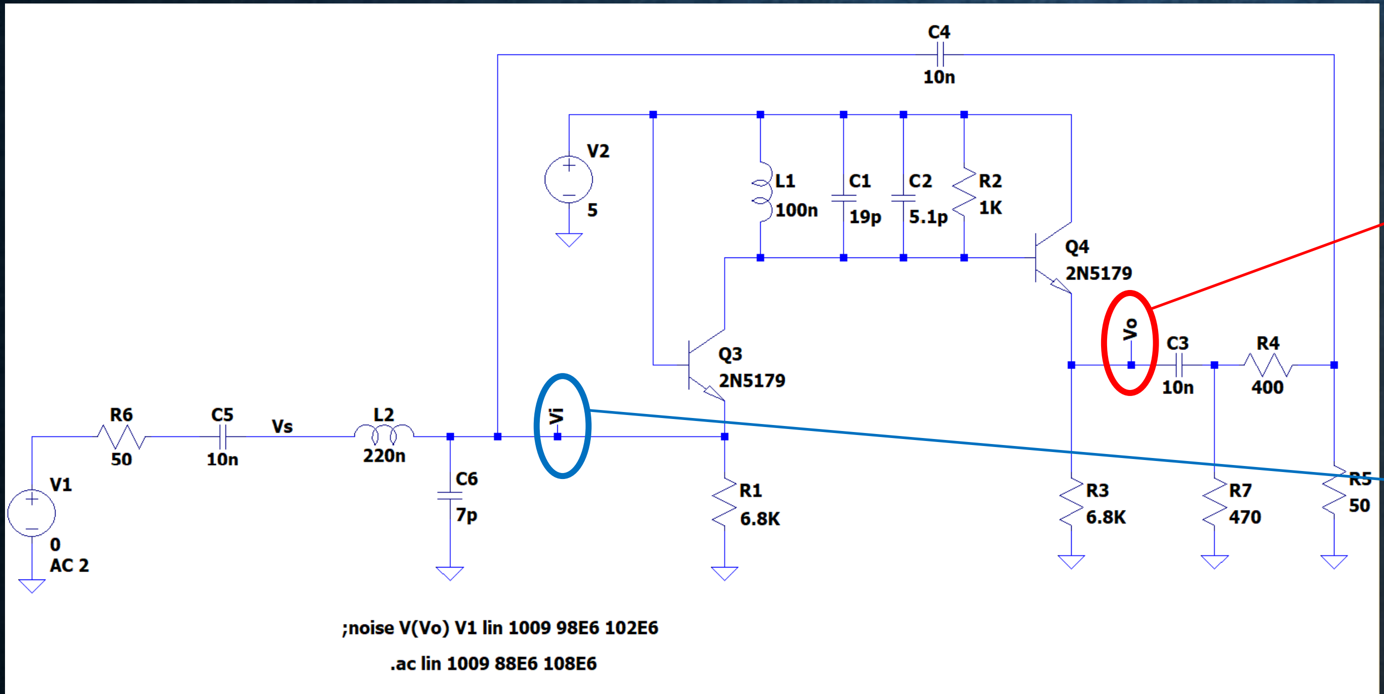
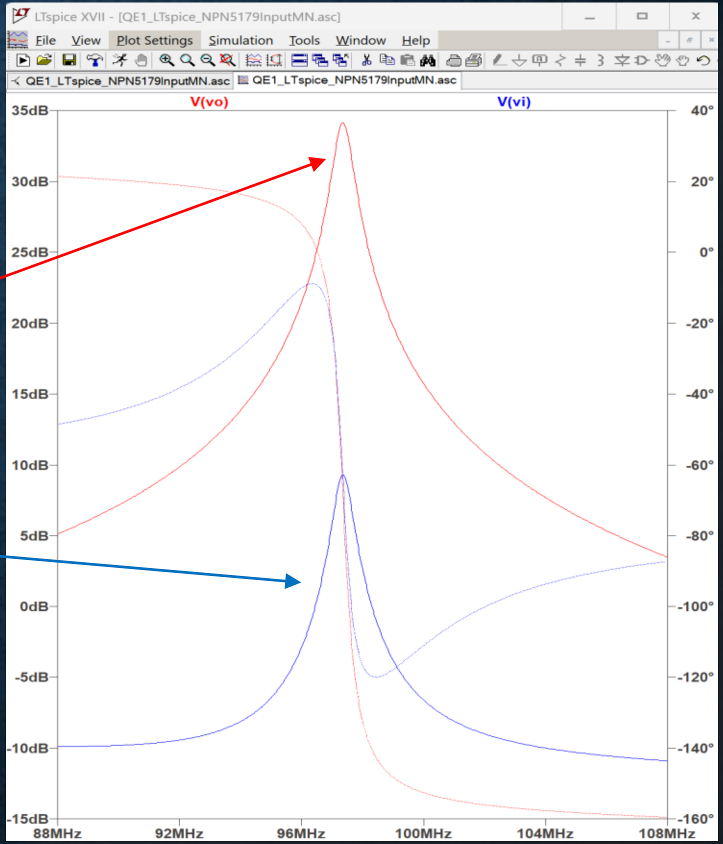
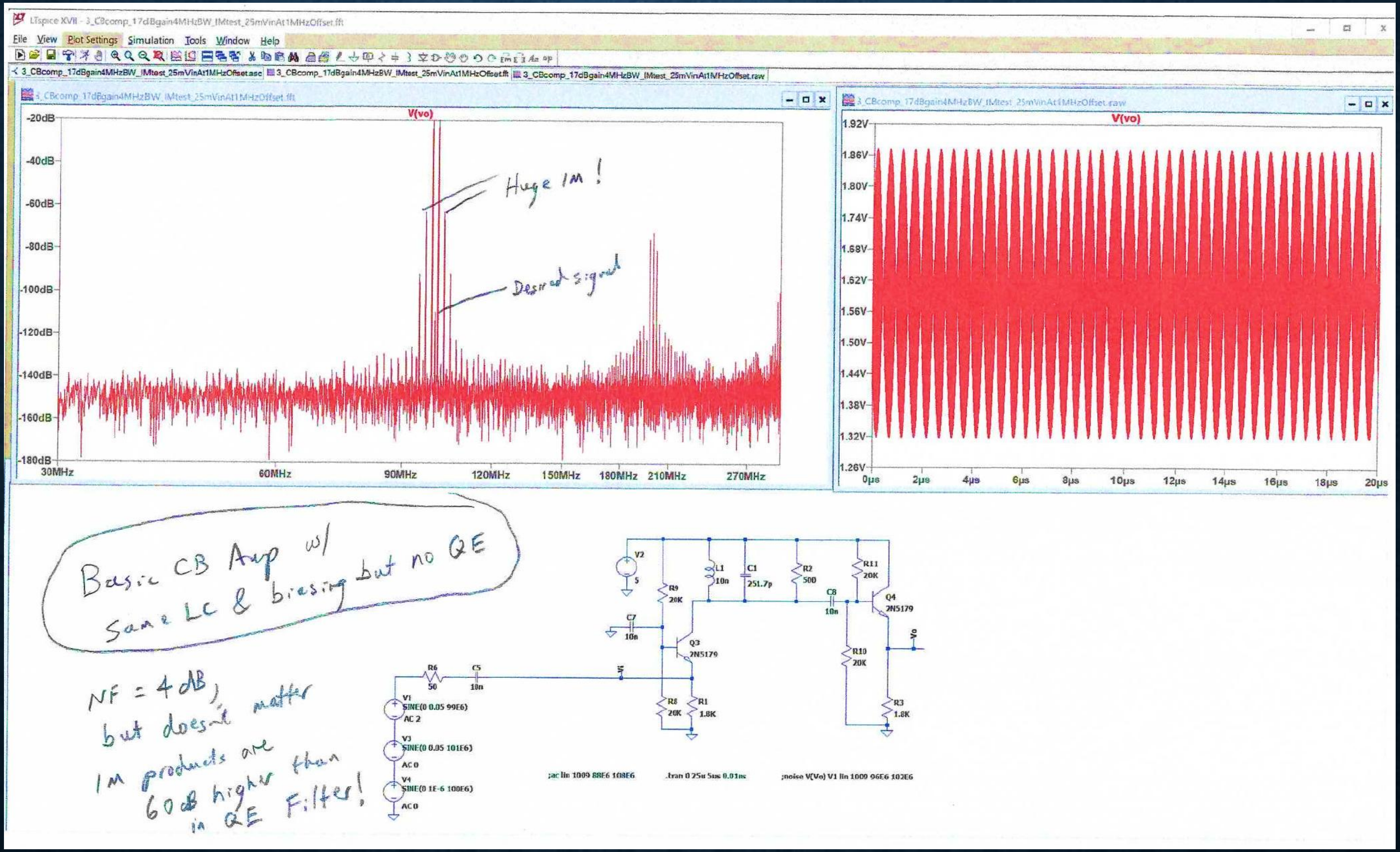
New Q-Enhanced LNA
From Radio Design 101 – Epilogue 3



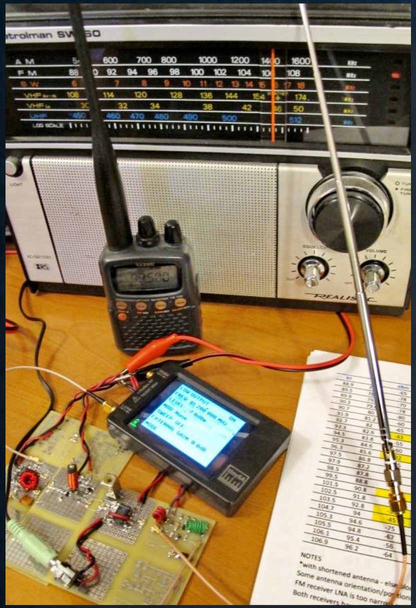


Intermod and Noise Figure Sims

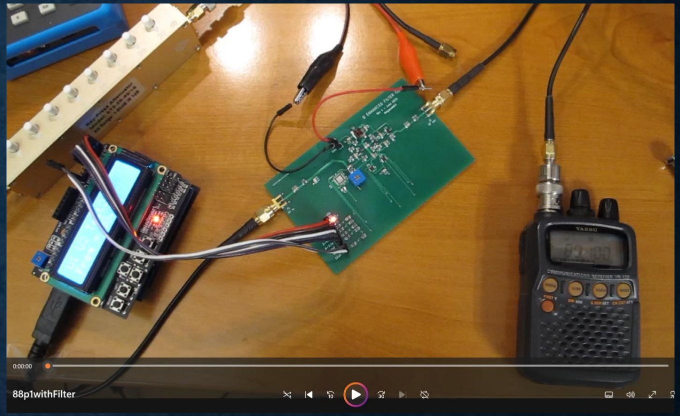
vs Traditional Low-Power LNA



Radio Design 401



Episode 1
Part 2



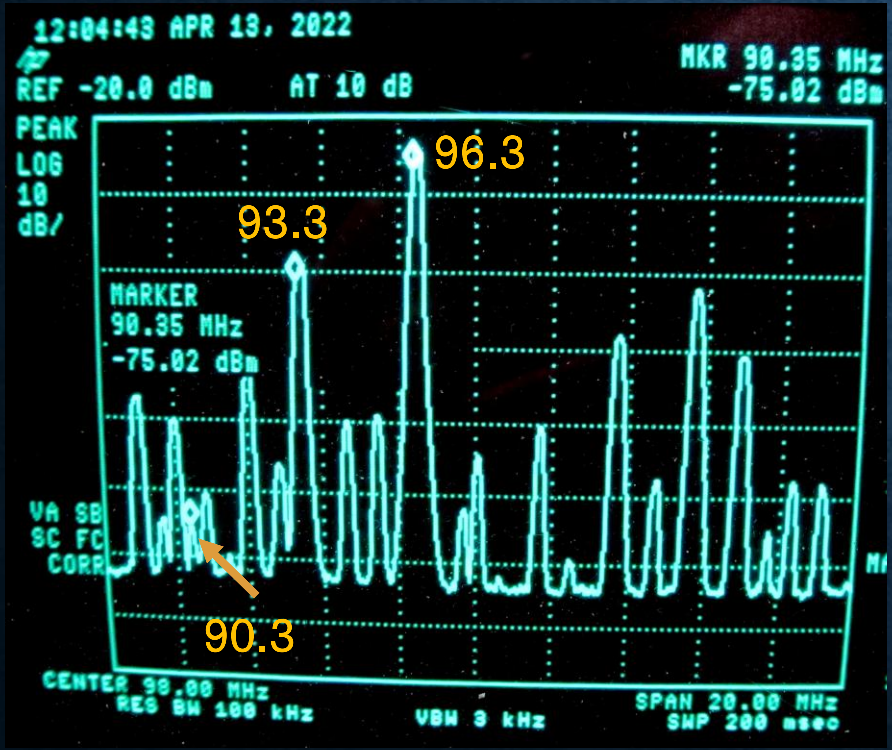
Low-power Receivers in Crowded Spectrum Environments

Today's Outline

→ • ***Intermodulation Problems and Solutions***
- ***Basic Research in Low Power Receivers***
- ***Circuit-level Solution Examples***
- ***Future Episodes in This Series***

Part 1 Review – The Intermod Problem

Two strong signals at 96.3 and 93.3 MHz 'mix' and block weaker (-75 dBm) signal at 90.3 MHz



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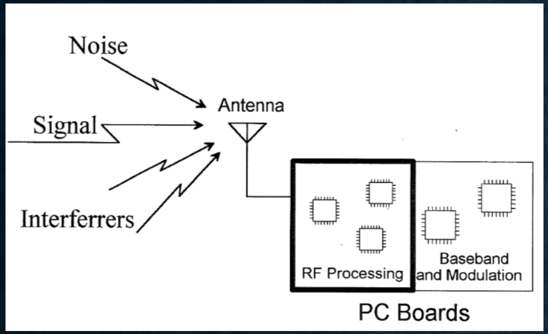
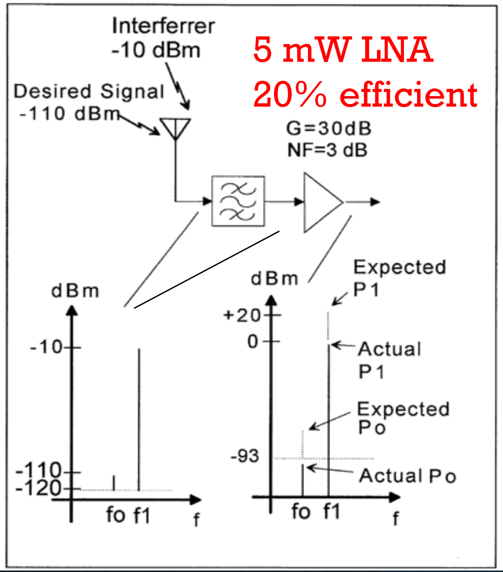
Problem Origins



Strong signals inside preselect filter passband can overwhelm weak ones !

Blocking Problem

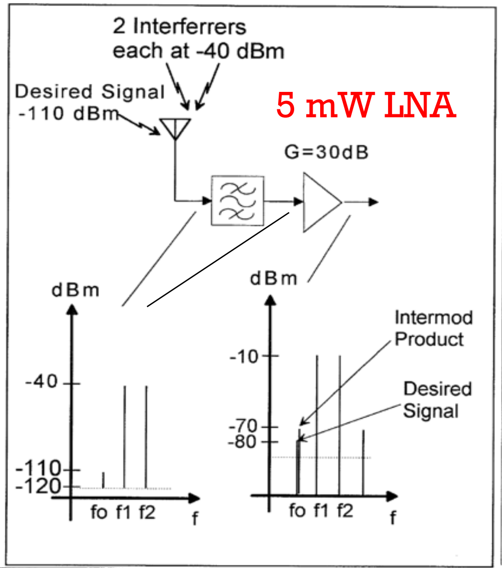


Effects
Gain compression
Desired signal below noise floor at output

Solutions
Use higher power LNA
Decrease LNA gain
Filter out f1

NOTE
Could occur in later stages also Like Mixer !!

