EEC 134 A&B

Design of RF & Microwave Systems

Lecture 5: Building Blocks of RF Systems – Mixers

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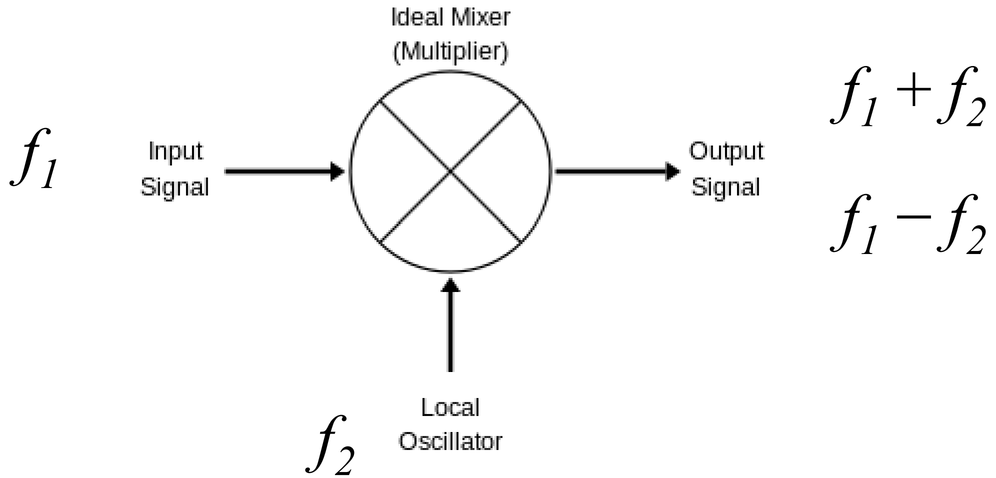
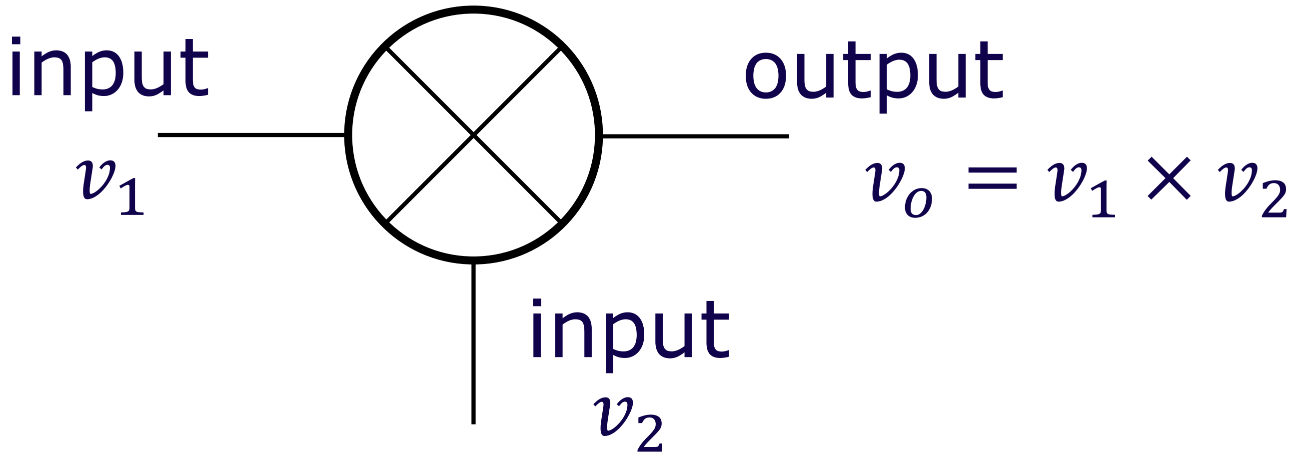
Heterodyne

- "Heterodyning is a radio signal processing technique popularized by Canadian inventor-engineer Reginald Fessenden in 1901, in which new frequencies are created by combining or mixing two frequencies."
- "The two frequencies are combined in a nonlinear signal-processing device such as a vacuum tube, transistor, or diode, usually called a *mixer*. In the most common application, two signals at frequencies f_1 and f_2 are mixed, creating two new signals, one at the sum $f_1 + f_2$ of the two frequencies, and the other at the difference $f_1 - f_2$. These new frequencies are called *heterodynes*. Typically only one of the new frequencies is desired, and the other signal is filtered out of the output of the mixer."



The Ideal Multiplier

- A multiplier can realize the mixer function



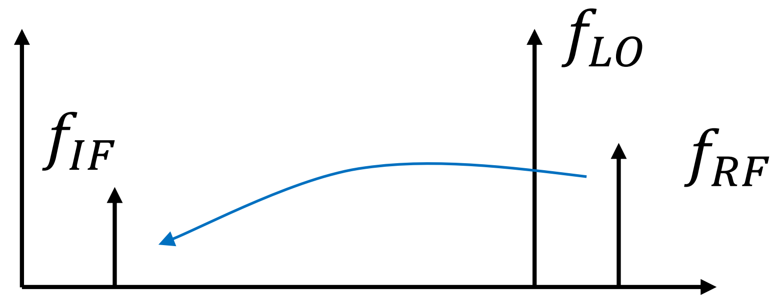
- Consider $v_1 = V_1 \cos \omega_1 t$, and $v_2 = V_2 \cos \omega_2 t$

$$
\begin{aligned}
v_o &= V_1 \cos \omega_1 t \cdot V_2 \cos \omega_2 t \\
&= \frac{1}{2} V_1 V_2 \cos(\omega_1 + \omega_2) t + \frac{1}{2} V_1 V_2 \cos(\omega_1 - \omega_2) t
\end{aligned}
$$

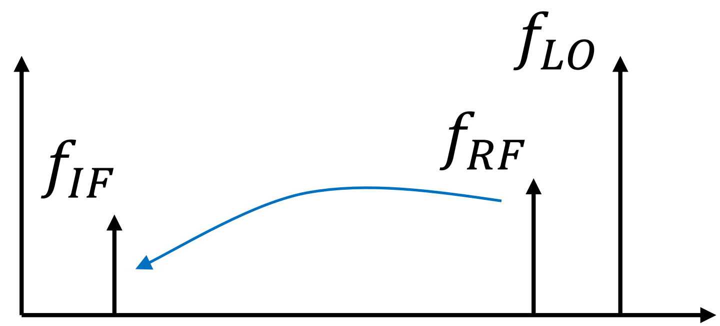
Sum and difference frequencies

Mixer in an RF System

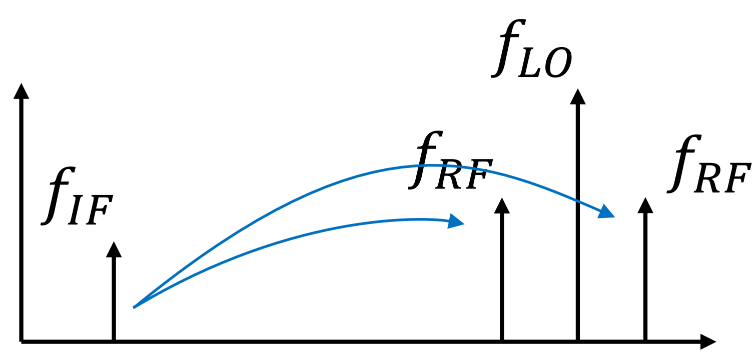
- Down-conversion example 1:
  - $f_{RF} = 2450\ MHz$
  - $f_{LO} = 2400\ MHz$
  - What is the IF frequency?



