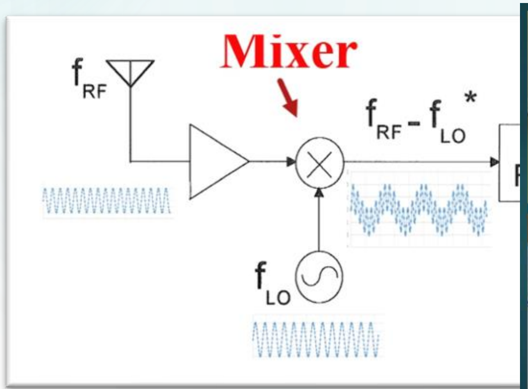
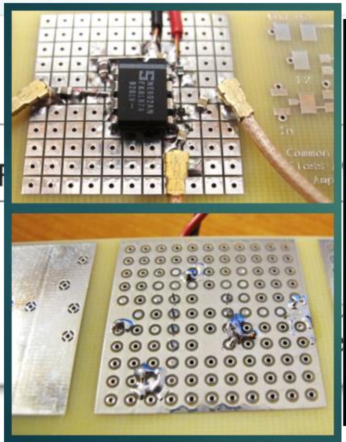
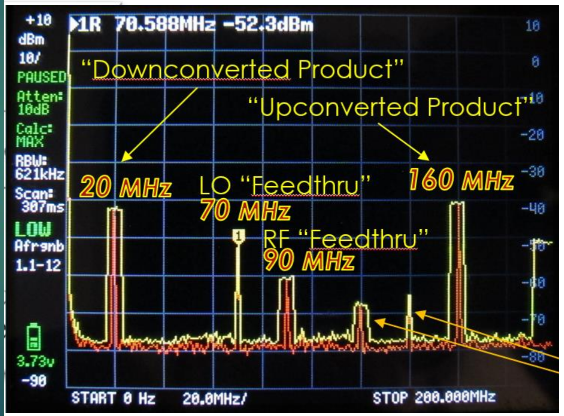
Radio Design 101
Episode 5 – RF Mixers and Frequency Conversion

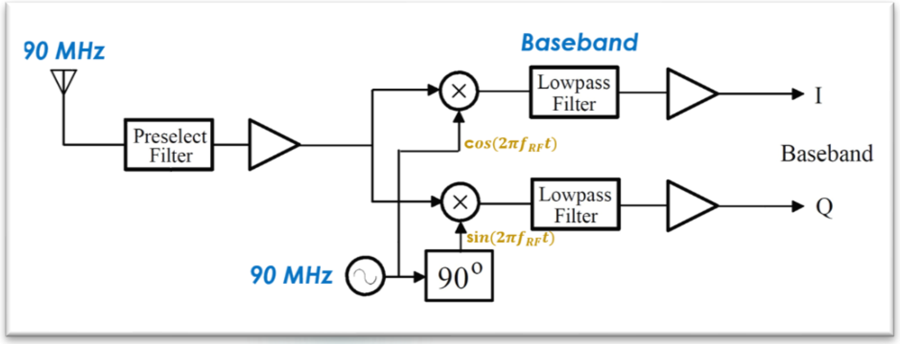
Slides downloaded from: https://ecefiles.org/rf-design/
Companion videos at: https://www.youtube.com/watch?v=uiTrCUNRUIA (Part 1)
and: https://www.youtube.com/watch?v=nGOxNGZQ0EM (Part 2)

This episode focuses on RF mixers, and on frequency conversion schemes commonly used in wireless hardware. Starting with the basics, the process of up and down conversion is described and then demonstrated using a TinySA spectrum analyzer and a homebrew mixer built from an NE602 integrated circuit. Superheterodyne and direct conversion architectures are covered in some detail, and the video concludes with an examination of the dual conversion design used in modern spectrum analyzers. The second half of Episode 5 covers some of the math behind mixing and discusses practical switching mixer circuits commonly used in radio hardware.





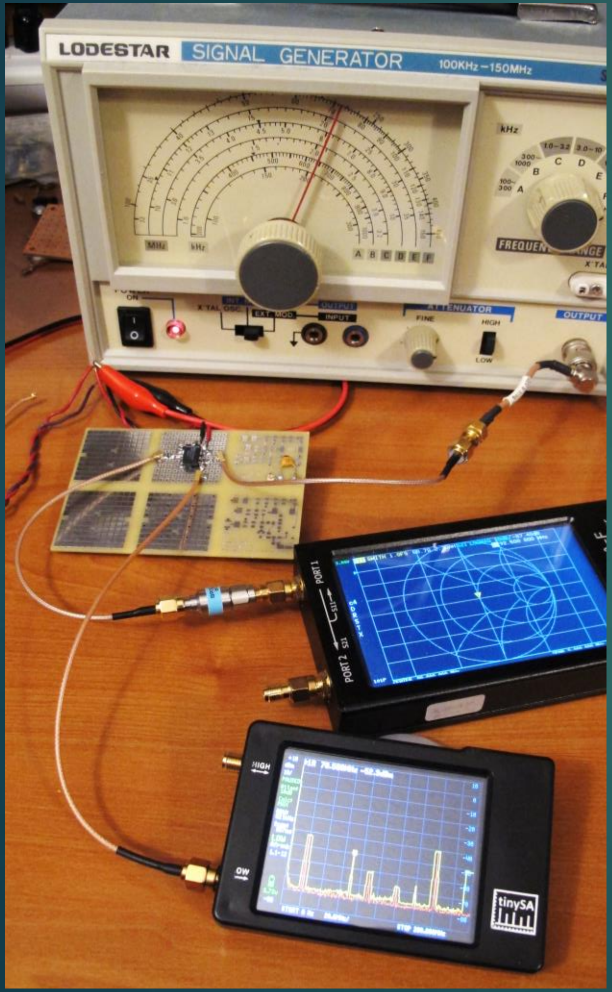


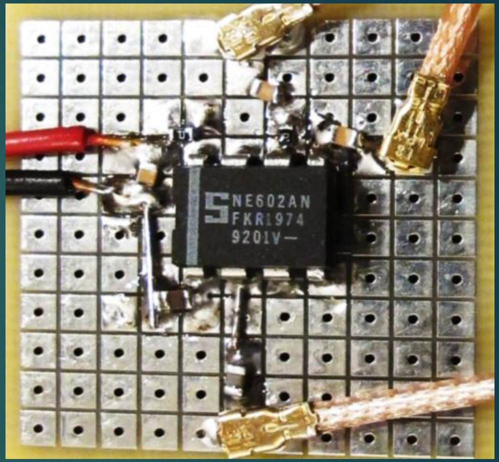


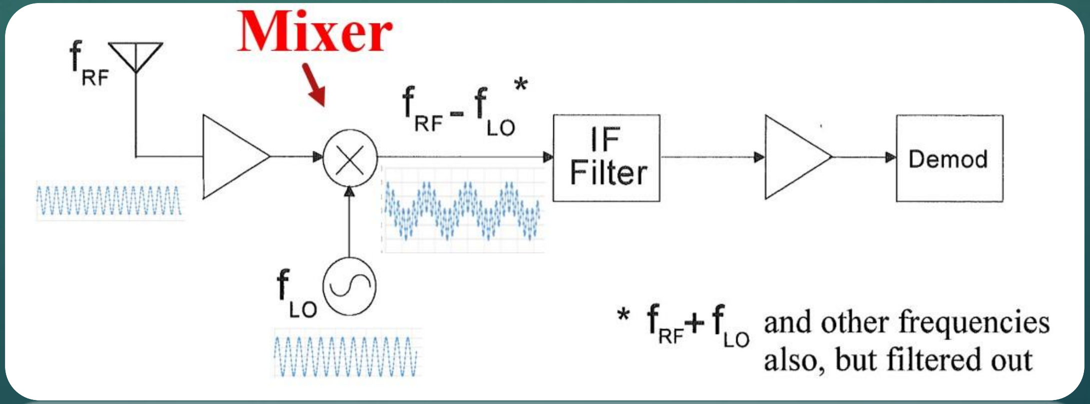
Radio Design 101

Episode 5

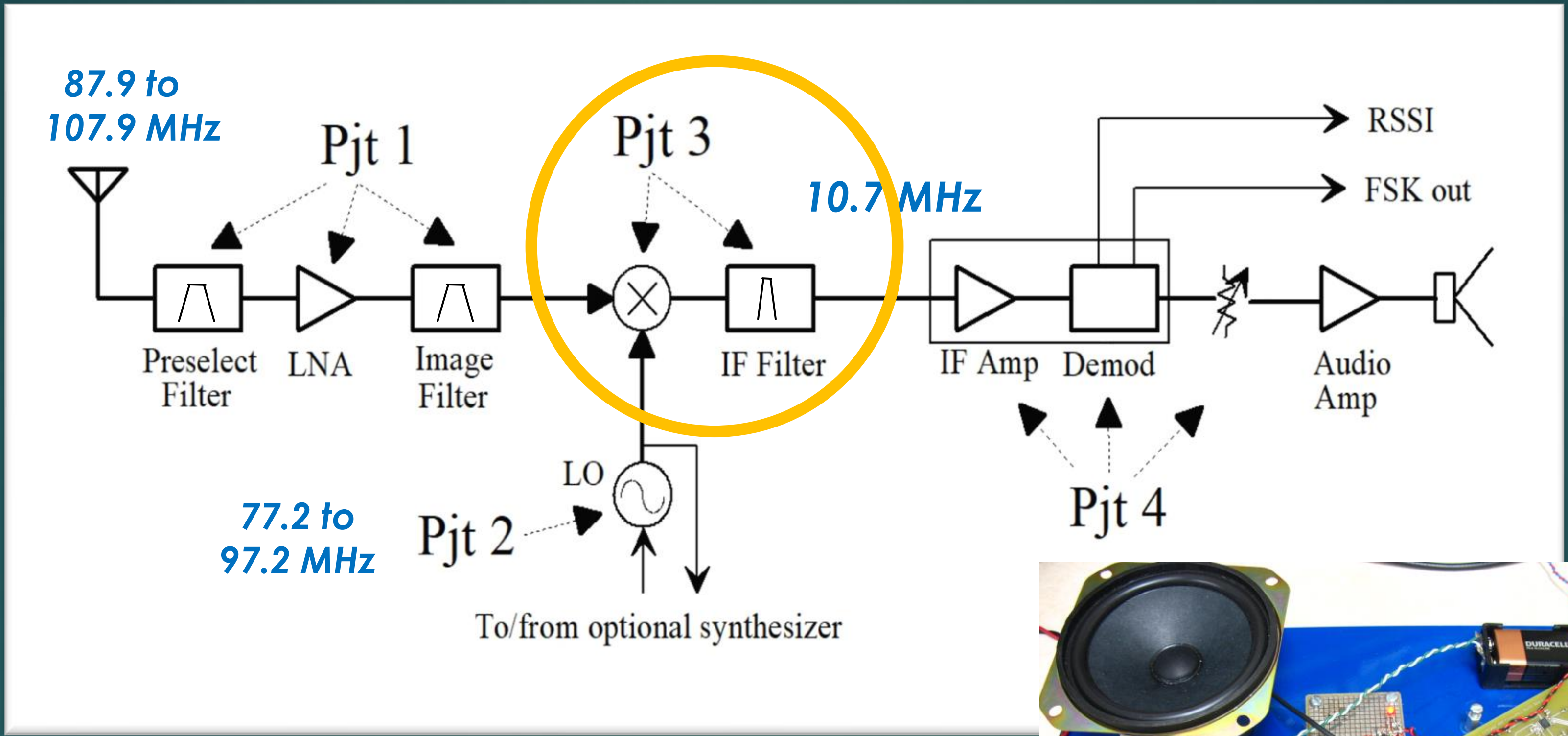
RF Mixers

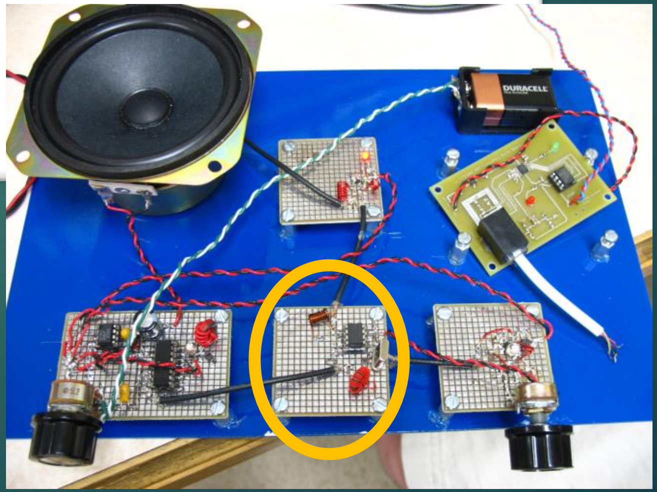






Class Project - FM Broadcast Receiver





Project 3 – Mixer / IF Filter

(This Video + Part 2)

Episode 5 Topics

- ***Overview, Demos, and Applications***
- ***A Quick Math Review / Description***
- ***Mixer Circuit Designs***
- ***FM Receiver Mixer and Spectrums***

Tuned-RF Receiver (without mixer)

Early radios amplified and demodulated directly at RF …

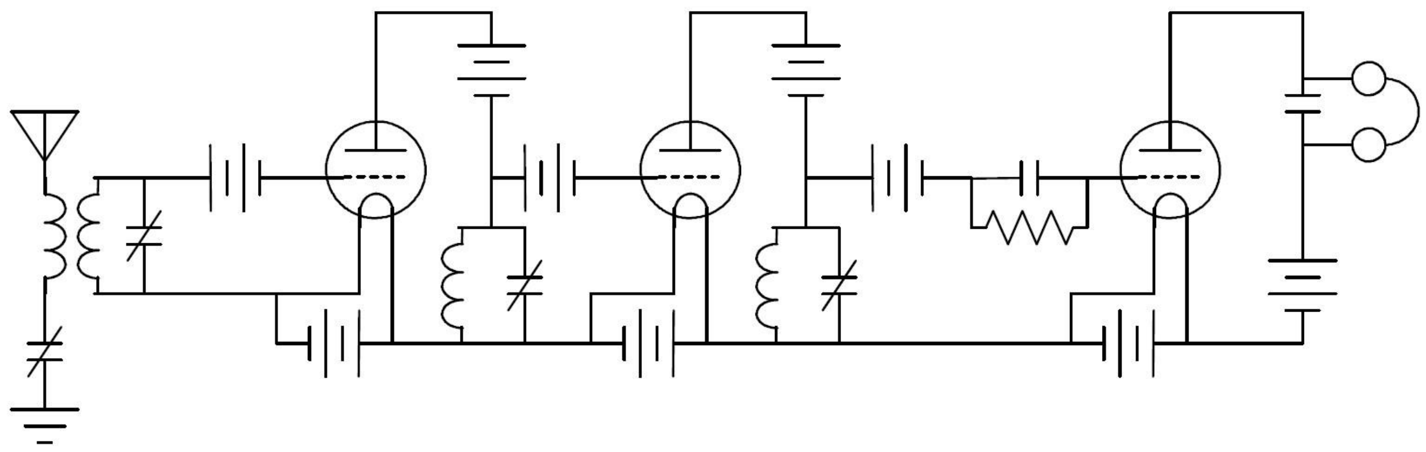


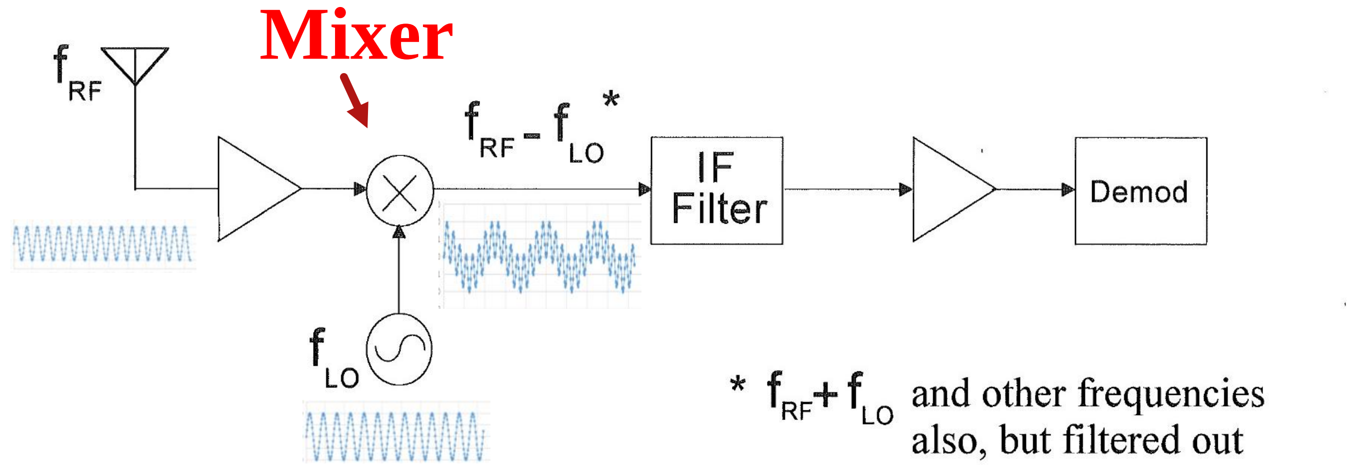
Figure 4.2: Early tuned-RF receiver circuit. [British patent no. 147,147]

Problems:

- Achieving high gain for good sensitivity becomes difficult at higher frequencies (more prone to oscillations)
- Filter Q required for good selectivity increases with RF frequency
- Filters have to be retuned when changing channels ☹

Mixers Do Frequency Conversions

A key function in virtually ***all*** modern high-frequency radio designs …



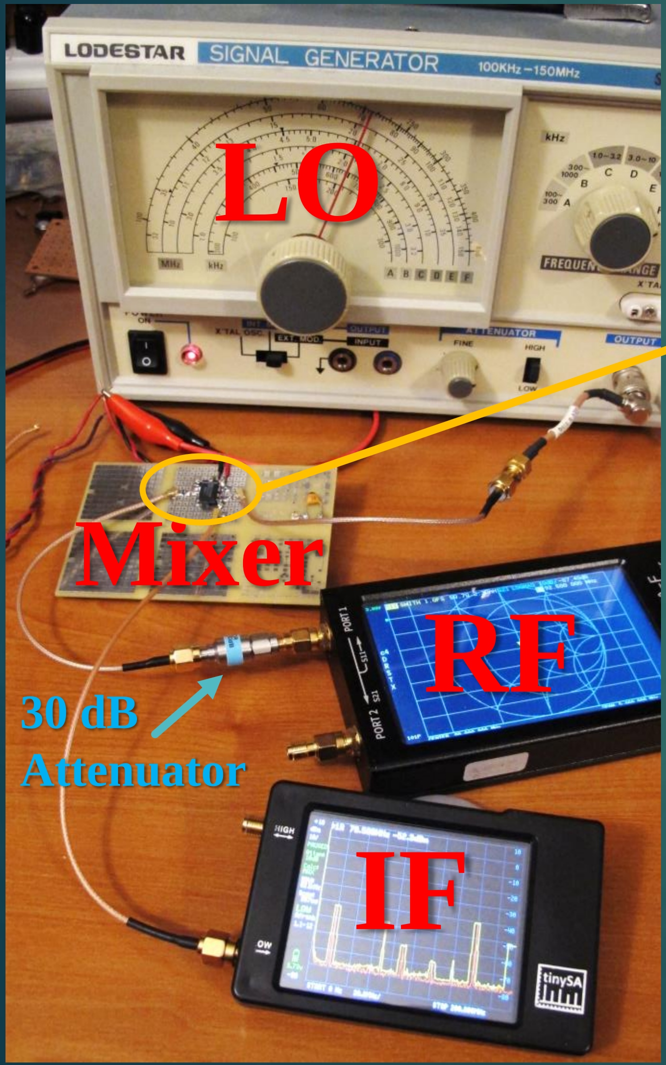
Advantages

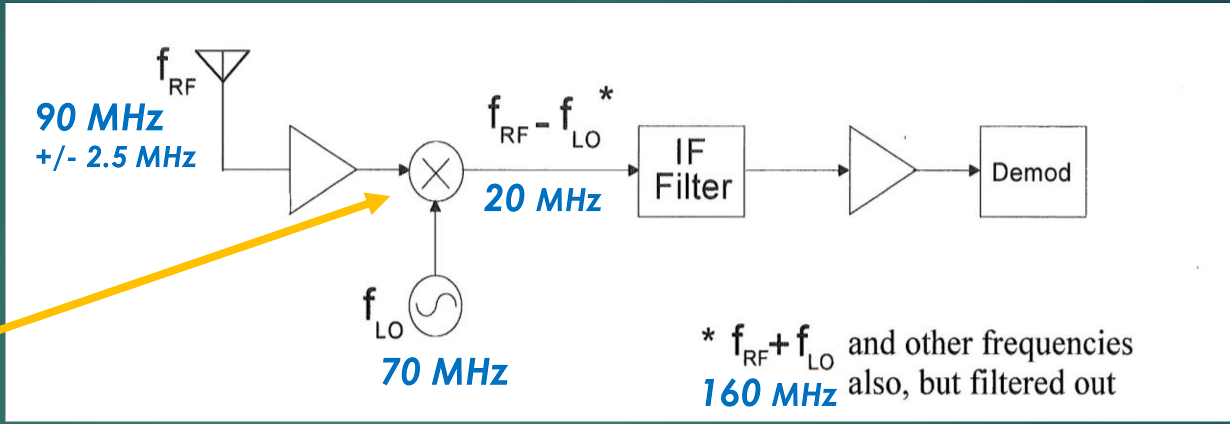
Amplification at two different frequencies
Easier to get high gain at lower intermediate frequency
Tuned by changing LO frequency
Better selectivity (high-quality, fixed-tuned IF filter)

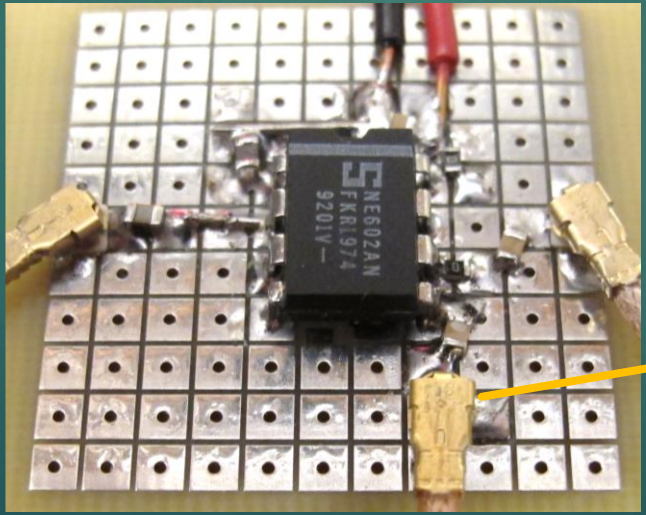
Including:

- Superheterodyne receivers like this one,
- Direct conversion receivers like in cellphones,
- Up/down conversion designs in Spectrum Analyzers,
- Receive channels in Vector Network Analyzers (VNAs)
- Transmitters, frequency synthesizers, and more !