Intermod Problem

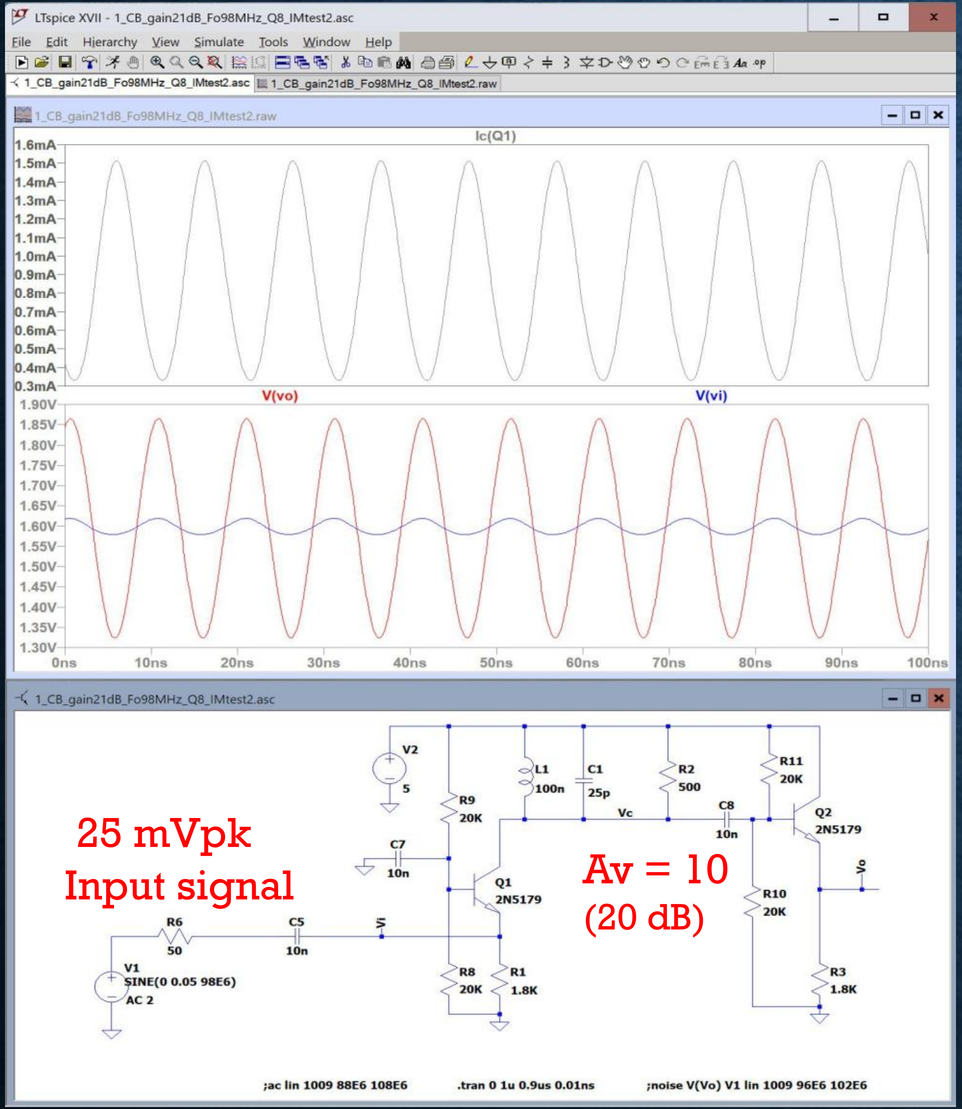


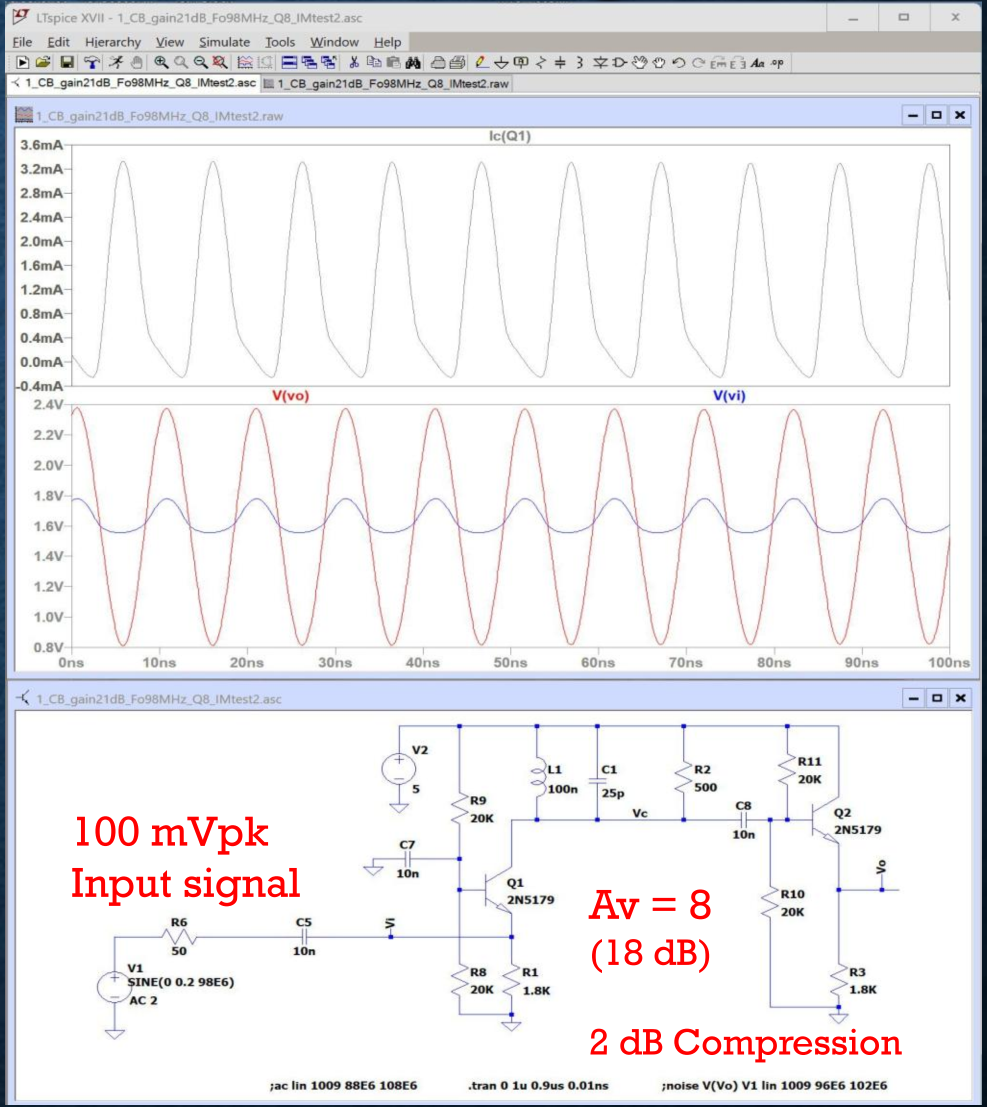
Effects
LNA generates "intermod products" at 2f2-f1 & 2f1-f2.
Product at 2f1-f2 = fo overpowers desired signal.

Solutions
Use higher power LNA.
Decrease LNA gain.
Filter out f1, f2

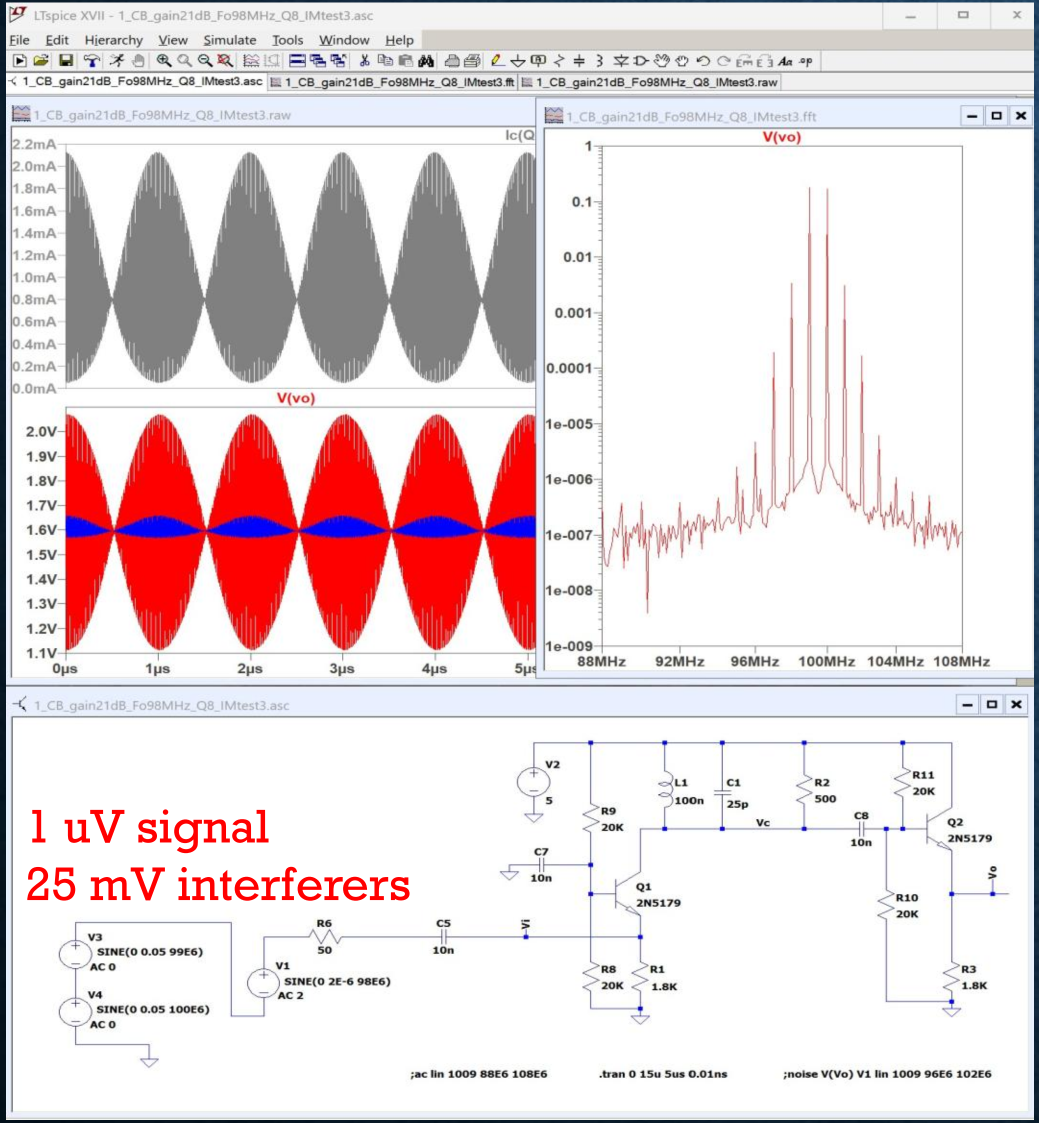
NOTE
Could occur in later stages also (especially mixer.)

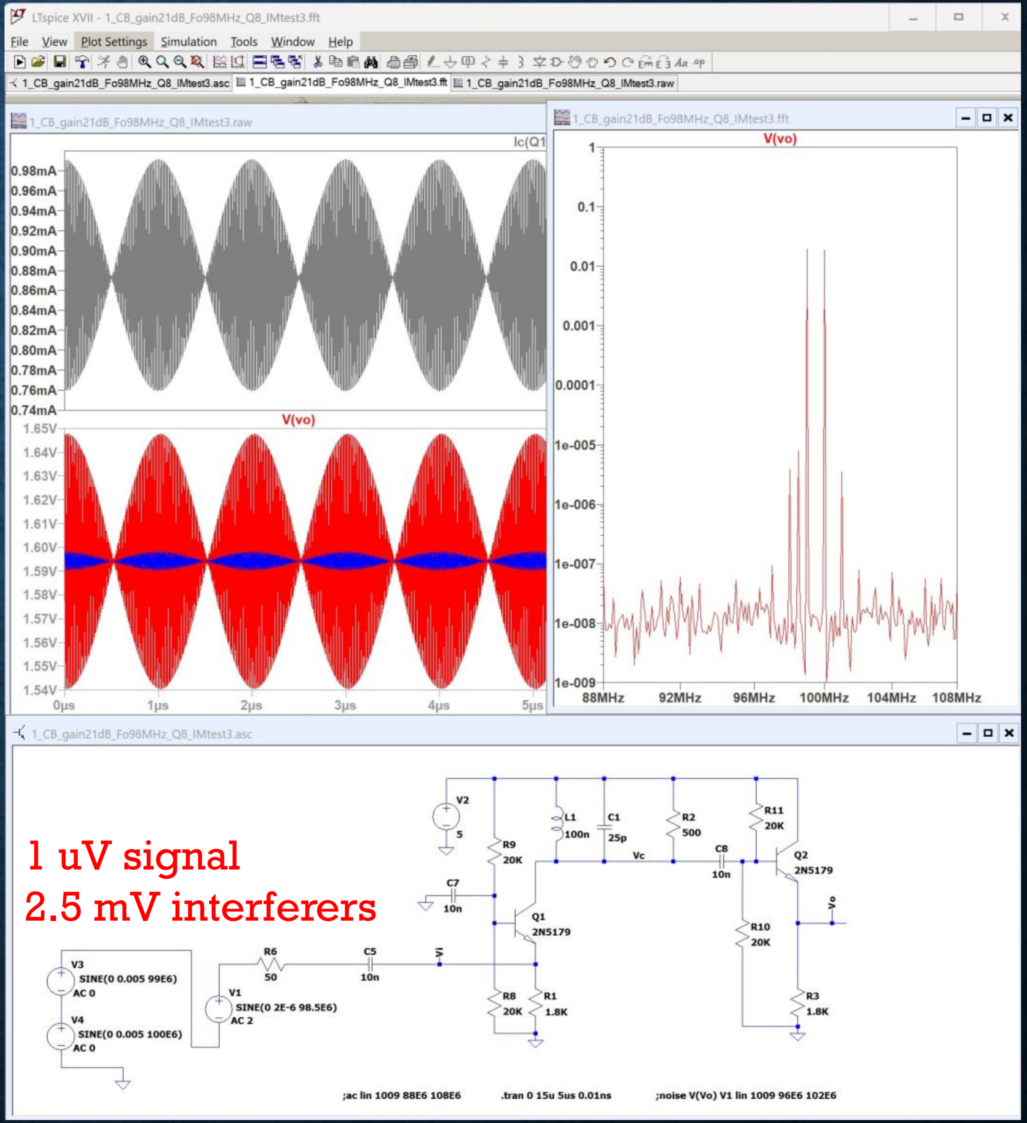
Non-linear Distortion & Compression





Intermod Simulation

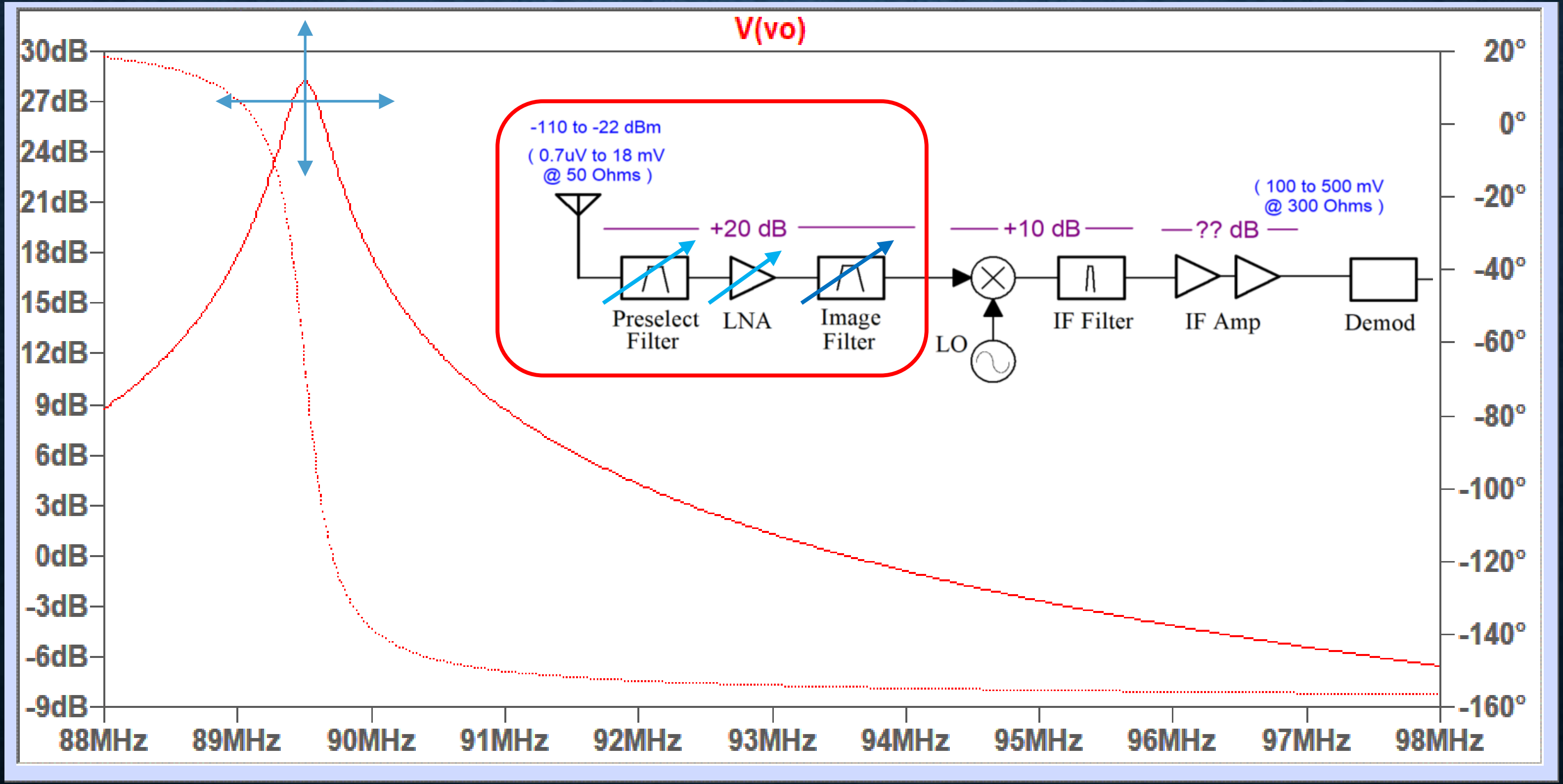




Proposed Solution

Reduce front end bandwidth to signal bandwidth,

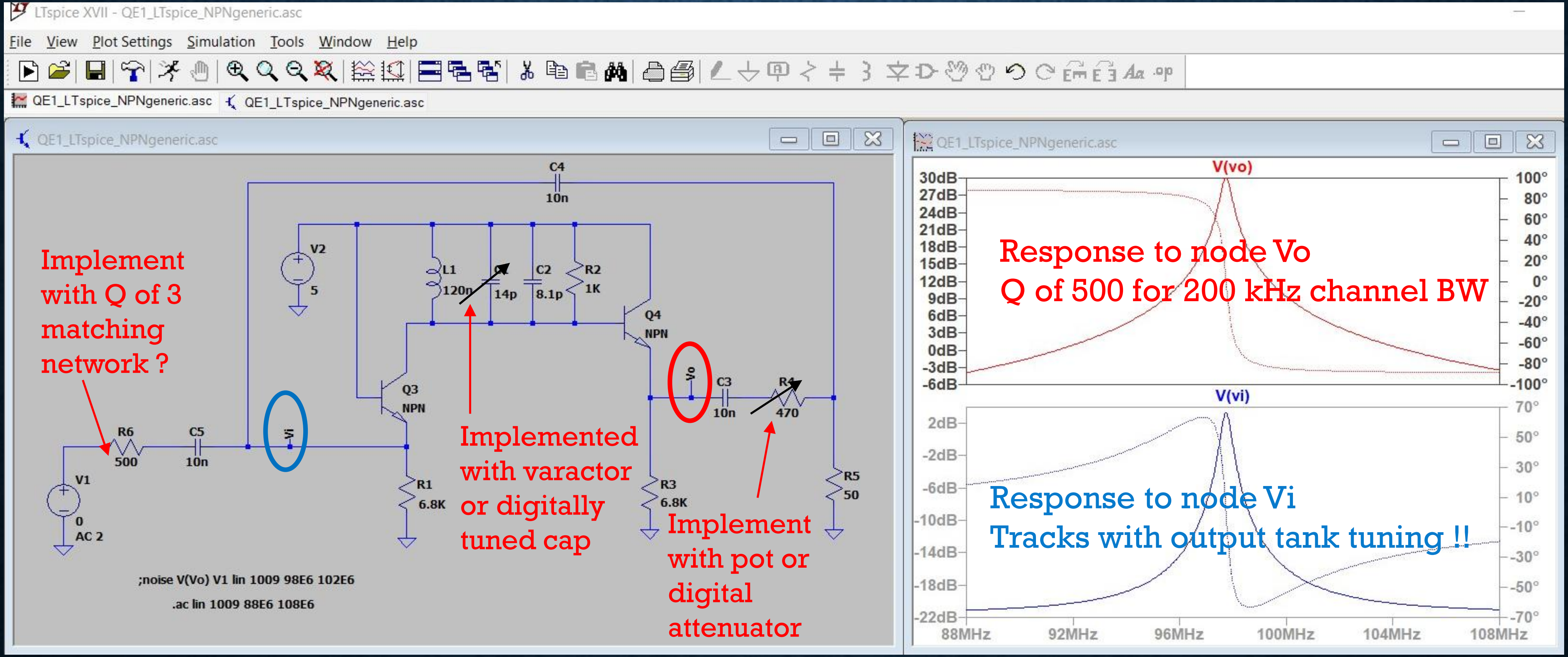
not just width of service-band



Q-enhanced Filter 1st Prototype

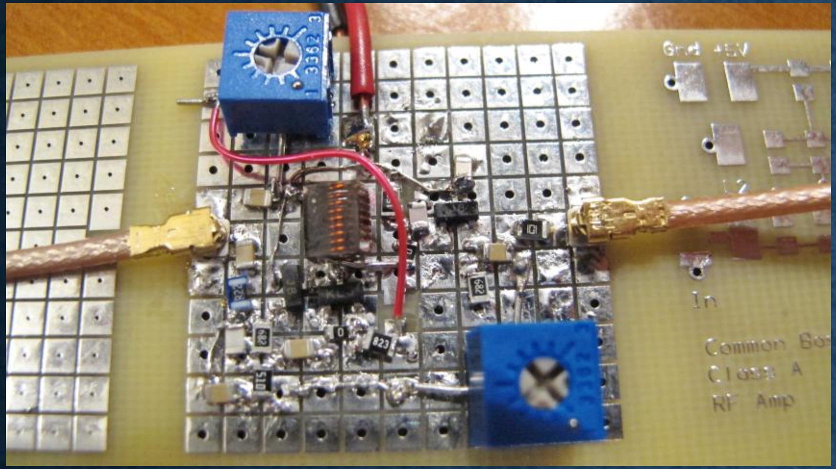
(From Radio Design 101 Epilogue 3)

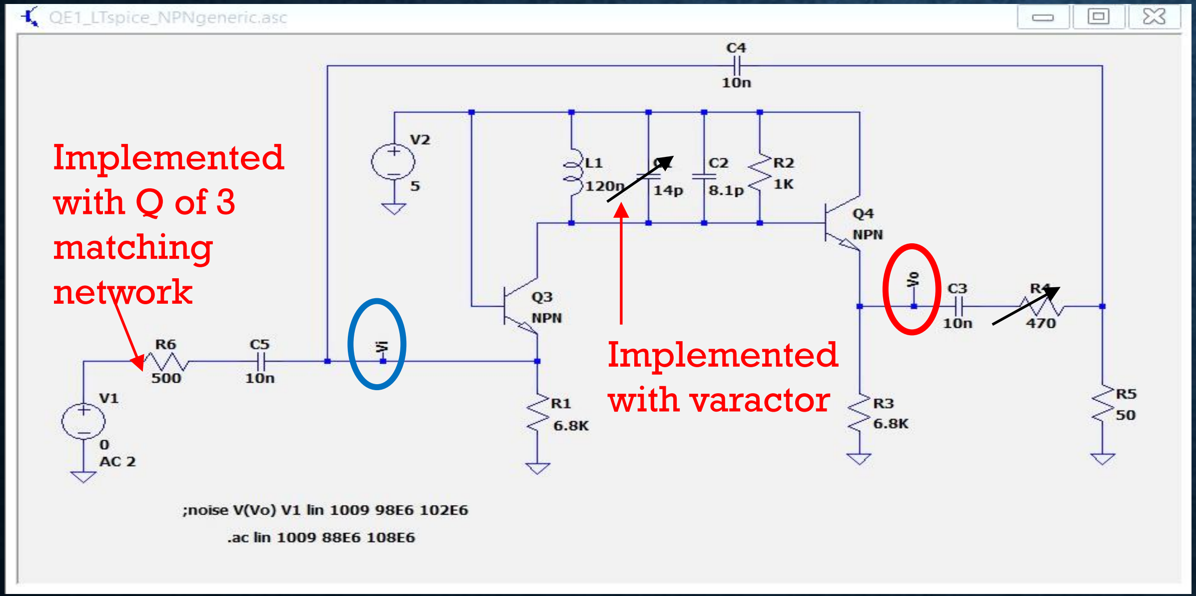
Important: Provides filtering <u>before</u> Q3 !