- Down-conversion example 2:
  - $f_{RF} = 2450\ MHz$
  - $f_{LO} = 2500\ MHz$
  - What is the IF frequency?



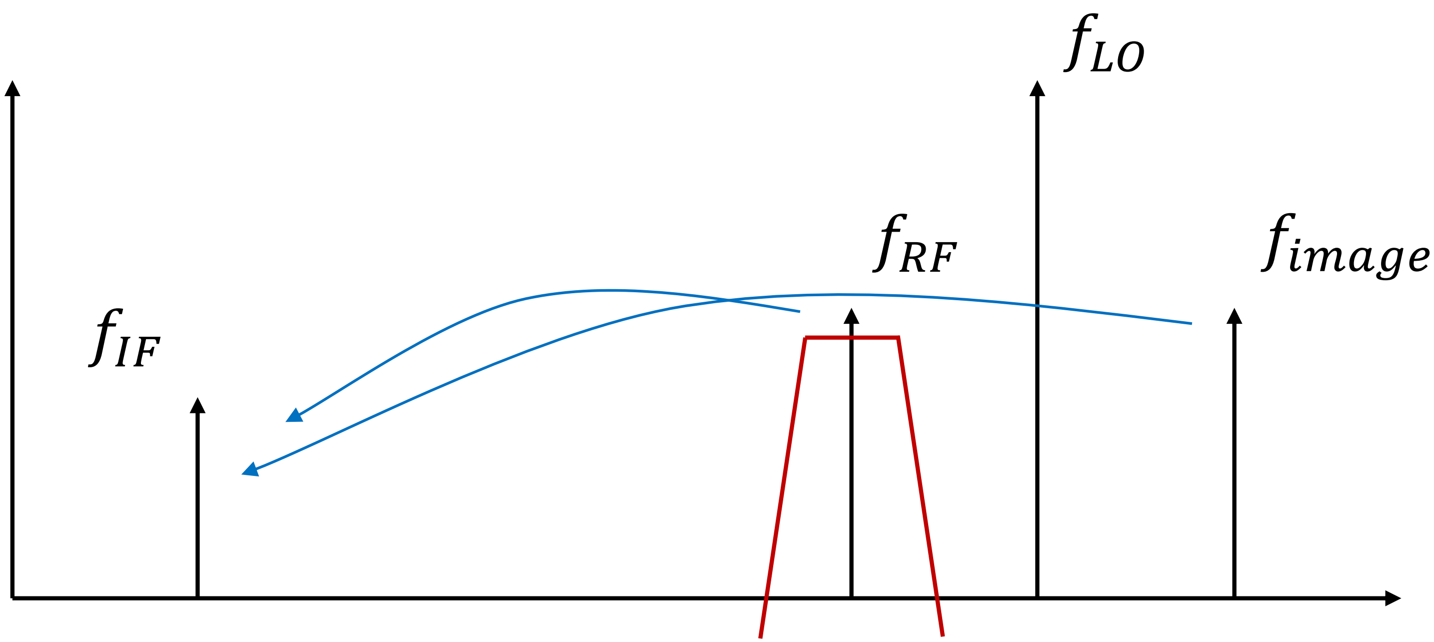
- Up-conversion example 1:
  - $f_{IF} = 200\ MHz$
  - $f_{LO} = 2400\ MHz$
  - What is the RF frequency?



http://www.digikey.com/en/articles/techzone/2011/oct/the-basics-of-mixers

Image Frequency

- Let's assume $f_{LO} = 2400\ MHz$,
  - If $f_{RF} = 2450\ MHz$, what is the IF?
  - If $f_{RF} = 2350\ MHz$, what is the IF?
- Signals at the image frequency will be down-converted to IF frequency and corrupted the desired signal
  - Even if there is no other signal at the image frequency, noise can still be down-converted, lowering your NF by 3 dB!
  - An image reject filter is usually put in front of the mixer to attenuate the signals and noise at the image frequency; more on this later!

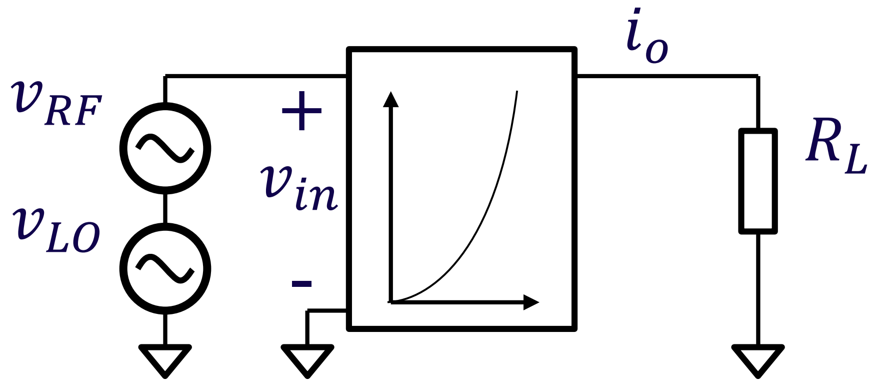


Mixer Implementations

- Fundamentally, mixing (heterodyning) can happen by two mechanisms
  - Non-linear circuit
  - Linear but time-variant circuit
  - (Of course!) non-linear and time-variant circuit

Mixing by Non-linear Circuit

- Example: consider a square-law device (could be a properly biased diode or FET transistor)



$$i_o = K v_{in}^2$$

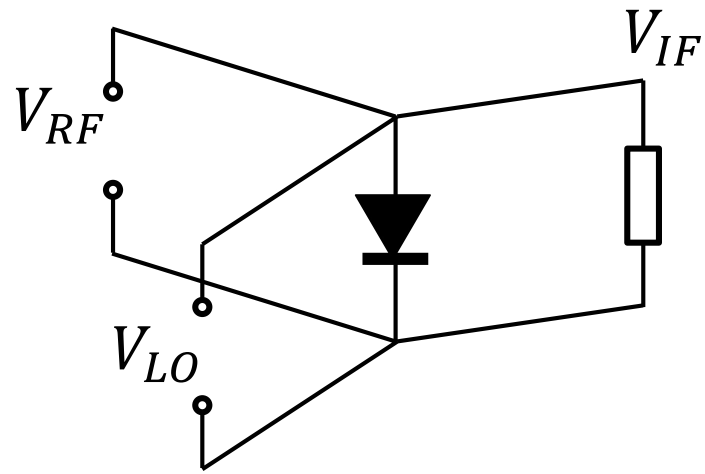
Spurious signals

$$\begin{aligned} v_o &= R_L K v_{in}^2 \\ &= R_L K (V_{RF} \cos \omega_{RF} t + V_{LO} \cos \omega_{LO} t)^2 \\ &= R_L K \left[\frac{1}{2} V_{RF} \cos 2\omega_{RF} t + \frac{1}{2} V_{LO} \cos 2\omega_{LO} t \right. \end{aligned}$$