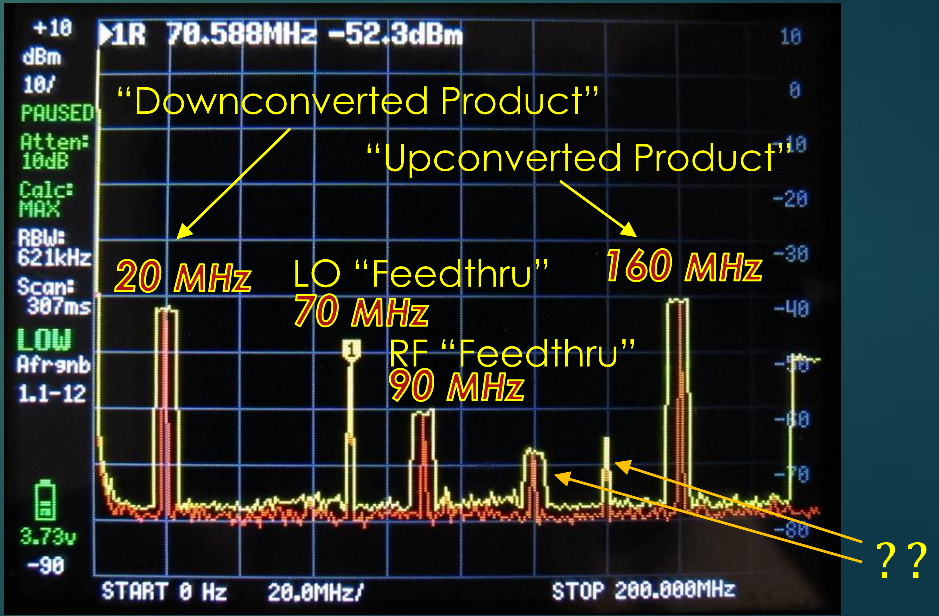
Frequency Conversion Demo



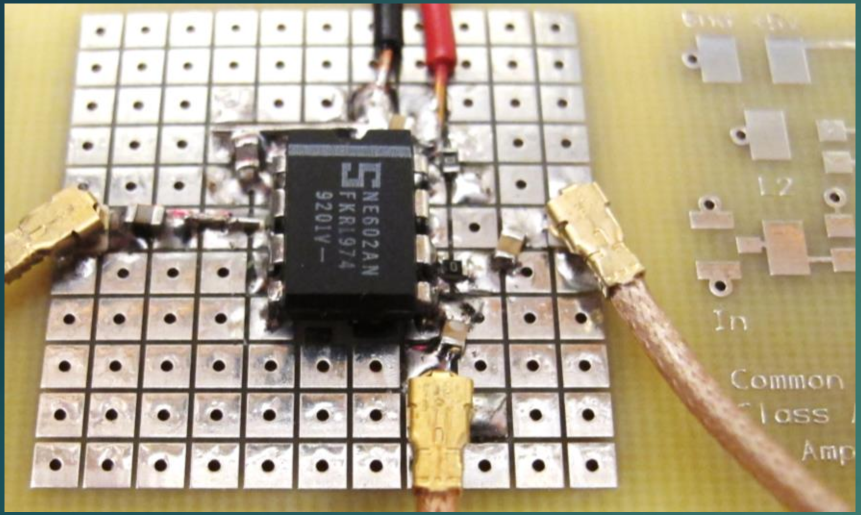


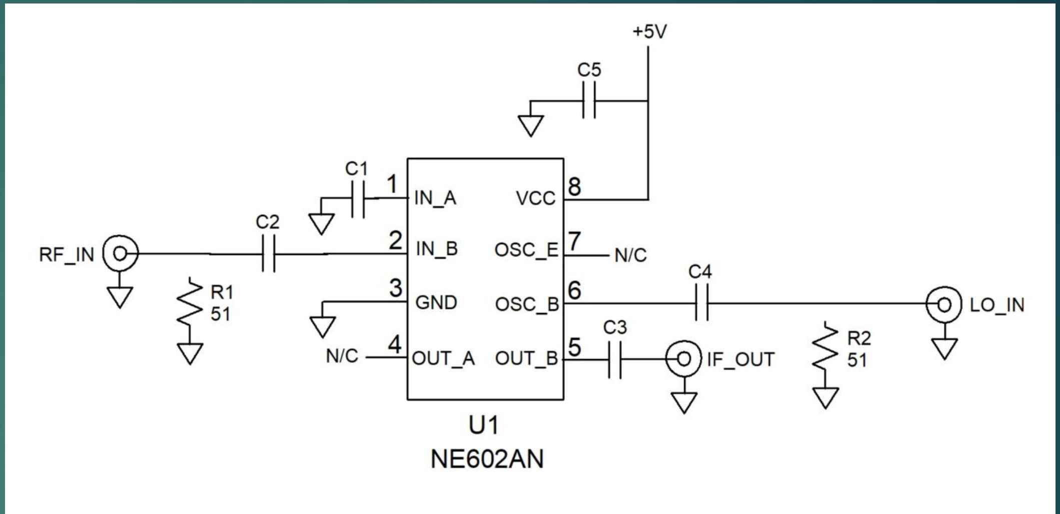


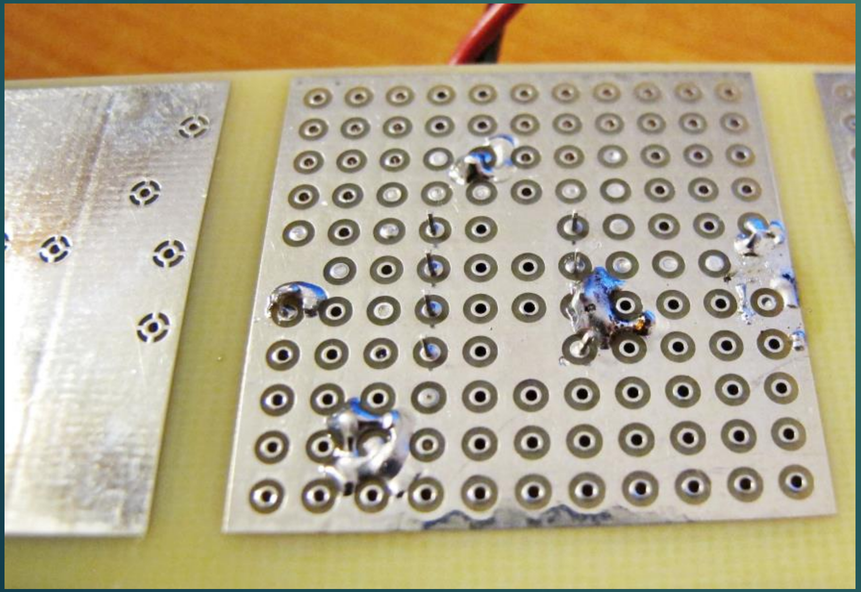
Classic NE/SA602 Mixer IC



Mixer Build on Protoboard





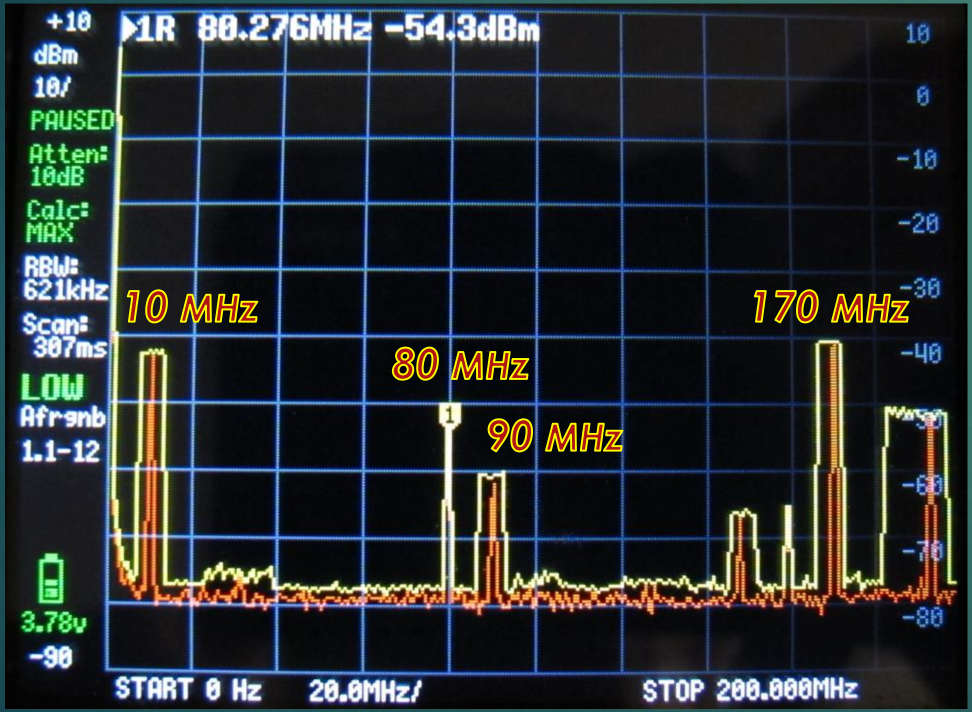


NOTES:

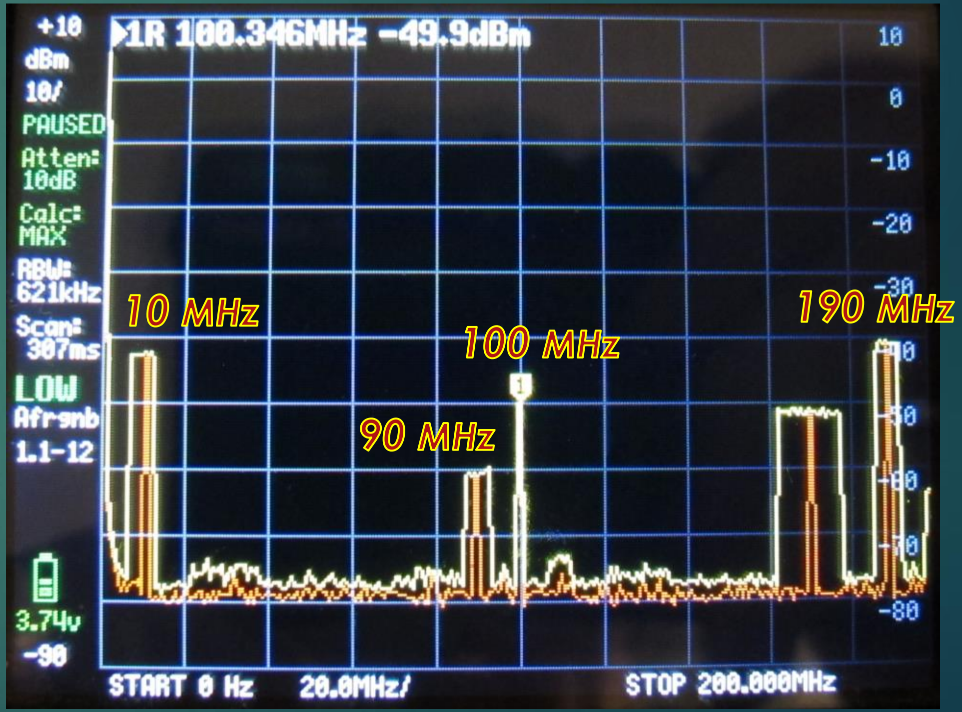
- **PCB is a modified version of RF prototyping boards used in senior RF design class, fabricated through ExpressPCB**
- **Used 1 uF for C1, C2 and 22nF for C3 through C5.**
- **R1, R2 not used in this build but might be wise**
- **Some zero Ohm resistors used to bridge pads.**
- **Grounds are a pain to solder on the backside (but no drilling needed ☺)**

IF Out Frequencies For Other f_{LO} Settings

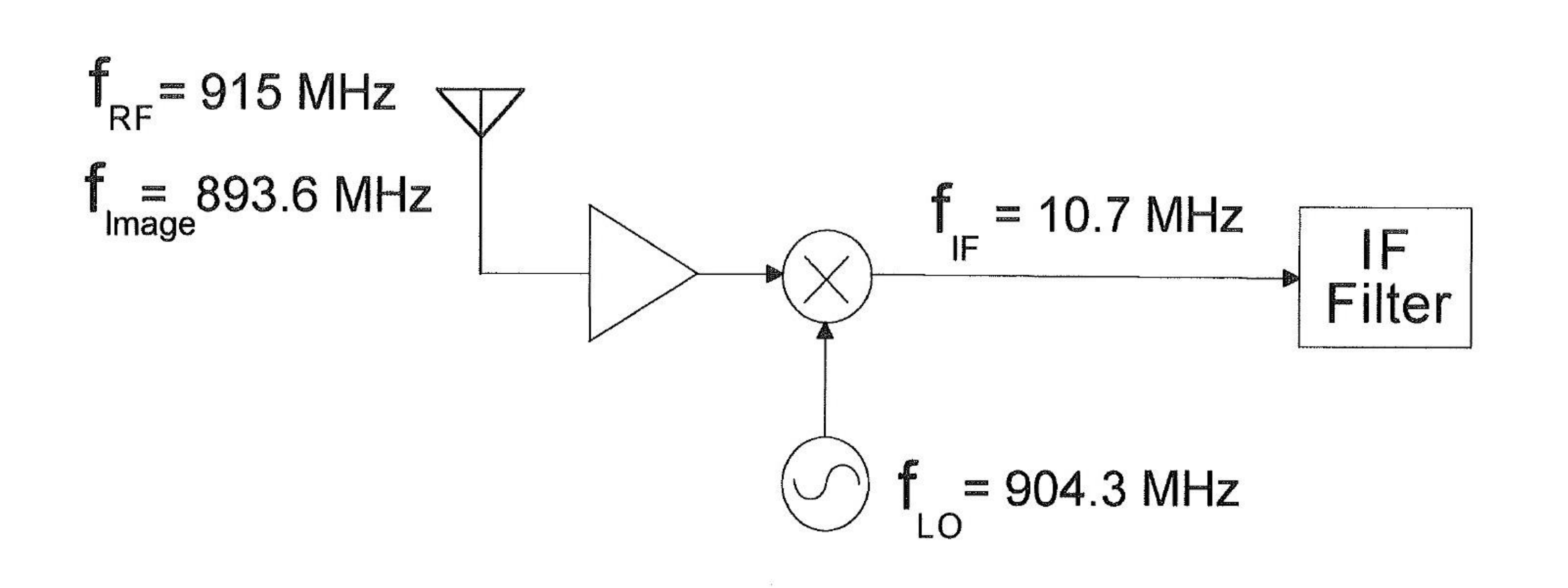
Low Side Injection: $f_{LO} < f_{RF}$



High Side Injection: $f_{LO} > f_{RF}$

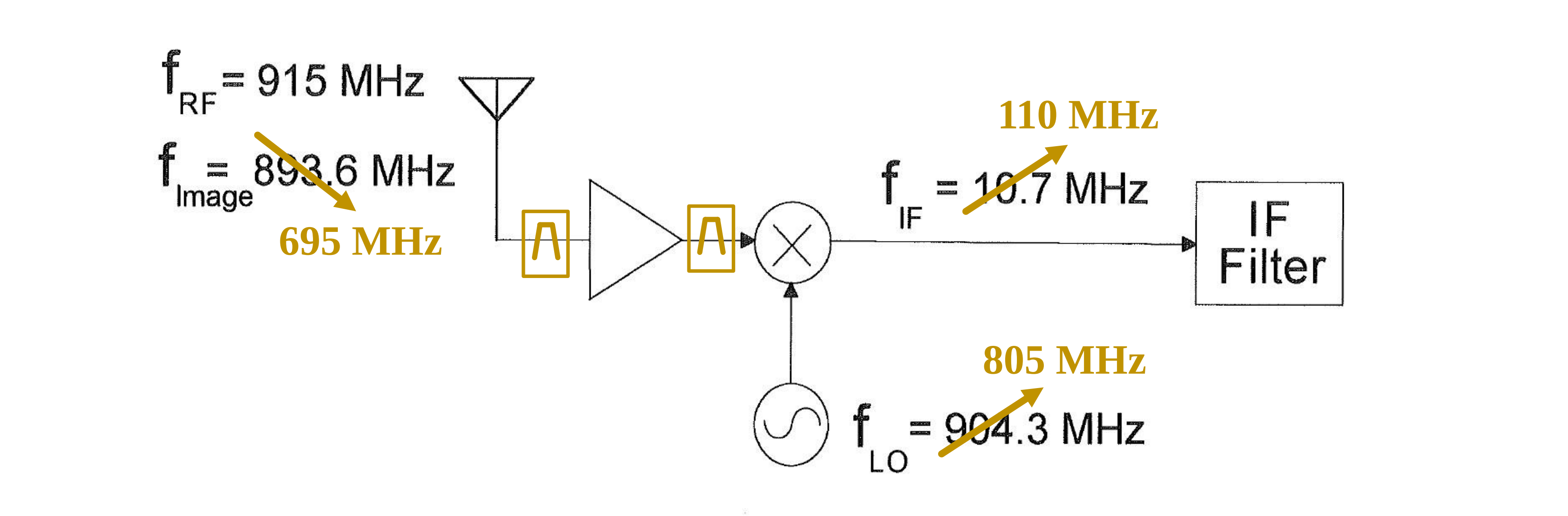


The Image Problem



- 915 MHz and 893.6 MHz will both produce 10.7 MHz and get through the IF channel-select filter
- The undesired response to 893.6 is called an image response
- Becomes a problem if there are signals (or noise) at that frequency

