

# RF Mixers

(Extracted heavily from the ARRL Handbook)

“When you can measure what you are speaking about, and express it in numbers, you begin to know something about it;”

Lord Kelvin

1842-1907

He also said:

“Radio has no Future”

# Mixers are used for:

- Frequency conversion in heterodynes
  - Up-conversion
  - Down-conversion
- Modulation (AM, SSB, PM and FM)
- De-modulation
- Phase detection
- Image rejection

# Superheterodyne Mixer

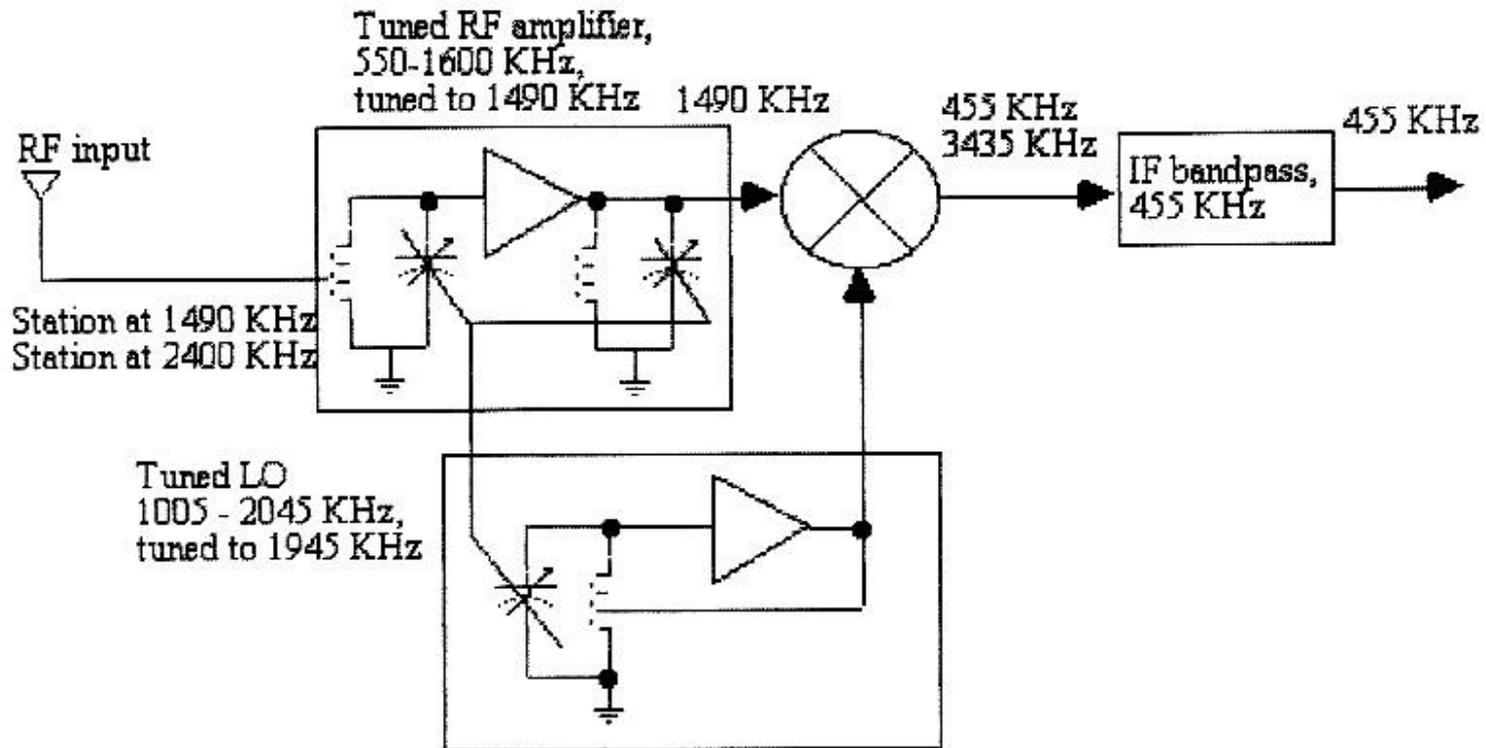


Figure 3. Superheterodyne AM radio front end with improved front end filtering

# Double Conversion Superhete.

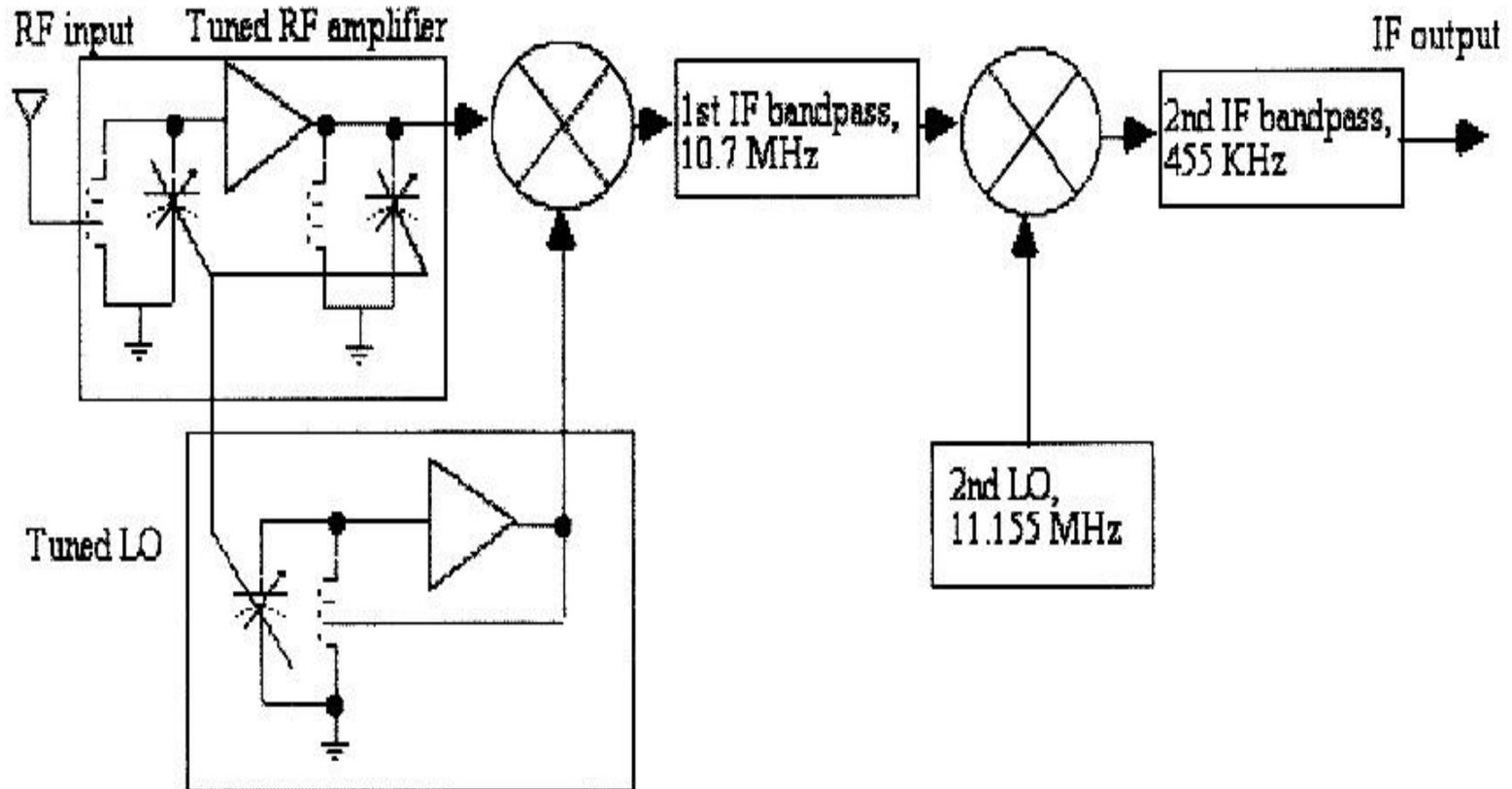
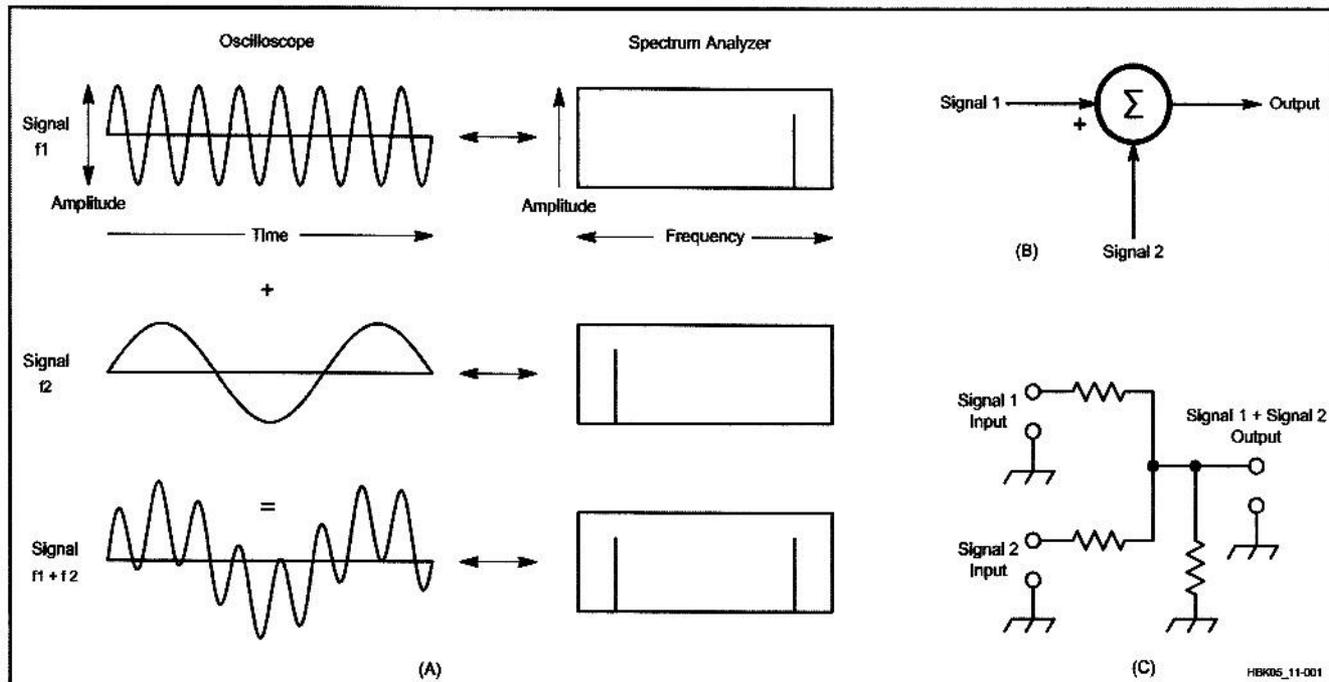