Mixing products

Mixing by Non-linear Circuit

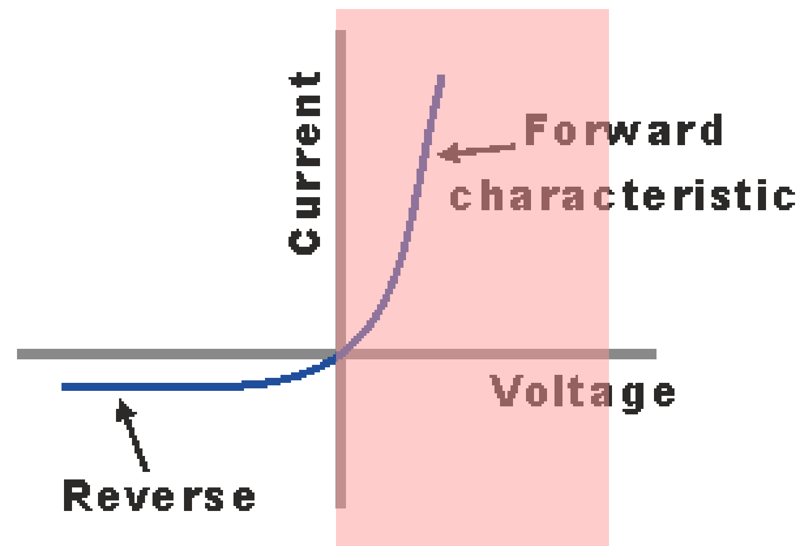
- Simple diode mixer
  - Diodes typically exhibit exponential I-V characteristics, which, at small signals, can be expanded to a polynomial
  - Schottky diodes are predominant in mixer applications, particularly at millimeter-wave frequencies, because of their fast transition time



$$I = I_S\left(e^{\frac{qV_d}{nkT}} - 1\right)$$
$$\approx I_S\left[\frac{qV_d}{nkT} + \left(\frac{qV_d}{nkT}\right)^2 + \left(\frac{qV_d}{nkT}\right)^3 + \cdots\right]$$

Mixing

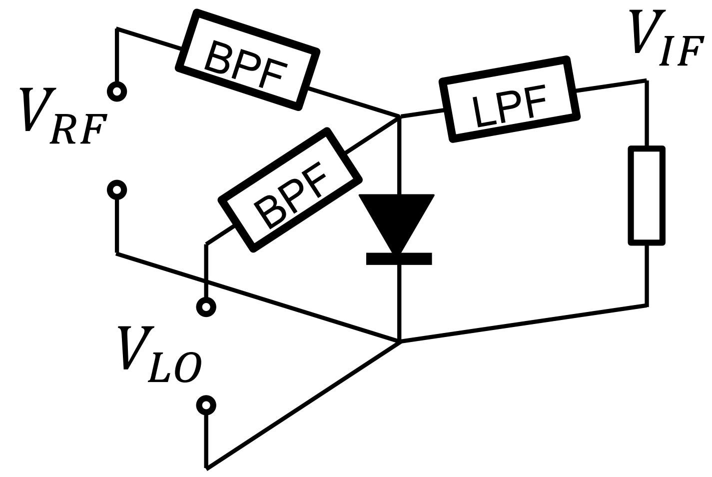
Non-linear region for mixer applications



Diode Mixer

- Mixing by non-linear circuit tend to generate a lot of spurious signals
- Output frequency spectrum is now more complex than a simple ideal multiplier

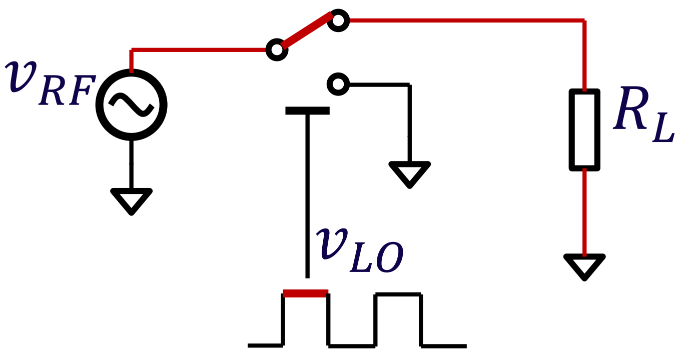
$$f_{IF} = \pm m \cdot f_{RF} \pm n \cdot f_{LO},$$
$$m = 0, 1, 2, 3, \ldots$$
$$n = 0, 1, 2, 3, \ldots$$



- We are mostly interested in $f_{IF} = |f_{RF} \pm f_{LO}|$, the rest of the frequencies are considered as undesired intermodulation products
- Isolations between the three ports are provided by filters
  - Still, single ended diode mixers are rarely used because of its bad isolation between the ports

Mixing by Linear Time Varying Circuit

- A simple time-variant circuit consisting of a switch controlled by the LO signal



A square wave can be expanded as

$$v_{SW} = \mathrm{V_{LO}}\left\{\frac{1}{2} + \frac{2}{\pi}\left[\sin\omega_{LO}t + \frac{\sin 3\omega_{LO}t}{3} + \frac{\sin 5\omega_{LO}t}{5} + \cdots\right]\right\}$$

$$v_o = V_{RF}\cos\omega_{RF}t \cdot V_{LO}\left\{\frac{1}{2} + 2/\pi\left[\sin\omega_{LO}t + \frac{\sin 3\omega_{LO}t}{3} + \frac{\sin 5\omega_{LO}t}{5} + \cdots\right]\right\}$$

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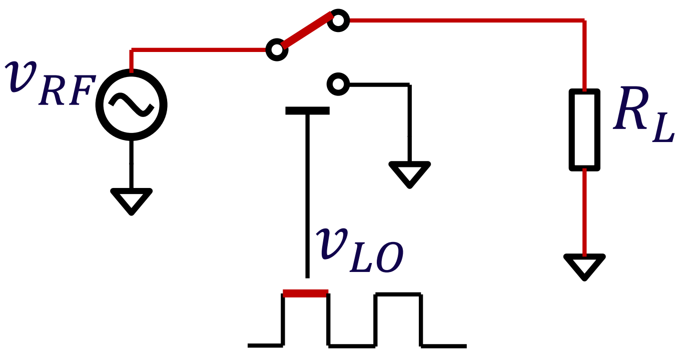
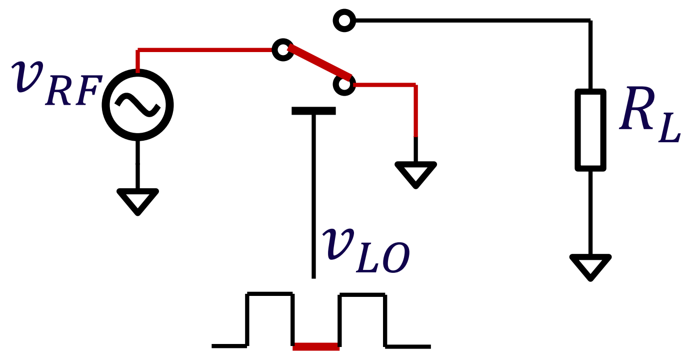
Mixing by Linear Time Varying Circuit

- A simple time-variant circuit consisting of a switch controlled by the LO signal