Solutions



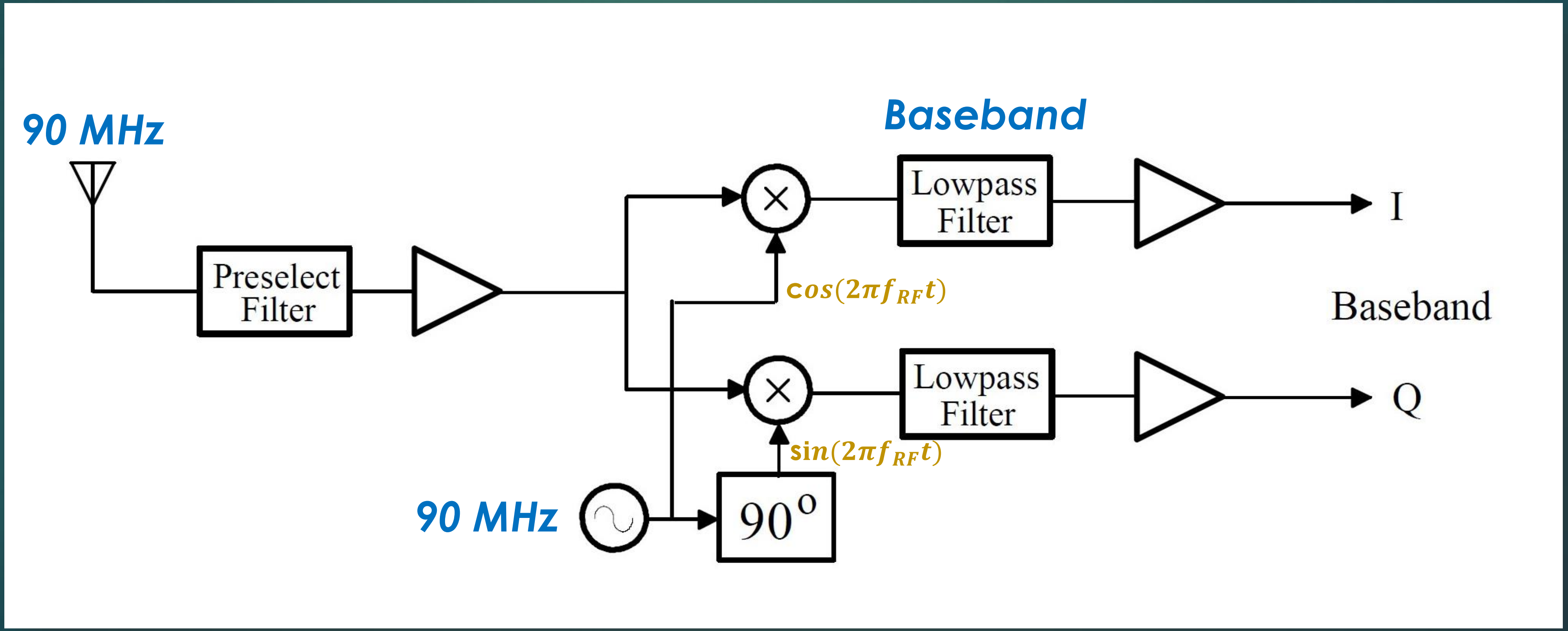
Mitigations:

- Add bandpass filter(s) before mixer
- Use a higher IF frequency
- Use image-reject mixers (20 to 40 dB rejection typical)
- Use “Zero-IF” / “direct-conversion” design
- Use dual-conversion architectures

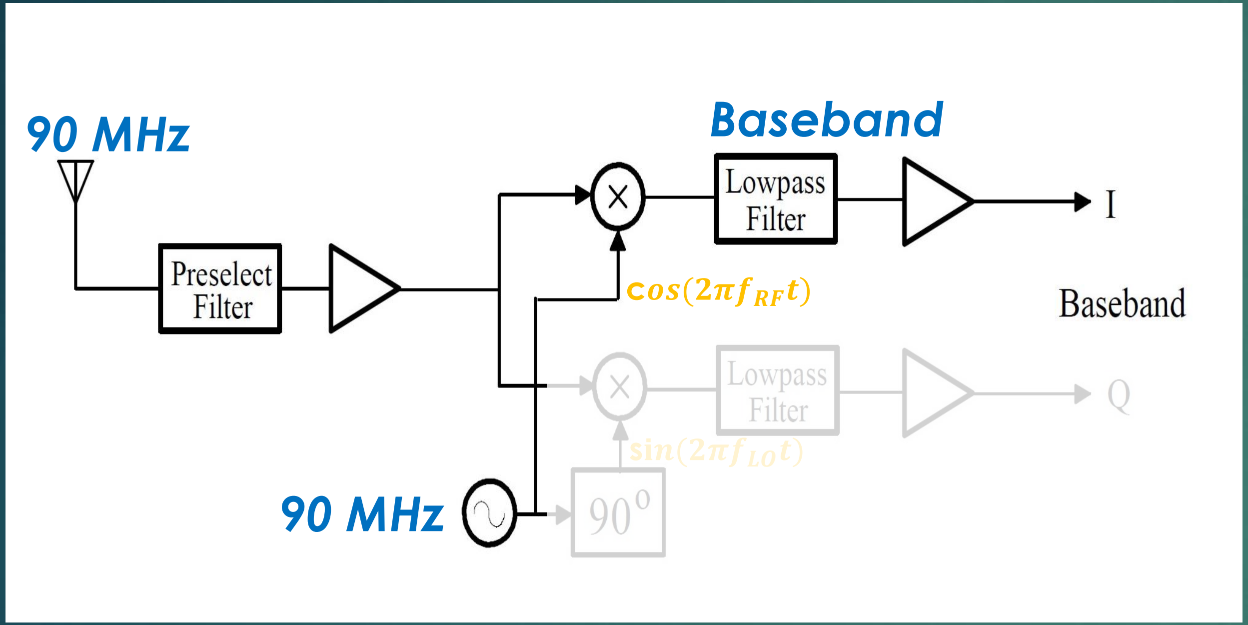
Next slides

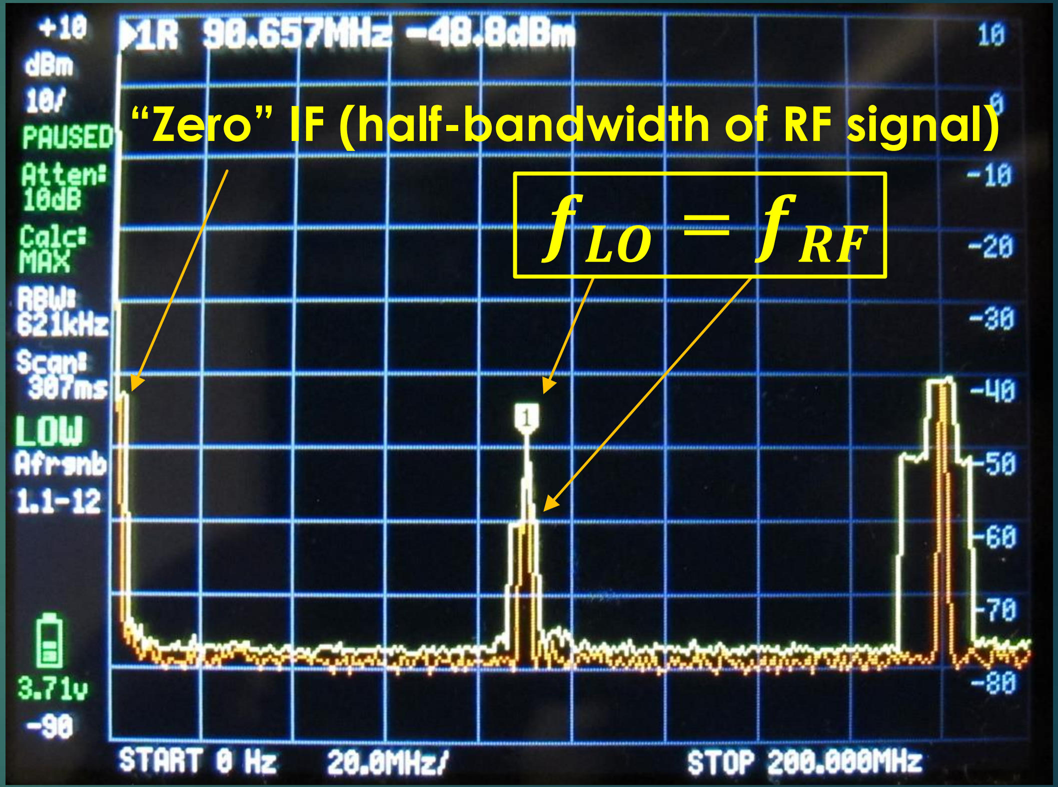
Solution Used in Modern Cell Phones

- **"Zero-IF" or "Direct Conversion" architecture**
- Needs "Quadrature LO" and processing of "IQ" outputs
- May not be ideal for narrowband systems



IF Output Frequencies for Direct Conversion



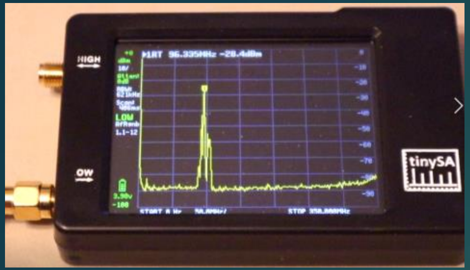


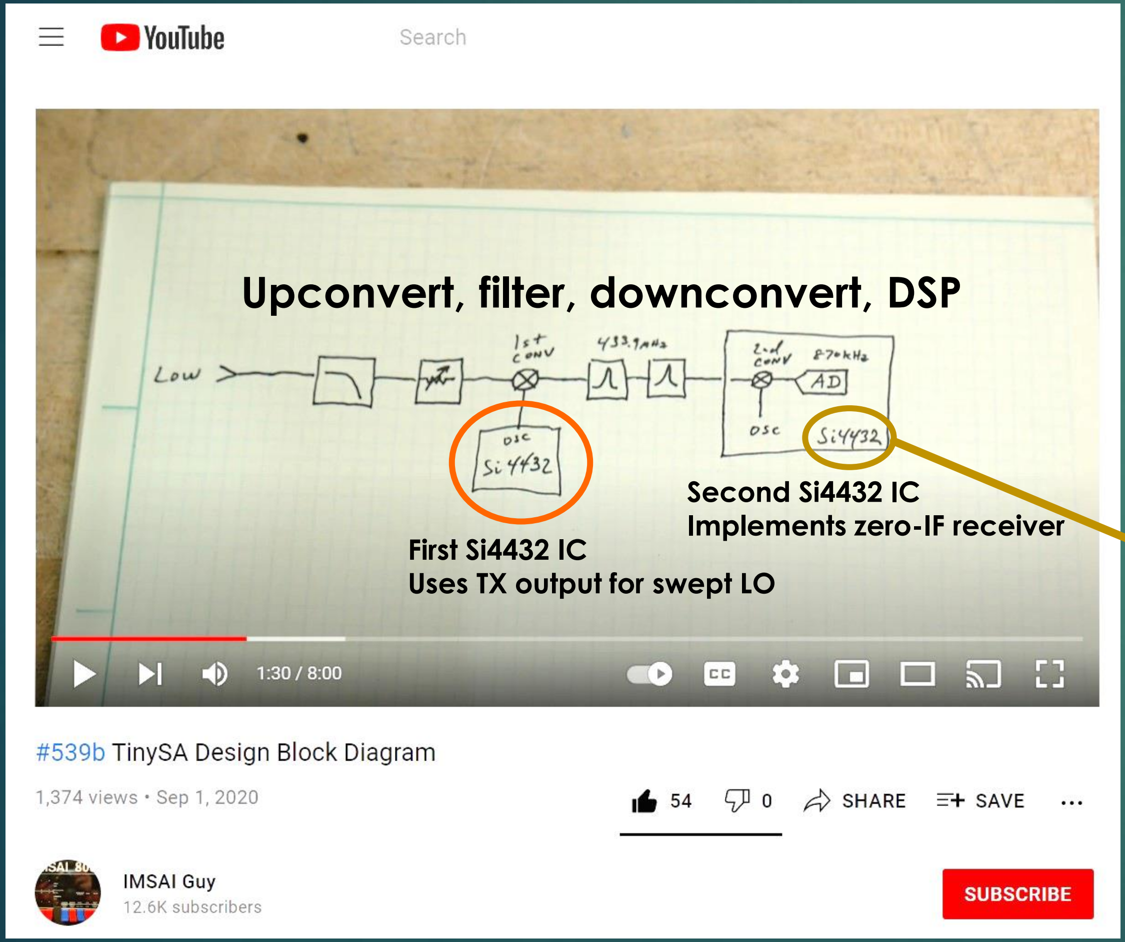
NOTE:

Only "in-phase" (I) output shown here.

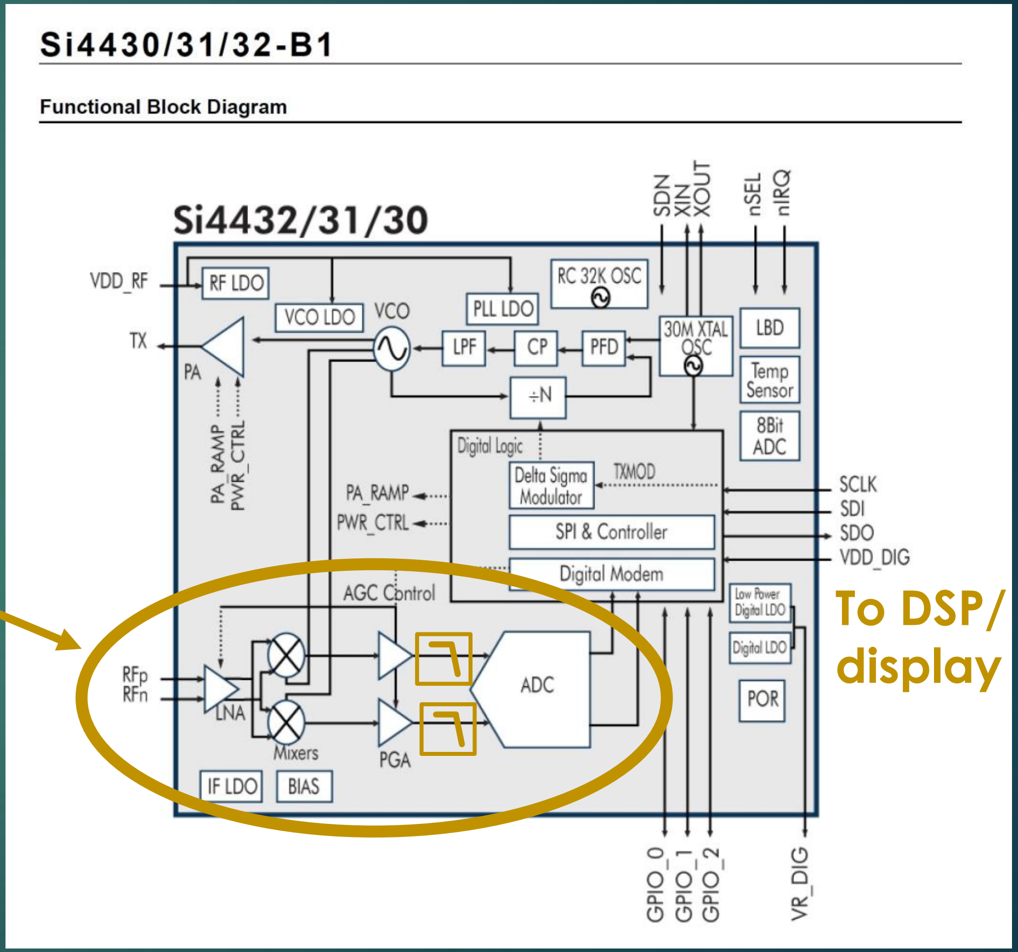
Requires both I and Q and complex math to process "negative frequencies" in general

Solution Used in TinySA
(Low Band)





From IMSAI Guy's YouTube channel

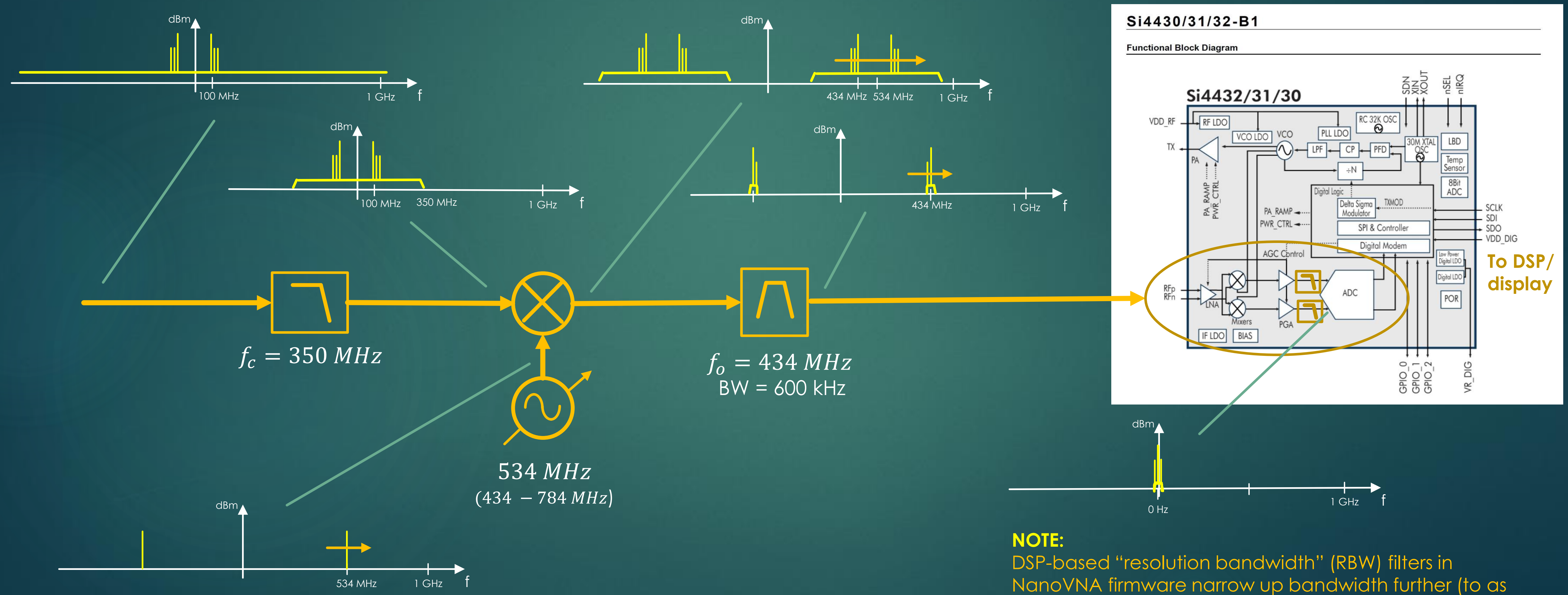


From Silicon Labs Si4432 datasheet

350 MHz

Up/Down Conversion Spectrums

(Low Band)

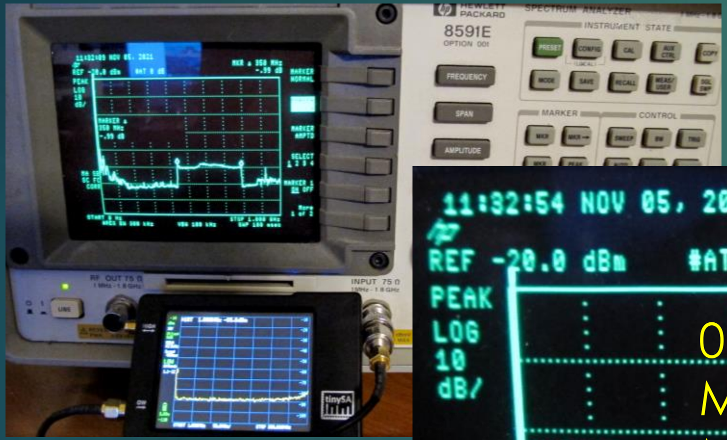


NOTE:
DSP-based “resolution bandwidth” (RBW) filters in NanoVNA firmware narrow up bandwidth further (to as low as 3 kHz)

1st LO Feedthrough at RF Input

(Low Band)

Full Low-Band (0 to 350 MHz sweep)