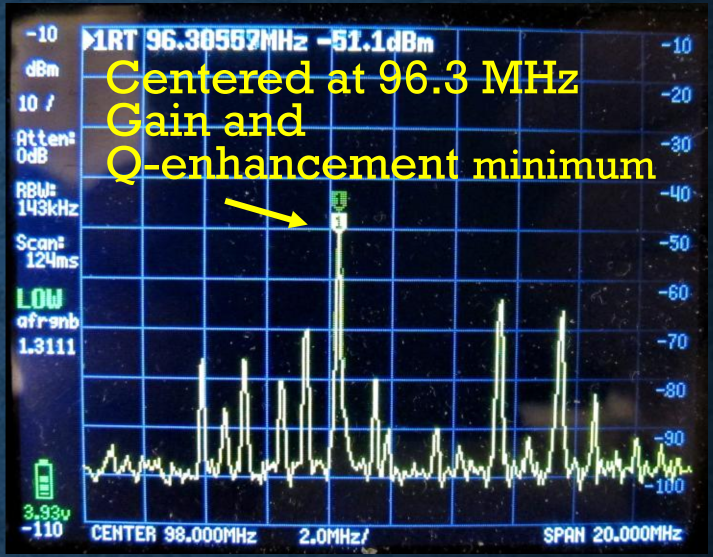


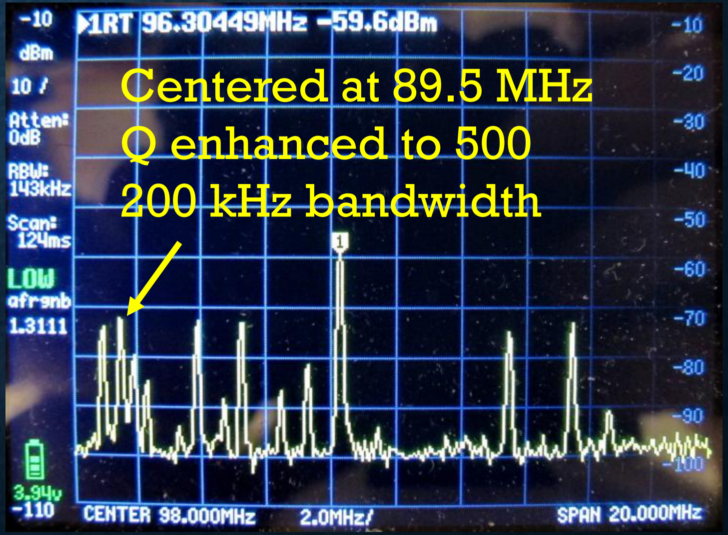
1.2 mA at 5 V (6 mW)

25+ dB Improvement in SIR

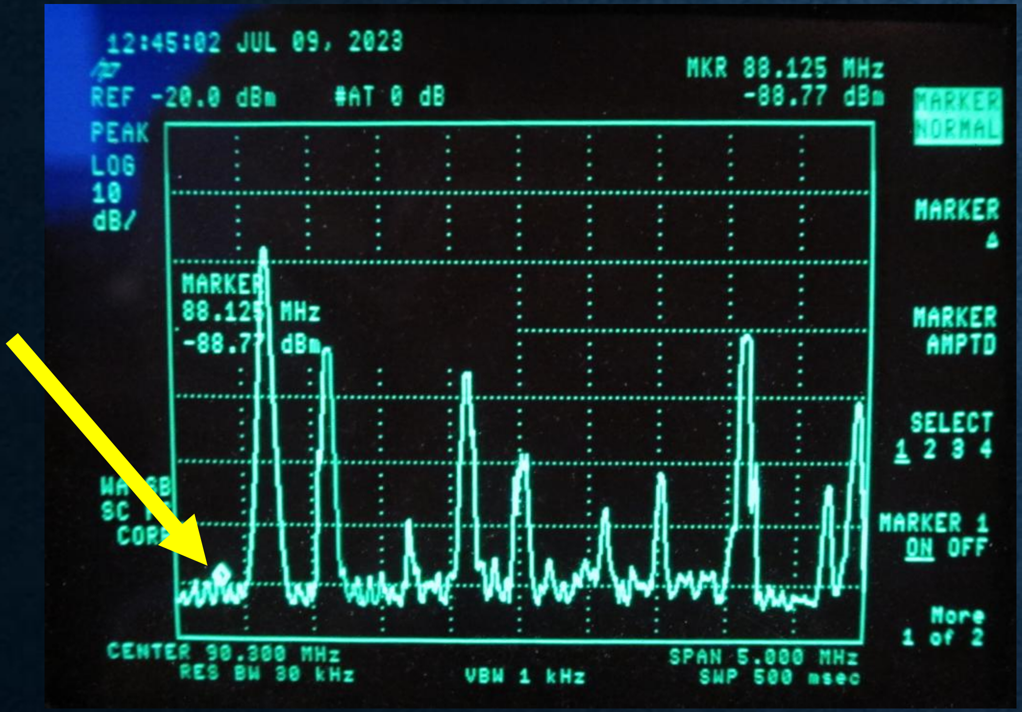


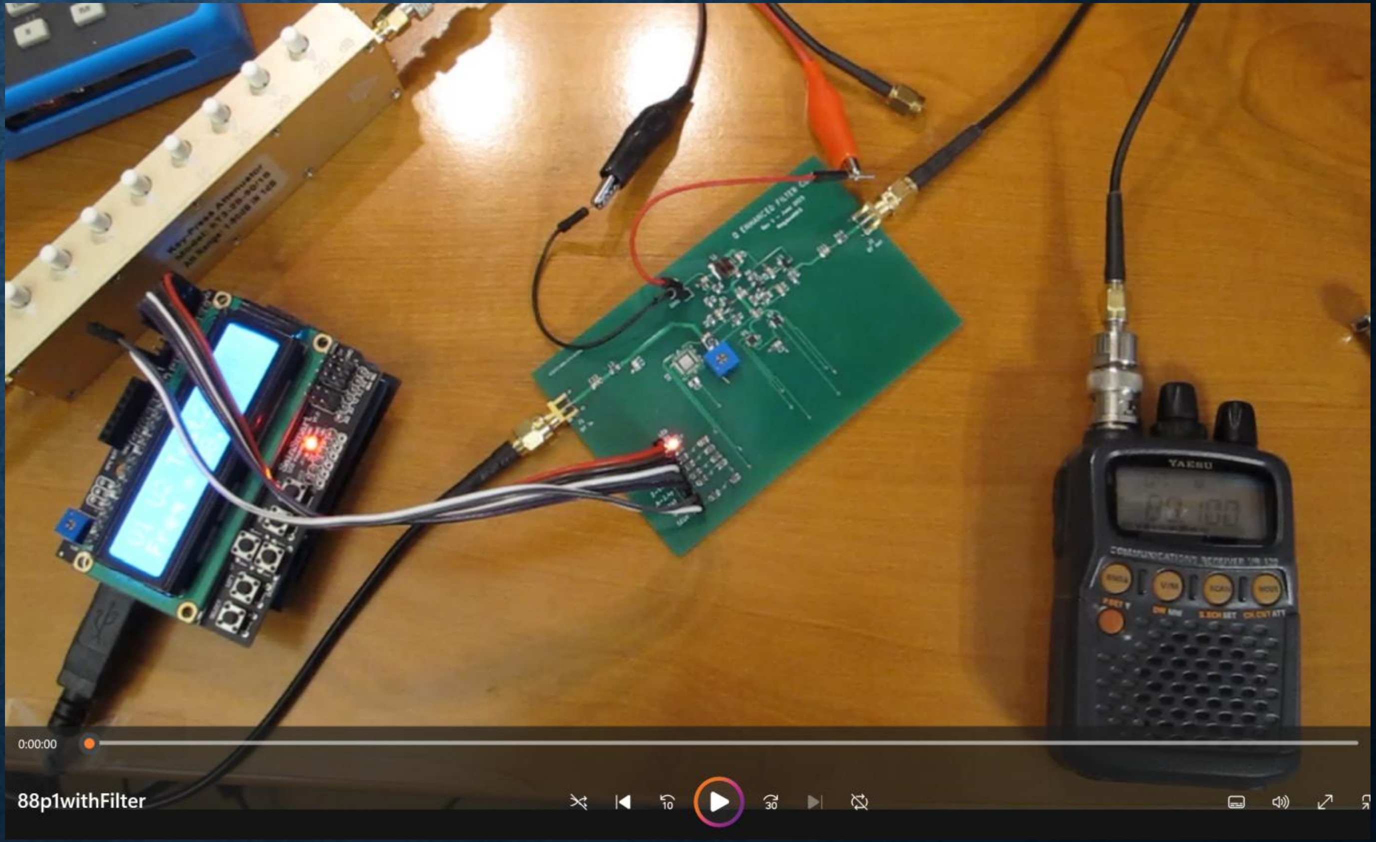






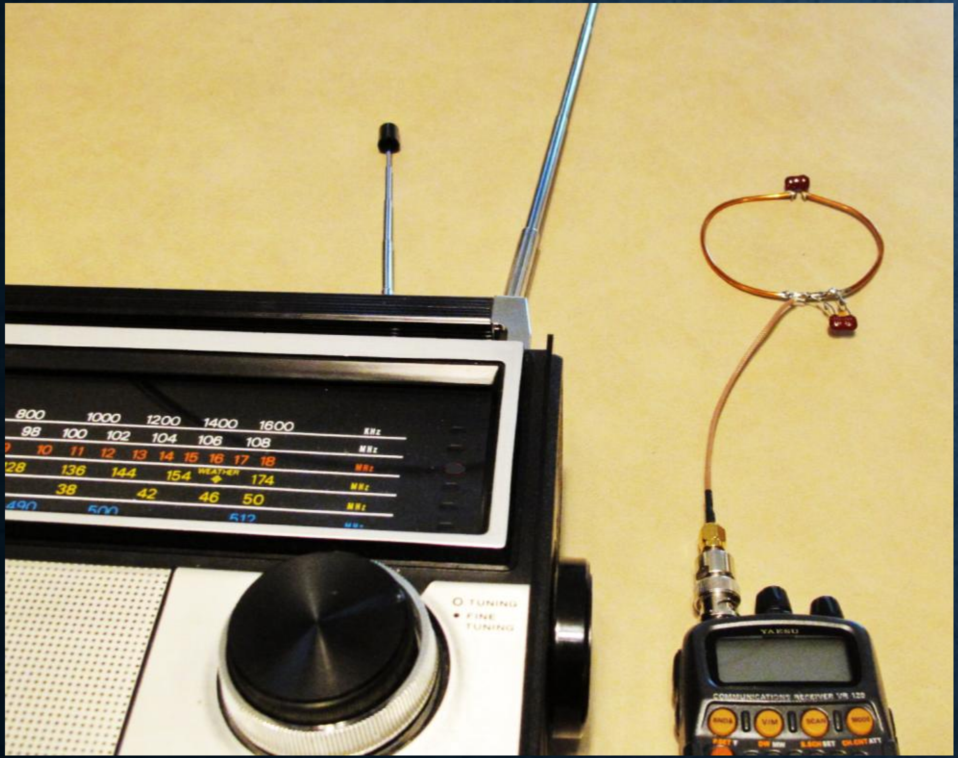
Pulling out Really Weak Signals !

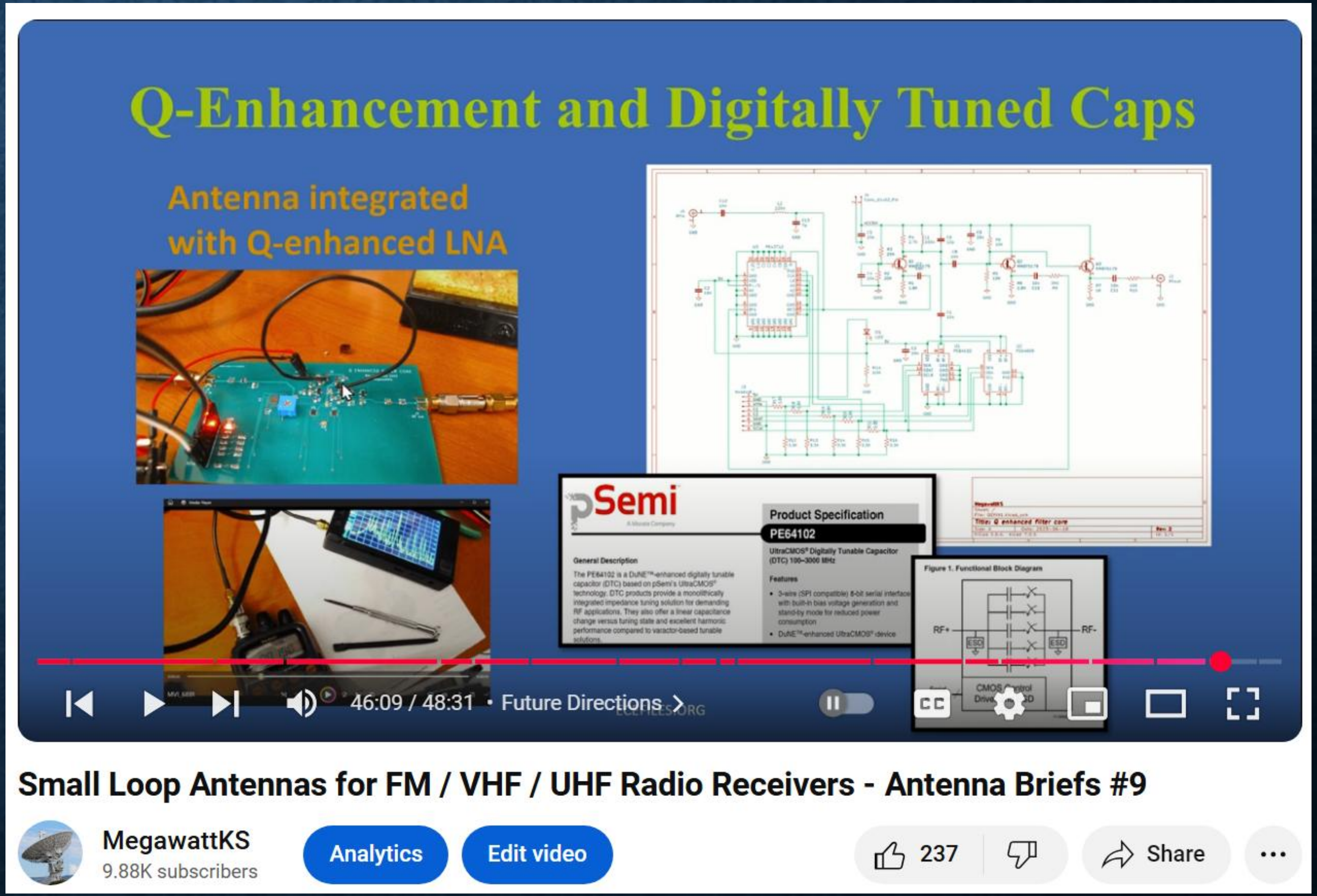




Additional Solutions

Directional and/or High Q Antennas





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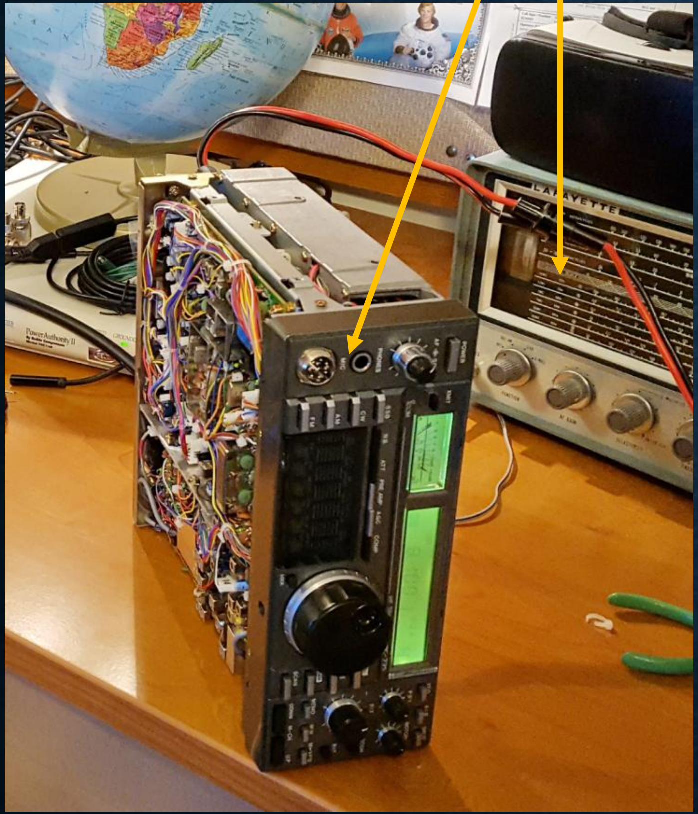
Today's Outline