Figure 4. Double conversion superheterodyne with good image rejection and selectivity

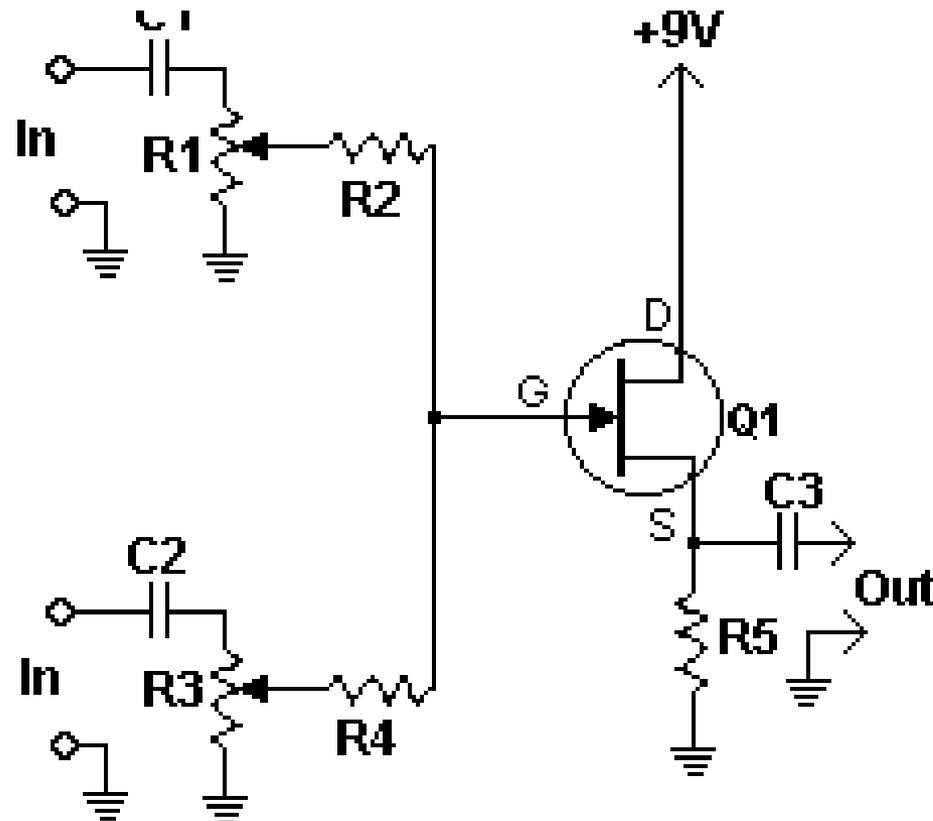
# Two types of “mixers”

## “Audio” (and “RF”)

- Audio mixers combine one sound track with another, *adding* voltages of the two tracks. Frequencies of the two tracks are unaffected.