NOTE:
0 dB attenuation setting used on both units

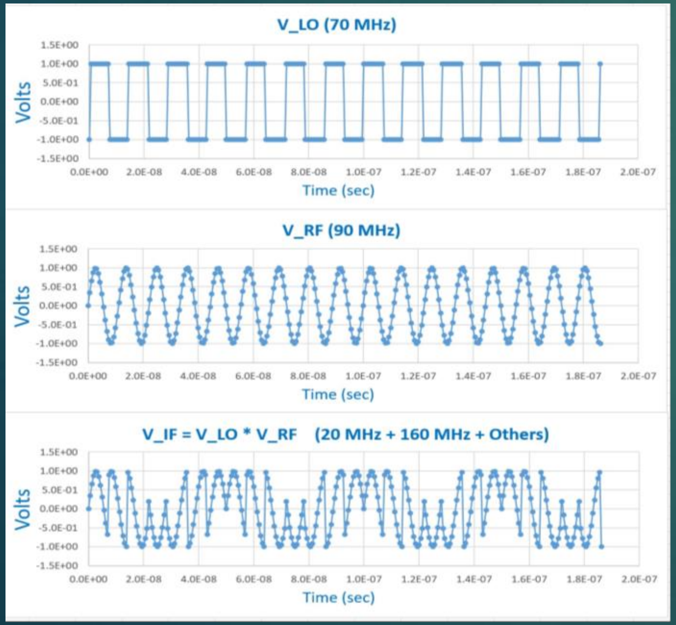
Zero-span mode at 100 MHz

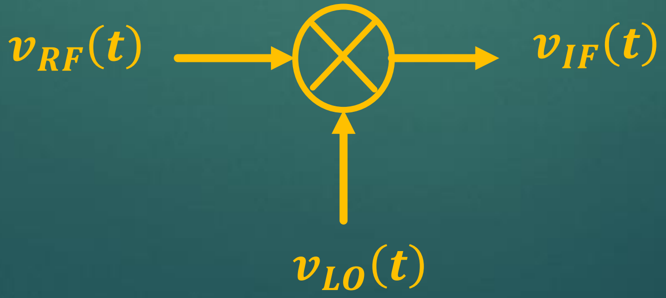
Radio Design 101

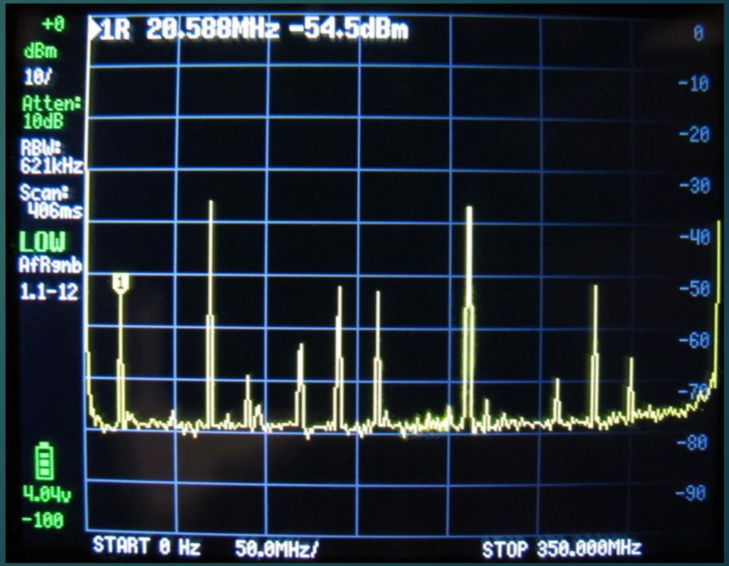
Episode 5

RF Mixers

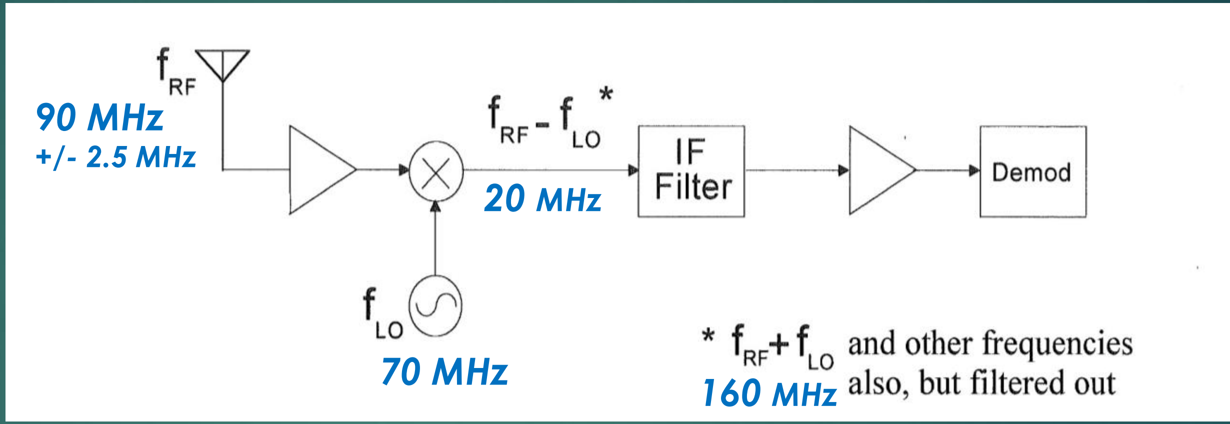
(Part 2)

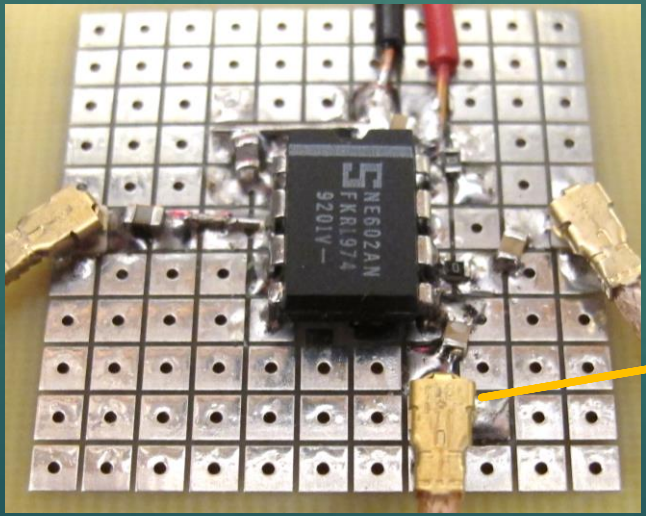




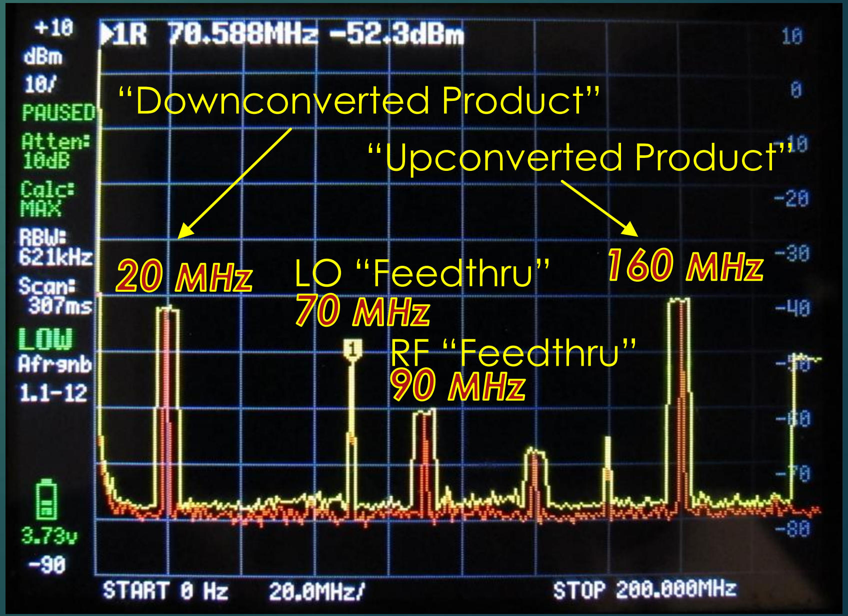


Frequency Conversion Demo





Classic NE/SA602 Mixer IC



Topic Outline

- ***A Quick Math Review / Description***
- ***Mixer Circuit Designs***
- ***FM Receiver Mixer and Spectrums***

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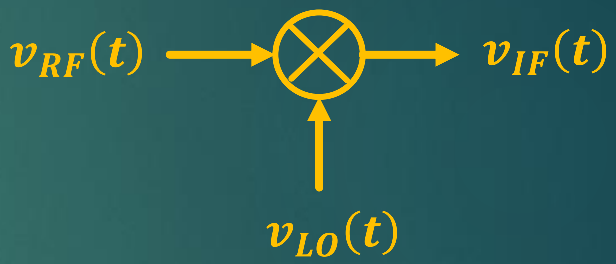
Co-sine Wave Parameters

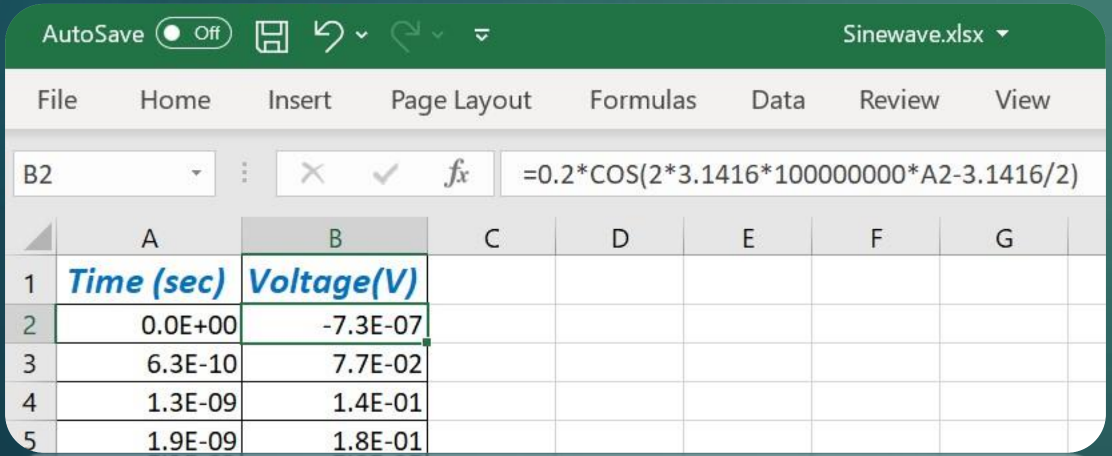
Recall time-domain description of sinewaves (or cosines):

$$v_{RF}(t) = V_{RF}\ \cos(2\pi\, f_{RF}\, t + \theta_{RF})$$

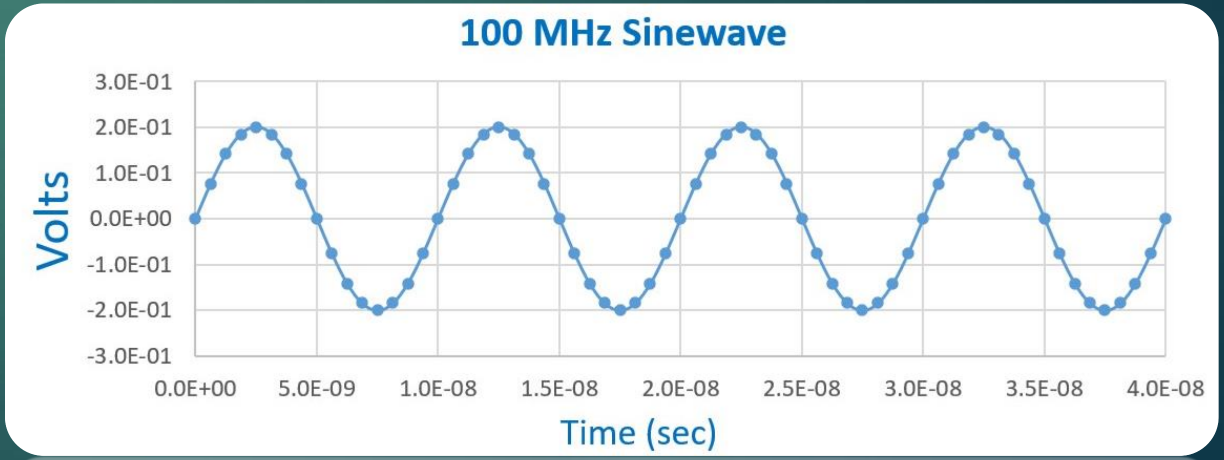


If $\boldsymbol{V_{RF}}$= 0.2, $\boldsymbol{f_{RF}}$= 100E6, and $\boldsymbol{\theta_{RF}} = -\frac{\pi}{2}$

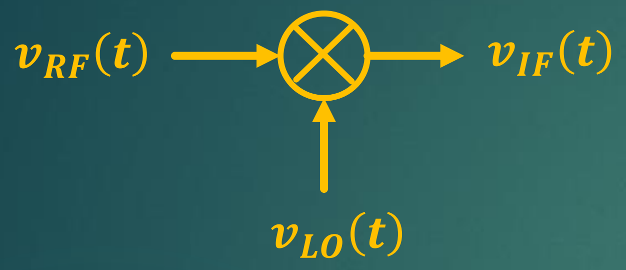
$(i.e.\ 0.2\ Vpeak, 100\ MHz, and\ -90\ degrees), we\ get\ this$:



	A	B	C	D	E	F	G
1	Time (sec)	Voltage(V)					
2	0.0E+00	-7.3E-07					
3	6.3E-10	7.7E-02					
4	1.3E-09	1.4E-01					
5	1.9E-09	1.8E-01					



Mixers Are Multipliers



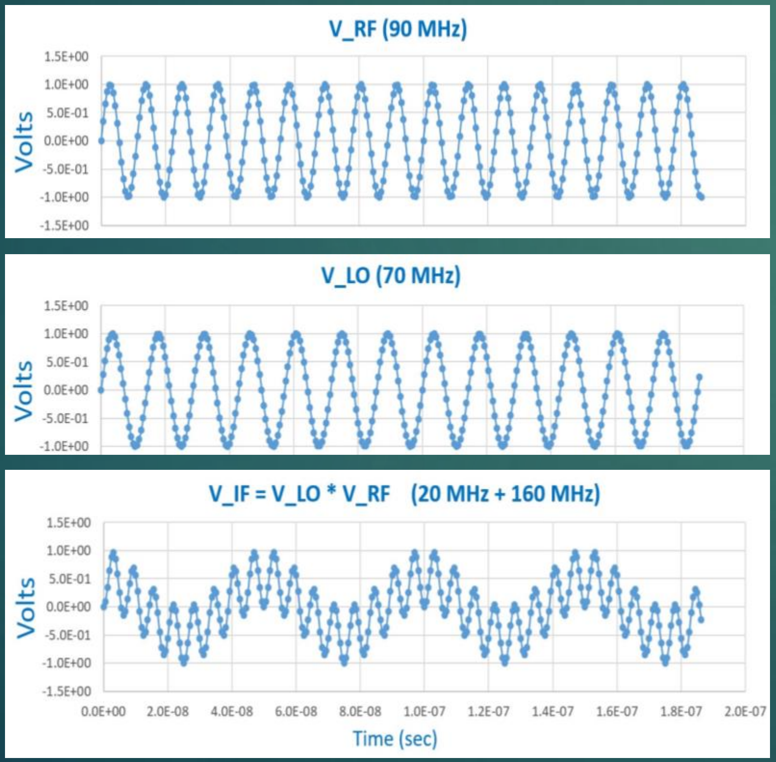
$$= v_{LO}(t)\, v_{RF}(t)$$

$$= [V_{LO}\, cos(2\pi f_{LO}\, t)]\; [V_{RF}\, cos(2\pi f_{RF}\, t + \theta_{RF})]$$

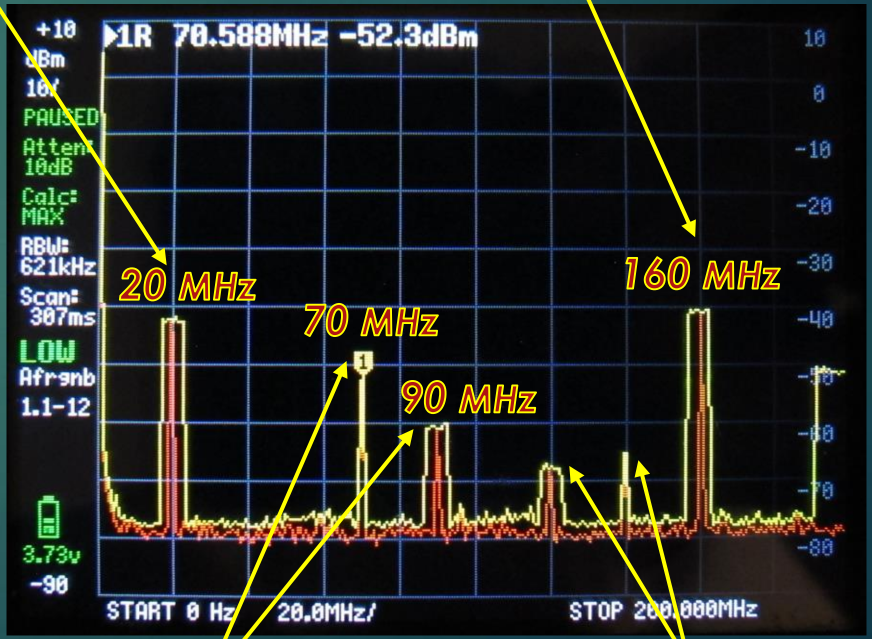
$$= \frac{1}{2} V_{LO} V_{RF}\, [cos(2\pi\, (f_{RF} - f_{LO})t + \theta_{RF}) + cos(2\pi\, (f_{RF} + f_{LO})t + \theta_{RF})]$$

"Downconverted Product" "Upconverted Product"

Time Domain



Frequency Domain

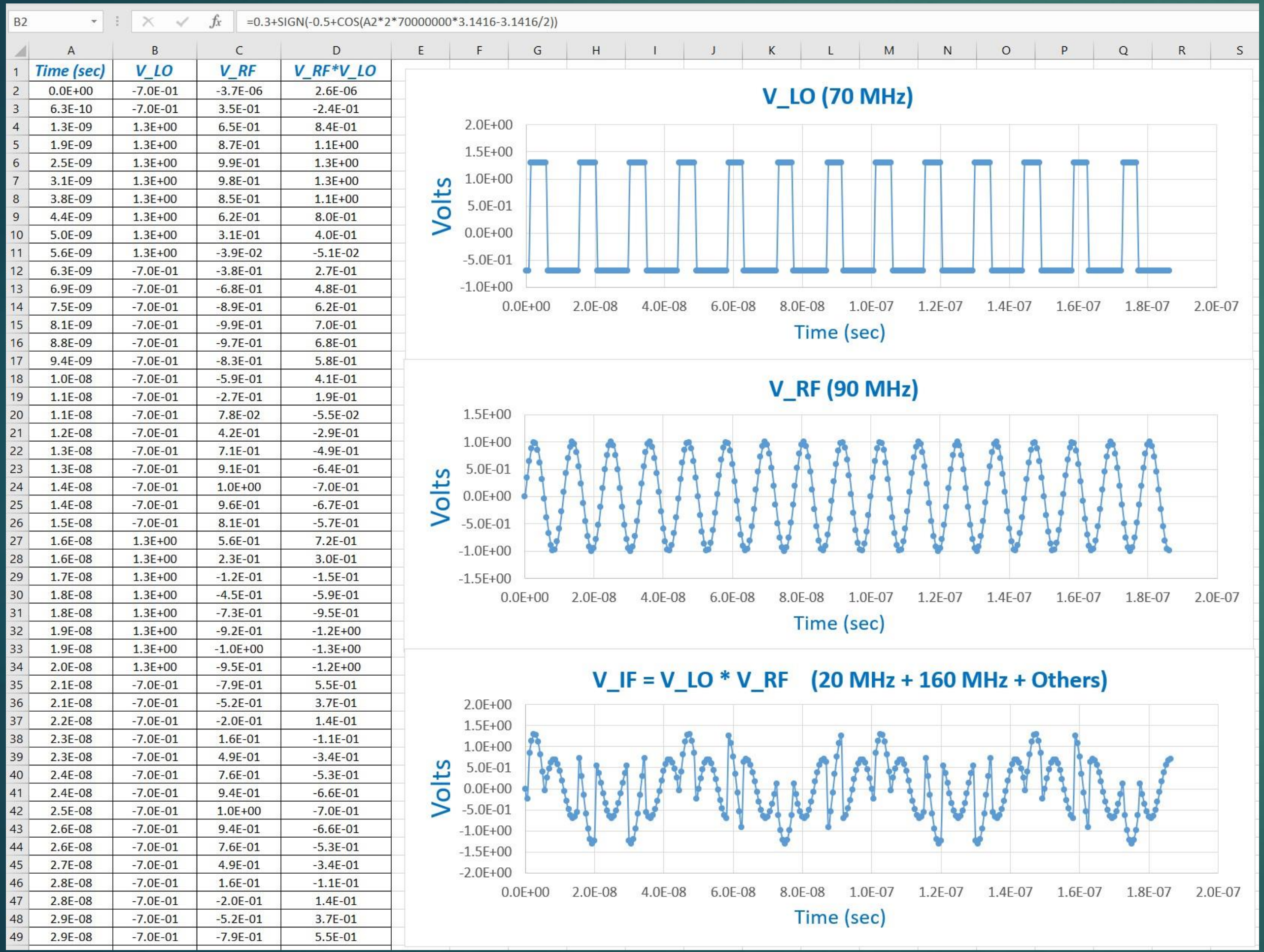


LO and RF "Feedthru"

? ?