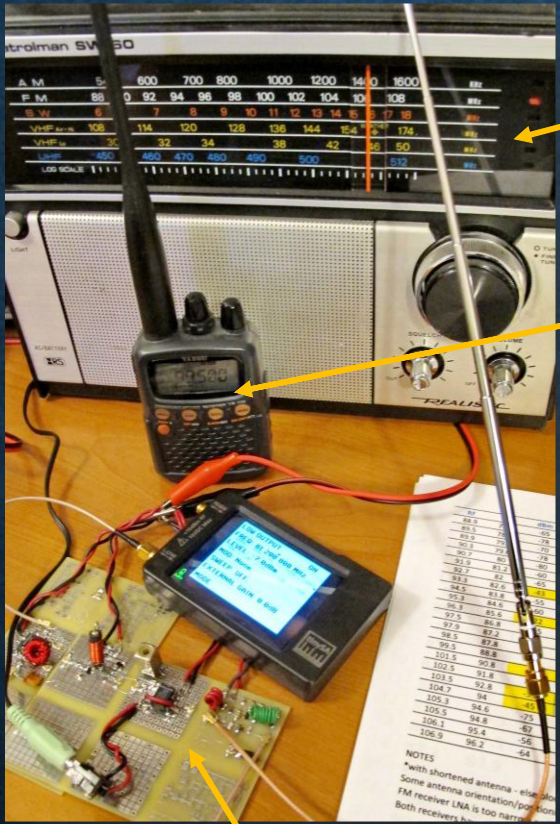
- *Introduction*
- ***Basic Research in Low Power Receivers***
- *Circuit-level Solution Examples*
- *Future Episodes in This Series*

Some Radios Through the Years

(See Part 1 & Radio Design 101, Epilogue 3)

1970s and 1980's HF radios





1990 Portable multi-band receiver (Patrolman SW-60)

2003 Yaesu wideband handheld receiver (VR-120)

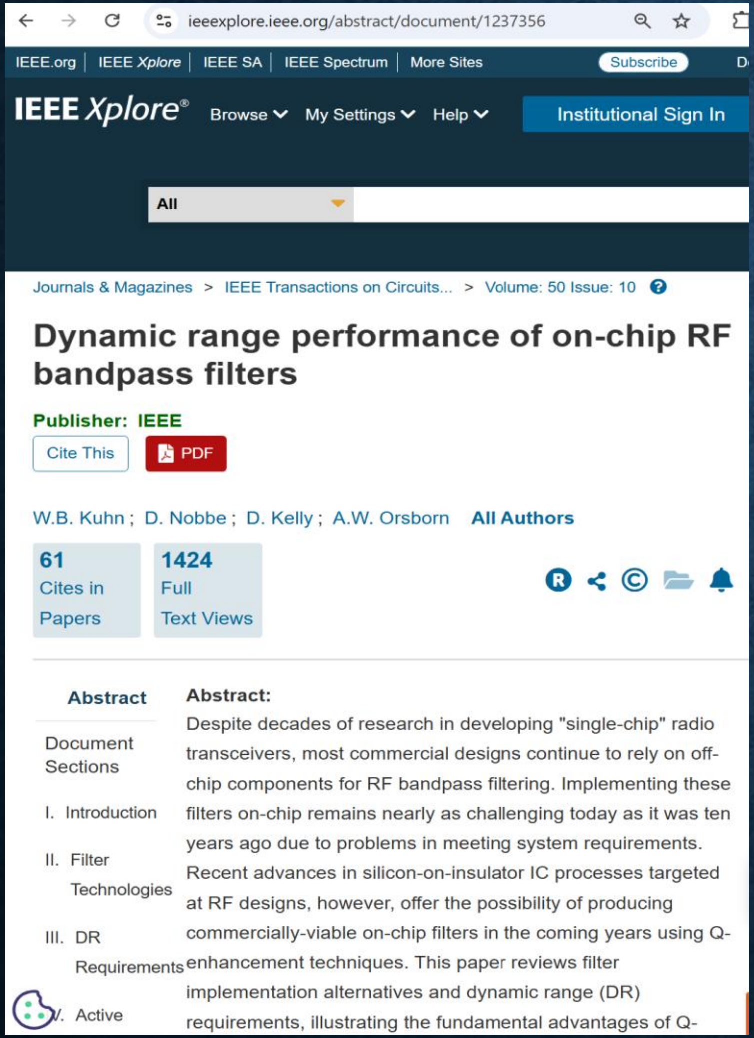
2022 Homebrew FM superhet (From Radio Design 101 series)

2024 Software-Defined Radio (ATS-25)

Origins of This Research

From: "Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies", William B. Kuhn, PhD dissertation, Virginia Tech, 1995 .

Some Related Research Papers



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Dynamic range performance of on-chip RF bandpass filters

Publisher: IEEE

Cite This | PDF

W.B. Kuhn ; D. Nobbe ; D. Kelly ; A.W. Orsborn **All Authors**

61 Cites in Papers | **1424** Full Text Views

Abstract

Document Sections

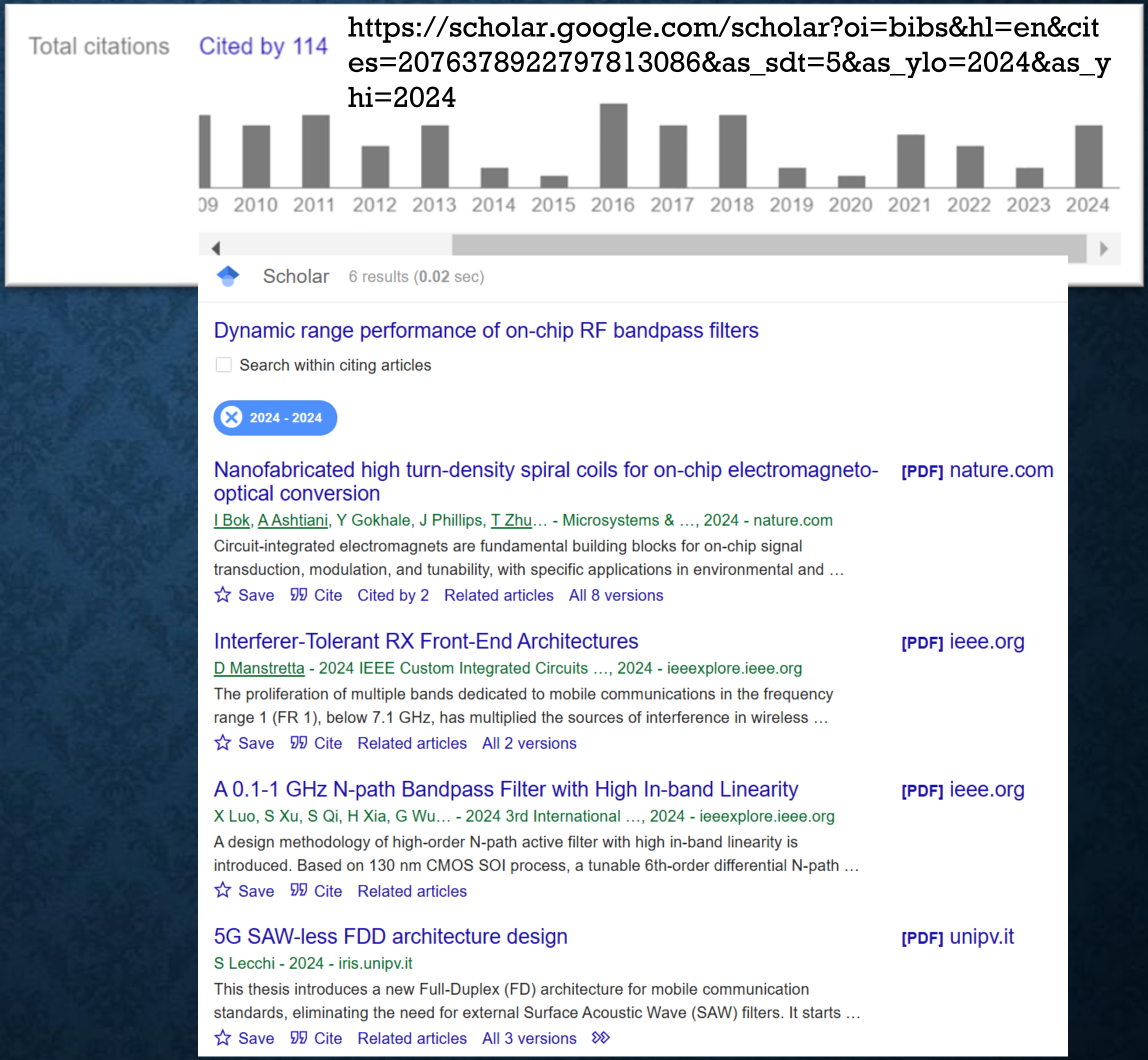
I. Introduction

II. Filter Technologies

III. DR Requirements

IV. Active

Abstract:
Despite decades of research in developing "single-chip" radio transceivers, most commercial designs continue to rely on off-chip components for RF bandpass filtering. Implementing these filters on-chip remains nearly as challenging today as it was ten years ago due to problems in meeting system requirements. Recent advances in silicon-on-insulator IC processes targeted at RF designs, however, offer the possibility of producing commercially-viable on-chip filters in the coming years using Q-enhancement techniques. This paper reviews filter implementation alternatives and dynamic range (DR) requirements, illustrating the fundamental advantages of Q-



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Dynamic range performance of on-chip RF bandpass filters

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Why Does this Research Matter ?

- Receive more stations !
- Also …
  - Spectrums have become more crowded
  - Need more efficient use of spectrum resources
  - Regulatory agencies are focusing increasingly on receiver performance
    - ITU Internationally
    - NTIA and FCC in United States
  - Low-power consumption is good for IOT and energy harvesting radios
  - Power reductions of 10x to 100x or more may be possible

Regulatory Focus on Receivers

2023

FCC FACT SHEET*

Principles for Promoting Efficient Use of Spectrum and Opportunities for New Services

Policy Statement, ET Docket No. 23-122

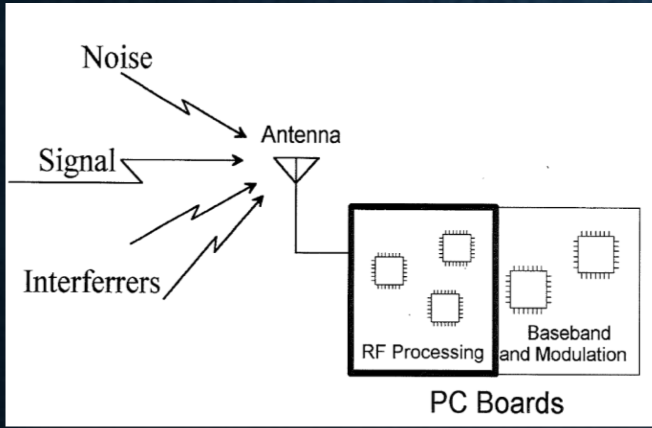
Background: The demand for spectrum continues to grow dramatically. As the Commission continuously evaluates opportunities to identify new sources of licensed, unlicensed, and shared spectrum to satisfy this growing demand, it must find ways to promote more intensive use of spectrum while ensuring coexistence among both new and existing services.

This Policy Statement takes a fresh look at the Commission's spectrum management principles and provides guidance on how the Commission intends to manage spectrum efficiently and effectively going forward. In particular, it seeks to promote a balanced and comprehensive approach to spectrum management that holistically considers both the transmitter and receiver components of wireless systems, consistent with the goals of the FCC's April 2022 *Notice of Inquiry on Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance* (ET Docket No. 22-173). The

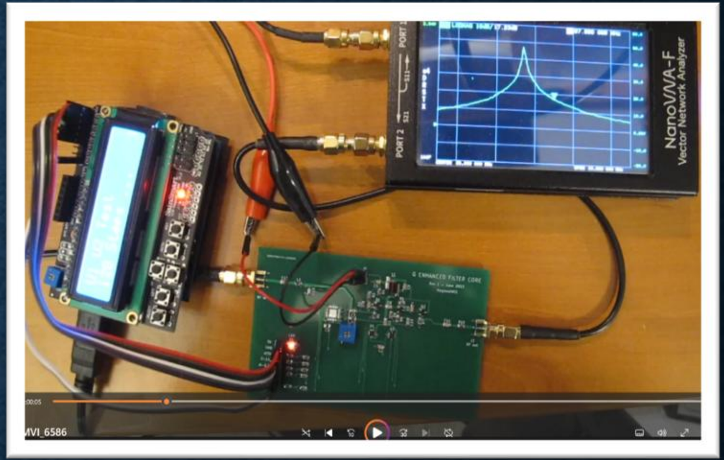
https://docs.fcc.gov/public/attachments/DOC-392197A1.pdf