Mixing products

RF Feed-through

$$v_o = V_{RF}\cos\omega_{RF}t\cdot V_{LO}\left\{\frac{1}{2}+\frac{2}{\pi}\left[\sin\omega_{LO}t+\frac{\sin 3\omega_{LO}t}{3}+\frac{\sin 5\omega_{LO}t}{5}+\cdots\right]\right\}$$

$$= V_{RF}V_{LO}\left\{\frac{1}{2}\boxed{\cos\omega_{RF}}+\frac{1}{\pi}\boxed{\sin(\omega_{RF}+\omega_{LO})t}-\frac{1}{\pi}\boxed{\sin(\omega_{RF}-\omega_{LO})t}\right.$$

$$+\frac{1}{3\pi}\boxed{\sin(\omega_{RF}+3\omega_{LO})t}-\frac{1}{3\pi}\boxed{\sin(\omega_{RF}-3\omega_{LO})t}+\frac{1}{5\pi}\boxed{\sin(\omega_{RF}+5\omega_{LO})t}$$

Spurs; but not with even order harmonics of the LO

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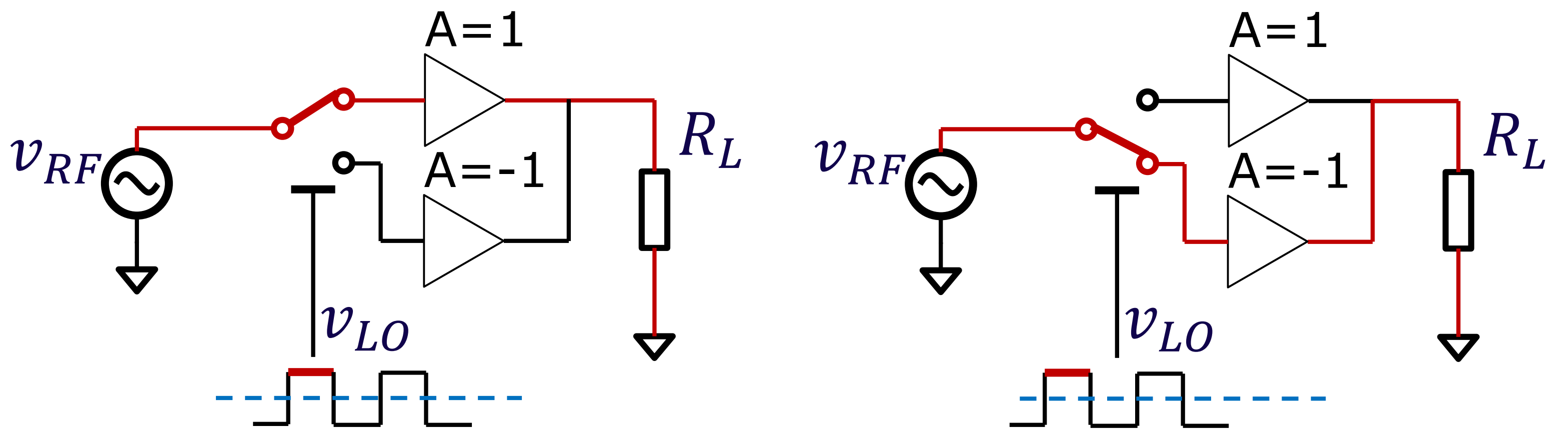
Mixing by Linear Time Varying Circuit

- A balanced LO drive can reduce RF feed-through



A balanced (centered at 0) square wave can be expanded as

$$v_{SW} = \mathrm{V_{LO}} \frac{2}{\pi} \left(\sin \omega_{LO} t + \frac{\sin 3\omega_{LO} t}{3} + \frac{\sin 5\omega_{LO} t}{5} + \cdots \right)$$

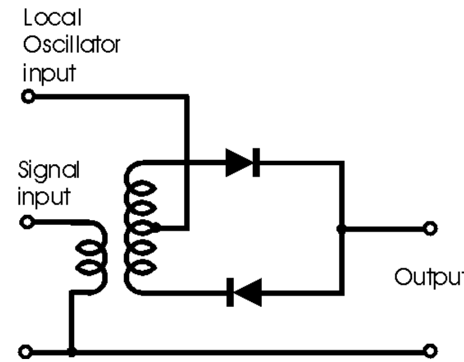
$$v_o = V_{RF} V_{LO} \left(\boxed{\cos \omega_{RF} t \sin \omega_{LO} t} + \boxed{\cos \omega_{RF} t \frac{\sin 3\omega_{LO} t}{3}} + \boxed{\cos \omega_{RF} t \frac{\sin 5\omega_{LO} t}{5}} + \cdot \right.$$

Mixing products

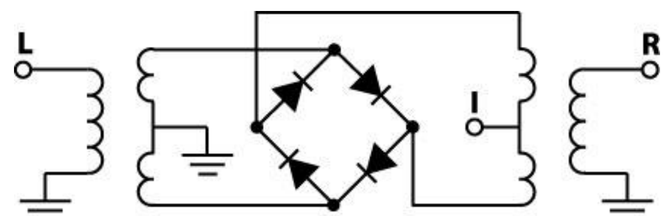
Spurs

Balanced Mixer Designs

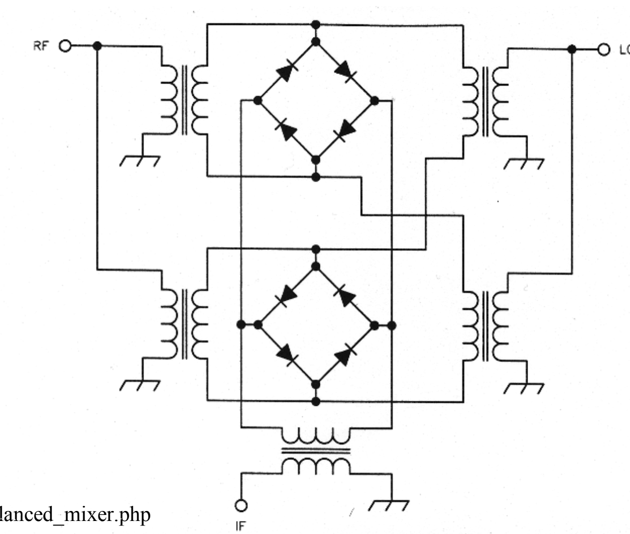
- Single balanced
  - 2 diodes for flipping the sign of the RF signal



- Double balanced
  - A ring of 4 diodes



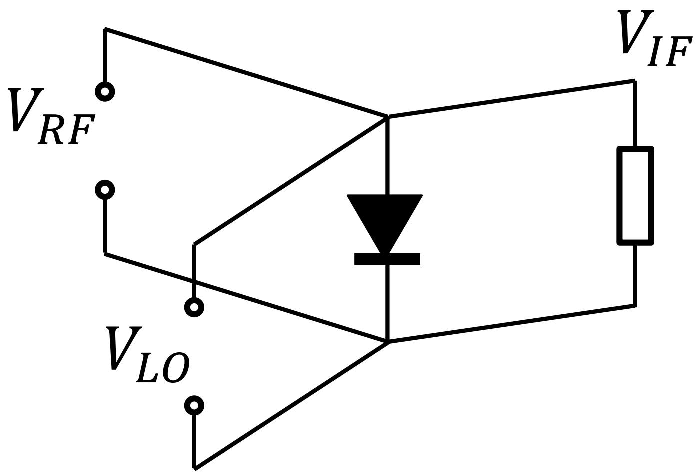
- Double Double-balanced
  - Double ring of 8 diodes