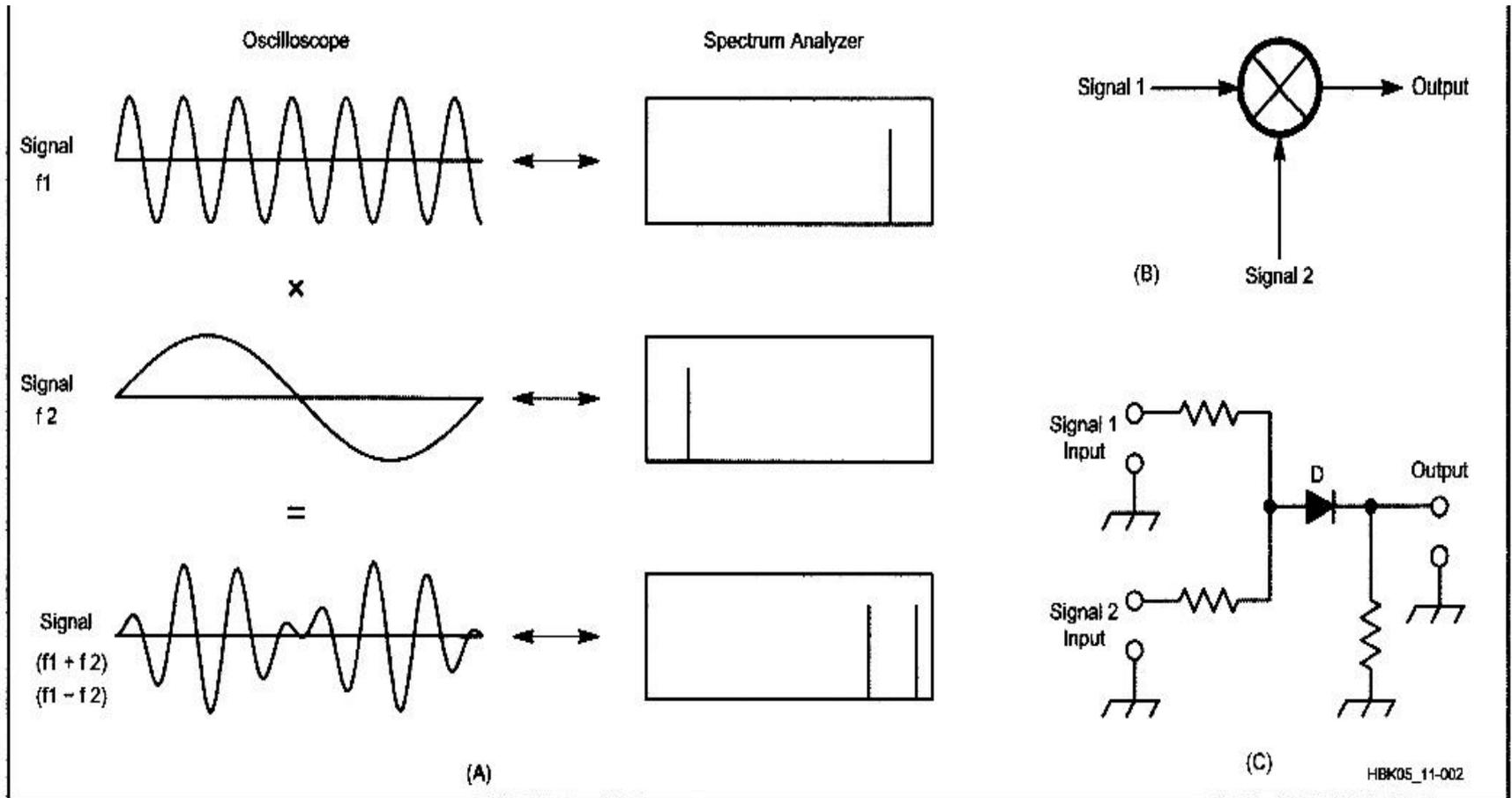
# Audio Mixer (Addition) Circuit



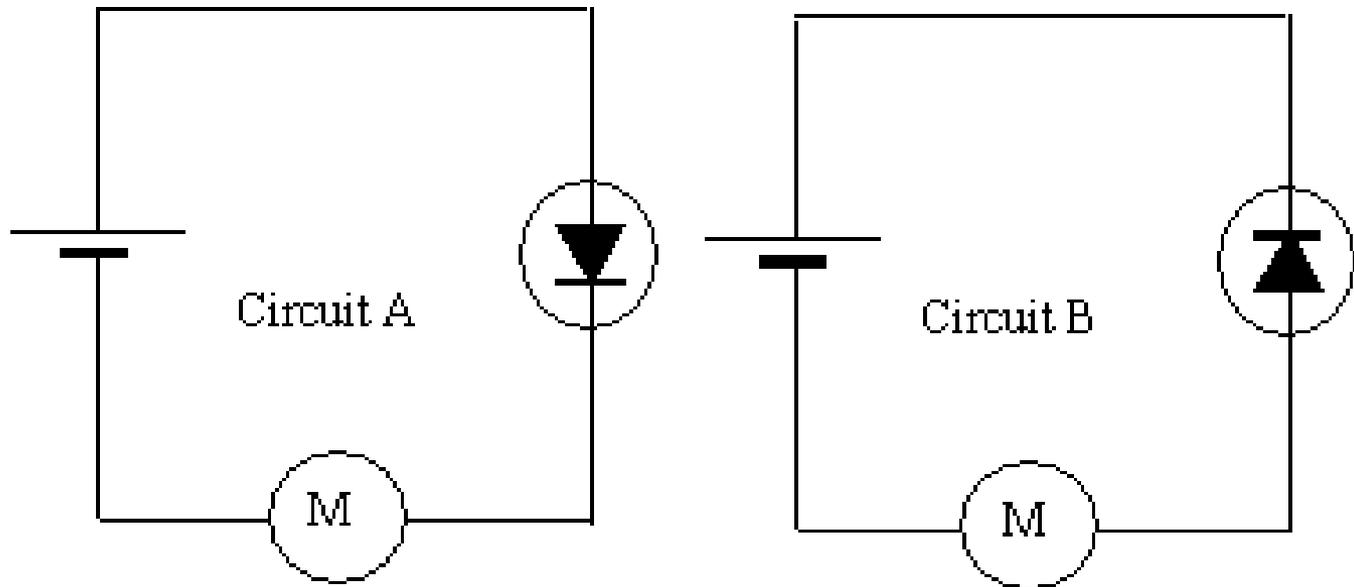
# “RF” Mixers

- RF mixers combine two RF signals to produce two different frequencies.
  - Usually, the lower (shifting) frequency, called “LO” (for local oscillator). It is mixed with a higher (constant) frequency, called “RF”, to produce two new (shifting) “IF” (for intermediate) frequencies, “RF + LO” and “RF – LO”.
  - Usually, the higher frequencies (“RF”, “LO” and “RF + LO” are filtered out. Leaving only “RF – LO”.

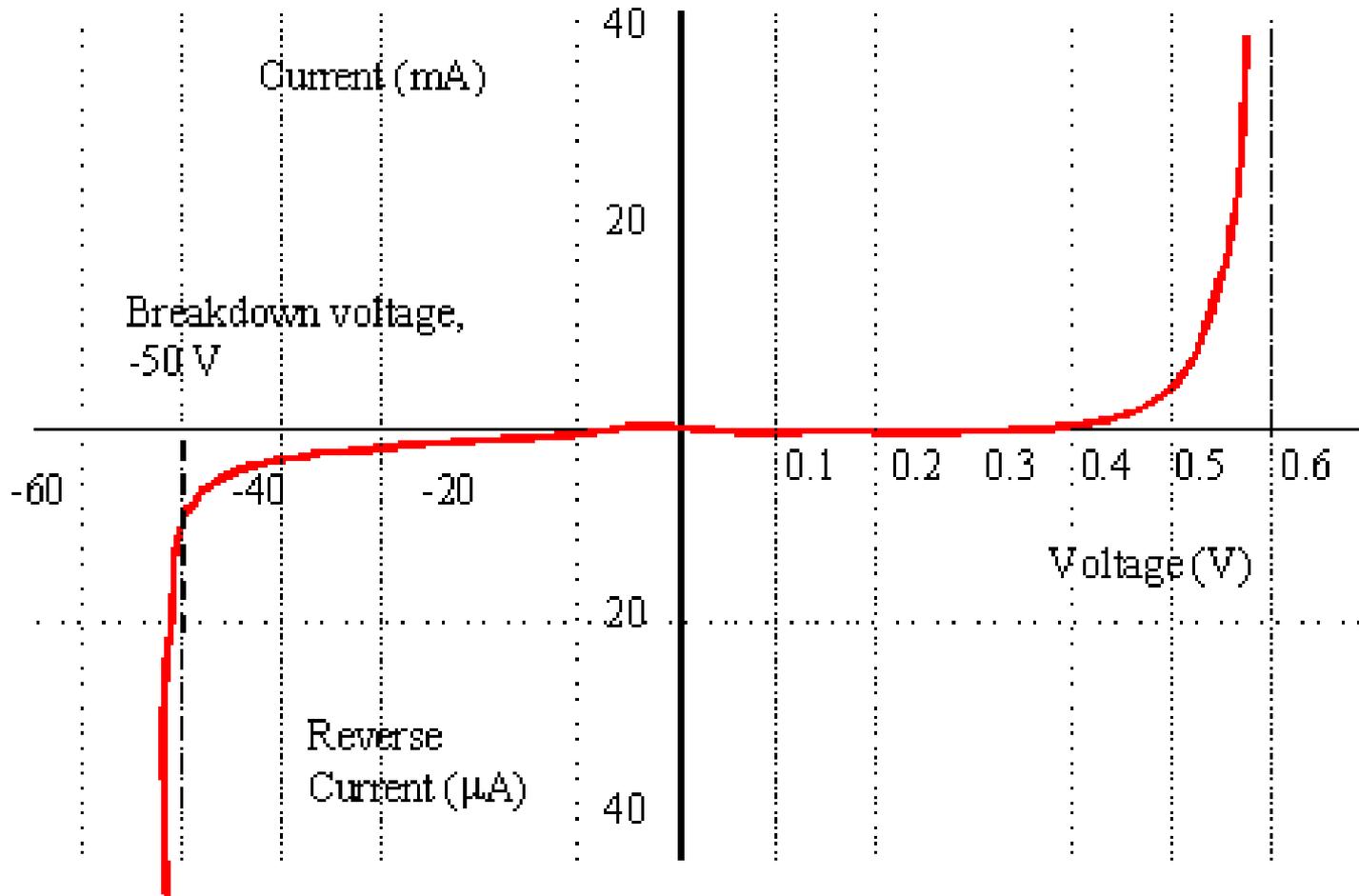
# RF Mixer – Why Does a Diode Do This?



