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

Mixer

\[ f_{RF} \rightarrow f_{RF} - f_{LO} \rightarrow \text{IF Filter} \rightarrow \text{Demod} \]

* \( f_{RF} + f_{LO} \) and other frequencies also, but filtered out

“Downconverted Product”
“Upconverted Product”

LO “Feedthru” 70 MHz
RF “Feedthru” 90 MHz

20 MHz
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 ...

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 😐

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

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

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!

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)
Frequency Conversion Demo

90 MHz 
+/ - 2.5 MHz

160 MHz

Mixer

LO

RF

IF

30 dB Attenuator

Classic NE/SA602 Mixer IC

90 MHz

20 MHz

70 MHz

160 MHz

"Downconverted Product"

"Upconverted Product"

LO "Feedthru"

RF "Feedthru"

30 dB Attenuator
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: $f_{LO} > f_{RF}$
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
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


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

![Diagram](image_url)
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
Up/Down Conversion Spectrums

(Low Band)

$f_c = 350 \text{ MHz}$

$f_o = 434 \text{ MHz}$
$\text{BW} = 600 \text{ kHz}$

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)

Zero-span mode at 100 MHz

NOTE:
0 dB attenuation setting used on both units
Radio Design 101
Episode 5

RF Mixers
(Part 2)
Frequency Conversion Demo

**Diagram:**
- **LO:** 90 MHz +/- 2.5 MHz
- **RF:** 160 MHz
- **IF:** 70 MHz
- **Mixer IC:** Classic NE/SA602
- **30 dB Attenuator**
- **20 MHz**
- **70 MHz**
- **160 MHz**

**Notes:**
- 1. 40 MHz
- 2. 100 MHz
- 3. 200 MHz
• A Quick Math Review / Description
• Mixer Circuit Designs
• FM Receiver Mixer and Spectrums
• A Quick Math Review / Description
• Mixer Circuit Designs
• FM Receiver Mixer and Spectrums
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 \( V_{RF} = 0.2 \), \( f_{RF} = 100\text{E6} \), and \( \theta_{RF} = -\frac{\pi}{2} \)
(i.e. 0.2 \text{Vpeak}, 100 \text{ MHz}, and \(-90\text{ degrees}\)), we get this:
Mixers Are Multipliers

\[ v_{RF}(t) \times v_{LO}(t) = v_{IF}(t) \]

\[ = v_{LO}(t) v_{RF}(t) \]

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

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

“Downconverted Product”

“Upconverted Product”

Time Domain

Frequency Domain

LO and RF “Feedthru”
Real Mixers Multiply by Squarewaves

**Time Domain**

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

Usually, \( N = 0, 1 \) and \( M = 0, 1, 2, 3, 4, 5, \ldots \)
Topic Outline

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

Simple, Unbalanced Designs

Simple Diode Mixer

Single Transistor Mixer (bias details not shown)
24 GHz Doppler Radar with Simple Diode Mixer

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

24.125 GHz transmit and receive signals to/from horn


http://cdn.macom.com/datasheets/MACS-007801-0M1RM0.pdf
BJT Mixer in FM Receiver

\[ i_c = I_0 e^{\frac{1}{nV_T}[V_{BE} + k_1 v_{LO} + k_2 v_{RF}]} \]

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

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

LO drive level about 100 mV peak
Pentode Mixer in SB-102 Transceiver

From modulator and first TX mixer

LO from V19 crystal oscillator

LO drive level about 1 to 2V peak

To driver and final amplifiers
Mixer Circuits

\[ v_{RF}(t) \rightarrow \times \rightarrow v_{IF}(t) \]

\[ v_{LO}(t) \]

Balanced Designs

Diode Ring Mixer

Gilbert Cell

Diode Ring Mixers

Surface Mount Frequency Mixer

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

Maximun Ratings
- Operating Temperature: -40°C to +85°C
- Storage Temperature: -65°C to 100°C
- RF Power: 500mW
- IF Current: 40mA
- Permanent damage may occur if any of these limits are exceeded. These electrical ratings are not intended for continuous normal operations.