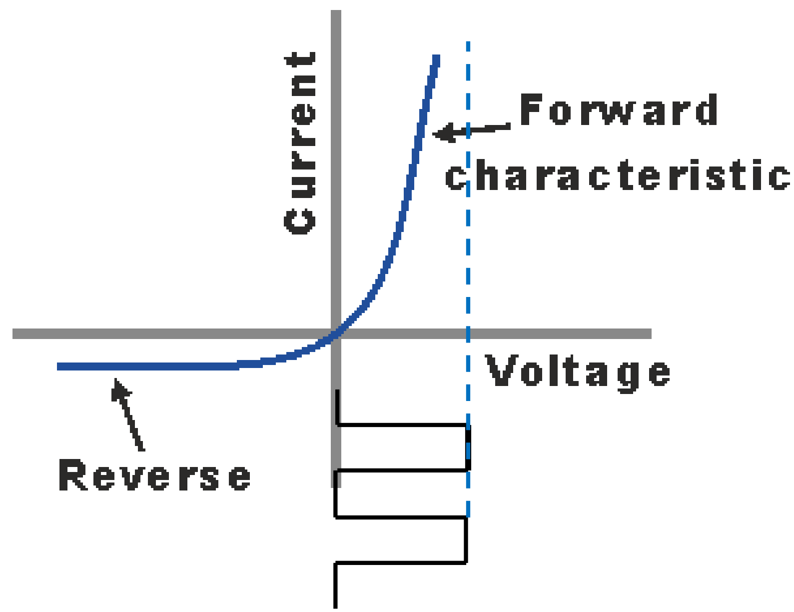


http://www.radio-electronics.com/info/circuits/diode_single_balanced_mixer/diode_single_balanced_mixer.php
http://www.minicircuits.com/pages/SIM_Upcon_U712H_int1.htm
http://www.robkalmeijer.nl/techniek/electronica/radiotechniek/hambladen/qst/1993/12/page32/

Realizing a Switching based Mixer

- Diode as a switch
  - Use a large (typically 20-dB larger than RF) LO to turn the diode on and off
  - Circuit would be identical to a non-linear diode mixer, but much less spurs

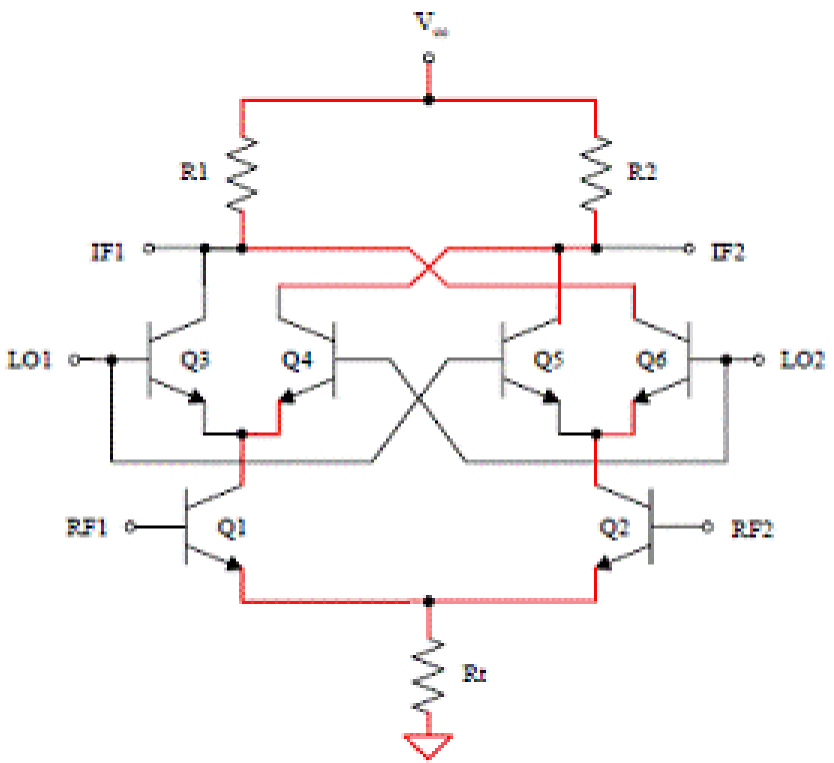




LO Drive

Circuit Implementation of a Multiplier

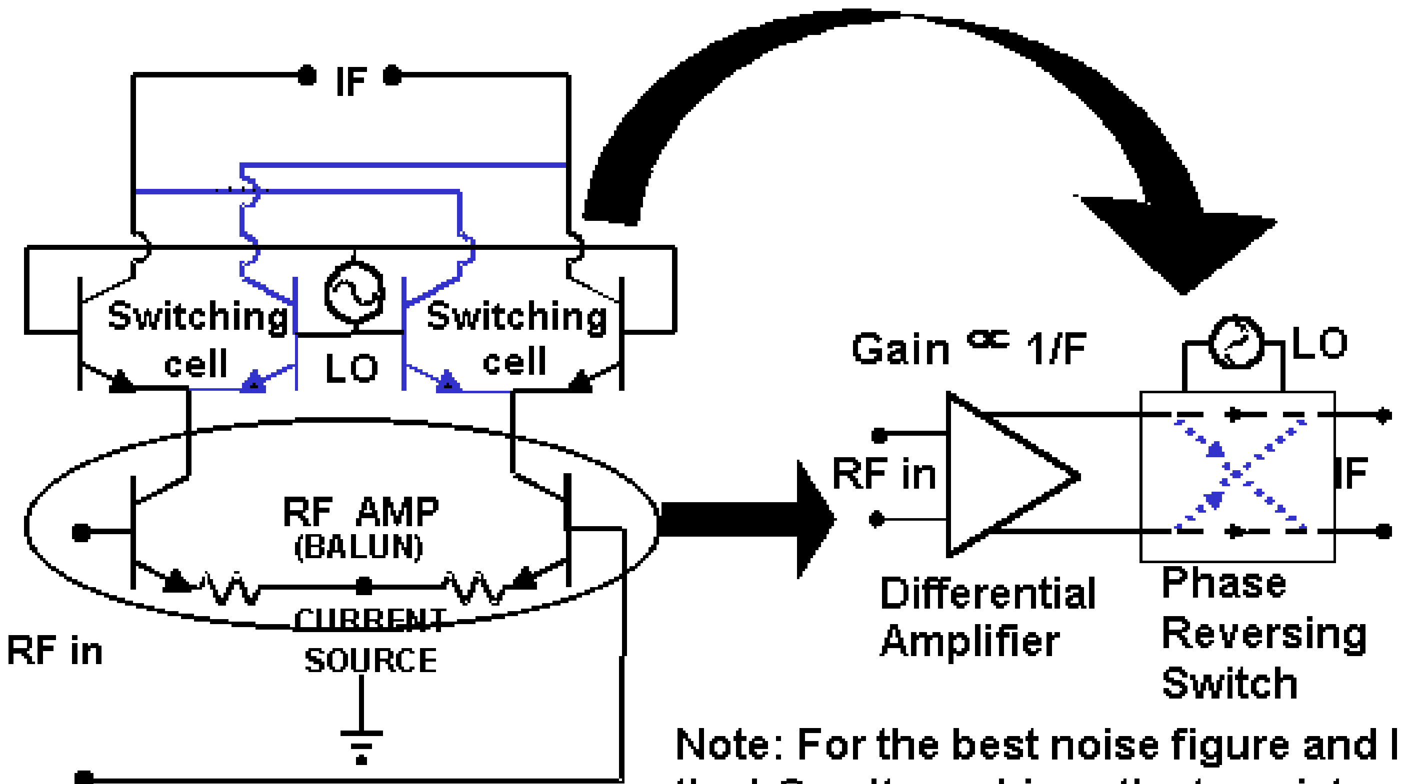
- Gilbert Cell
  - A general 4-quadrand multiplier
  - Active circuit, so it give gain to the RF signal
  - Double balanced
  - When used as an RF-mixer, LO signal needs to be large in amplitude so that they can switch the transistors fast