Circuit "A" is Forward-biased  
Circuit "B" is Reverse-biased

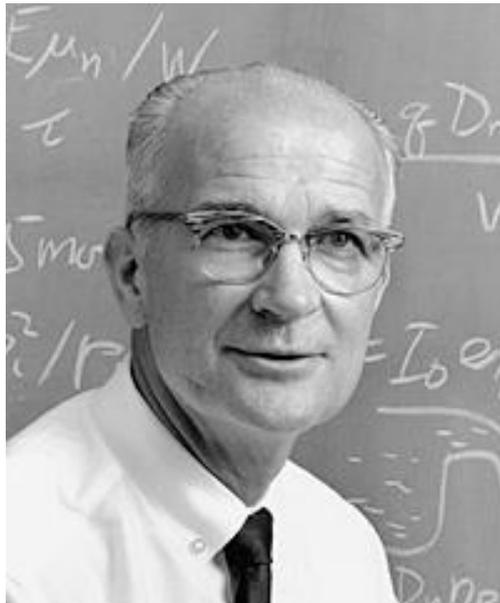
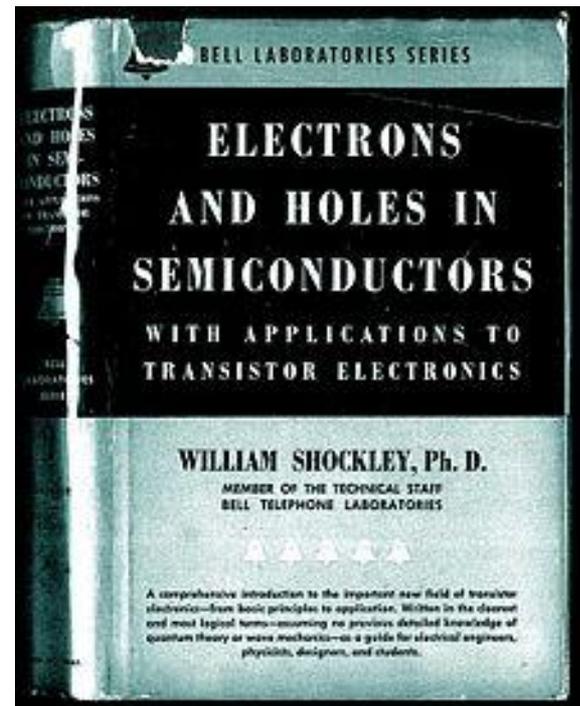


# Diode non-linearity



# William Shockley (1910 – 1989)

- Nobel Prize in physics (1956) for invention of the junction transistor.



# Shockley (non-linear) Diode Equation

$$I = I_S \cdot (e^{qV/kT} - 1) \approx I_S \cdot e^{qV/kT} = I_S \cdot e^{V/0.026}$$

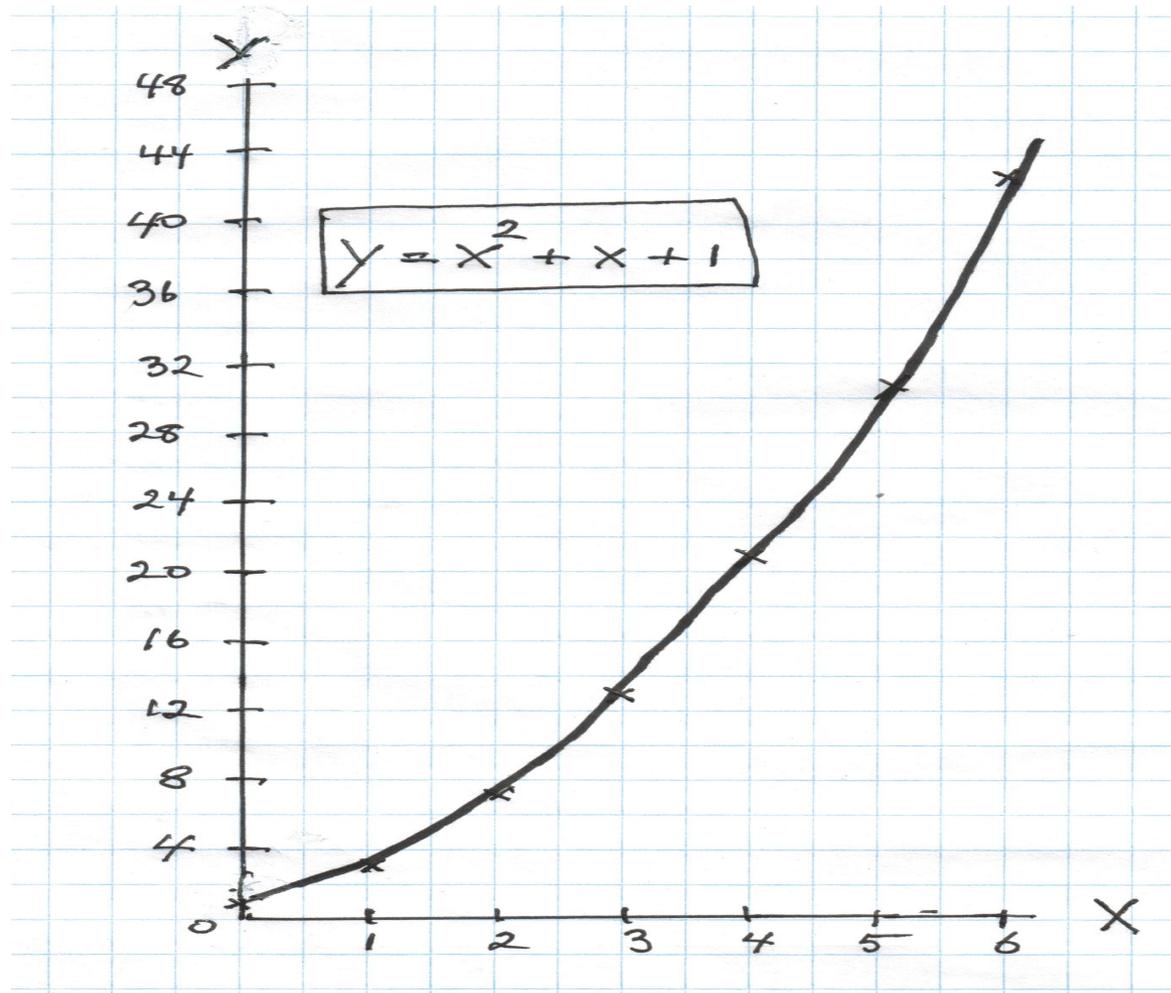
where:

- $I$  is the forward-biased current
- $I_S$  is the saturation current  $\approx 3 \times 10^{-15}$  A
- $e$  is Euler's "decay" constant = 2.718...
- $q$  is the charge on the electron  $\approx 1.6 \times 10^{-19}$  C
- $V$  is the forward-biased volts (volt = J/C)
- $k$  is Boltzmann's constant =  $1.38 \times 10^{-23}$  J/degK
- $T$  is the absolute temperature in degrees K

# Shockley Diode Equation

- From a test on a forward-biased 1N4004,  $0.73\text{V} \approx 5.0\text{ mA}$
- $I = I_S \cdot e^{V/0.026}$
- where  $I_S$  is the saturation current  $\approx 3 \times 10^{-15}\text{ A}$
- $V/0.026 = 0.73/0.026 \approx 28$
- $e^{28} \approx 1.6 \times 10^{12}$
- So  $I_S = 5 \times 10^{-3}\text{ A} / 1.6 \times 10^{12} \approx 3 \times 10^{-15}\text{ A}$