Pin Connections
- LO: 6
- IF: 3
- GROUND: 2

Applications
- VHF/UHF

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

ZAD-1+
Level 7, Double Balanced Mixer, RF/LO Freq 0.5 - 500 MHz
Connector Type: BNC

LO drive level +4 to +10 dBm

Electrical Schematic
NE/SA602 Gilbert Cell IC Mixer

Double-balanced mixer and oscillator

SA602A

BLOCK DIAGRAM

Figure 2. Block Diagram

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_i$</td>
<td>input frequency</td>
<td></td>
<td>-</td>
<td>500</td>
<td>-</td>
<td>MHz</td>
</tr>
<tr>
<td>$f_{osc}$</td>
<td>oscillator frequency</td>
<td></td>
<td>-</td>
<td>200</td>
<td>-</td>
<td>MHz</td>
</tr>
<tr>
<td>NF</td>
<td>noise figure</td>
<td>at 45 MHz</td>
<td>-</td>
<td>5.0</td>
<td>5.5</td>
<td>dB</td>
</tr>
<tr>
<td>IP3i</td>
<td>input third-order</td>
<td>RF input = -45 dBm; RF1 = 45.0 MHz; RF2 = 45.06 MHz</td>
<td>-</td>
<td>-13</td>
<td>-15</td>
<td>dBm</td>
</tr>
<tr>
<td>$G_{conv}$</td>
<td>conversion gain</td>
<td>at 45 MHz</td>
<td>14</td>
<td>17</td>
<td>-</td>
<td>dB</td>
</tr>
<tr>
<td>$R_{(RF)}$</td>
<td>RF input resistance</td>
<td>at 45 MHz</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>kΩ</td>
</tr>
<tr>
<td>$C_{(RF)}$</td>
<td>RF input capacitance</td>
<td></td>
<td>-</td>
<td>3</td>
<td>3.5</td>
<td>pF</td>
</tr>
<tr>
<td>$R_{(mix)}$</td>
<td>mixer output resistance</td>
<td>OUT_A, OUT_B pins</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
<td>kΩ</td>
</tr>
</tbody>
</table>

$T_{amb} = 25 \, ^\circ C; V_{CC} = +6 \, V; unless specified otherwise.$
Add 1.5K to 300 Ohm matching for typical 10.7 MHz IF filters

Oops!
Mixers Used in NanoVNA

NanoVNA uses an “ultra-low IF” receiver architecture…

3 receiver channels

(Low Band)

Visit

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

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

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### SPECIFICATIONS

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Nominal Center Frequency (fn) (MHz)*</th>
<th>3dB Bandwidth from fn (kHz)</th>
<th>Spurious Attenuation min.</th>
<th>Insertion Loss at fn (dB) max.</th>
<th>Input/Output Impedance (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFECV10.7MA21S-TC</td>
<td>10.7</td>
<td>400 min.</td>
<td>20dB (10.7 to 15.0MHz)</td>
<td>3.0 ± 2.0</td>
<td>470</td>
</tr>
<tr>
<td>SFECV10.7MA19S-TC</td>
<td>10.7</td>
<td>350 min.</td>
<td>20dB (10.7 to 15.0MHz)</td>
<td>3.0 ± 2.0</td>
<td>470</td>
</tr>
<tr>
<td>SFECV10.7MA23S-A-TC</td>
<td>10.7</td>
<td>330 ± 50</td>
<td>30dB (9 to 12MHz)</td>
<td>4.0 ± 2.0</td>
<td>330</td>
</tr>
<tr>
<td>SFECV10.7MA5S-A-TC</td>
<td>10.7</td>
<td>280 ± 50</td>
<td>35dB (9 to 12MHz)</td>
<td>3.0 ± 2.0</td>
<td>330</td>
</tr>
<tr>
<td>SFECV10.7MS2S-A-TC</td>
<td>10.7</td>
<td>230 ± 50</td>
<td>35dB (9 to 12MHz)</td>
<td>3.5 ± 2.0</td>
<td>330</td>
</tr>
<tr>
<td>SFECV10.7MS3S-A-TC</td>
<td>10.7</td>
<td>180 ± 40</td>
<td>35dB (9 to 12MHz)</td>
<td>4.0 ± 2.0</td>
<td>330</td>
</tr>
<tr>
<td>SFECV10.7MS-A-TC</td>
<td>10.7</td>
<td>150 ± 30</td>
<td>35dB (9 to 12MHz)</td>
<td>5.9 ± 2.0</td>
<td>330</td>
</tr>
<tr>
<td>SFECV10.7MHS-A-TC</td>
<td>10.7</td>
<td>110 ± 30</td>
<td>35dB (9 to 12MHz)</td>
<td>6.0 ± 2.0</td>
<td>330</td>
</tr>
</tbody>
</table>

*Nominal Center Frequency (fn) (MHz)*

**10.7 MHz center, 200 kHz/div horz, 10dB/div vert**
Project 4
IF Subsystem and Audio Amp
(Next Episode)
Thanks For Watching !