See also: https://its.ntia.gov/publications/download/TR-03-404.pdf

Radio Design 401

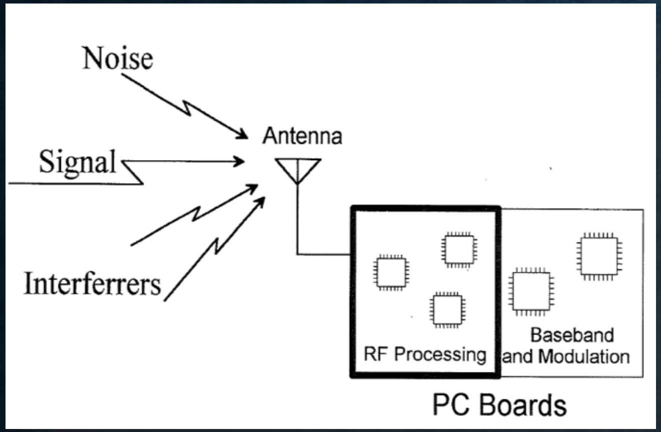


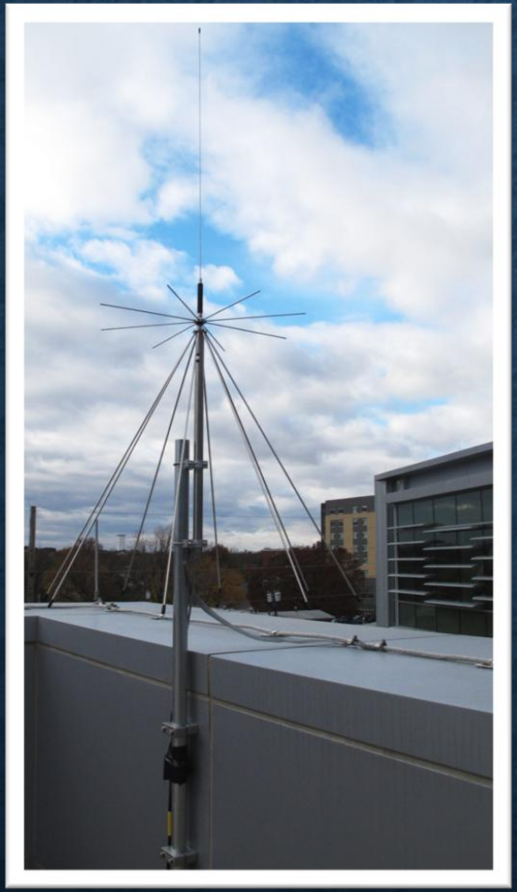
Episode 1
Part 3 of 3

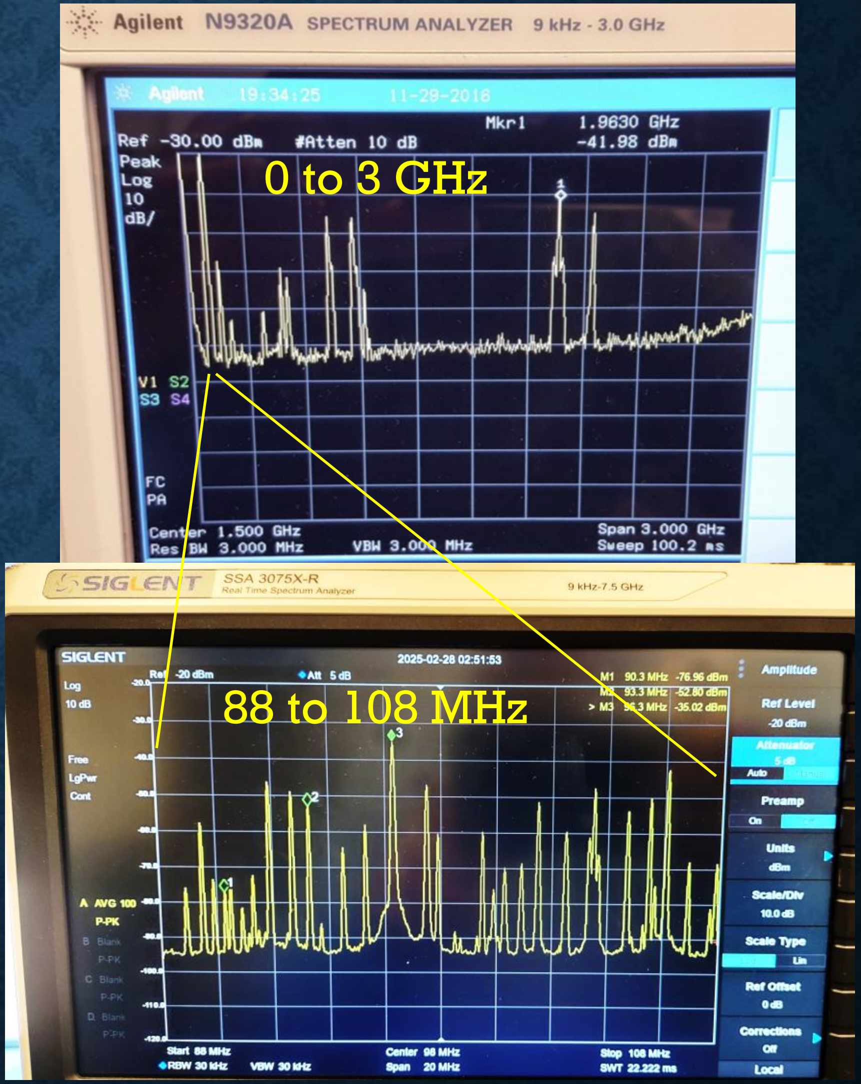


Low-power Receivers in Crowded Spectrum Environments

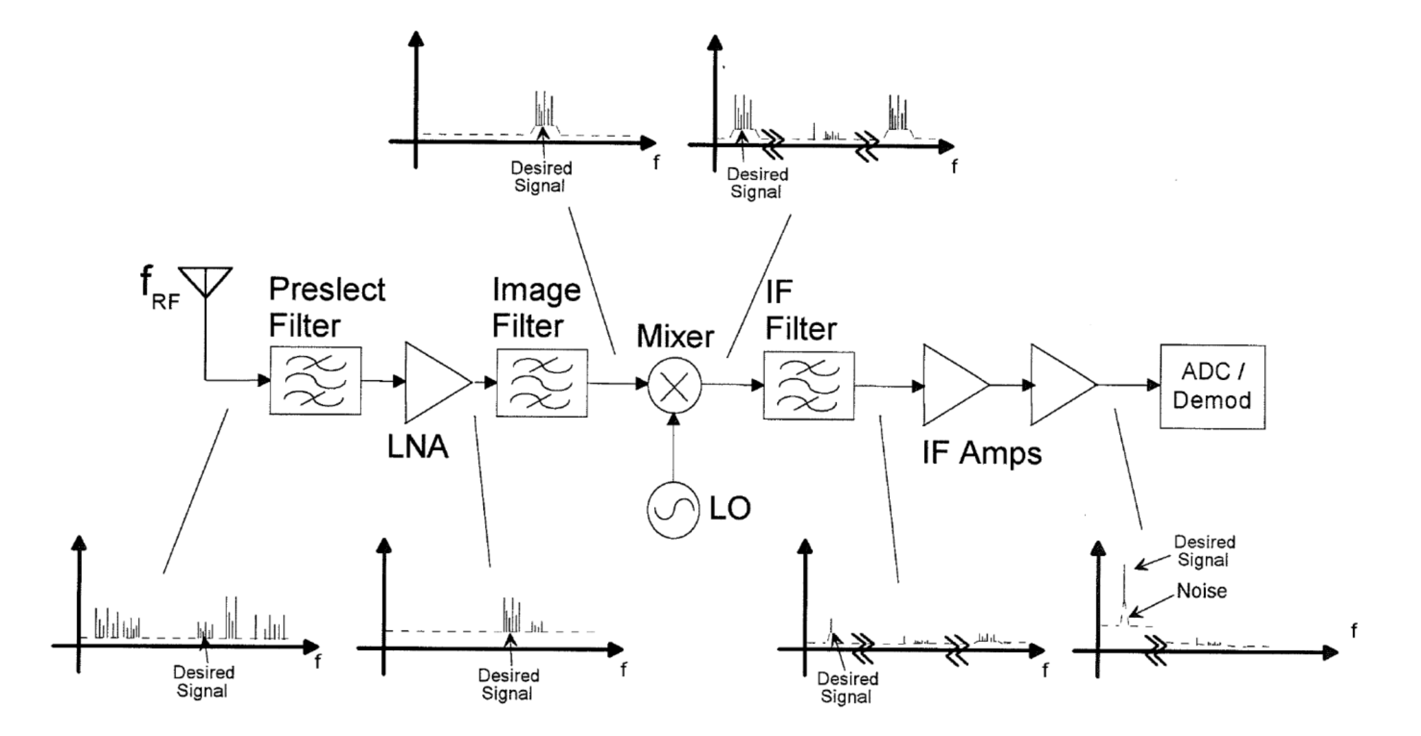
Receiver Signal Environment







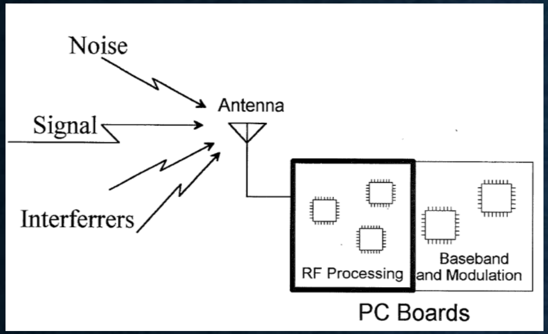
Classic Superhet Receiver



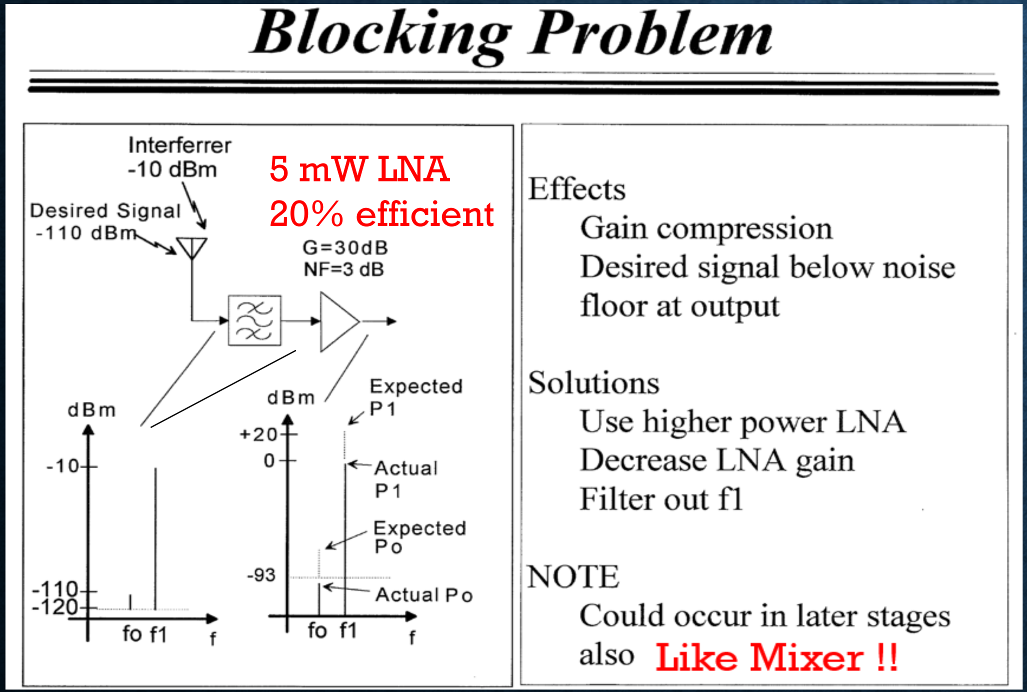
Passes entire "service band" to LNA and mixer

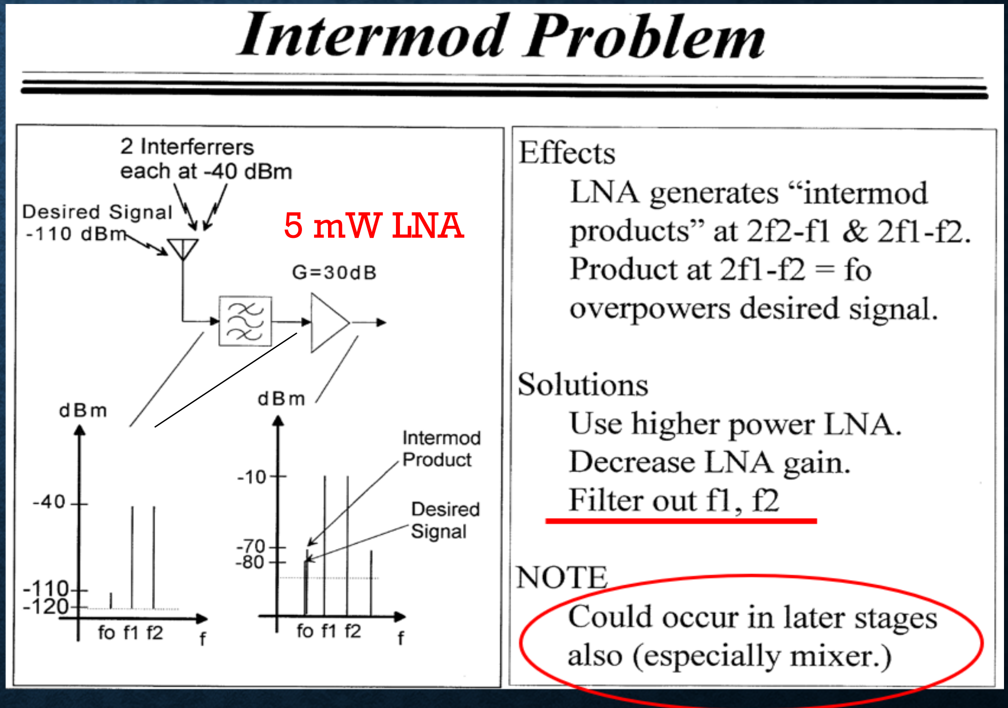
☹

Blocking and Intermod Issues

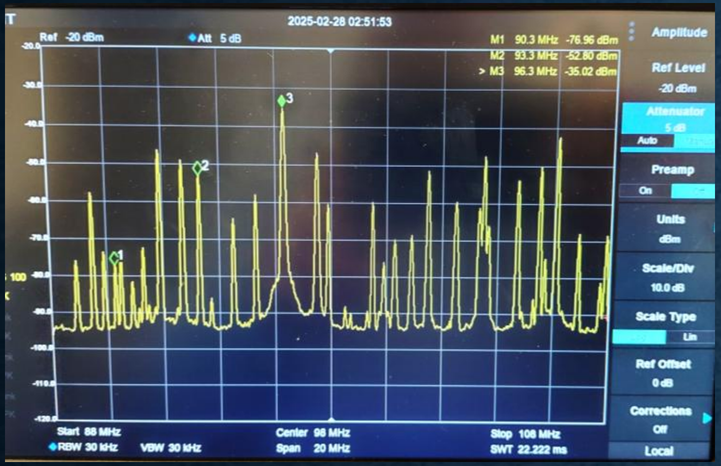


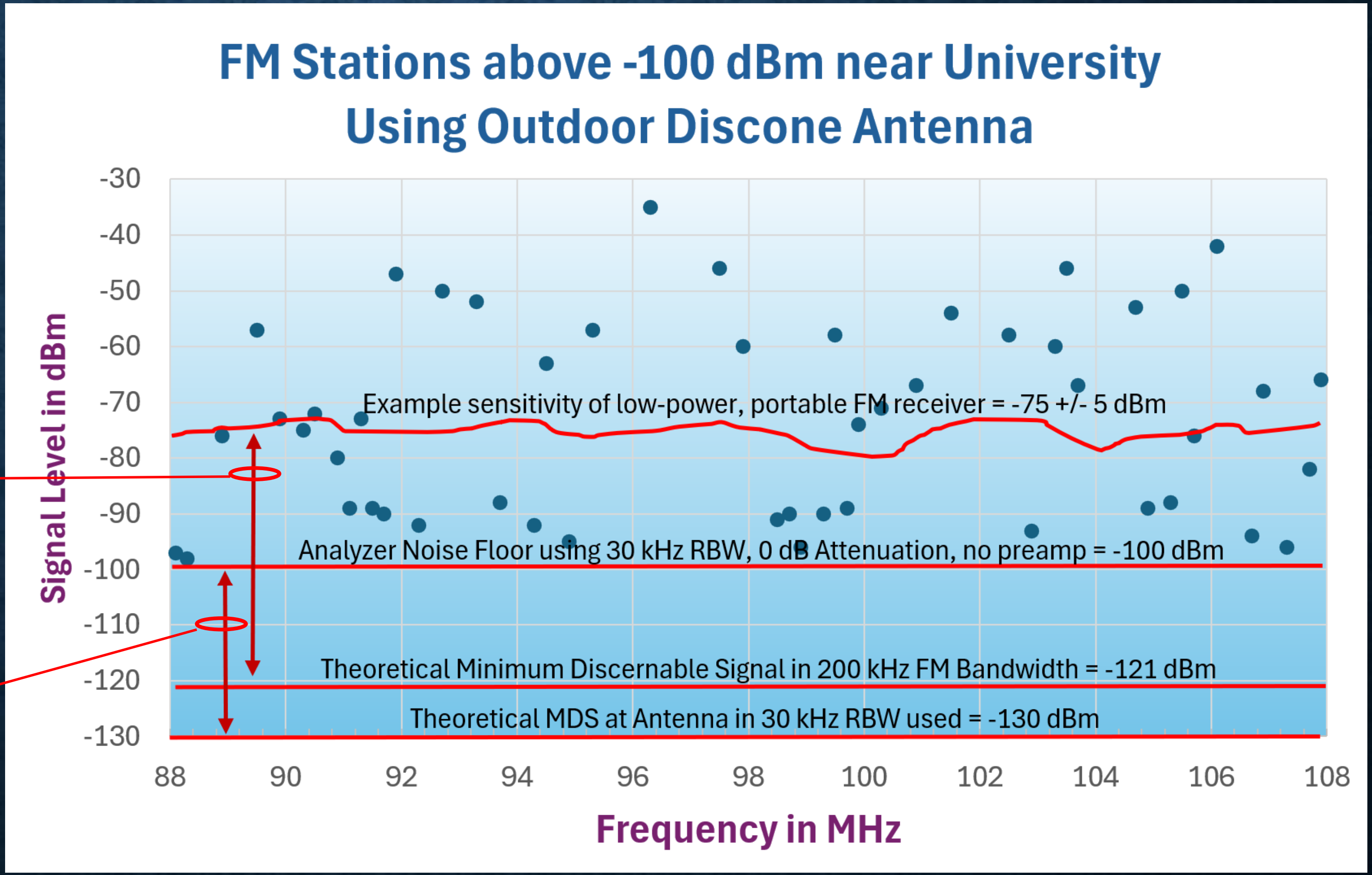
Strong interferers can overwhelm weak signals !





Receiver Sensitivity Limitations





Typical receiver may miss half the available signals or more (Car radios are better, depending on where they're parked)

Spectrum analyzer Noise Figure = 30 dB !

Additional Receiver Architectures

Motivated mostly by "image" problems in down-conversion.
Still passes all (or most) of service band to LNA and mixer ☹

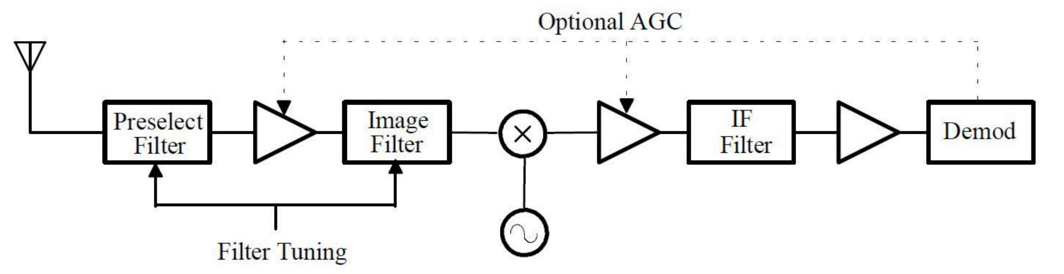


Figure 4.7: Single conversion superheterodyne with tracking preselect.

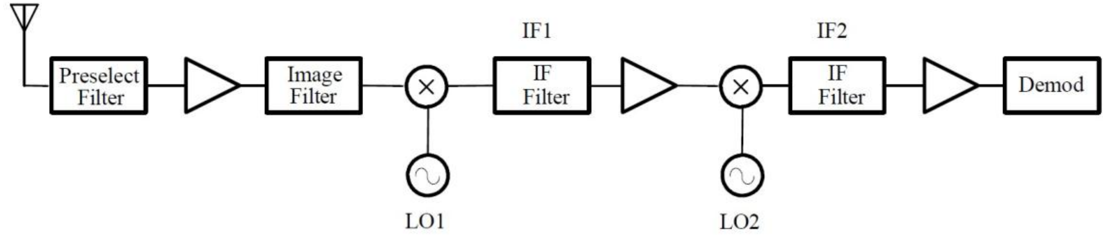


Figure 4.8: Multiple conversion superheterodyne.

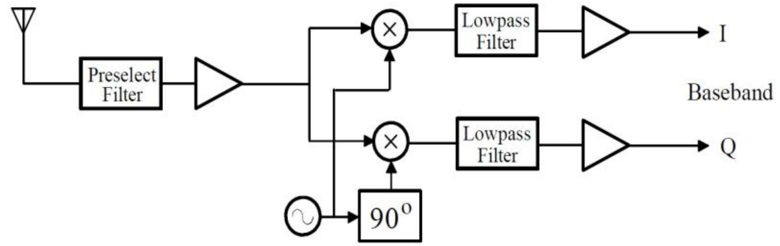


Figure 4.13: Direct conversion receiver architecture.

See Radio Design 101 video series, Epilogue 3

Ideal Low Power Receiver

Reduce Preselect Filter bandwidth to signal bandwidth !

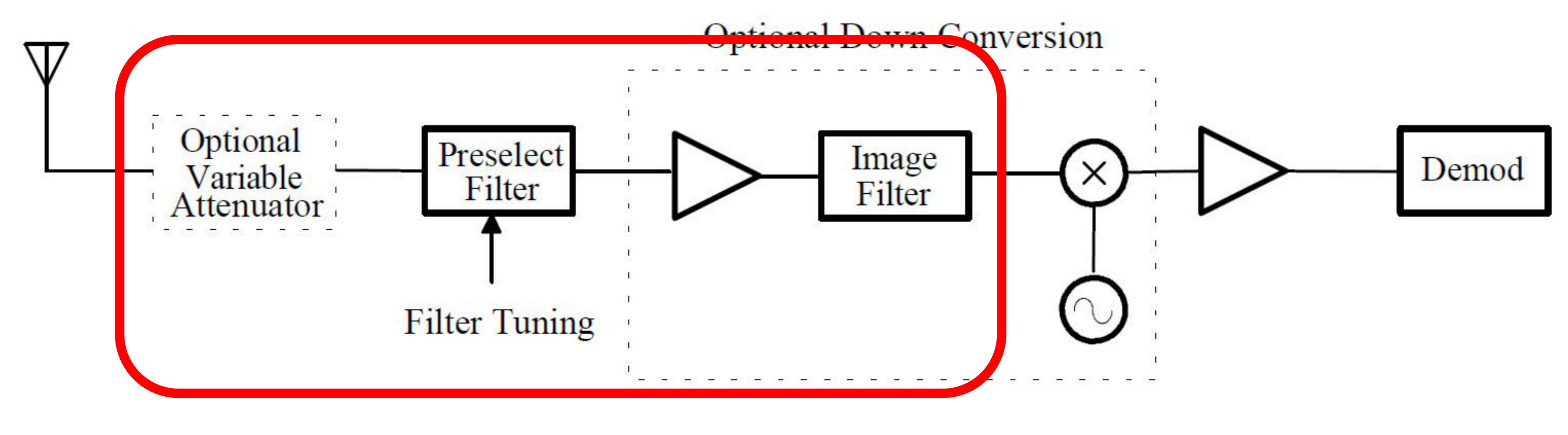


Figure 4.16: Ideal receiver architecture.