http://www.bessernet.com/articles/mixernoise/mixerNoise6.htm

Circuit Implementation of a Multiplier

A Gilbert Cell Mixer is an Amplifier Followed by a Phase Reversing Switch

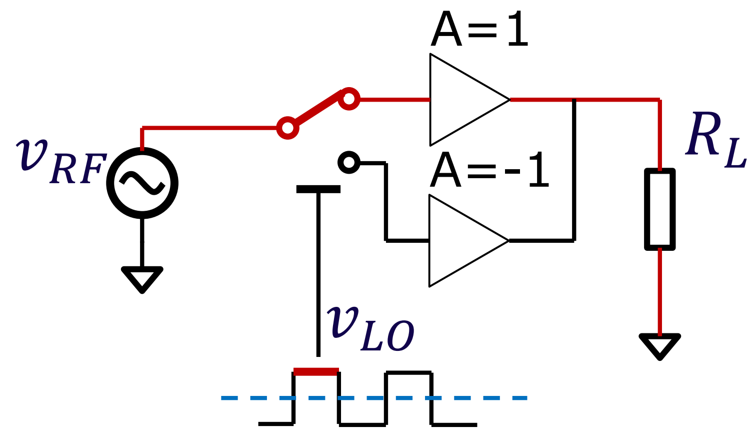


(Gilbert, IEEE JSSC, Dec., 1968)

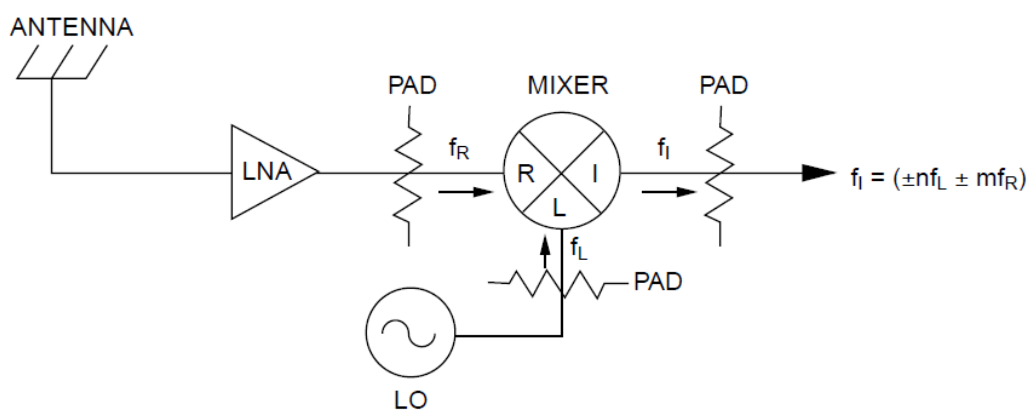
Note: For the best noise figure and IIP3 the LO voltage drives the transistors rapidly through the crossover, or phase reversing region.

Mixer Specifications – Impedance Matching

- The need for impedance matching doesn't need further explanation
- However, for switching based mixers, impedance matching can be difficult of the time-varying nature of the circuit
  - Impedance matching is really a LTI concept
  - Pay attention to the VSWR or return loss specs of mixers!

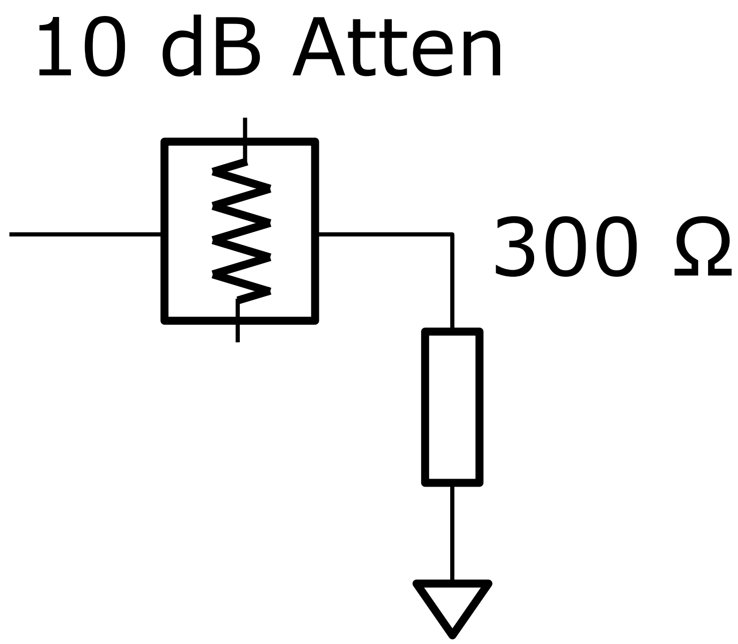


- Attenuators or isolator/circulators may be needed to improve matching



Attenuator (Pad) as Matching Network

- Attenuators can indeed work as a matching network, and in fact a very wideband one
  - Albeit with a lot of signal loss!



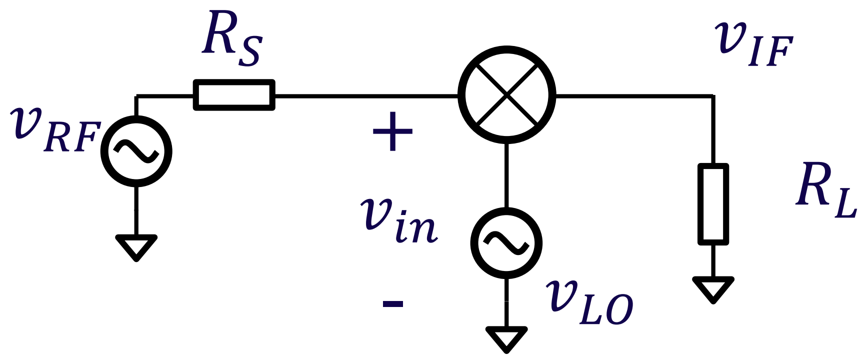
Mixer Specifications – Conversion Gain (Loss)