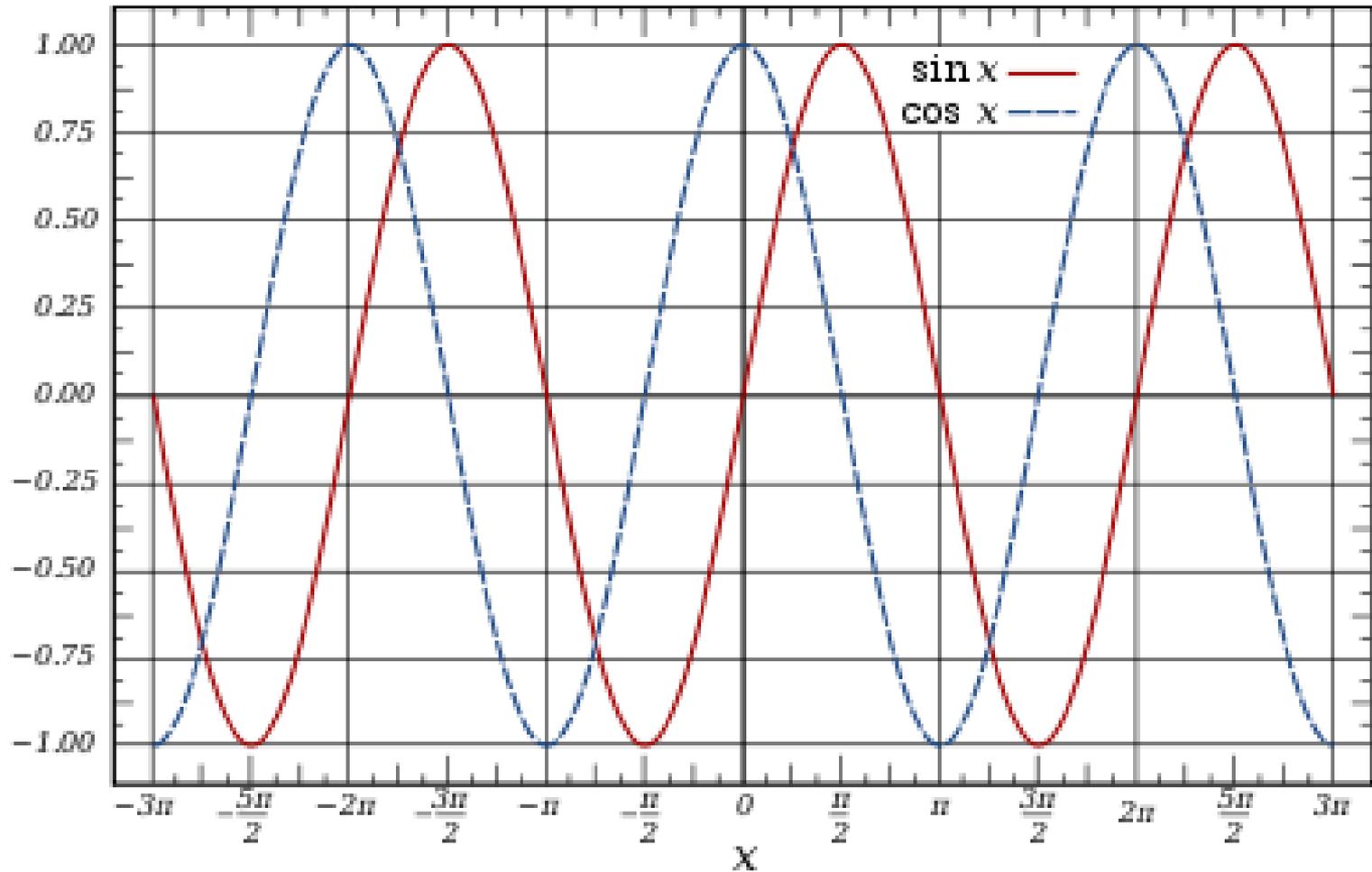
# Non-linear Equation



# Diode non-linearity

- On the earlier graph, between  $\approx 0.3$  V and 0.58 V the current in a forward-biased diode is non-linear (a curve)
- Above 0.58 V the current is approximately linear (a straight line)
- A linear equation is  $I = aV + b$ , where  $I$  is the current,  $V$  the voltage and  $a$  and  $b$  are constants.
- The Shockley diode equation, because it's a curve, can be approximated by  $I = aV^2 + bV + c$ , where  $a$ ,  $b$  and  $c$  are constants.
- It's the  $V^2$  non-linear term that makes an RF mixer produce the additional frequencies. Let's see how.

# Sine and Cosine Waves



# RF Mixer Math

- For the “RF” signal, let  $V_1 = A \cdot \cos(\omega_1 t)$
- For the “LO” signal, let  $V_2 = B \cdot \cos(\omega_2 t)$   
where the  $V$ 's are voltages,  $A$  and  $B$  are amplitudes,  $\omega$ 's are frequencies and  $t$  is time.
- For a non-linear diode,  $I = aV^2 + bV + c$   
where  $V = V_1 + V_2$

# RF Mixer Math (cont)

- So  $I = a(V_1 + V_2)^2 + b(V_1 + V_2) + c$
- The non-linear part of this equation is:  
 $= a(V_1 + V_2)^2.$
- We'll focus this term because this is what produces the frequency shifts to produce (RF + LO) and (RF – LO)

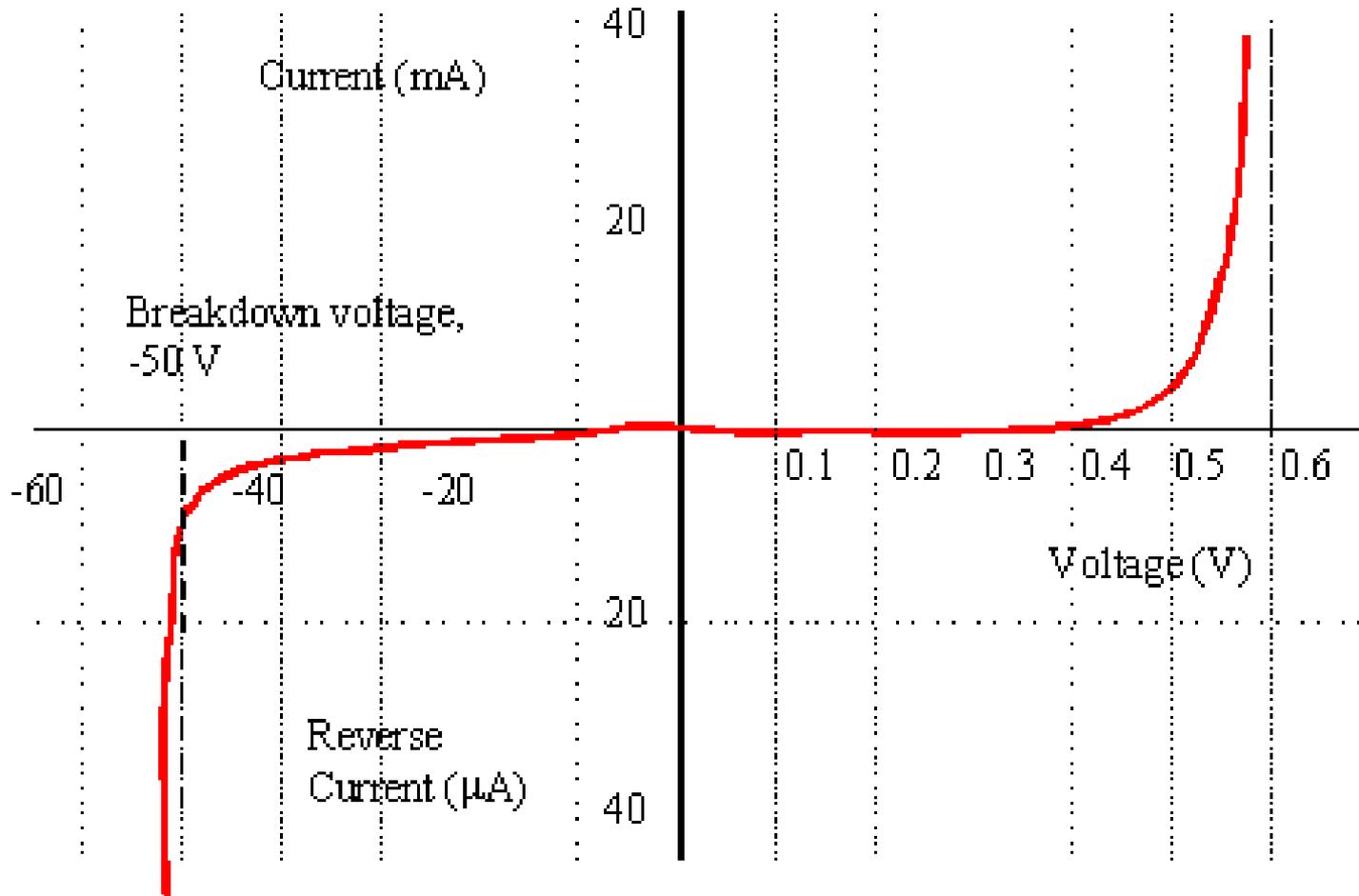
# A Little High School Trigonometry

- $a(V_1 + V_2)^2 = a \cdot [V_1^2 + 2 \cdot V_1 \cdot V_2 + V_2^2]$
- $= a \cdot [A^2 \cdot \cos^2(\omega_1 t) + 2 \cdot A \cdot B \cdot \cos(\omega_1 t) \cdot \cos(\omega_2 t) + B^2 \cdot \cos^2(\omega_2 t)]$
- Focus on the term “ $2 \cdot A \cdot B \cdot \cos(\omega_1 t) \cdot \cos(\omega_2 t)$ ”
- From trig.  $\cos X \cdot \cos Y = \frac{1}{2} [\cos(X + Y) + \cos(X - Y)]$
- So,  $2 \cdot a \cdot A \cdot B \cdot \cos(\omega_1 t) \cdot \cos(\omega_2 t)$   
 $= 2 \cdot a \cdot A \cdot B \cdot [\cos(t(\omega_1 + \omega_2)) + \cos(t(\omega_1 - \omega_2))]$