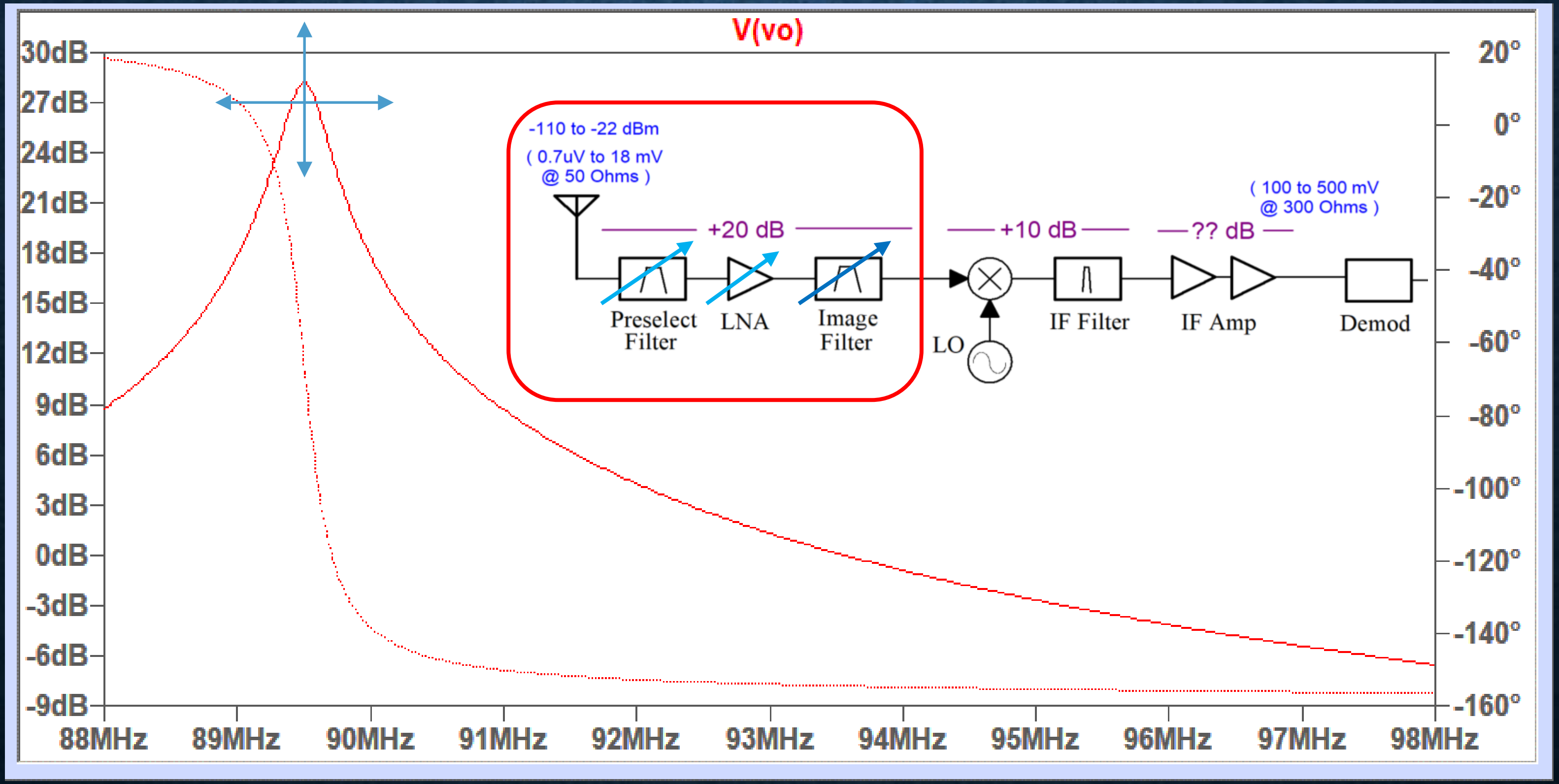
From: "Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies", PhD dissertation, Virginia Tech, 1995

Today's Outline

- *Introduction*
- *Basic Research in Low Power Receivers*
- *Circuit-level Solution Examples*
- *Key Takeaways*
- *Future Episodes in This Series*

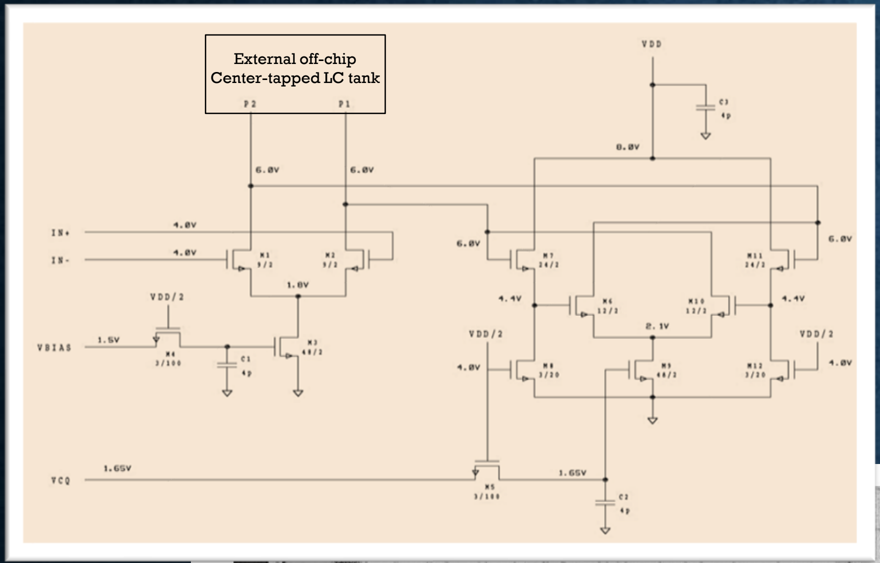
Proposed Solution

Reduce front end bandwidth to <u>signal bandwidth,</u>
<u>not just width of service-band</u>



Early Common-source Design 1

No Preselect Filtering ☹



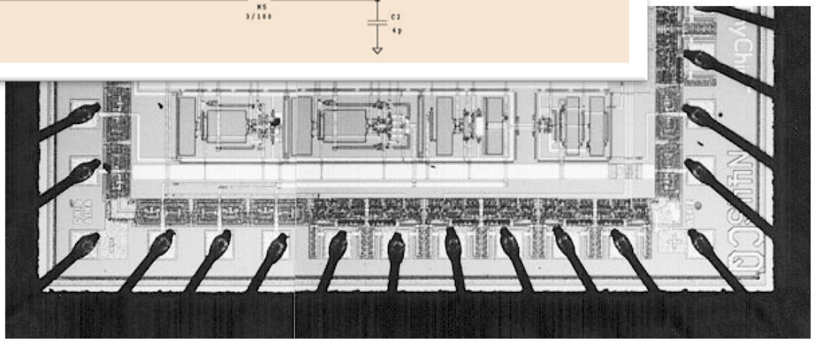


Figure 9.5: VHF front-end IC photograph.

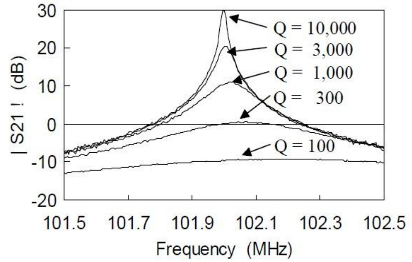


Figure 9.8: Measured transfer functions of Q-enhanced filter.

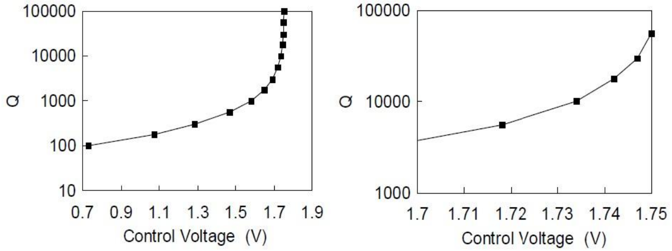


Figure 9.9: Measured Q factor versus control voltage.

Short-term stability of both frequency and Q were found to be excellent as shown in Table 9.1, indicating that the filter is suitable for use with either the self-tuning or orthogonal reference tuning techniques and their simplifications discussed in Chapter 7.

From: "Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies", William B. Kuhn, PhD dissertation, Virginia Tech, 1995

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Early 2-pole Design

For 200 MHz IF - No Preselect Filtering ☹

A photograph of the fabricated circuitry is shown in Figure 9.14. To provide minimum possible inductor coupling between the two identical second-order sections implemented on the die, the inductors were oriented diagonally opposite to each other. Chip area not used by the circuits discussed above was used to provide on-chip decoupling and supply bypass capacitors and to implement test structures. Total chip area for both second-order sections, excluding pads, is 3.3 mm^2.

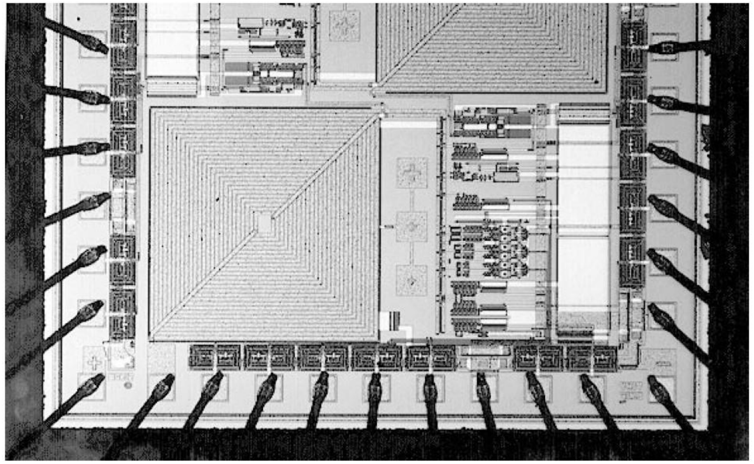


Figure 9.14: Photograph of chip layout.

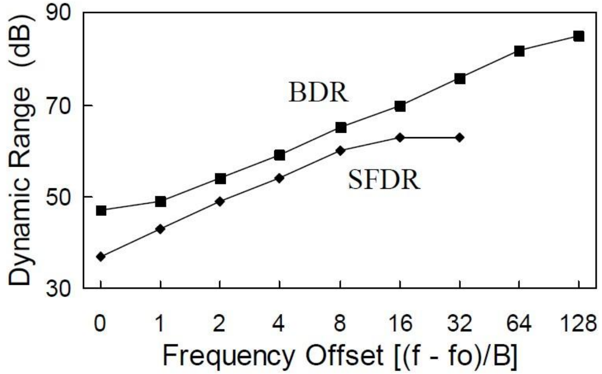


Figure 9.18: Measured blocking and spurious-free dynamic range.

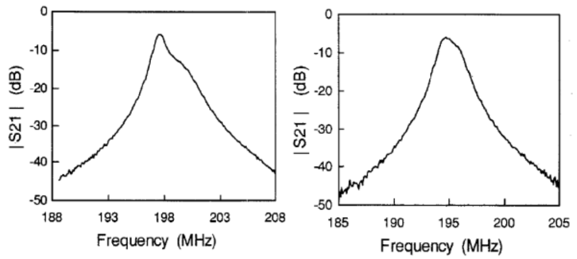
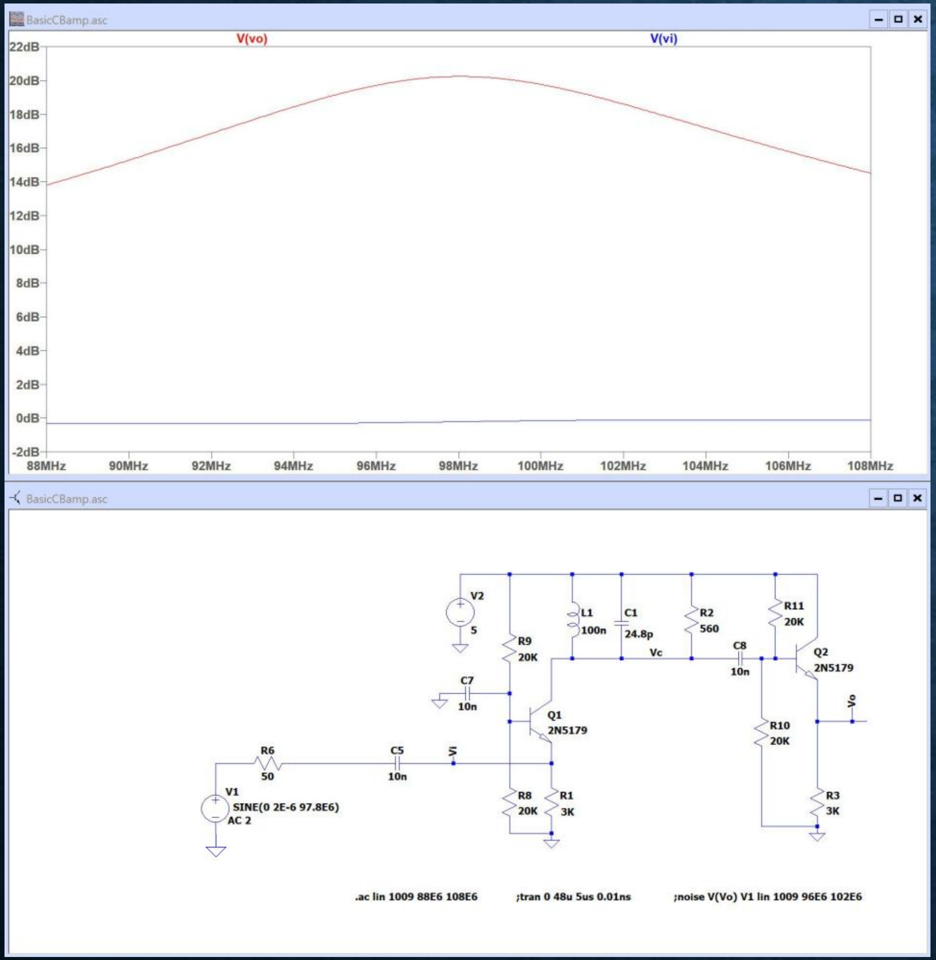


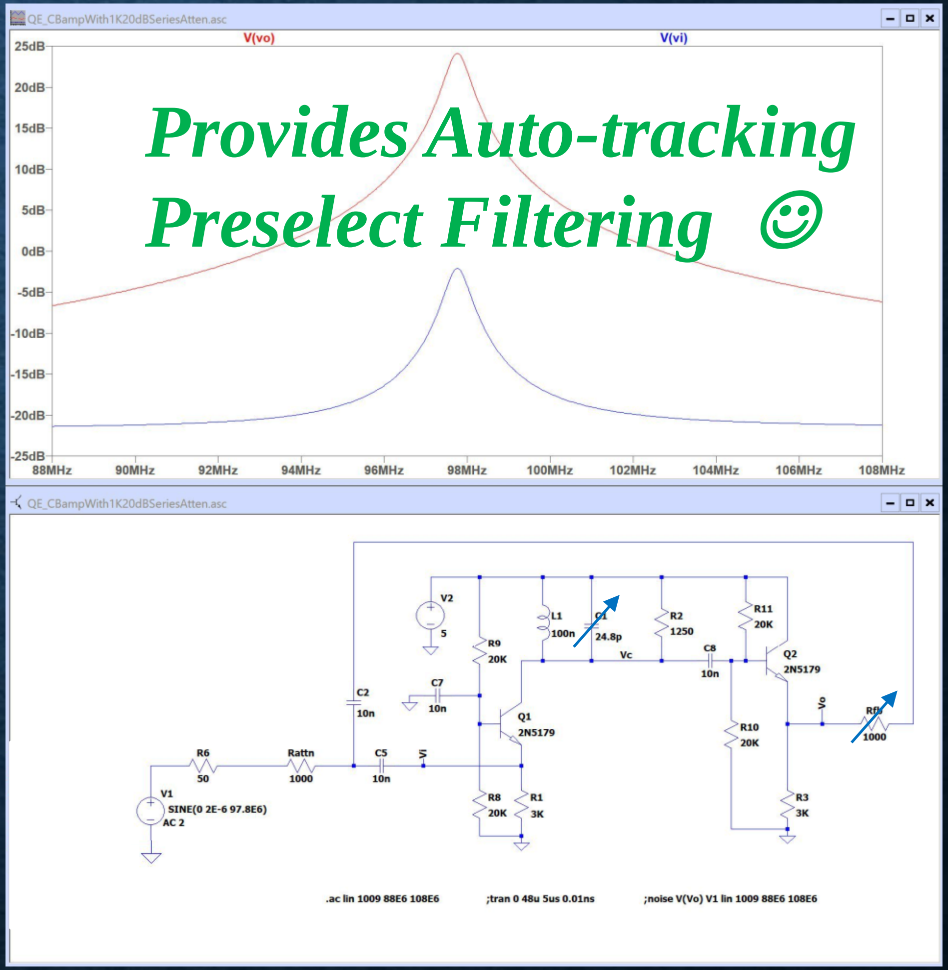
Fig. 15. Measured fourth-order response: (a) without neutralization and (b) with neutralization.

From: "A 200 MHz CMOS Q-enhanced LC Bandpass Filter"

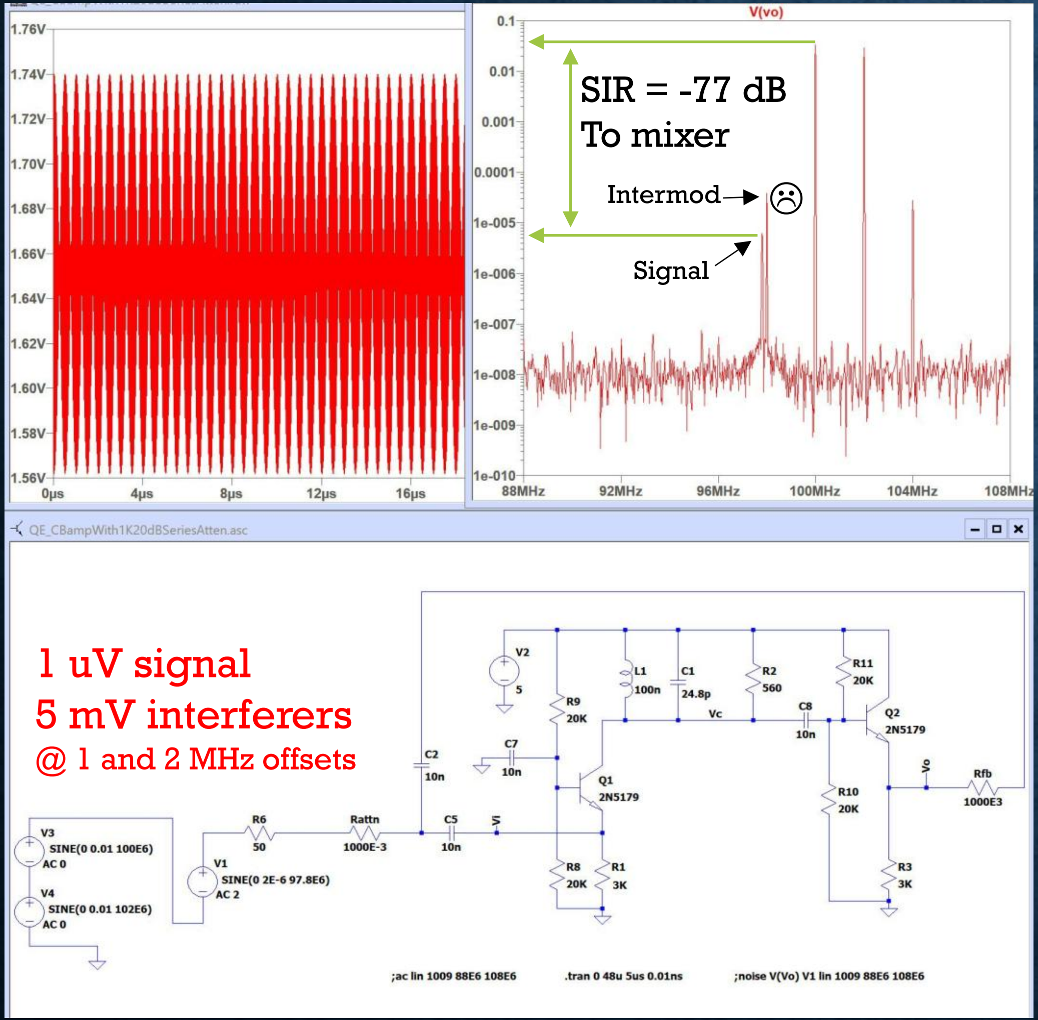
W B Kuhn, F W Stephenson, A Elshabini-Riad - IEEE Journal of Solid-State Circuits, 1996