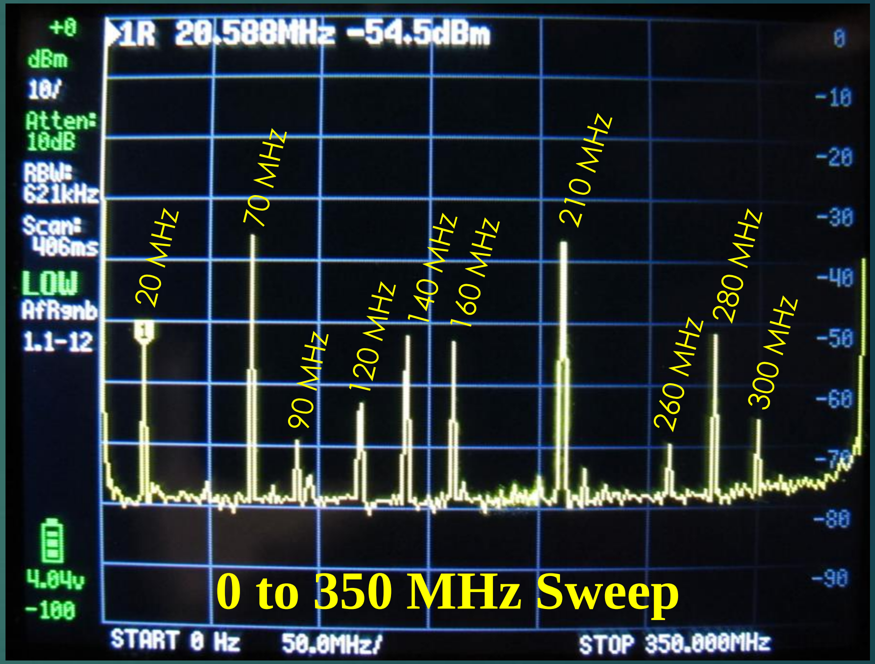
Real Mixers Multiply by Squarewaves

Time Domain


B2 =0.3+SIGN(-0.5+COS(A2*2*70000000*3.1416-3.1416/2))

	Time (sec)	V_LO	V_RF	V_RF*V_LO
2	0.0E+00	-7.0E-01	-3.7E-06	2.6E-06
3	6.3E-10	-7.0E-01	3.5E-01	-2.4E-01
4	1.3E-09	1.3E+00	6.5E-01	8.4E-01
5	1.9E-09	1.3E+00	8.7E-01	1.1E+00
6	2.5E-09	1.3E+00	9.9E-01	1.3E+00
7	3.1E-09	1.3E+00	9.8E-01	1.3E+00
8	3.8E-09	1.3E+00	8.5E-01	1.1E+00
9	4.4E-09	1.3E+00	6.2E-01	8.0E-01
10	5.0E-09	1.3E+00	3.1E-01	4.0E-01
11	5.6E-09	1.3E+00	-3.9E-02	-5.1E-02
12	6.3E-09	-7.0E-01	-3.8E-01	2.7E-01
13	6.9E-09	-7.0E-01	-6.8E-01	4.8E-01
14	7.5E-09	-7.0E-01	-8.9E-01	6.2E-01
15	8.1E-09	-7.0E-01	-9.9E-01	7.0E-01
16	8.8E-09	-7.0E-01	-9.7E-01	6.8E-01
17	9.4E-09	-7.0E-01	-8.3E-01	5.8E-01
18	1.0E-08	-7.0E-01	-5.9E-01	4.1E-01
19	1.1E-08	-7.0E-01	-2.7E-01	1.9E-01
20	1.1E-08	-7.0E-01	7.8E-02	-5.5E-02
21	1.2E-08	-7.0E-01	4.2E-01	-2.9E-01
22	1.3E-08	-7.0E-01	7.1E-01	-4.9E-01
23	1.3E-08	-7.0E-01	9.1E-01	-6.4E-01
24	1.4E-08	-7.0E-01	1.0E+00	-7.0E-01
25	1.4E-08	-7.0E-01	9.6E-01	-6.7E-01
26	1.5E-08	-7.0E-01	8.1E-01	-5.7E-01
27	1.6E-08	1.3E+00	5.6E-01	7.2E-01
28	1.6E-08	1.3E+00	2.3E-01	3.0E-01
29	1.7E-08	1.3E+00	-1.2E-01	-1.5E-01
30	1.8E-08	1.3E+00	-4.5E-01	-5.9E-01
31	1.8E-08	1.3E+00	-7.3E-01	-9.5E-01
32	1.9E-08	1.3E+00	-9.2E-01	-1.2E+00
33	1.9E-08	1.3E+00	-1.0E+00	-1.3E+00
34	2.0E-08	1.3E+00	-9.5E-01	-1.2E+00
35	2.1E-08	-7.0E-01	-7.9E-01	5.5E-01
36	2.1E-08	-7.0E-01	-5.2E-01	3.7E-01
37	2.2E-08	-7.0E-01	-2.0E-01	1.4E-01
38	2.3E-08	-7.0E-01	1.6E-01	-1.1E-01
39	2.3E-08	-7.0E-01	4.9E-01	-3.4E-01
40	2.4E-08	-7.0E-01	7.6E-01	-5.3E-01
41	2.4E-08	-7.0E-01	9.4E-01	-6.6E-01
42	2.5E-08	-7.0E-01	1.0E+00	-7.0E-01
43	2.6E-08	-7.0E-01	9.4E-01	-6.6E-01
44	2.6E-08	-7.0E-01	7.6E-01	-5.3E-01
45	2.7E-08	-7.0E-01	4.9E-01	-3.4E-01
46	2.8E-08	-7.0E-01	1.6E-01	-1.1E-01
47	2.8E-08	-7.0E-01	-2.0E-01	1.4E-01
48	2.9E-08	-7.0E-01	-5.2E-01	3.7E-01
49	2.9E-08	-7.0E-01	-7.9E-01	5.5E-01

Frequency Domain



$$f_{IF} = | \pm N f_{RF} \pm M f_{LO} |$$

Usually, N = 0, 1 and M = 0, 1, 2, 3, 4, 5, …

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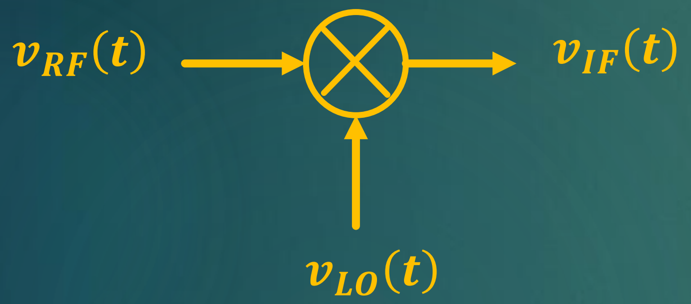
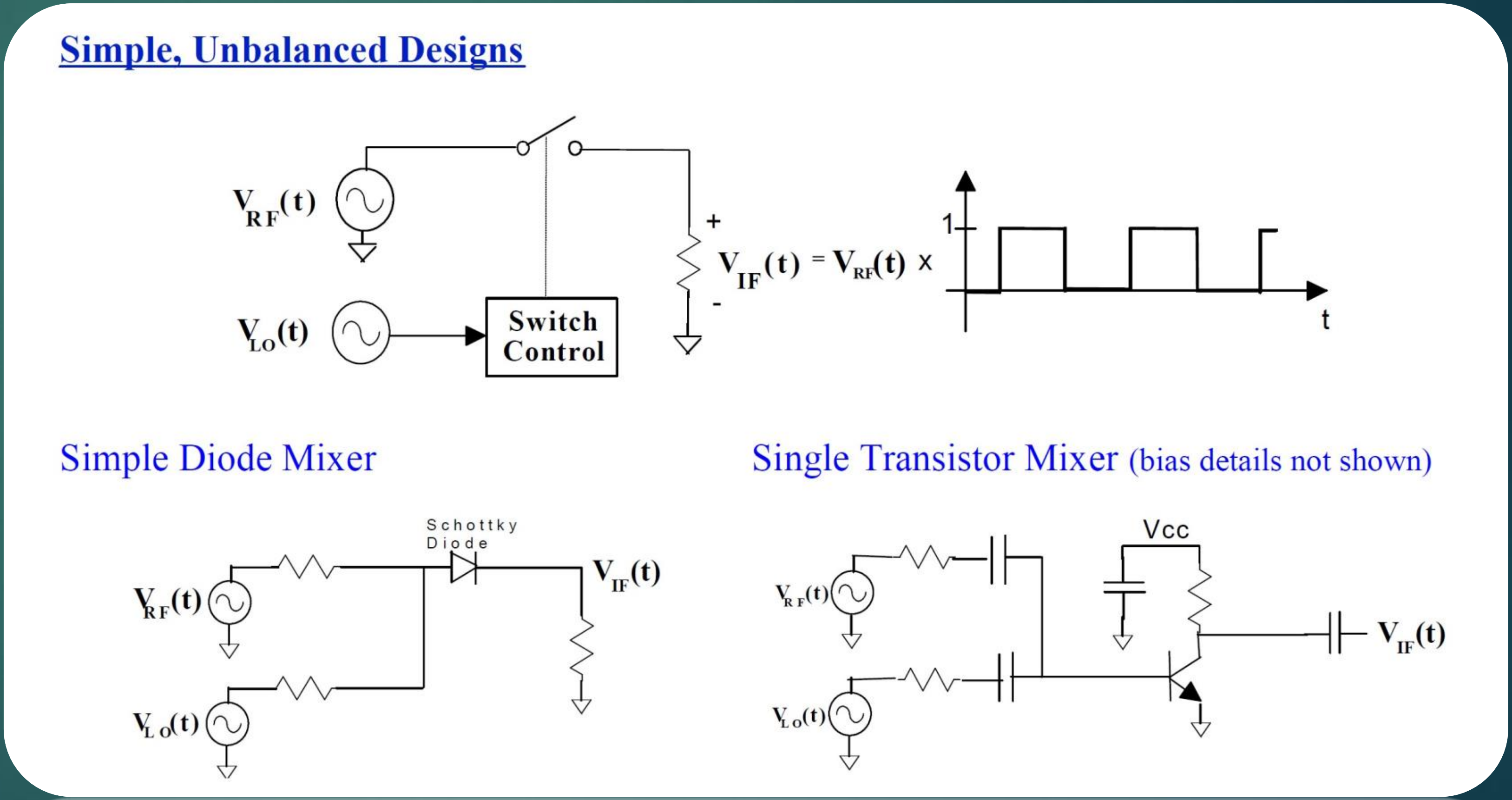
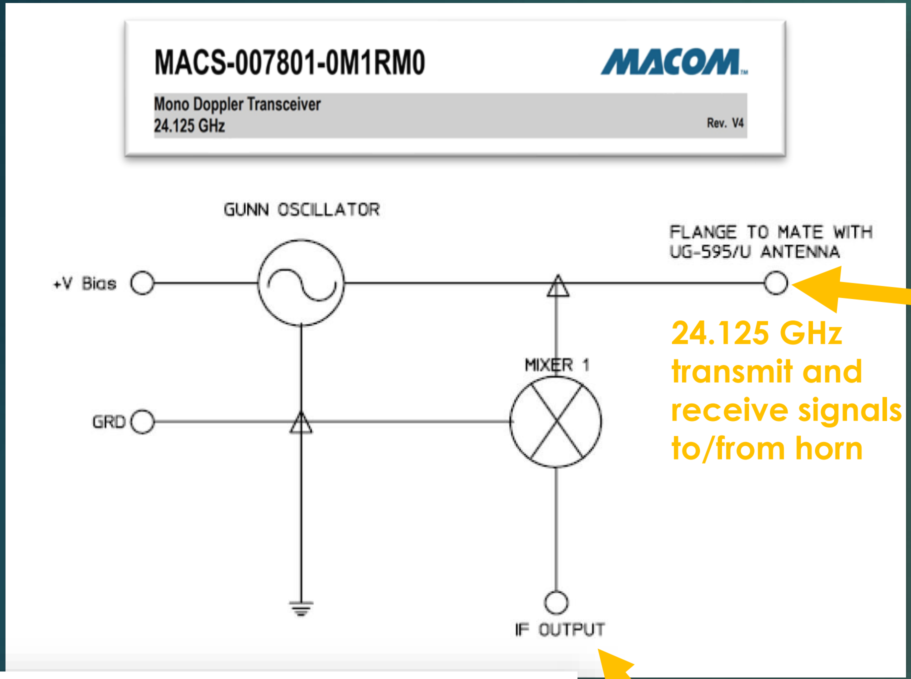
Mixer Circuits

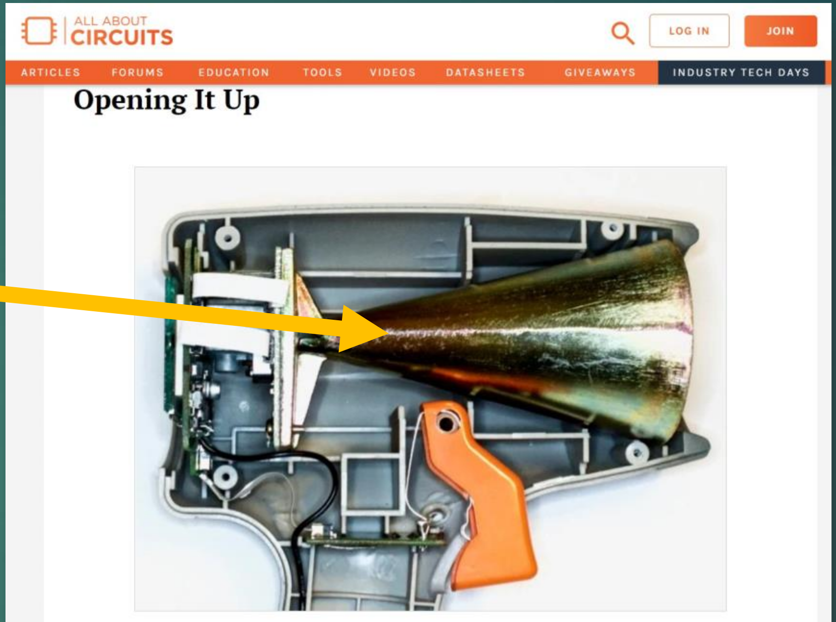




24 GHz Doppler Radar with Simple Diode Mixer



24.125 GHz transmit and receive signals to/from horn



The opened up radar gun

The Bushnell Velocity Speed Gun

Product Specifications

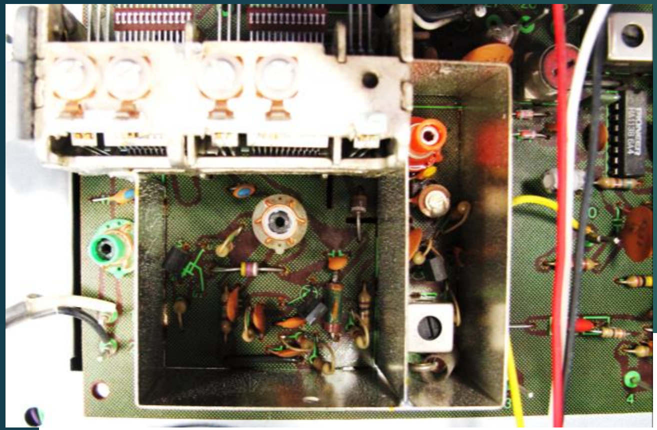
Parameter	Test Conditions	Units	Min.	Typ.	Max.
Operating Frequency	+25 °C	GHz	24.100	24.125	24.150
Output Power	+25 °C	mW	5.0		
Operating Current	+25 °C	mA	60	85	100
Operating Voltage	+25 °C	VDC		5.0	
Schottky Diode Noise	+25 °C	micro-Volts		2.5	5.0
Transceiver Sensitivity	+25 °C	-dBc	-93	-103	

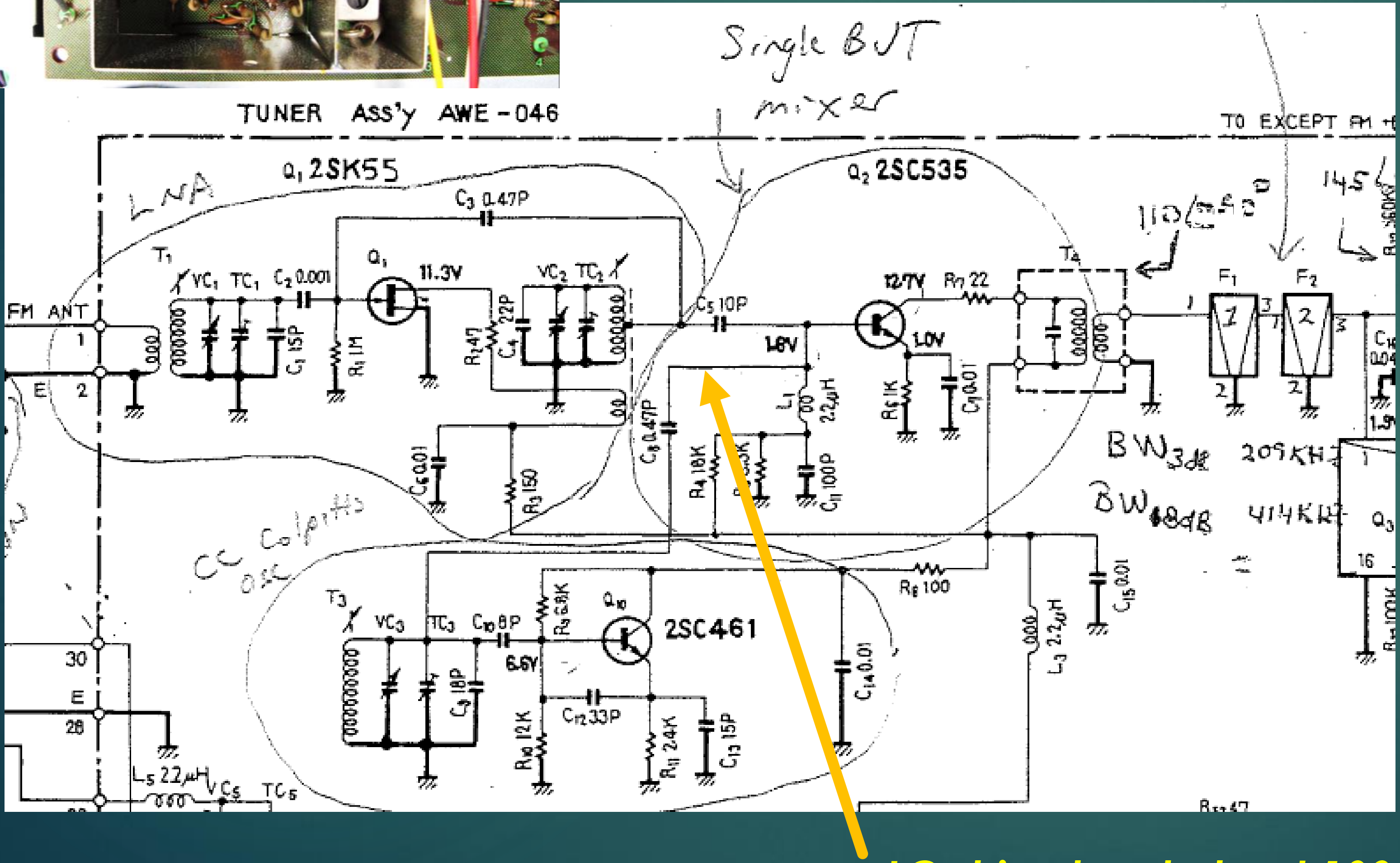
https://www.allaboutcircuits.com/news/teardown-tuesday-radar-gun/