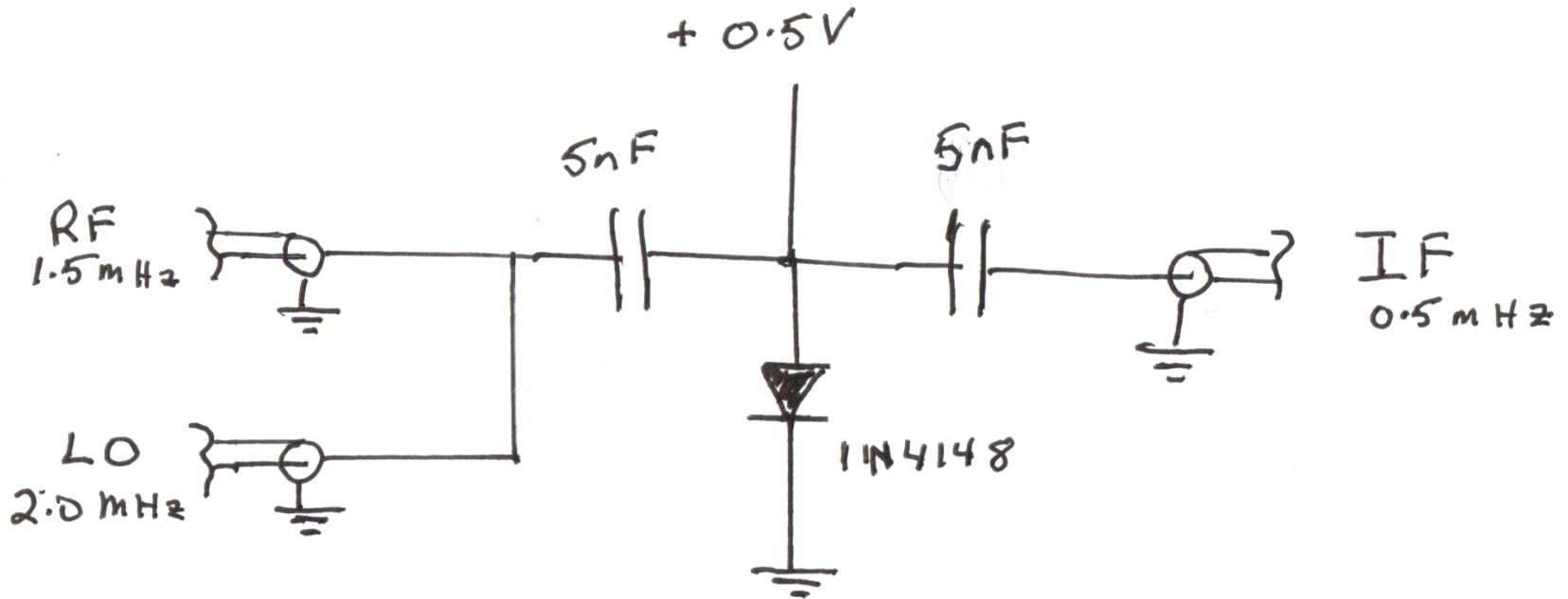
# A Little High School Trig. (cont)

- Voila! The “ $2 \cdot V_1 \cdot V_2$ ” term gives us  $\cos(t(\omega_1 + \omega_2)) + \cos(t(\omega_1 - \omega_2))$ , which are the (RF + LO) and (RF – LO) frequencies!
- The other two  $\cos^2$  terms generate multiple “ $2 \cdot \omega$ ” terms, which are higher-frequency, even harmonics, which can be filtered out.
- And if  $LO > RF$ , that’s OK  
because  $\cos X = \cos (-X)$