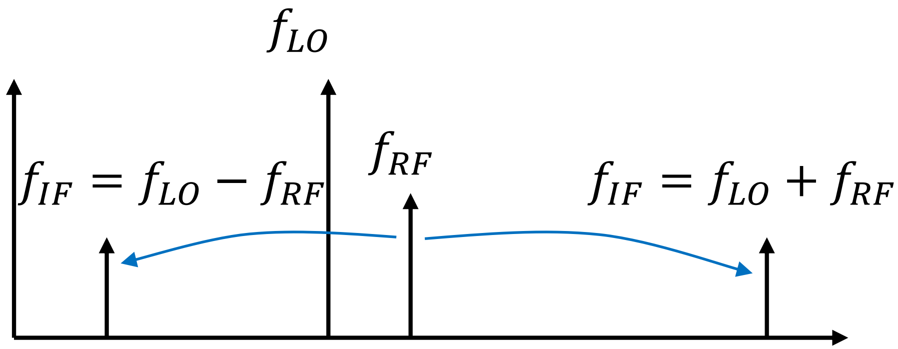
- Conversion Gain (Loss): energy conversion efficiency from RF to IF

$$ConvGain(CG) = \frac{v_{IF}}{v_{in}}$$

Or

$$CG = \frac{Output\ Power\ at\ IF}{Available\ RF\ power} = \frac{\frac{v_{IF}^2}{2R_L}}{\frac{v_{RF}^2}{8R_s}}$$

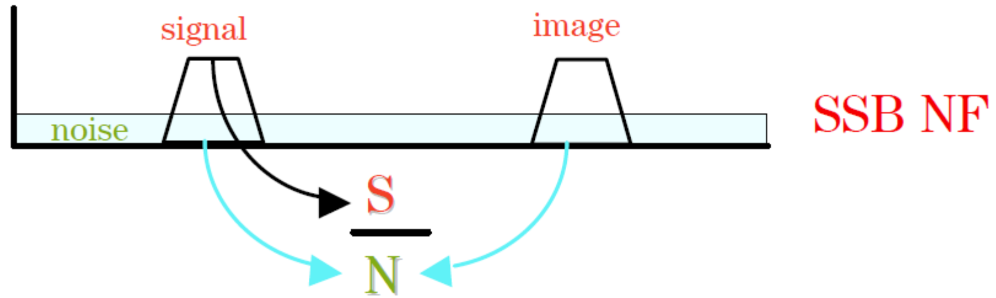




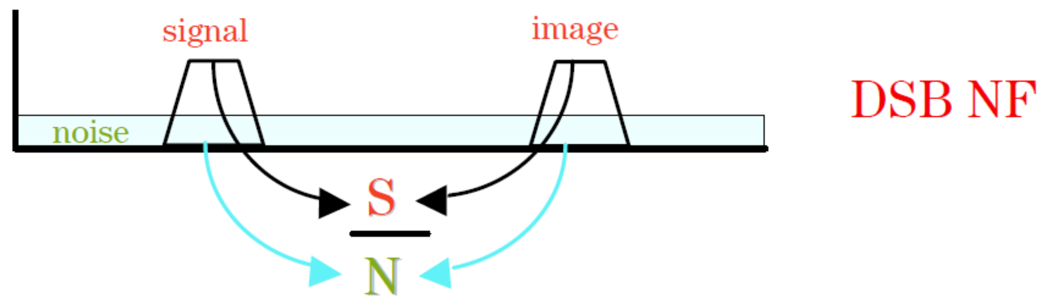
- Note that because two mixing products (sum and difference) are generated, there is an automatic 3-dB loss
- Active mixers may give gain; while passive mixers (e.g. diode mixers) give loss

Mixer Specifications – Noise

- Single-sideband noise: takes signal from one sideband but noise from both



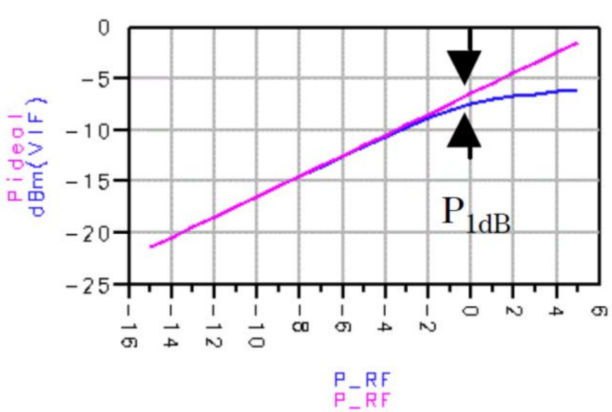
- Double-sideband noise: takes signals and noise from both sidebands

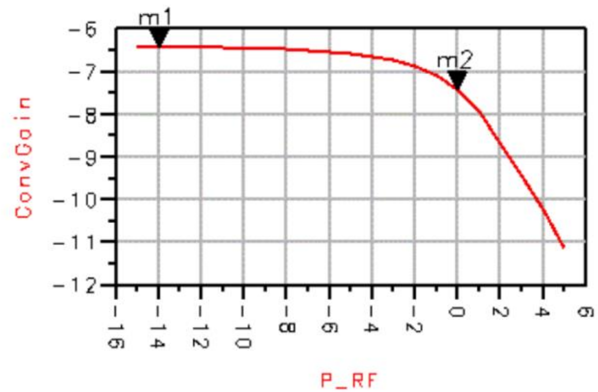


- DSB NF would usually be 3-dB less than the SSB NF
- For passive mixers, the NF is usually equal to the conversion gain (under the assumption that the mixer is well matched at the RF and IF ports)

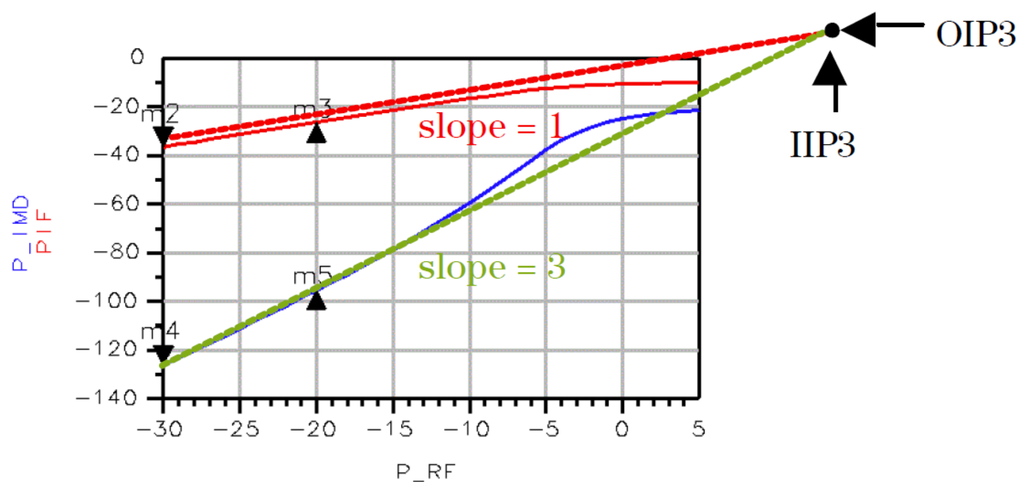
Mixer Specifications – Power Handling

- The concept of nonlinearity metrics such as P1dB and IP3 are the same as in amplifiers we studied before
- Gain compression – P1dB