Doppler audio (10Hz to 5 kHz) to LPF, amps, ADC, microcontroller/DSP, and display

http://cdn.macom.com/datasheets/MACS-007801-0M1RM0.pdf

BJT Mixer in FM Receiver



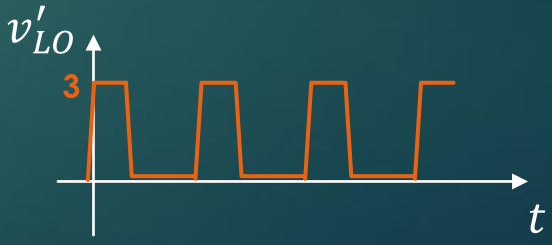


LO drive level about 100 mV peak

$$i_c = I_o\, e^{\frac{1}{nV_T}[V_{BE}+k_1 v_{LO}+k_2 v_{RF}]}$$

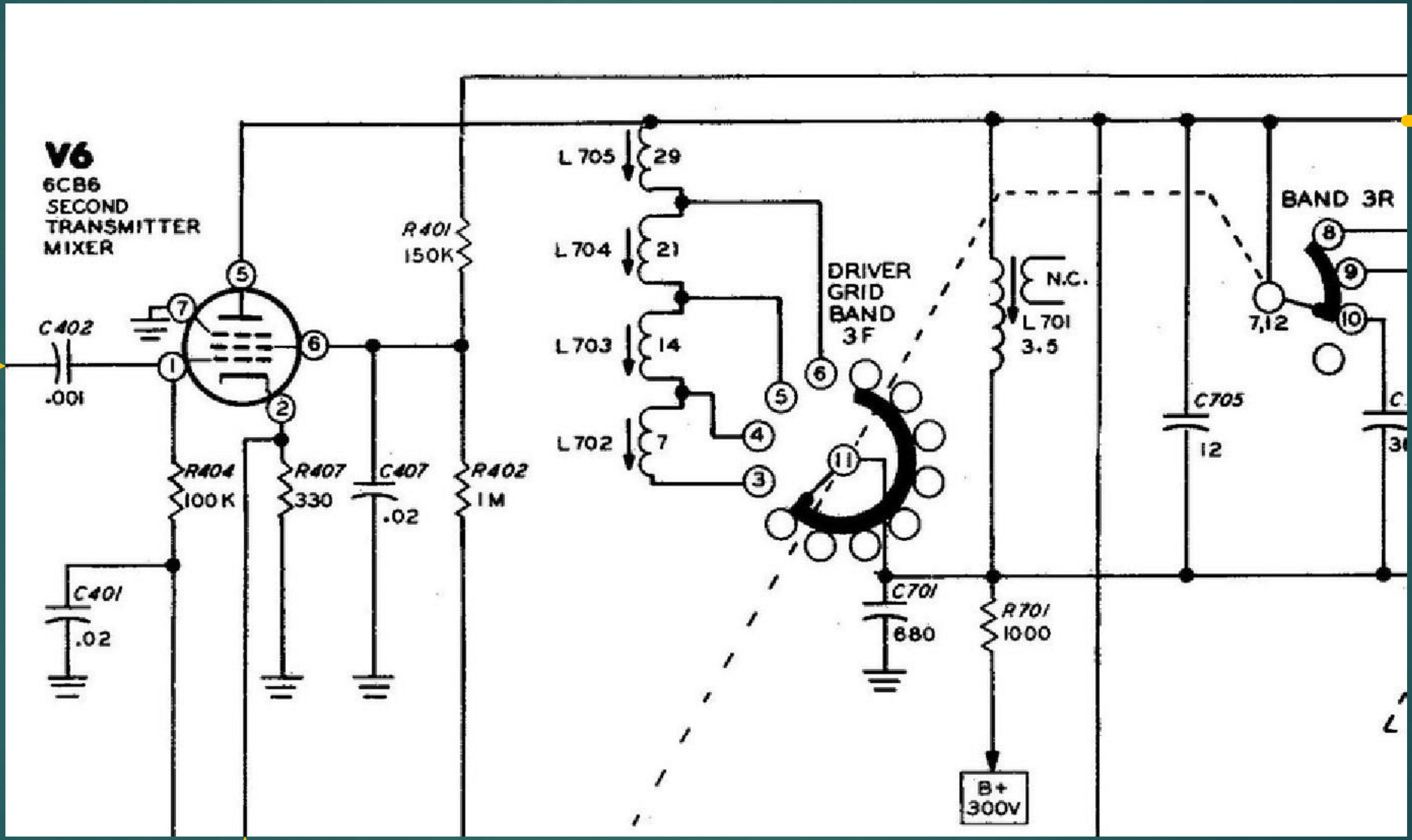
$$i_c(t) \approx I_{BIAS}\; v'_{LO}(t)\left[1+\frac{1}{nV_T}k_2 v_{RF}(t)\right]$$

$$= I_{BIAS}\, v'_{LO}(t) + [g_m v'_{LO}(t) k_2 v_{RF}(t)]$$



Pentode Mixer in SB-102 Transceiver

From modulator and first TX mixer

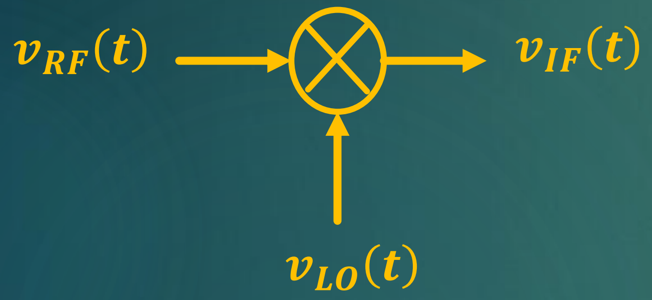


To driver and final amplifiers

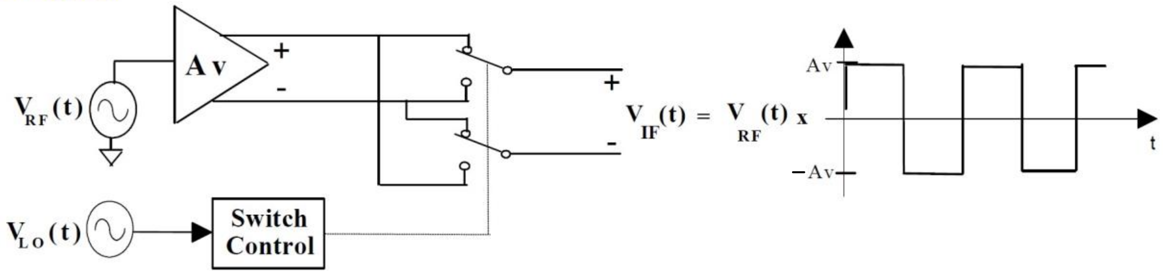
LO from V19 crystal oscillator

LO drive level about 1 to 2V peak

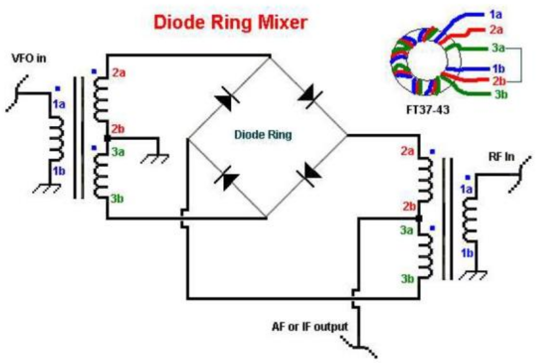
Mixer Circuits



Balanced Designs

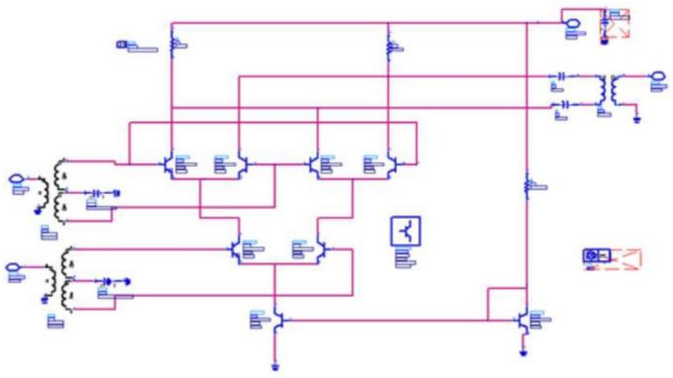


Diode Ring Mixer



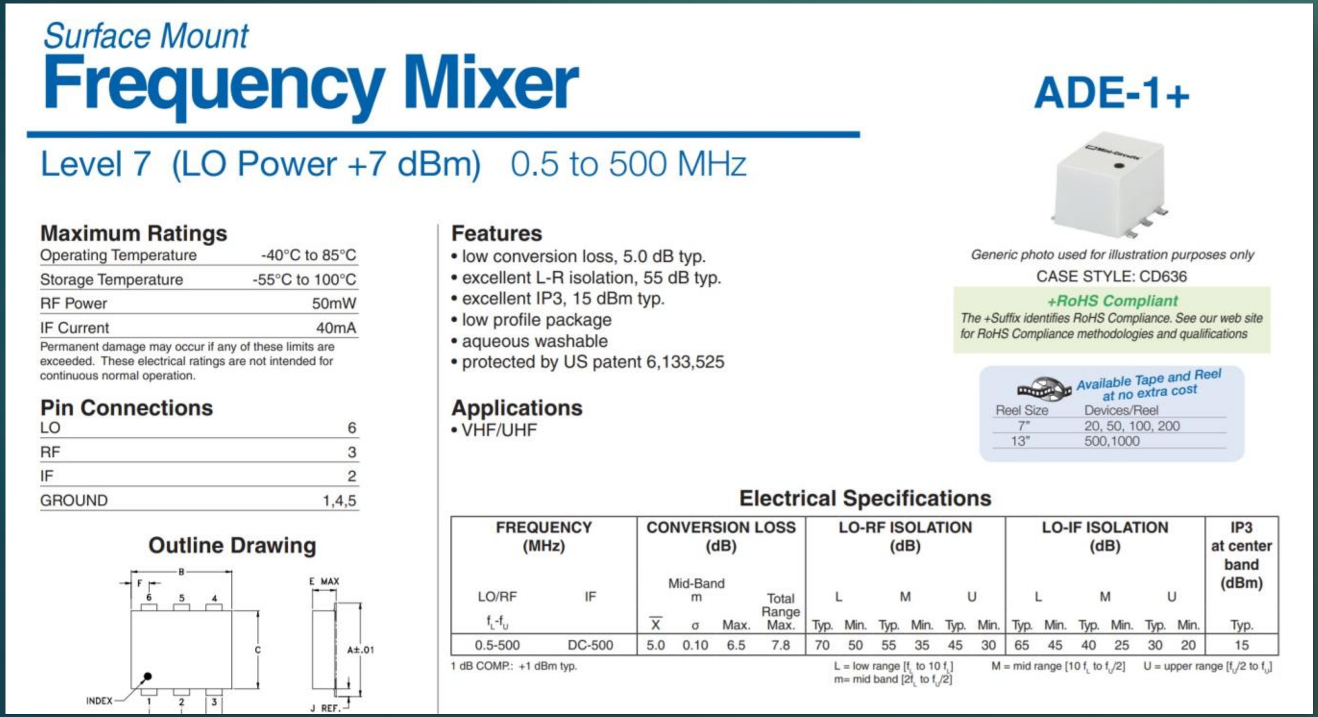
http://www.qrp.pops.net/images/2008/2008-larger/big_dbm.gif

Gilbert Cell



http://edocs.soco.agilent.com/download

Diode Ring Mixers



Surface Mount

Frequency Mixer

ADE-1+

Level 7 (LO Power +7 dBm) 0.5 to 500 MHz

Generic photo used for illustration purposes only

CASE STYLE: CD636

+RoHS Compliant

The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Available Tape and Reel at no extra cost

Reel Size	Devices/Reel
7"	20, 50, 100, 200
13"	500,1000

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
RF Power	50mW
IF Current	40mA

Permanent damage may occur if any of these limits are exceeded. These electrical ratings are not intended for continuous normal operation.

Pin Connections

LO	6
RF	3
IF	2
GROUND	1,4,5

Outline Drawing

Features

- low conversion loss, 5.0 dB typ.
- excellent L-R isolation, 55 dB typ.
- excellent IP3, 15 dBm typ.
- low profile package
- aqueous washable
- protected by US patent 6,133,525

Applications

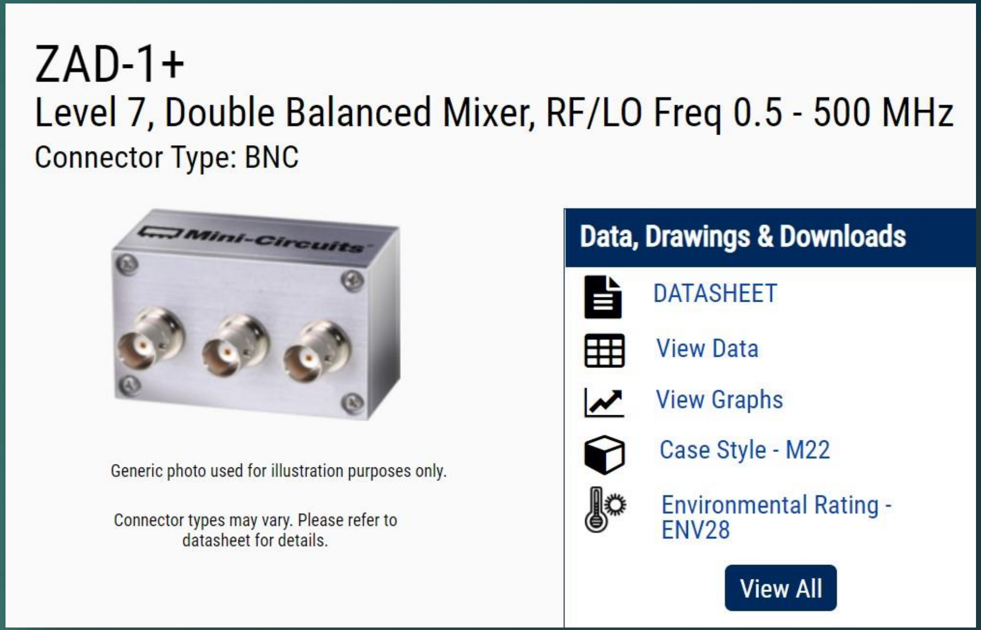
- VHF/UHF

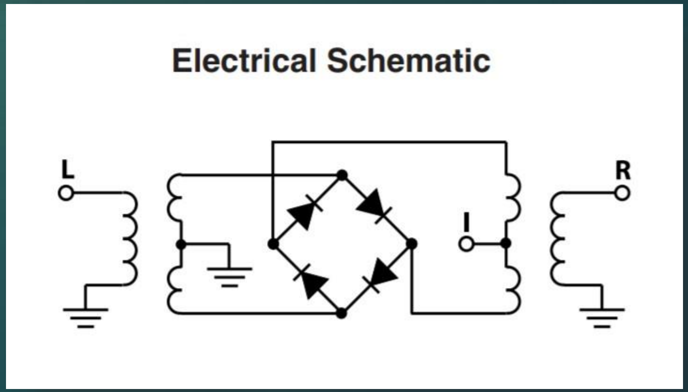
Electrical Specifications

FREQUENCY (MHz)		CONVERSION LOSS (dB)				LO-RF ISOLATION (dB)						LO-IF ISOLATION (dB)						IP3 at center band (dBm)
LO/RF	IF	Mid-Band m			Total Range	L		M		U		L		M		U		
f_L-f_U		$\overline{X}$	σ	Max.	Max.	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.
0.5-500	DC-500	5.0	0.10	6.5	7.8	70	50	55	35	45	30	65	45	40	25	30	20	15

1 dB COMP.: +1 dBm typ.

L = low range [f_L to 10 f_L] M = mid range [10 f_L to f_U/2] U = upper range [f_U/2 to f_U]
m= mid band [2f_L to f_U/2]





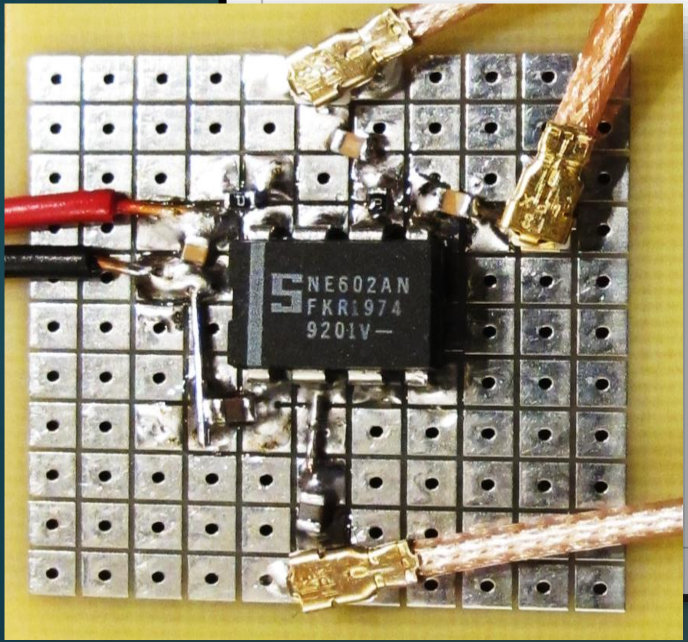
LO drive level +4 to +10 dBm

NE/SA602 Gilbert Cell IC Mixer

Philips Semiconductors — Product specification

Double-balanced mixer and oscillator — SA602A

BLOCK DIAGRAM



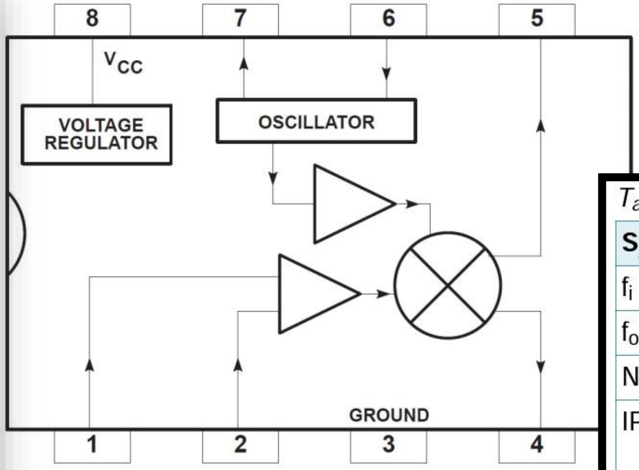


Figure 2. Block Diagram

T_{amb} = 25 °C; V_{CC} = +6 V; unless specified otherwise.

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_i	input frequency		-	500	-	MHz
f_{osc}	oscillator frequency		-	200	-	MHz
NF	noise figure	at 45 MHz	-	5.0	5.5	dB
$IP3_i$	input third-order intercept point	RF input = −45 dBm; RF1 = 45.0 MHz; RF2 = 45.06 MHz	-	−13	−15	dBm
G_{conv}	conversion gain	at 45 MHz	14	17	-	dB
$R_{i(RF)}$	RF input resistance		1.5	-	-	kΩ
$C_{i(RF)}$	RF input capacitance		-	3	3.5	pF
$R_{o(mix)}$	mixer output resistance	OUT_A, OUT_B pins	-	1.5	-	kΩ

SA602A Datasheet Info

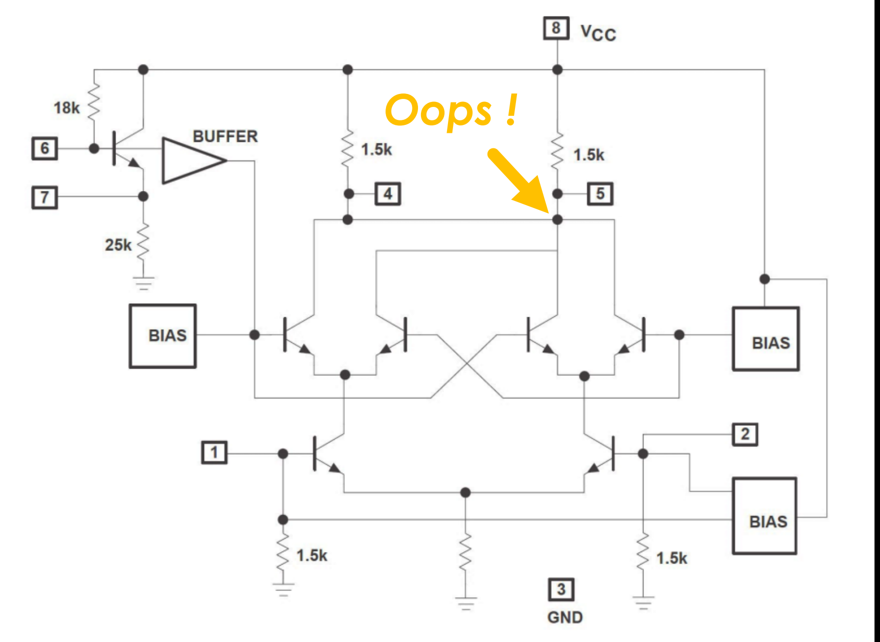
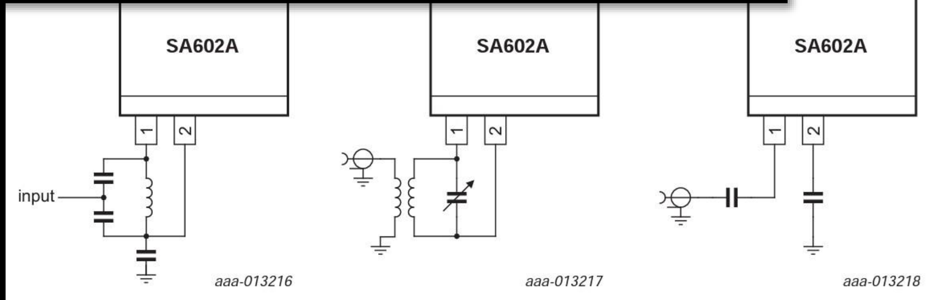