# Diode non-linearity



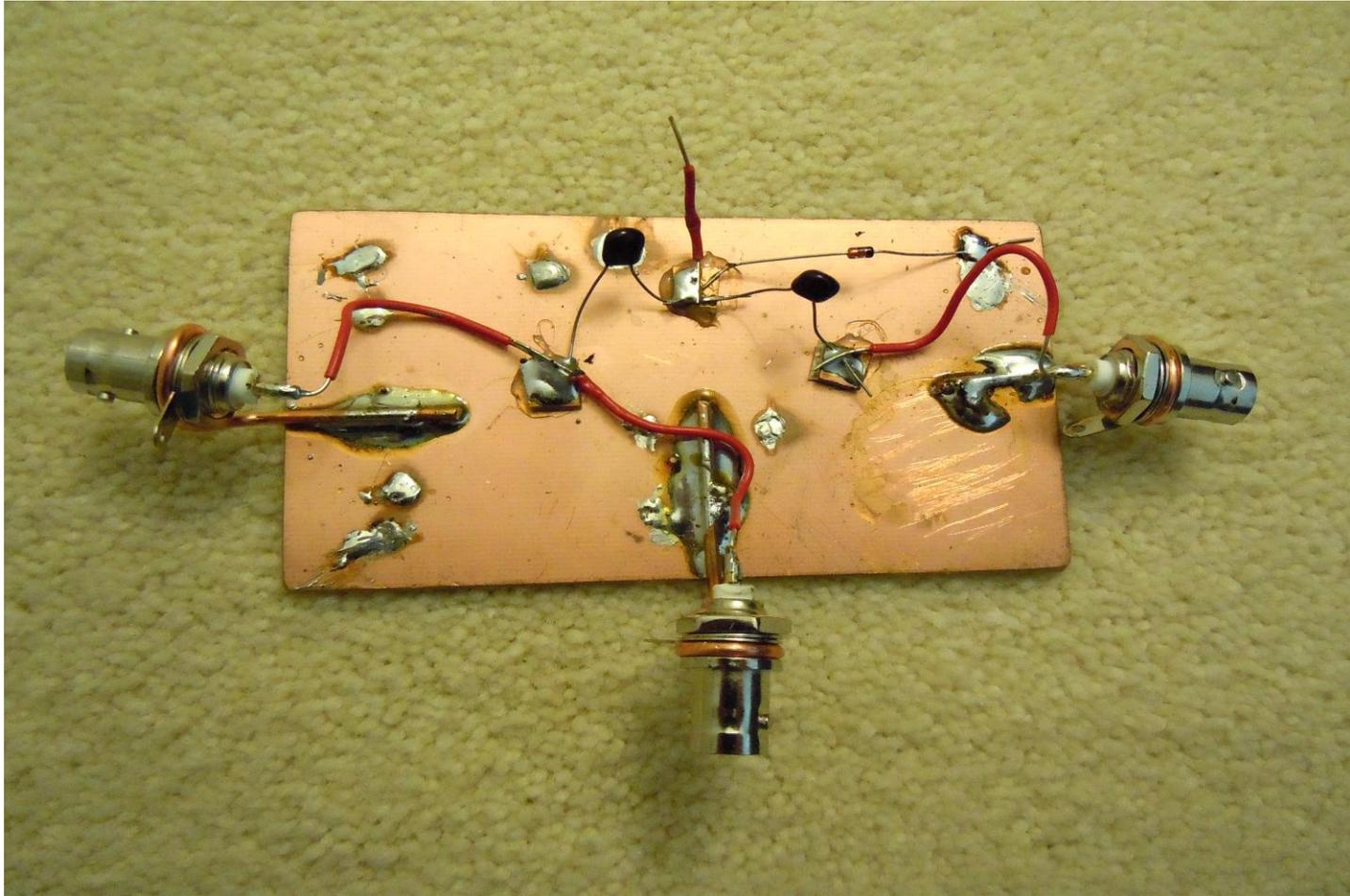
# Simplest Possible Mixer



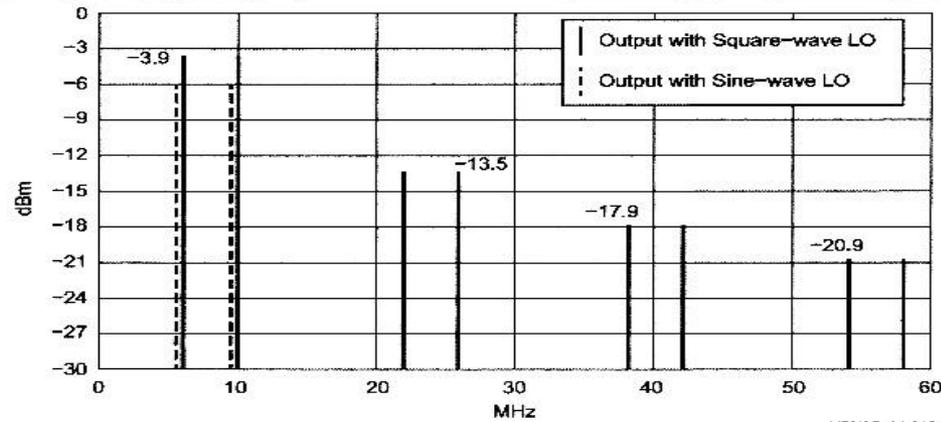
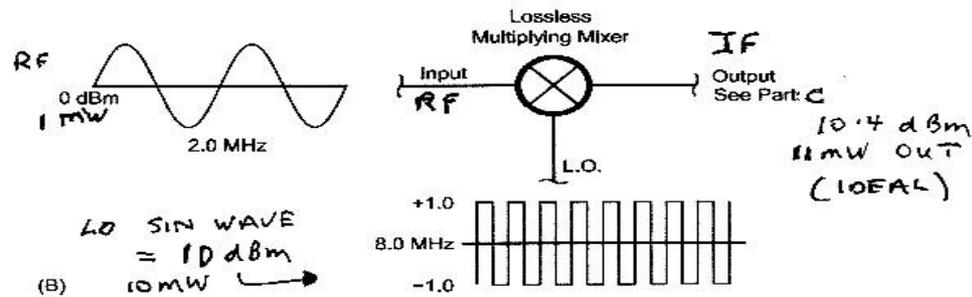
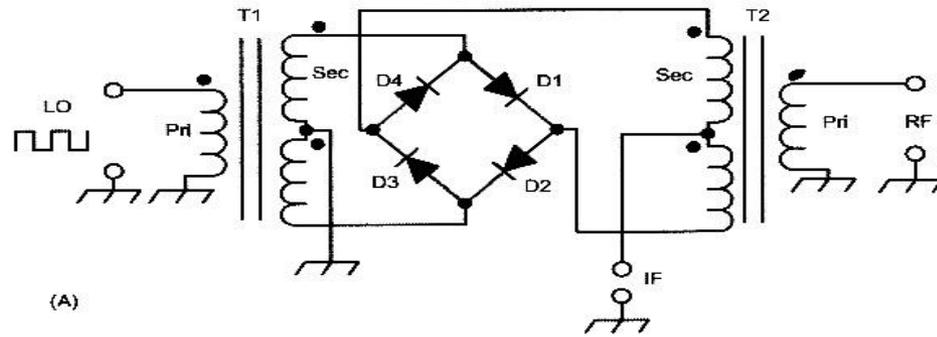
SINGLE DIODE MIXER

gms  
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# Ugly Simplest Possible Mixer

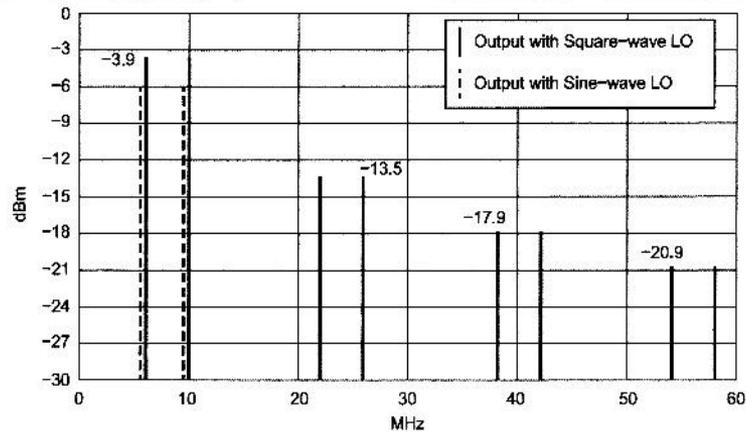
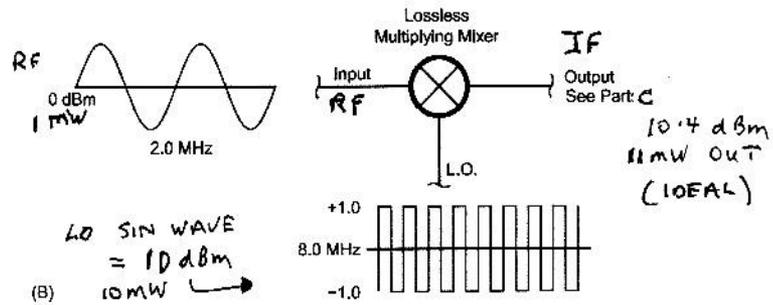
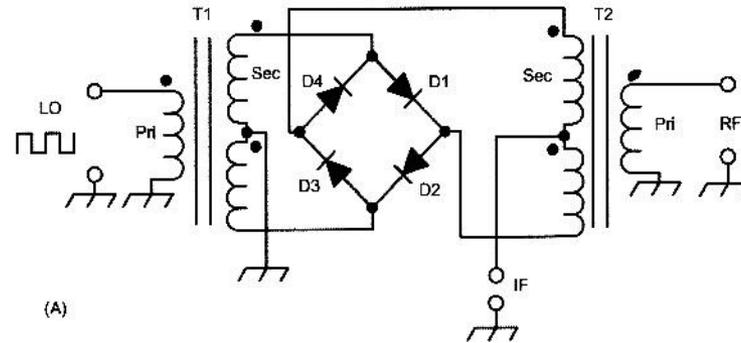


# Ring Diode Double-Balanced Mixer



# Diode Double-balanced Reversing-switch Mixer

- When no LO applied, none of the diodes conduct and there is no IF out.
- Applying LO, 50% of time D1 and D2 or on and D3 and D4 are reverse-biased.
- This unbalances T2's secondary, leaving its upper wire floating and connecting its lower wire to ground through T1's lower secondary and center tap.
- This causes RF and LO energy to emerge from the IF port.
- The other 50% of the time, the reverse occurs, except that the RF energy is shifted 180 degrees in phase.
- The square wave consists of multiple successively weaker odd-harmonics that mix with the RF signal.
- Spectrum analysis shows that this also occurs with a sin-wave LO, but with a greater loss.
- Theoretically, all of the energy is split between the IF fundamental and its harmonics.