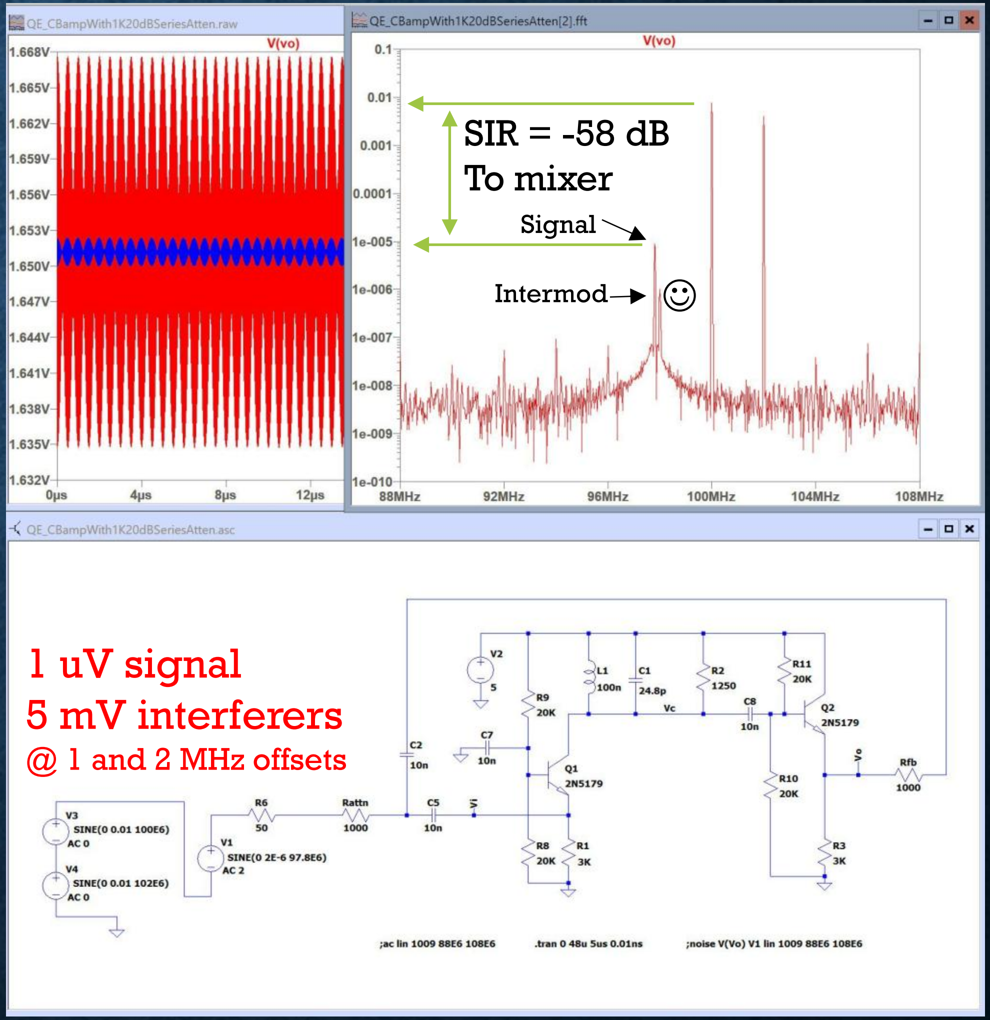
Basic LNA vs <u>New</u> CB QE LNA



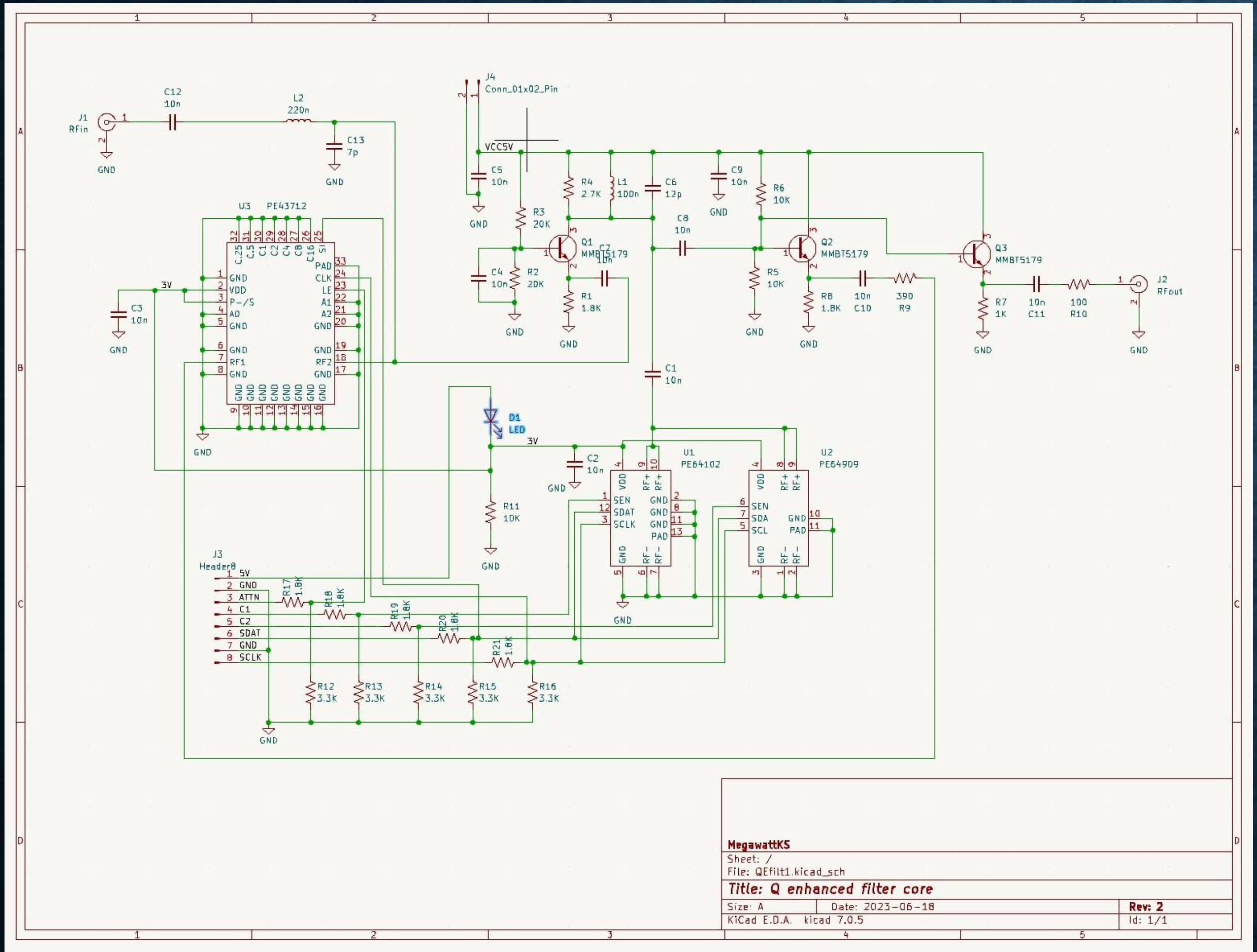


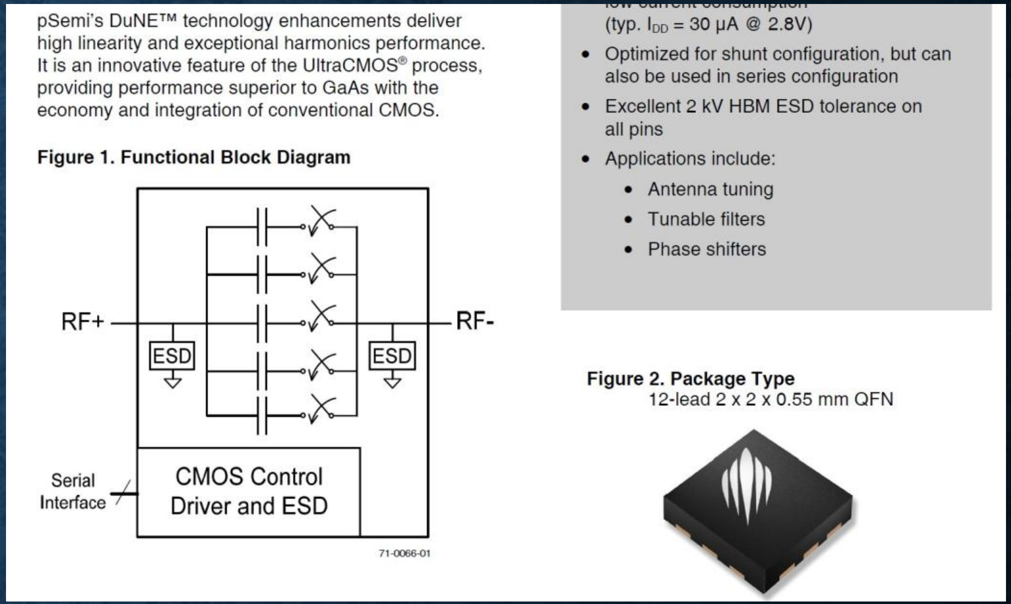
Basic LNA vs QE LNA Intermod Sims





CB Q-enhanced Filter Prototype 2 (2023)




(typ. I_{DD} = 30 µA @ 2.8V)

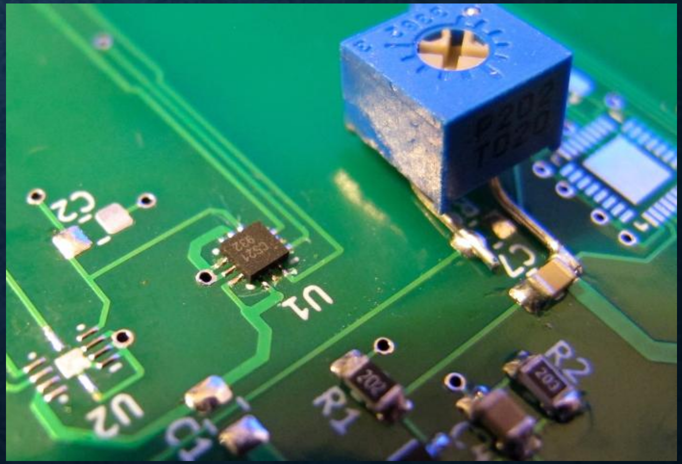
pSemi's DuNE™ technology enhancements deliver high linearity and exceptional harmonics performance. It is an innovative feature of the UltraCMOS® process, providing performance superior to GaAs with the economy and integration of conventional CMOS.

- Optimized for shunt configuration, but can also be used in series configuration
- Excellent 2 kV HBM ESD tolerance on all pins
- Applications include:
  - Antenna tuning
  - Tunable filters
  - Phase shifters

Figure 1. Functional Block Diagram

Figure 2. Package Type
12-lead 2 x 2 x 0.55 mm QFN

https://www.psemi.com/pdf/datasheets/pe64102ds.pdf



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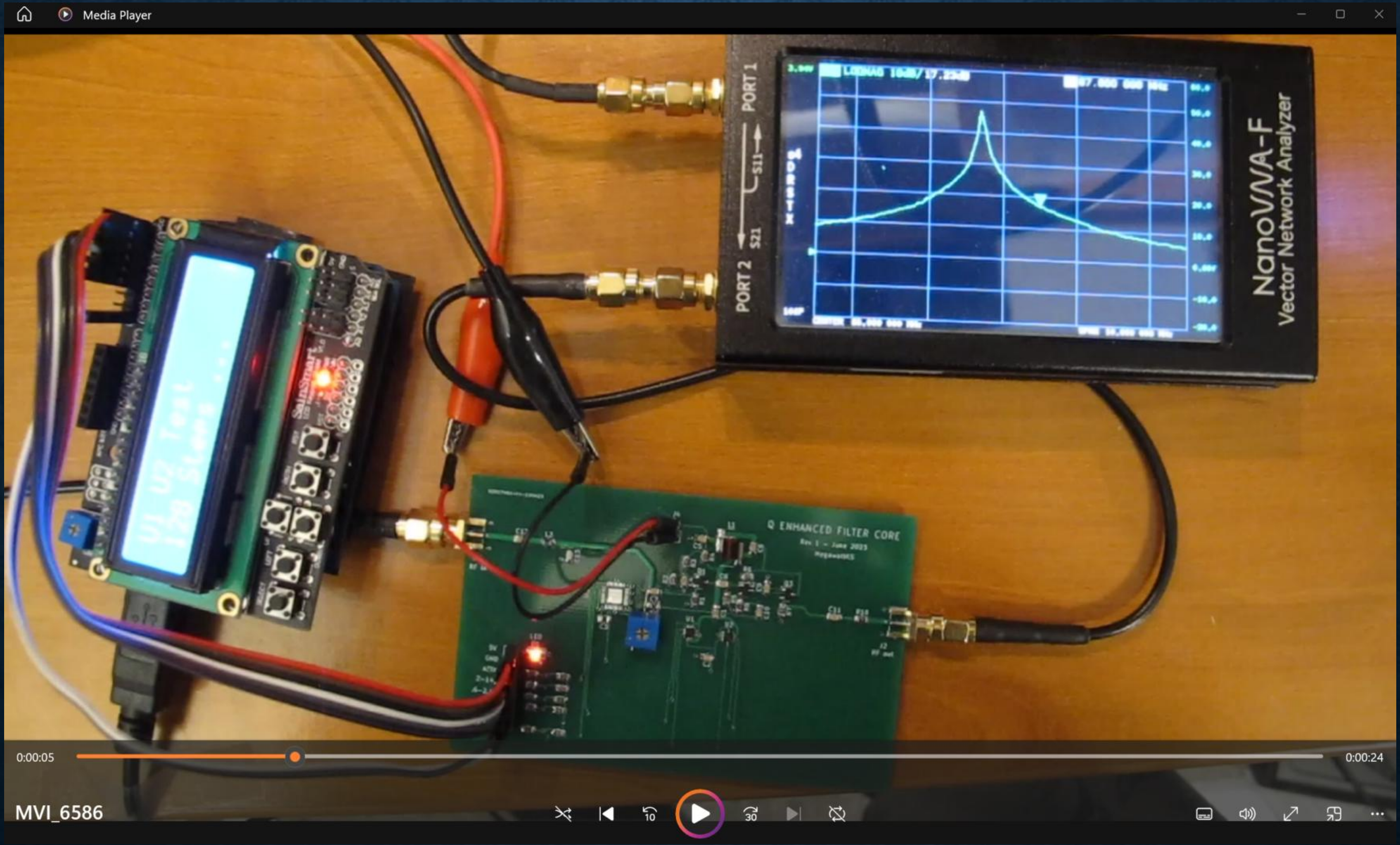
Digitally Controlled Tuning



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KIS Self-Tuning

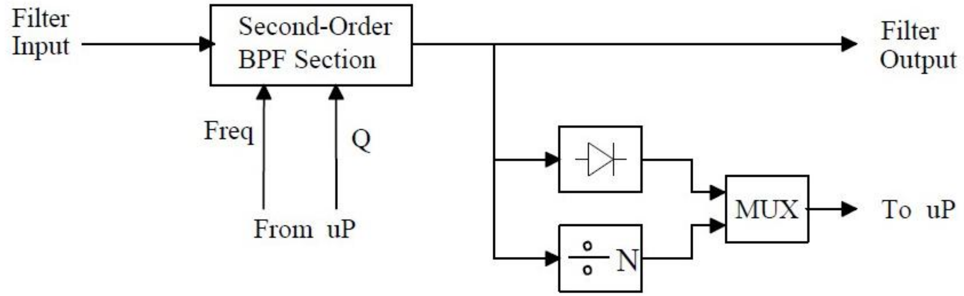


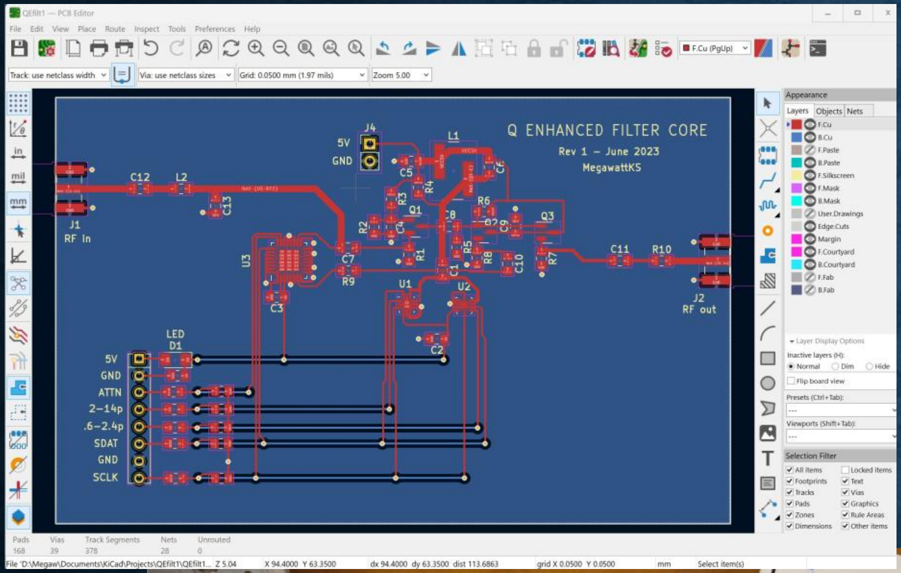
Figure 7.18: Self-tuning simplifications in superheterodyne receivers.