Figure 4. Equivalent Circuit

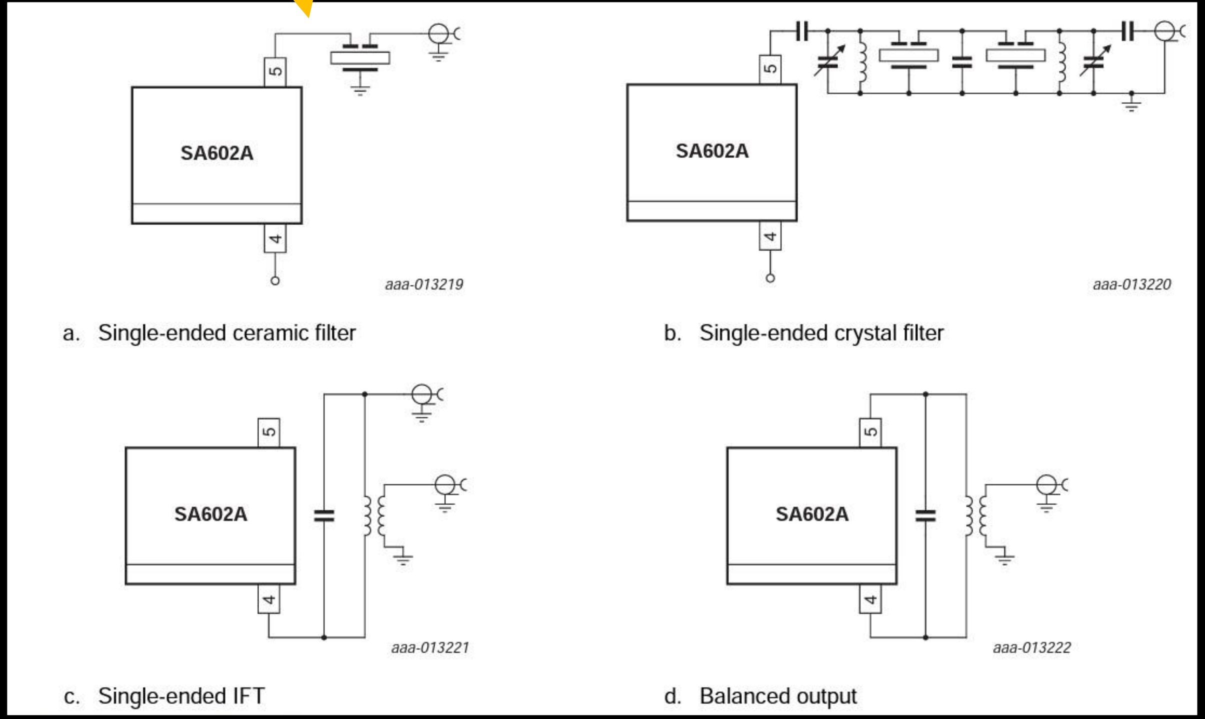


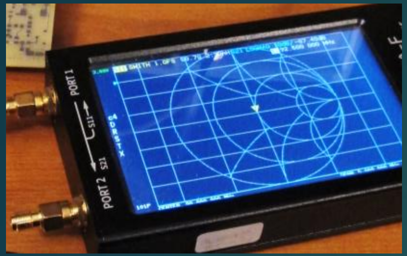
a. Single-ended tuned input

b. Balanced input (for attenuation of second-order products)

c. Single-ended untuned input

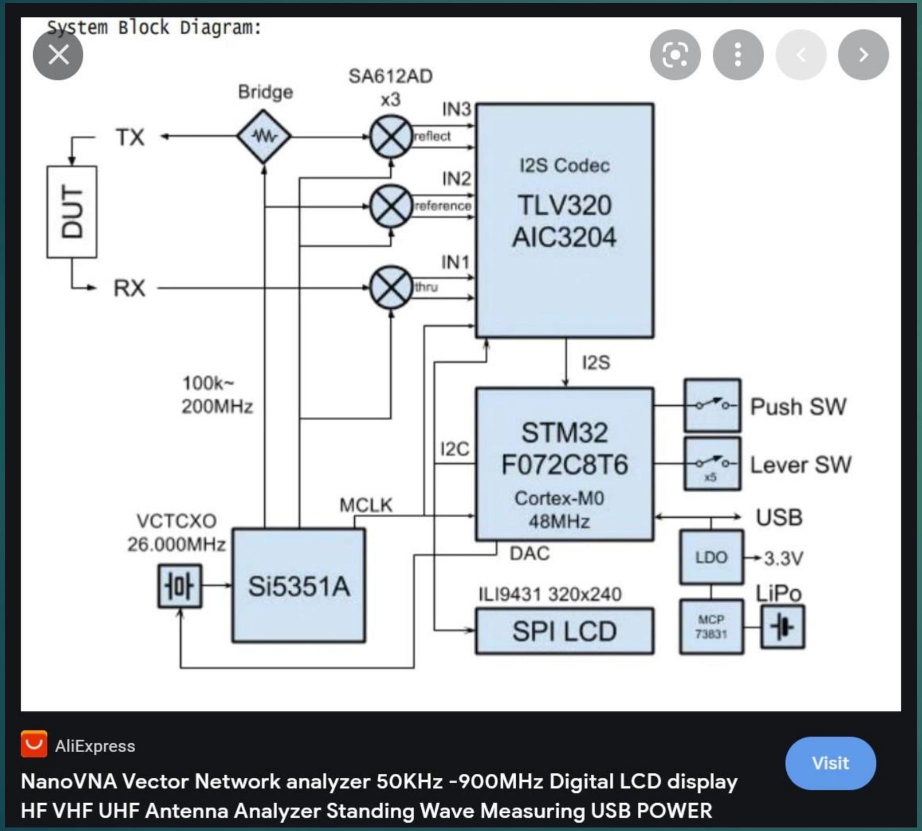
Add 1.5K to 300 Ohm matching for typical 10.7 MHz IF filters





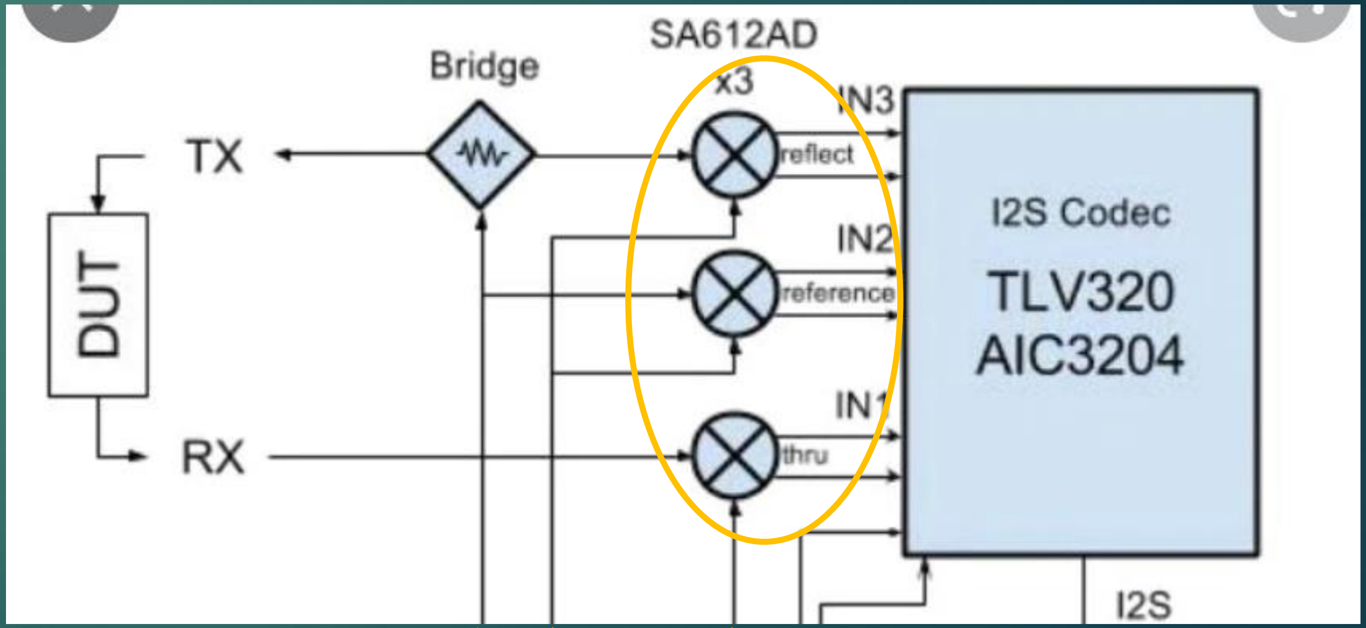
Mixers Used in NanoVNA

NanoVNA uses an "ultra-low IF" receiver architecture…



https://www.aliexpress.com/item/33011709985.html

3 receiver channels



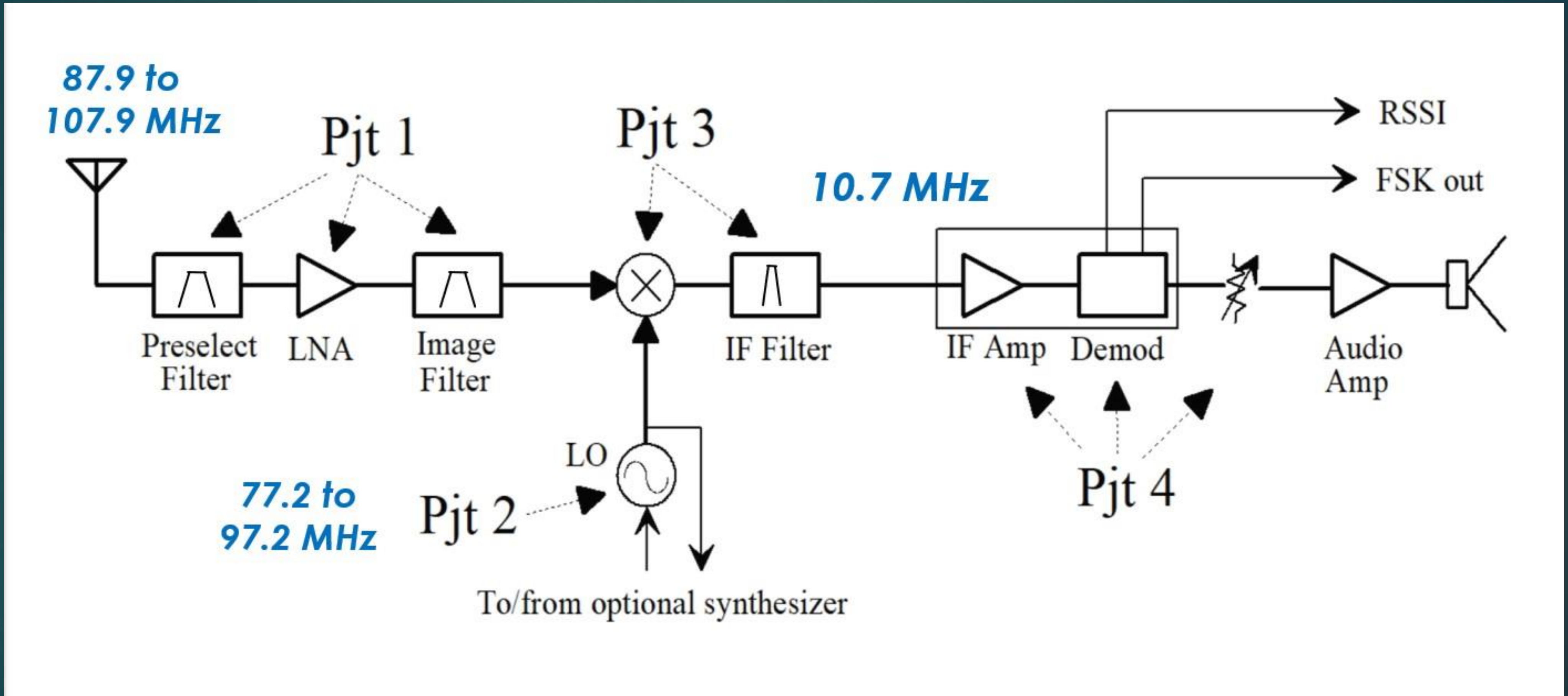
fo **fo + 5 kHz**

(Low Band)

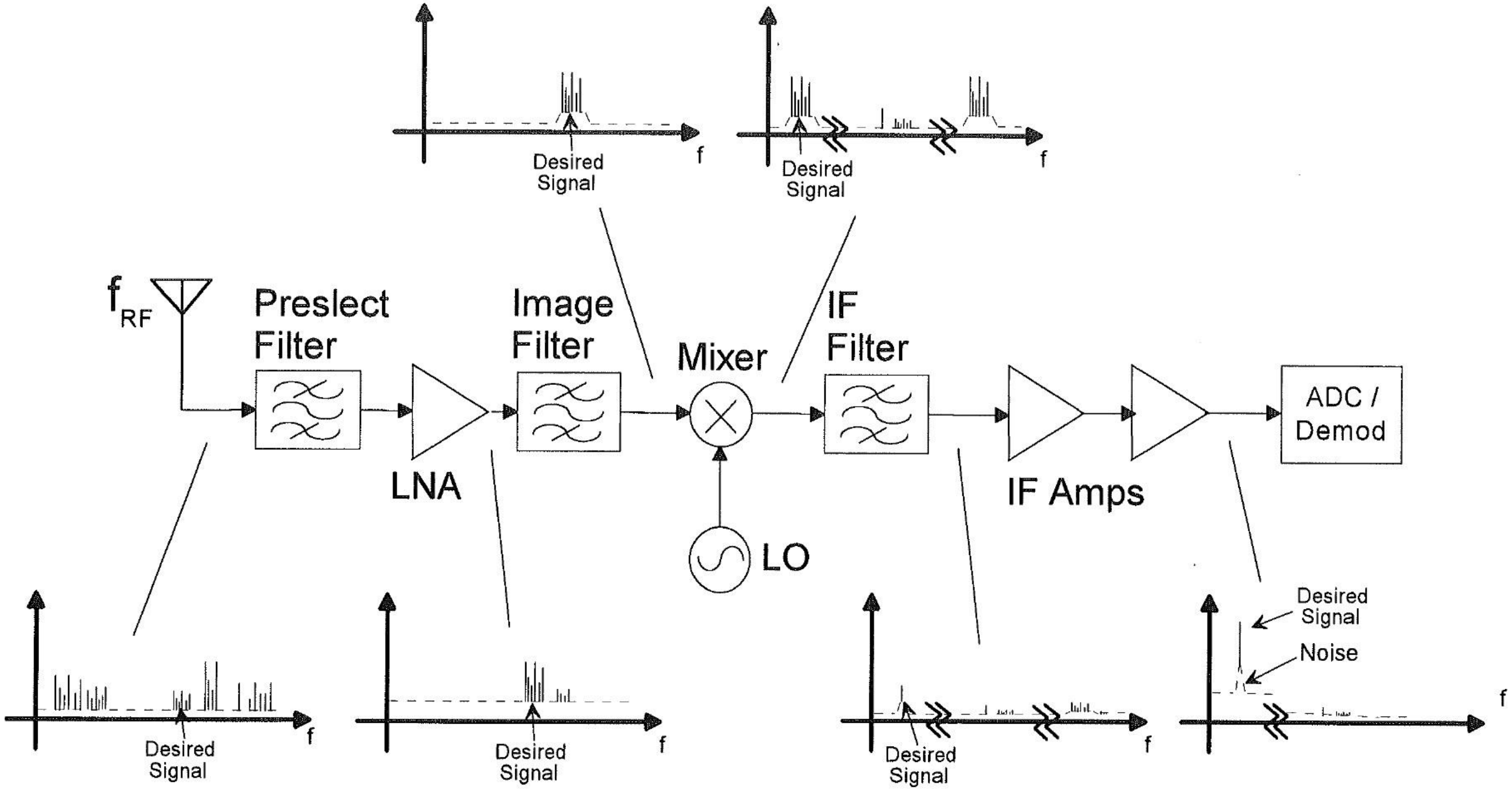
Topic Outline

- ***A Quick Math Review / Description***
- ***Mixer Circuit Designs***
- ***FM Receiver Mixer and Spectrums***

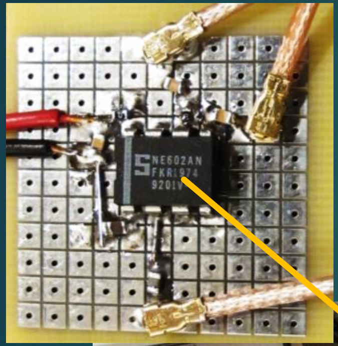
Recall Semester Project

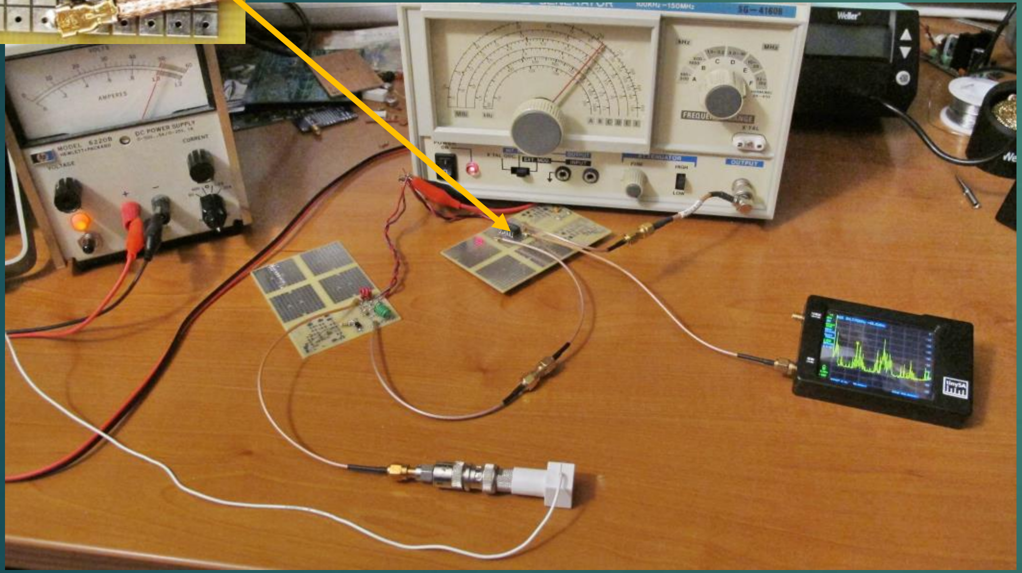


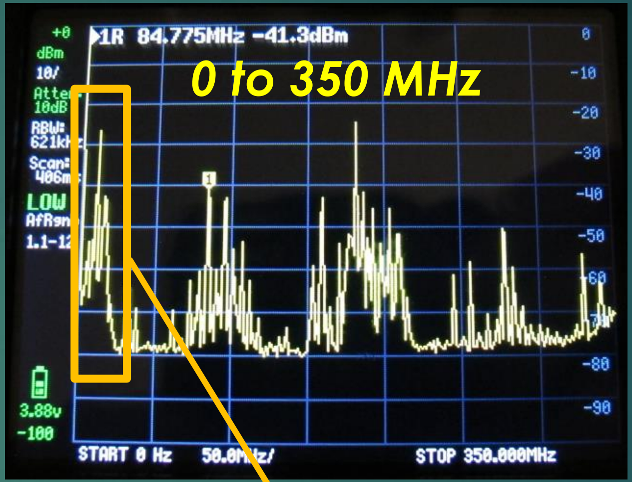
Superhet Receiver Spectrums

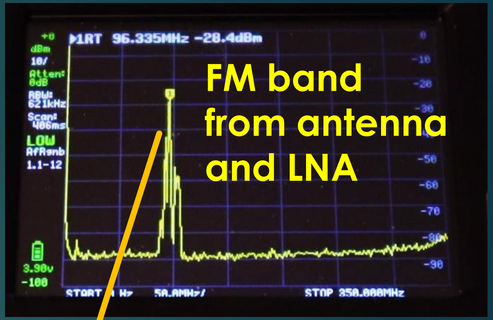


Down-converting the FM Band !