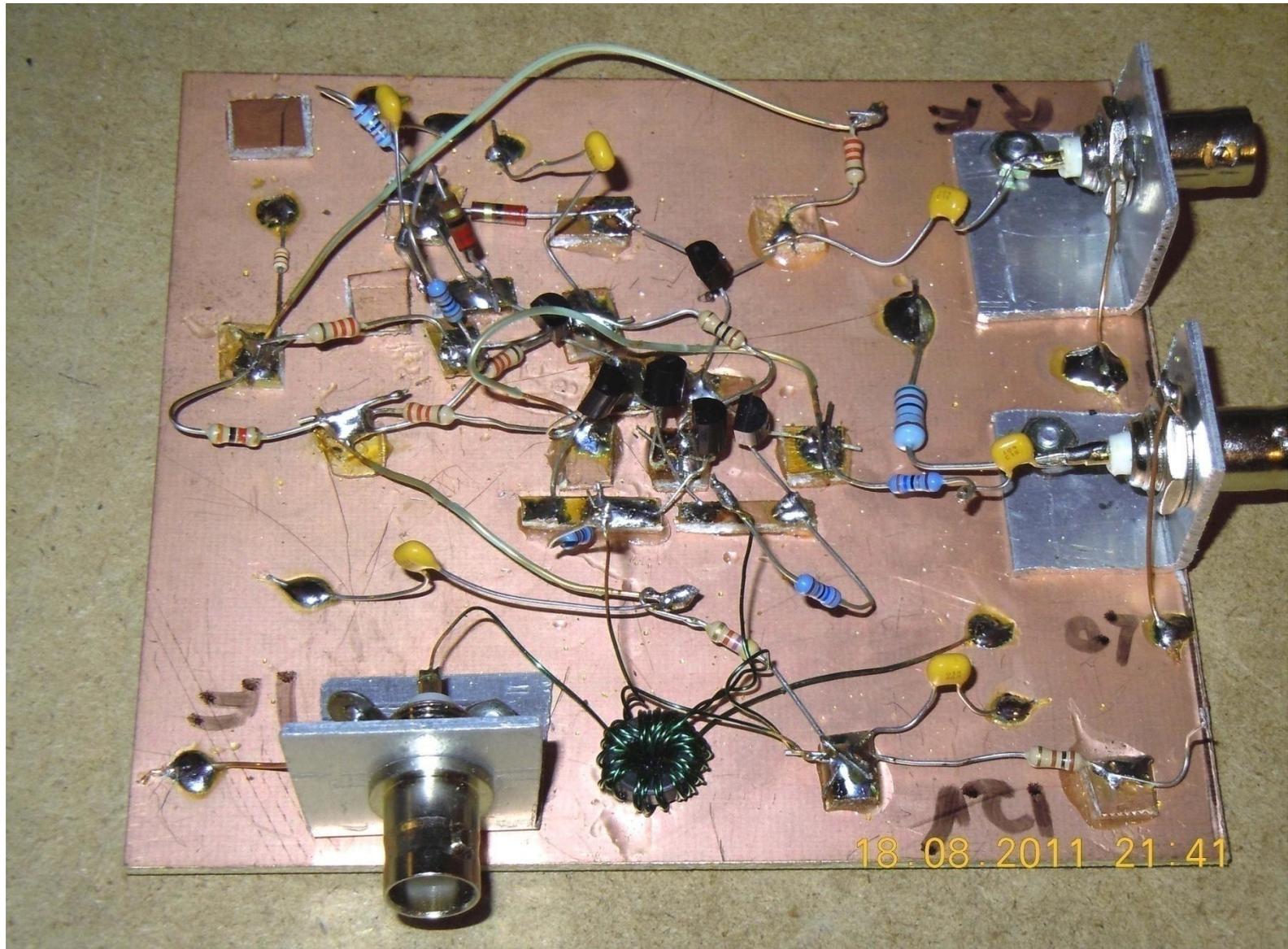
# Ugly Diode Ring Mixer







# Ugly Gilbert Cell



# Other Mixer Designs

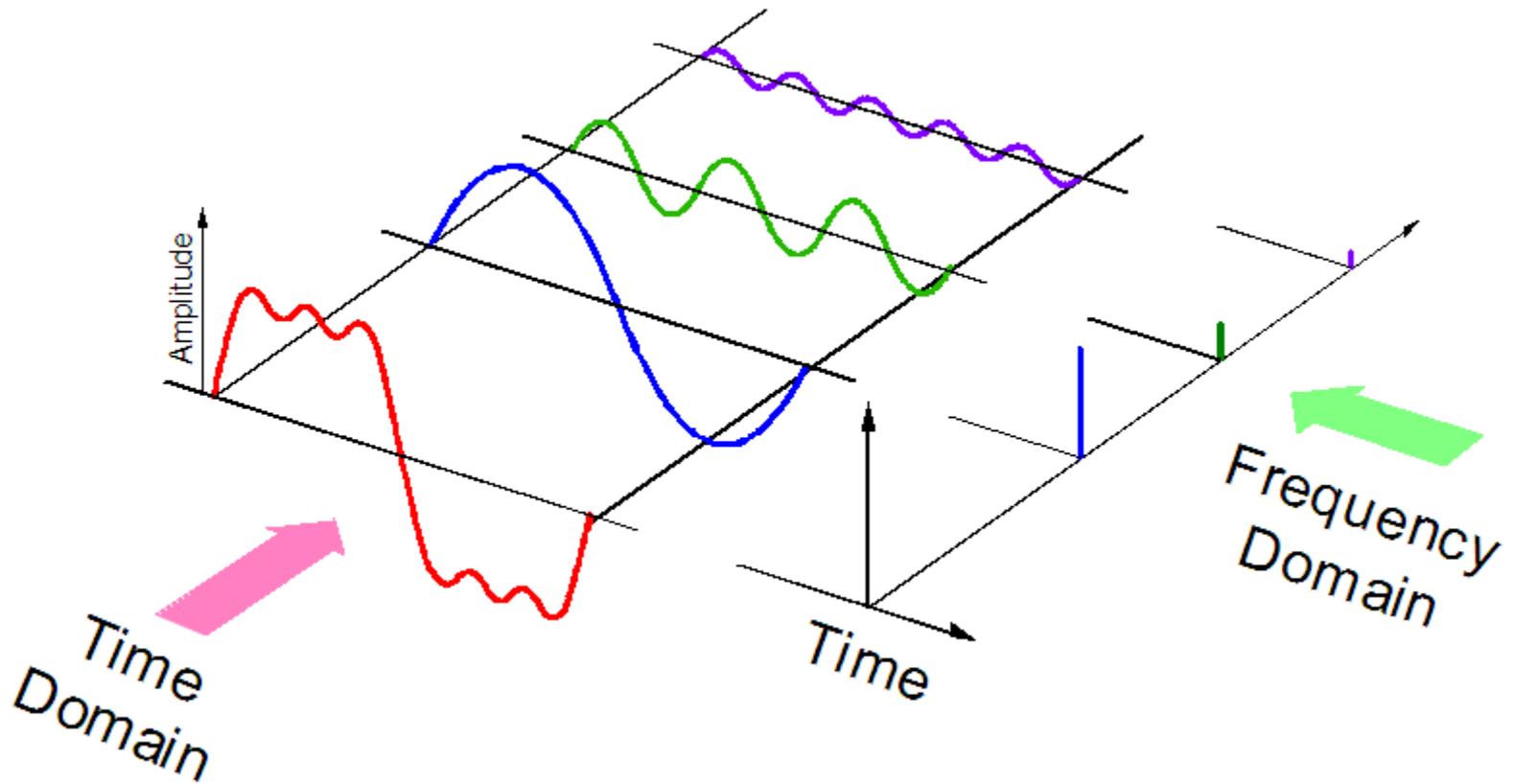
- Many other mixer designs also employ transistors or high speed switches instead of diodes, and are optimized for different end uses.
- Some design objectives
  - Minimize conversion loss (weaker harmonics)
  - Minimize non-linear distortion
  - Minimize phase (linear) distortion
  - Minimize over-modulation
  - Maximize carrier suppression

Enough theory - let's have a demo.

but first

a couple of reminders

# Time vs. Frequency Domain



# Review of dB

- Comparative measure of power
- $\text{dB} = 10 \log_{10}(P_1 / P_2)$
- At 0 dB,  $P_1 = P_2$
- At 20 dB,  $P_1 = 100 P_2$
- At 40 dB,  $P_1 = 10,000 P_2$
- At 60 dB,  $P_1 = 1,000,000 P_2$
- dBm is power relative to one milliwatt

# dBm Range

dBm	S-meter	
+10		Maximum input for Signal Hound = 10 mW
-13 to -18	60 dB over S9	= 0.02 to 0.05 mW (receivers vary)
-73	S9	For a correctly calibrated S-meter
-97	S1	On my ICOM transceiver
-109		Man-made noise, quiet site @ 3 KHz. BW
-121	S1	Ideal S-meter @ 6 dB per S-unit
-123		Typical noise floor @ 7 MHz @ 3 KHz. BW
-125		Signal Hound Min. Disc. Signal < 1 GHz.
-135		ICOM Min. Discernable Signal @ 3 KHz. BW with pre-amp off.
-139		Electron noise at 20 deg. C. (Shockley's $e^{kV/QT}$ )

# Demonstration

- The demonstration consisted of passing two RF signals, from two separate signal generators, through each of the three mixers and observing the strengths of the sum and difference frequencies out (on a spectrum analyzer) as well as various other higher sum and difference frequencies.
- The single diode mixer had the poorest performance, and the Gilbert cell, the best.