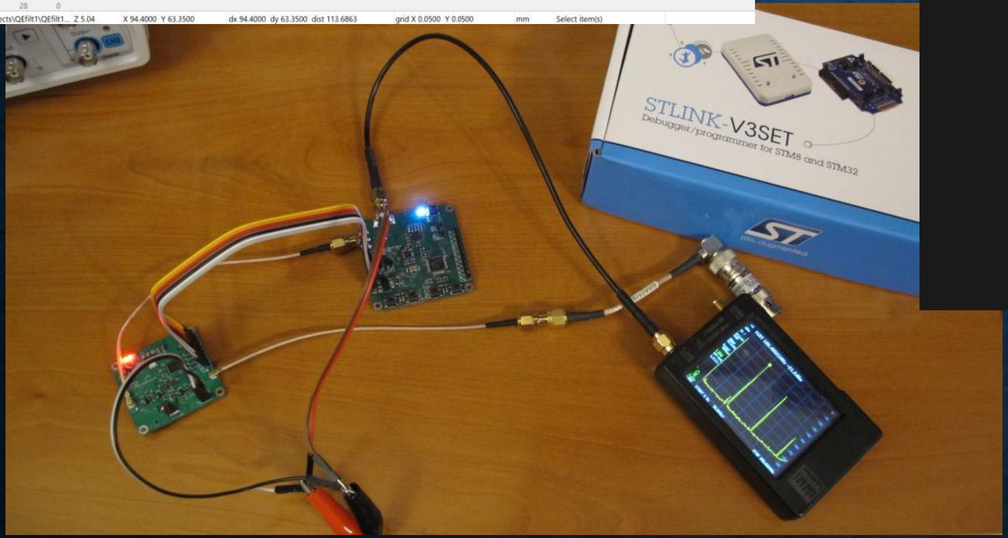
As before, filter frequency and Q control inputs are derived from the host receiver's microprocessor. However, measurement of frequency and Q is now performed using an amplitude detector and frequency prescaler incorporated into the filter die. Periodically, the filter is taken off-line and the Q is increased until the amplitude detector indicates that oscillation is present. The frequency of oscillation is then measured by the microprocessor's built-in

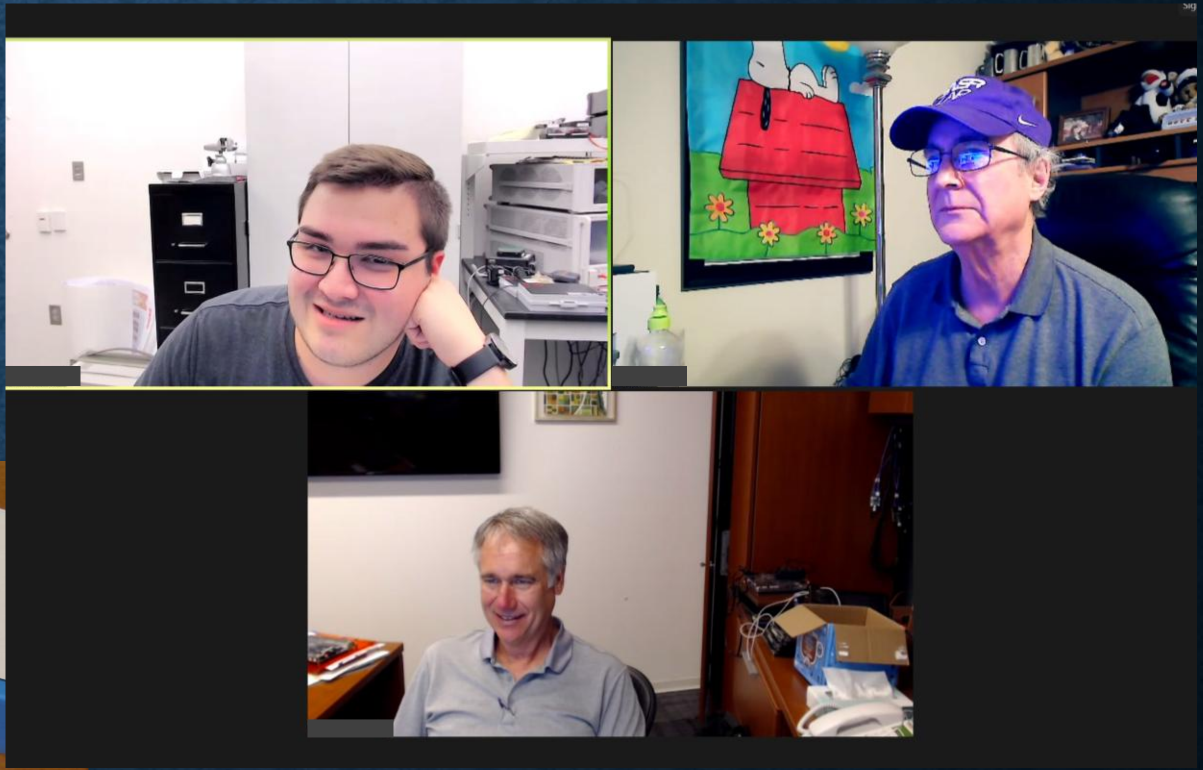
189

From: "Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies", William B. Kuhn, PhD dissertation, Virginia Tech, 1995.

Recent Prototyping







Today's Outline

- Introduction
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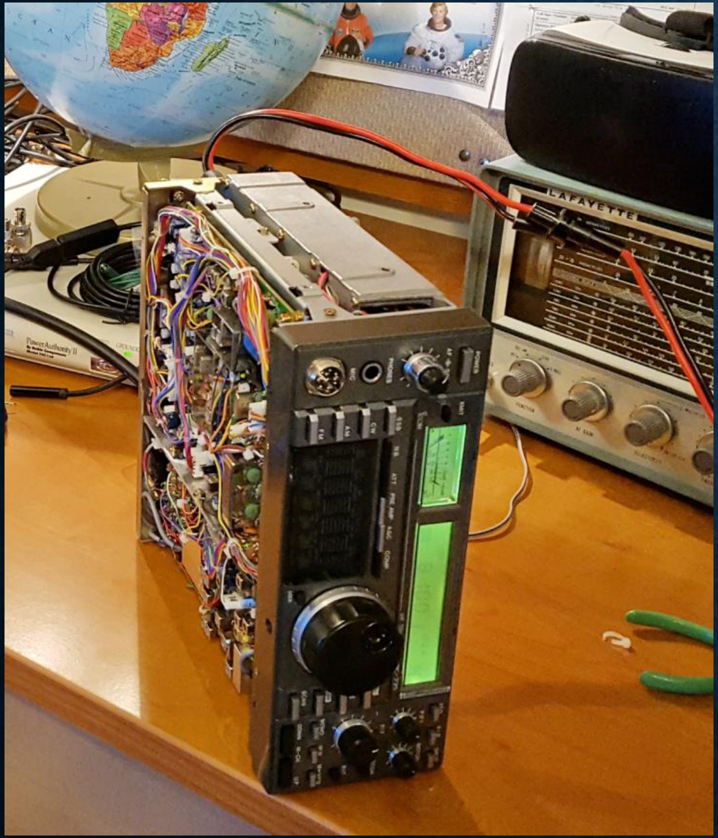
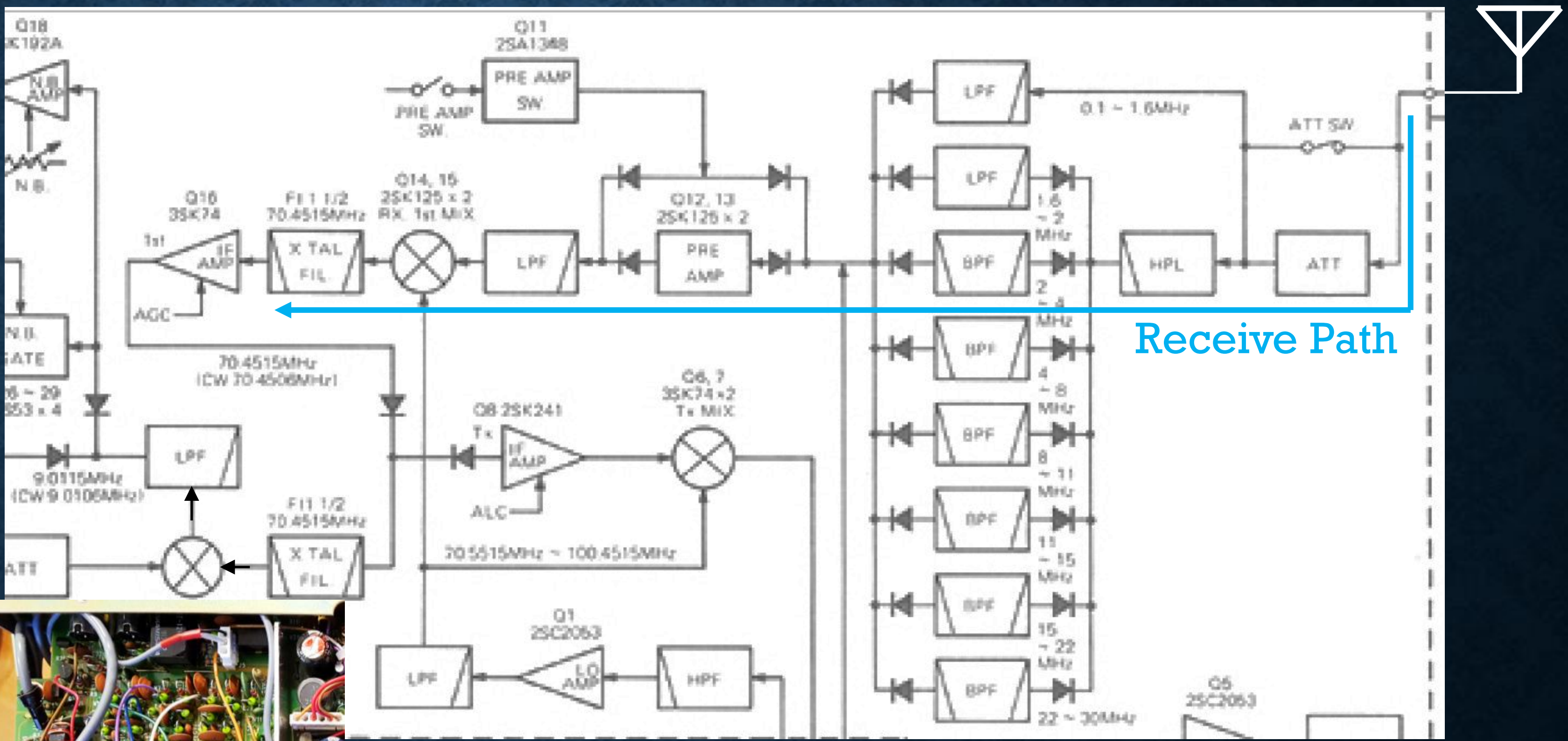
Key Takeaways from Episode 1

- Strong-signals can create blocking and intermod problems in existing receivers (from ***<u>in-band</u>*** interferers)
- Traditional solutions
  - Preselect (and image) filtering – Fixed bandwidth or (low-Q) tracking preselect architecture
  - Use RF (and IF) gain control and/or **<u>attenuators</u>**/AGC (trades noise figure for intermod mitigation)
  - Selective antennas (Directional and/or high-Q resonant)
  - **<u>Burn more power in LNA and mixer</u>** !

High-Power HF Radio Receiver Circuits

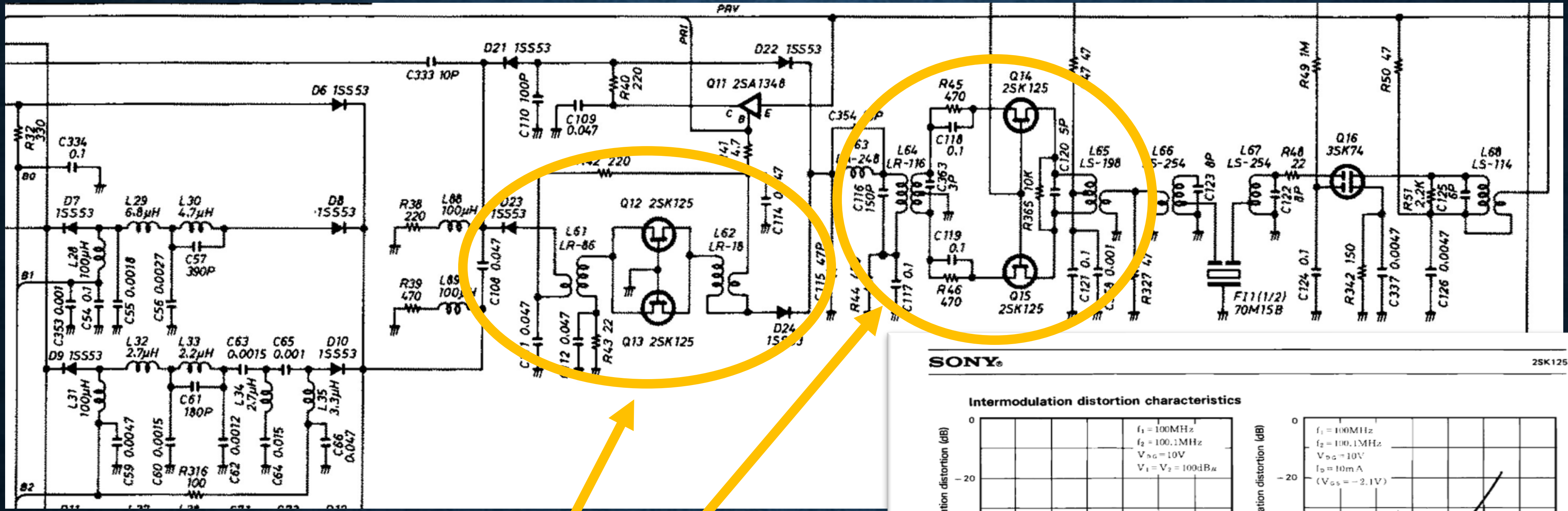
Icom 735 HF Transceiver





(See: https://www.rigpix.com/icom/ic735.htm)

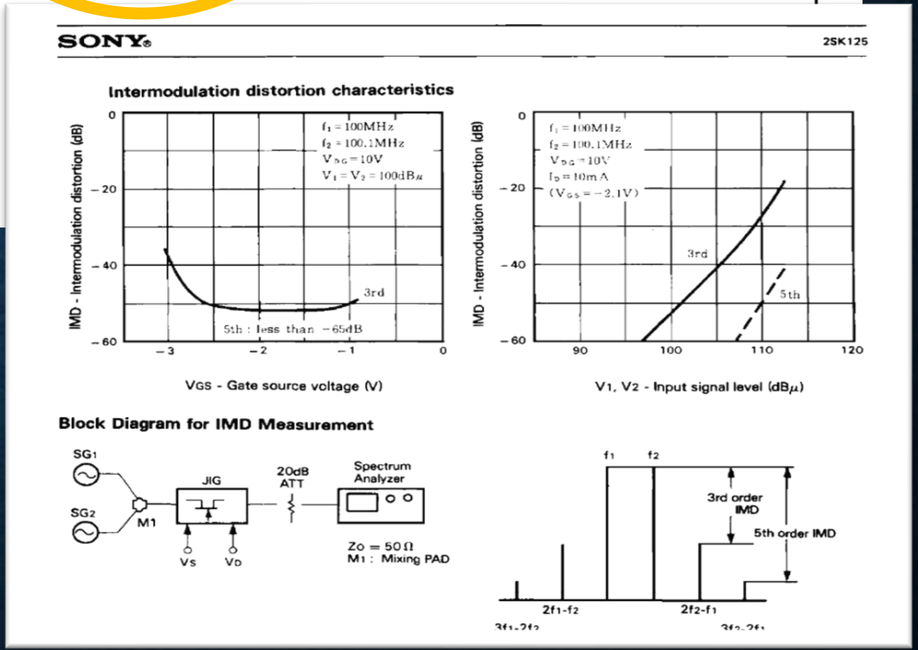
High-Power HF Receiver Circuits



High Power (1/2 Watt) LNA

High Power (1/2 Watt) Mixer (upconversion to 70 MHz)

2SK125 FET Intermod Characteristics



Key Takeaways (continued)

- Leveraging vintage technique of regeneration (positive feedback) in common-base form, using modern uP control (Q-enhanced filtering) is an easy way to make a significantly improved (low power) LNA

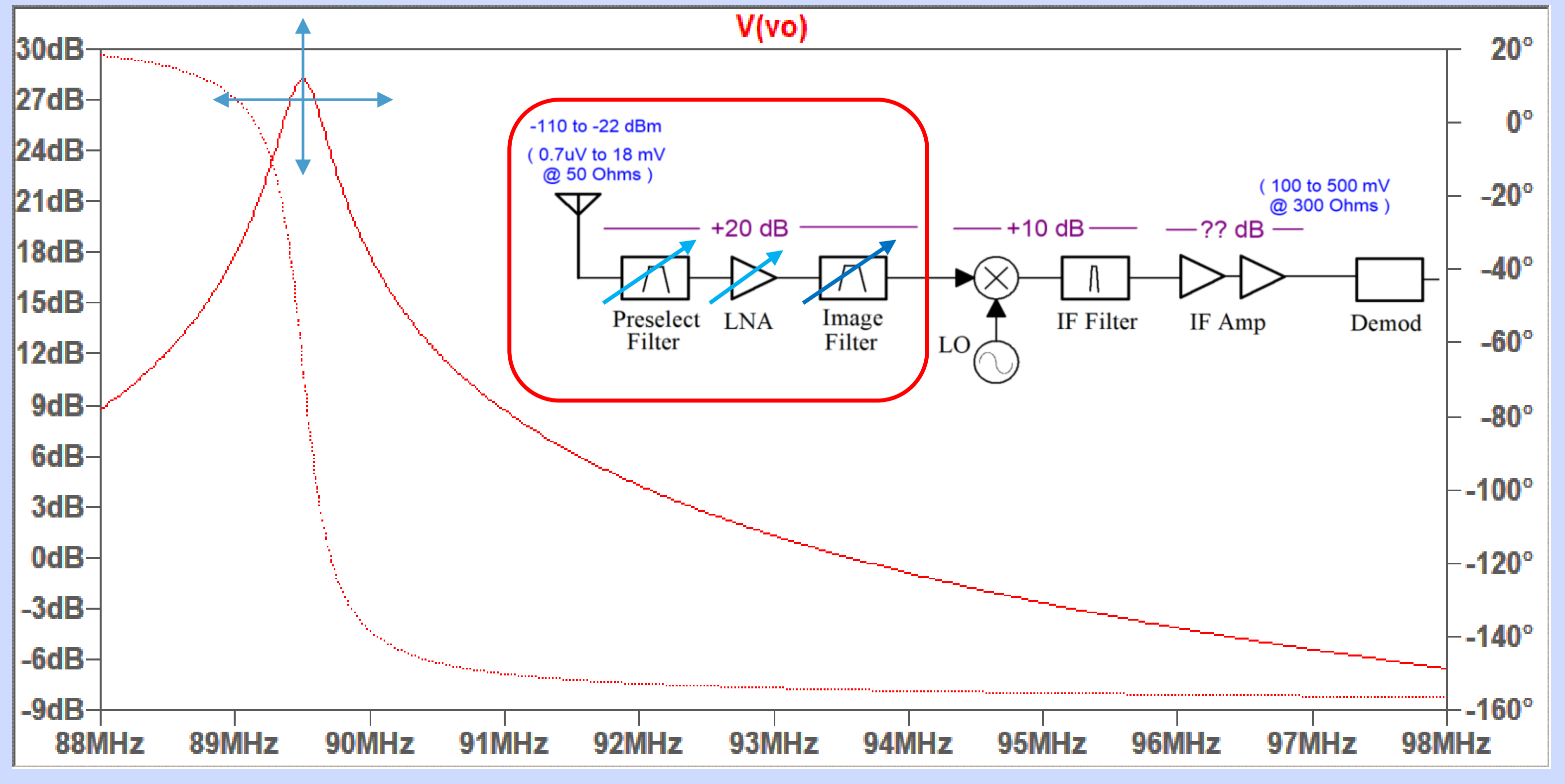
- CB QE-filter LNA architecture provides *channel-width pre-select filtering that automatically tracks LC tank image-reject filter tuning* ☺

- Can reduce power consumption required in receiver significantly (e.g. 10x to 100x reduction for front-end) !

- Not a panacea (yet… ☺)

Proposed Low Power Solution

Reduce front end bandwidth to signal bandwidth, not just width of service-band



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Limitations and Alternatives

- Filter response of current design is only "one-pole"
- It's still partly an active filter - but superior to earlier types, and traditional LNA designs
- Requires real-time tuning

- A (tunable, very-high-Q) electro-mechanical/acoustic design might be superior, if possible and sufficiently small (MEMs anyone?), and low cost
- **Always remember :** Antenna is also a very important part of the receiver system, and using attenuators can also work wonders !

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Possible Future Videos

- *Receiver Performance Measures* **(the math)**
  - *Compression, Intermodulation and 3rd Order Intercept Point*
  - *Noise Figure and Tradeoffs with Intermod Performance*
- *Design and simulation of common-base Q-enhanced Filters*
- *Self-tuning hardware and software*
- *Effects of LED lighting, switch-mode power-supplies, and general EMC on actual system noise floor and receiver sensitivity*

Thanks For Watching !

For research publications, please cite:
https://www.youtube.com/user/MegawattKS
https://ecefiles.org
or specific sub-pages/publication/video

Thanks !