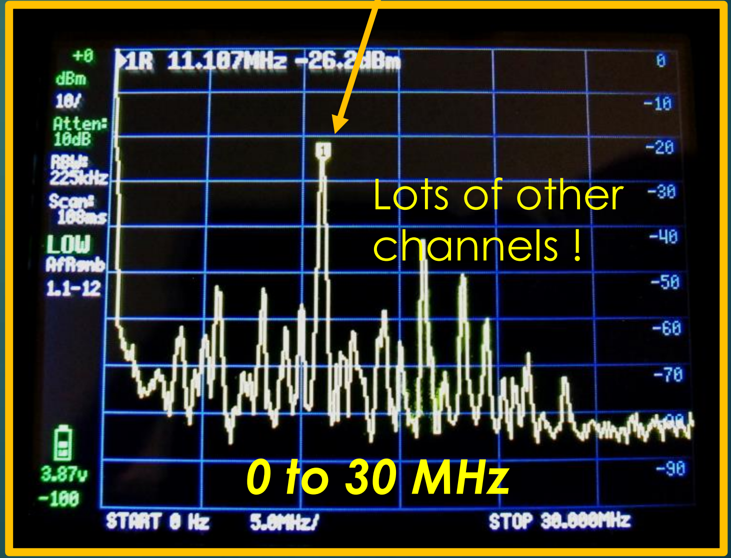






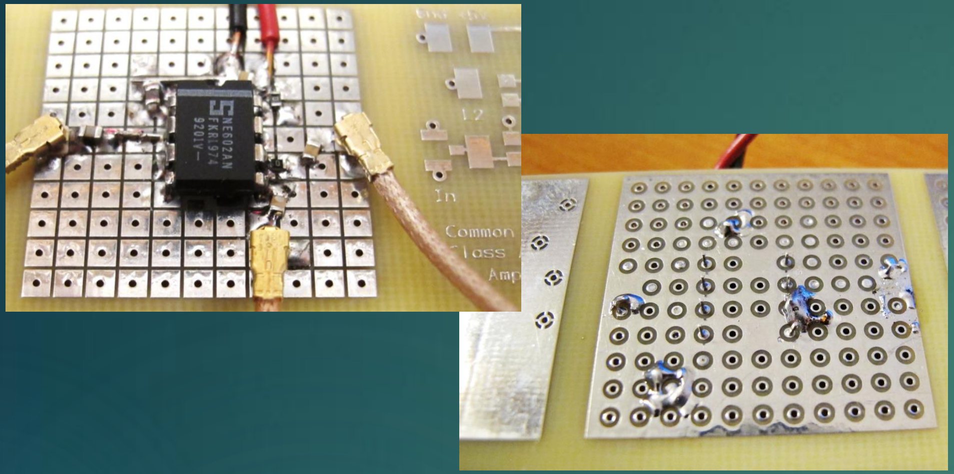


96 MHz is converted to 11 MHz



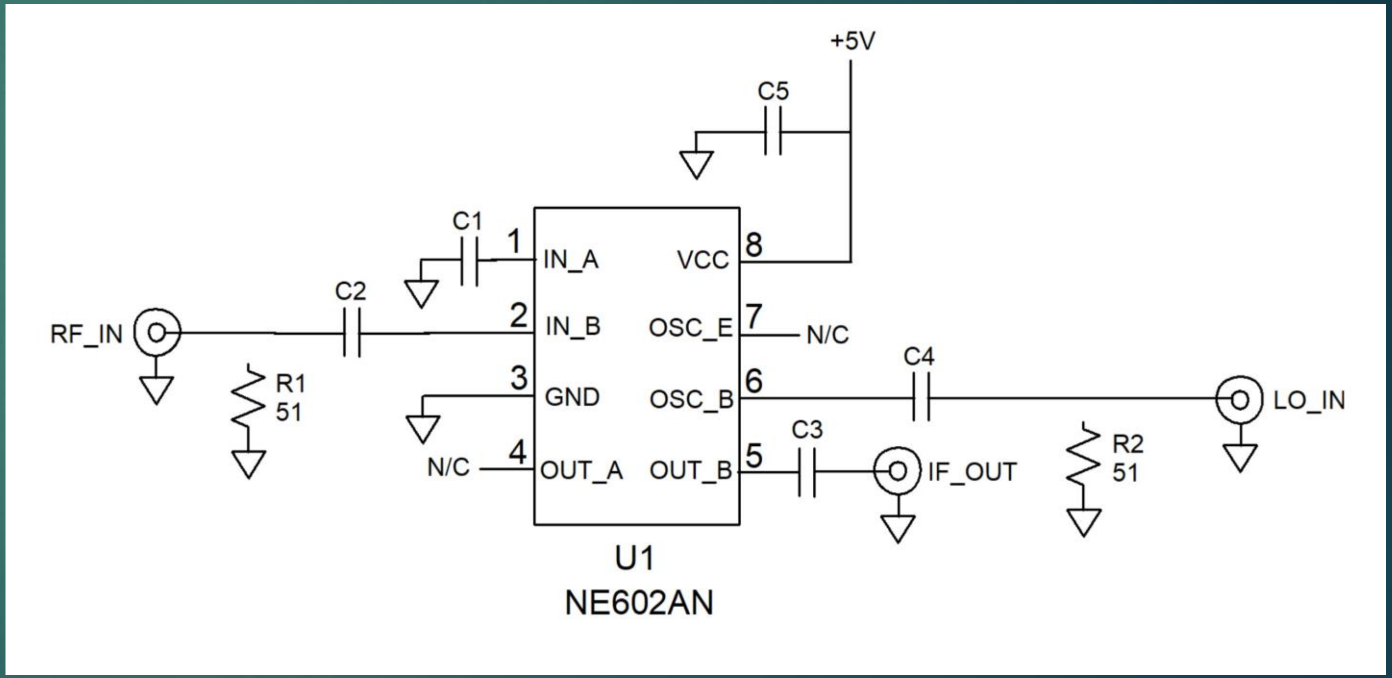
NOTE: IF filter not yet added and no matching networks used, so full IF output can be seen, at expense of low gain

TBDs



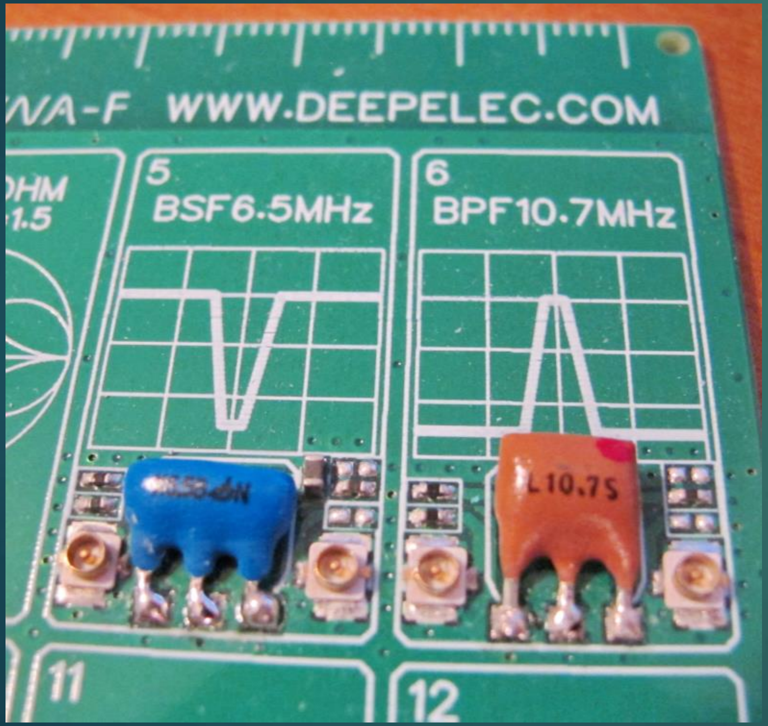
To Be Done (TBDs):

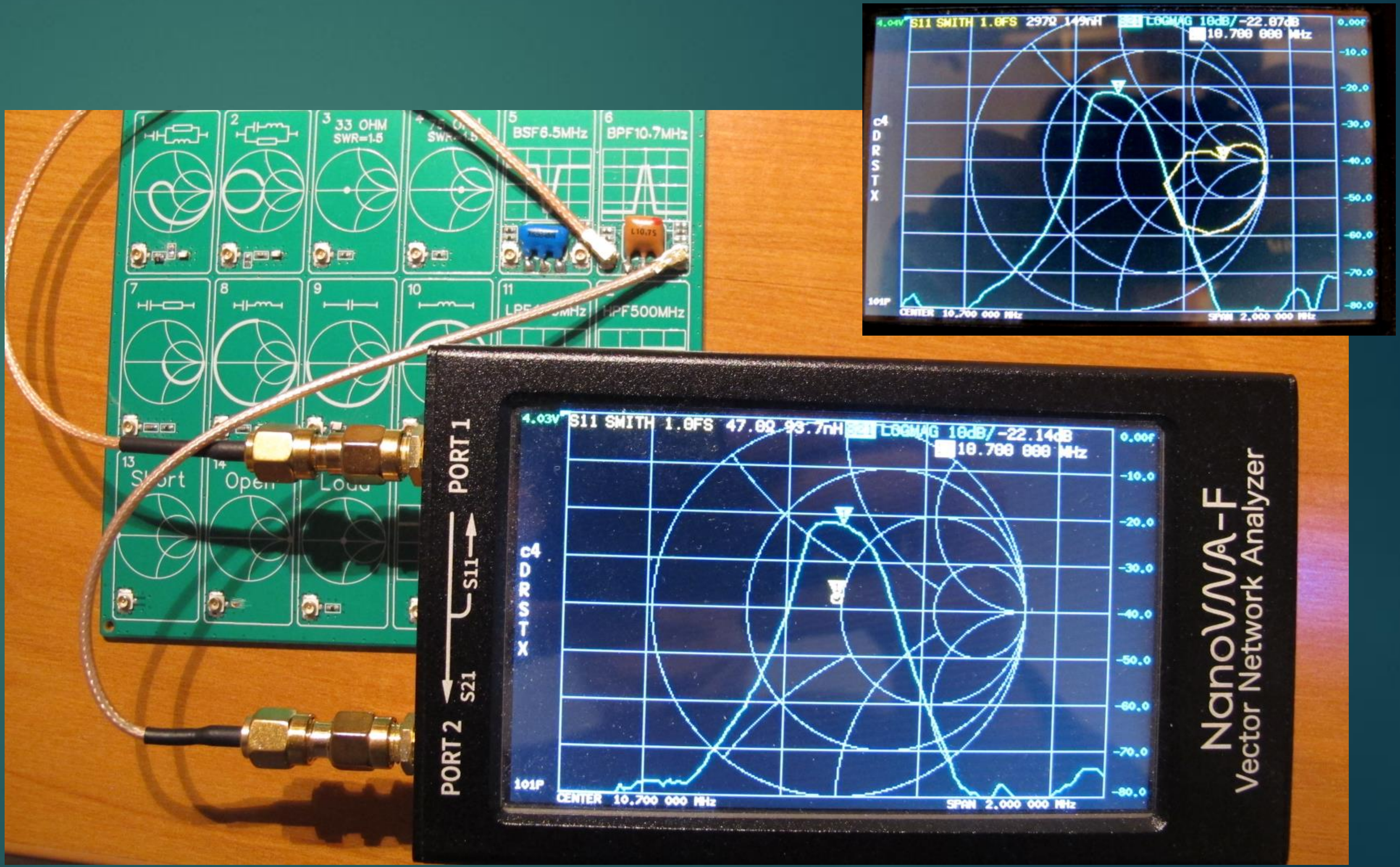
- **Add IF filter at output**
- **Add matching networks at RF and IF ports of mixer**
- **Do project 4 (IF amp, demod, and audio amp)**
- **Order some parts ☺**



Piezo-electric IF Filters

10.7 MHz Center, 200 kHz/div horz, 10dB/div vert





SMD IF Filters

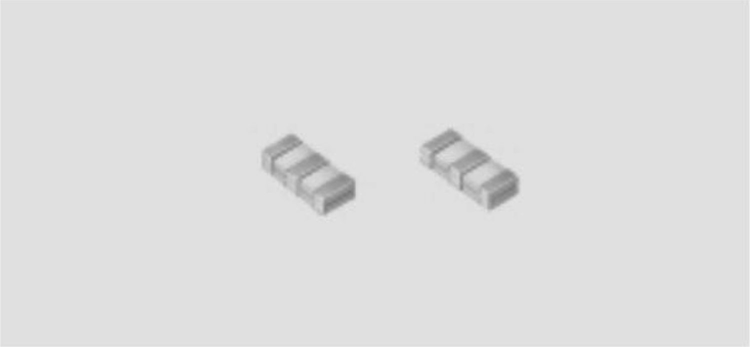
Test with 4:1 impedance transformers

PIEZO FILTERS

SURFACE MOUNTED CHIP PIEZOELECTRIC CERAMICS FILTERS FOR AM AND FM APPLICATIONS

SFECV 10.7MHz, SFECS 10.7MHz

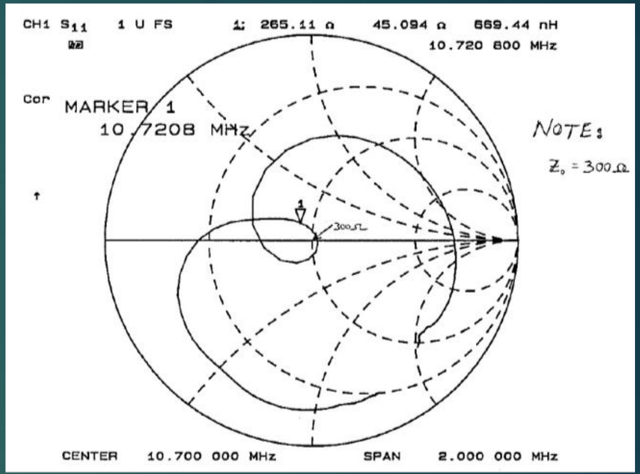
muRata
Innovator in Electronics

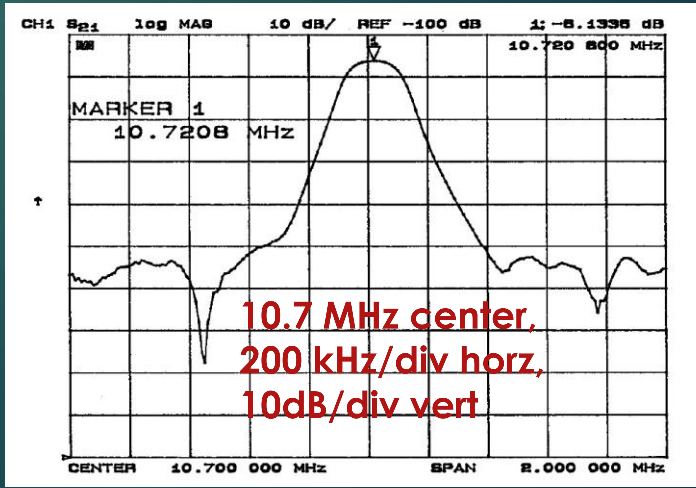


Along with the development of the AM chip filter, IF filters for AM/FM radios have also been made smaller, thinner and in a chip configuration for surface mounting. This is one more example of Murata Electronics' leadership in converting conventional electronic components to chip technology.

SPECIFICATIONS — **SFECV10.7**

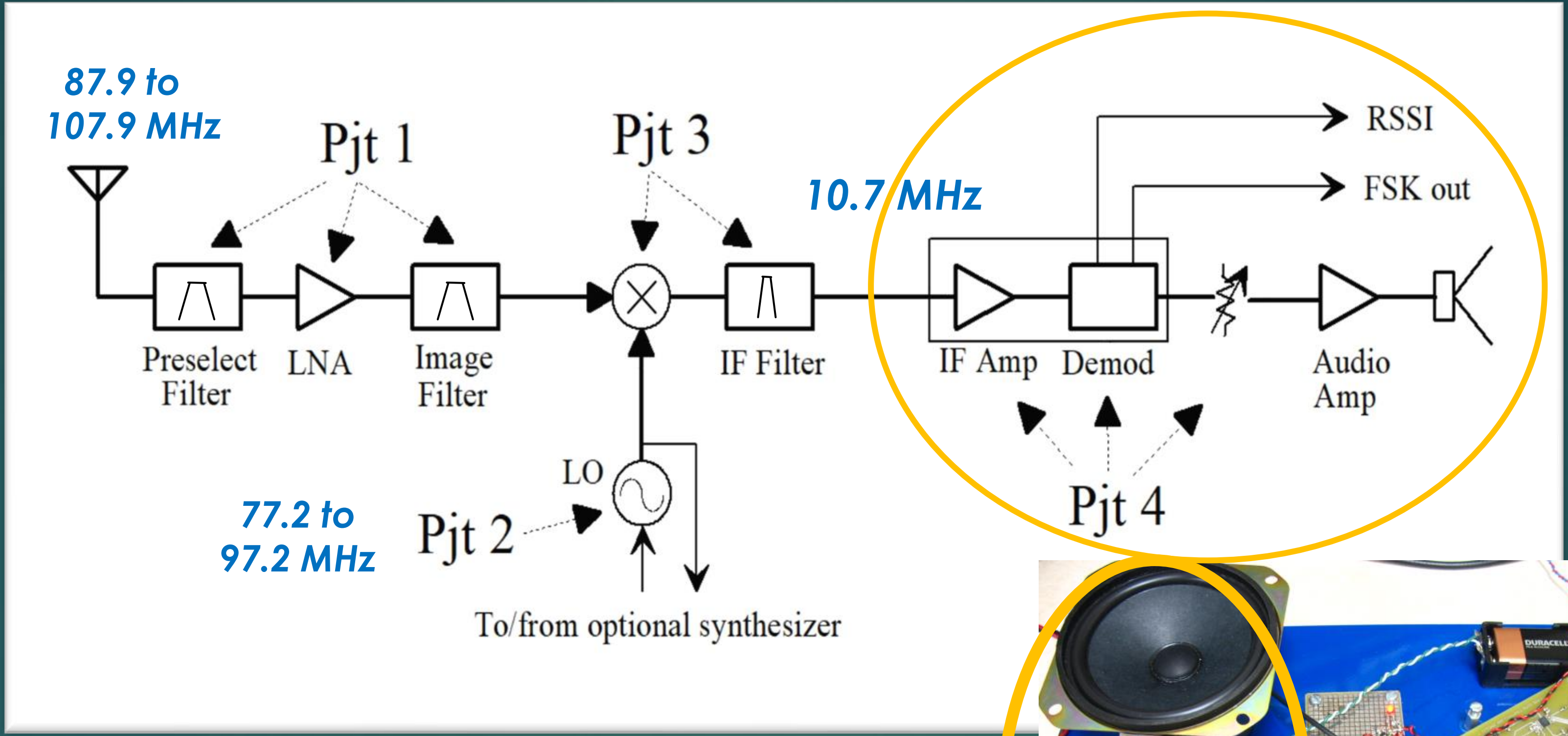
Part Number	Nominal Center Frequency (fn) (MHz)*	3dB Bandwidth from fn (kHz)	Spurious Attenuation min.	Insertion Loss at fn (dB) max.	Input/Output Impedance (Ohms)
SFECV10.7MA21S-TC	10.7	400 min.	20dB (10.7 to 15.0MHz)	3.0 ±2.0	470
SFECV10.7MA19S-TC	10.7	350 min.	20dB (10.7 to 15.0MHz)	3.0 ±2.0	470
SFECV10.7MA2S-A-TC	10.7	330 ± 50	30dB (9 to 12MHz)	4.0 ±2.0	330
SFECV10.7MA5S-A-TC	10.7	280 ± 50	35dB (9 to 12MHz)	3.0 ±2.0	330
SFECV10.7MS2S-A-TC	10.7	230 ± 50	35dB (9 to 12MHz)	3.5 ±2.0	330
SFECV10.7MS3S-A-TC	10.7	180 ± 40	35dB (9 to 12MHz)	4.0 ±2.0	330
SFECV10.7MJS-A-TC	10.7	150 ± 30	35dB (9 to 12MHz)	5.5 ±2.0	330
SFECV10.7MHS-A-TC	10.7	110 ± 30	35dB (9 to 12MHz)	6.0 ±2.0	330

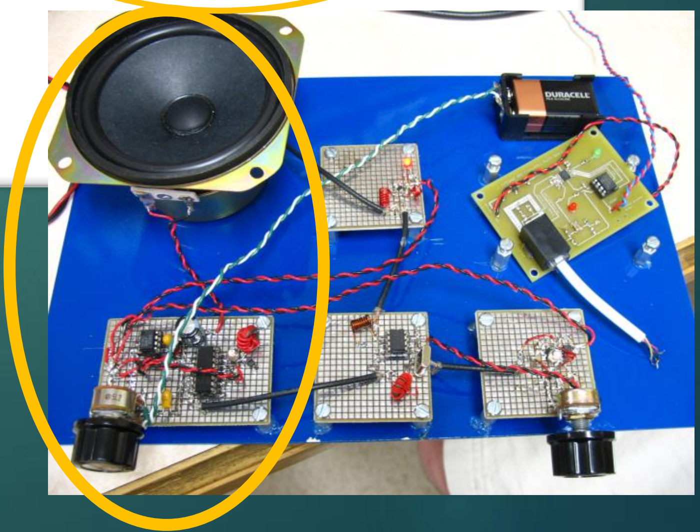




10.7 MHz center,
200 kHz/div horz,
10dB/div vert

Class Project - FM Broadcast Receiver





Project 4

IF Subsystem and Audio Amp

(Next Episode)

Thanks For Watching !