- Intermodulation – IP3



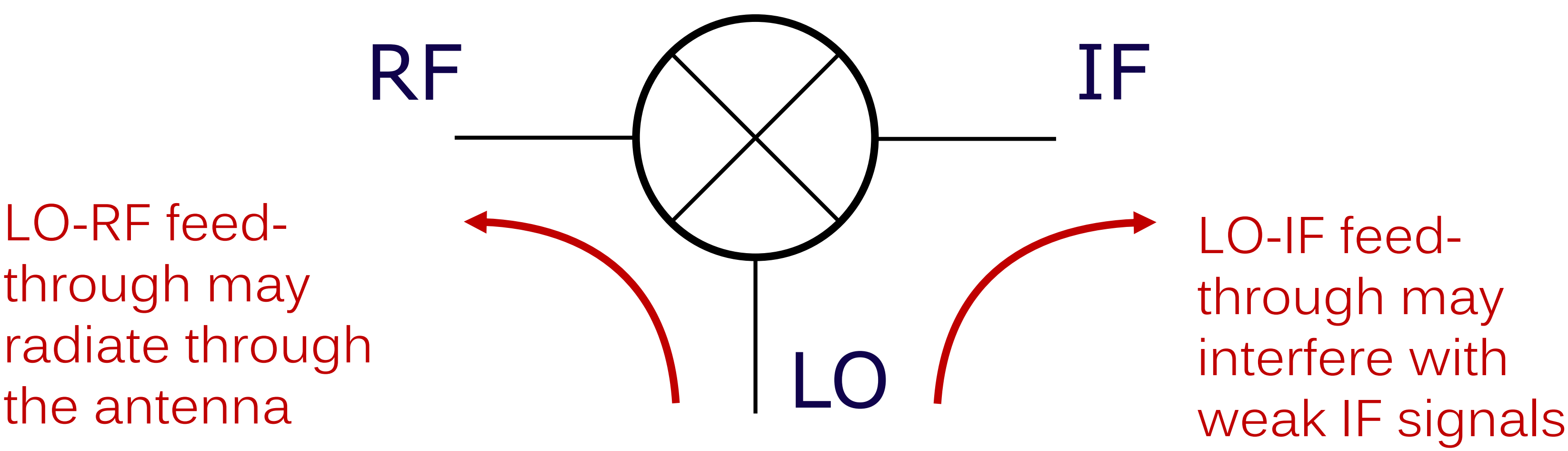
Mixer Specifications – Intermodulation

- At the IF output, you may have a lot of intermodulation products
- Some vendors provide tables of these intermod products (often specified relative to the IF output power)

HARMONICS OF f_R	7	79	>99	>99	69	79	>99	88	>99	>99	74	78	>99	83	>99	>99	63	78	>99
		>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	87	>90	>90
	6	90	>99	>99	86	>99	>99	91	>99	>99	91	>99	97	90	>99	>99	84	>99	>99
		>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90	>90
	5	72	93	>99	70	73	96	71	87	>99	52	72	95	77	88	>99	46	66	>99
		>90	>90	>90	80	>90	>90	>90	>90	>90	71	>90	>90	>90	>90	>90	68	>90	>90
	4	80	96	83	79	80	91	82	96	>99	77	80	92	82	95	90	76	82	95
		86	>90	>90	>90	>90	>90	86	>90	>90	88	>90	>90	88	>99	>99	85	>90	>90
	3	51	63	81	49	58	73	53	65	85	51	60	69	55	65	85	48	55	68
		67	87	>90	64	77	>99	69	87	>99	50	78	>99	77	>99	>99	47	75	>90
	2	69	68	64	72	67	71	79	76	62	67	67	70	75	80	63	66	66	70
		73	86	73	73	75	83	74	84	75	70	75	79	71	86	80	64	74	80
	1	25	25	24	0	0	0	39	39	35	13	11	11	45	50	42	22	16	19
		24	23	24	0	0	0	35	39	34	13	11	11	40	46	42	24	14	18
	0				36	39	29	45	42	20	52	46	32	63	58	24	45	37	29
					26	27	18	35	31	10	39	36	23	50	47	14	41	36	19
		0			1			2			3			4			5		
		HARMONICS OF f_L																	

Mixer Specifications -- Isolation

- Isolation (feed-through): insertion loss between ports (at the same frequency)
  - Important ones: LO->RF feed-through, LO->IF feed-through
  - Not so important ones:
    - RF->IF: typically too small compared with the IF signals
    - IF->RF: typically too small compared with the LO->RF feed-through
    - IF->LO and RF->LO: typically too small to interfere with the LO circuit



Mixer Example: Analog Devices ADL5801

FEATURES

Broadband upconverter/downconverter
Power conversion gain of 1.8 dB
Broadband RF, LO, and IF ports
SSB noise figure (NF) of 9.75 dB
Input IP3: 28.5 dBm
Input P1dB: 13.3 dBm
Typical LO drive: 0 dBm
Single-supply operation: 5 V at 130 mA
Adjustable bias for low power operation
Exposed paddle, 4 mm × 4 mm, 24-lead LFCSP package

FUNCTIONAL BLOCK DIAGRAM

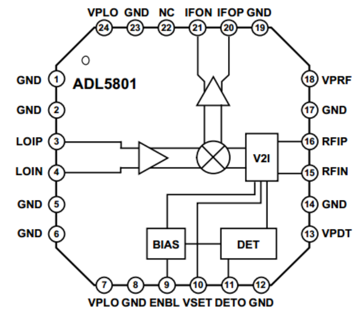
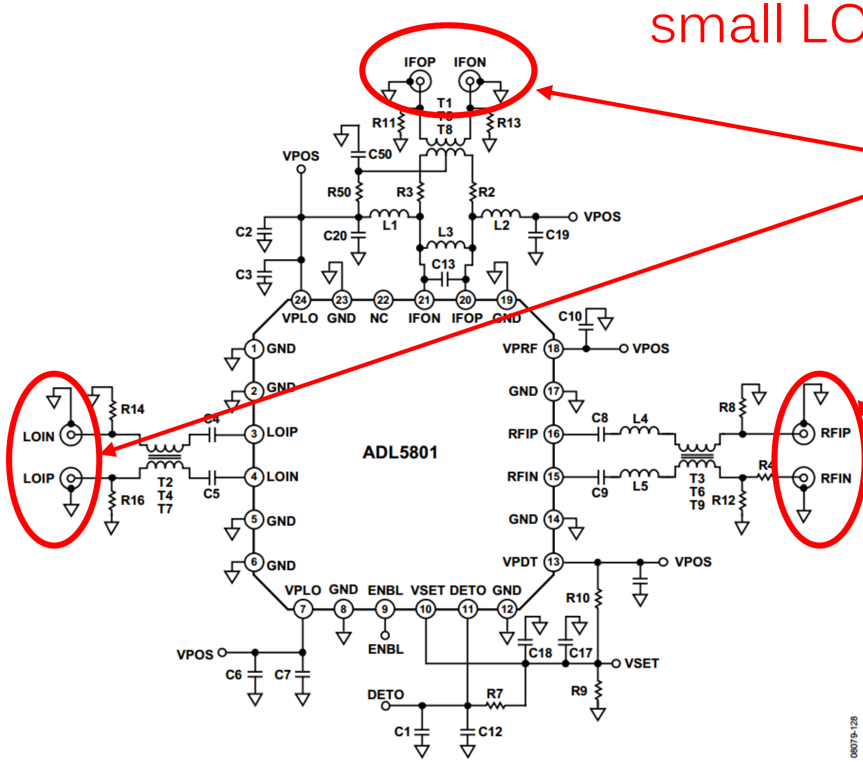


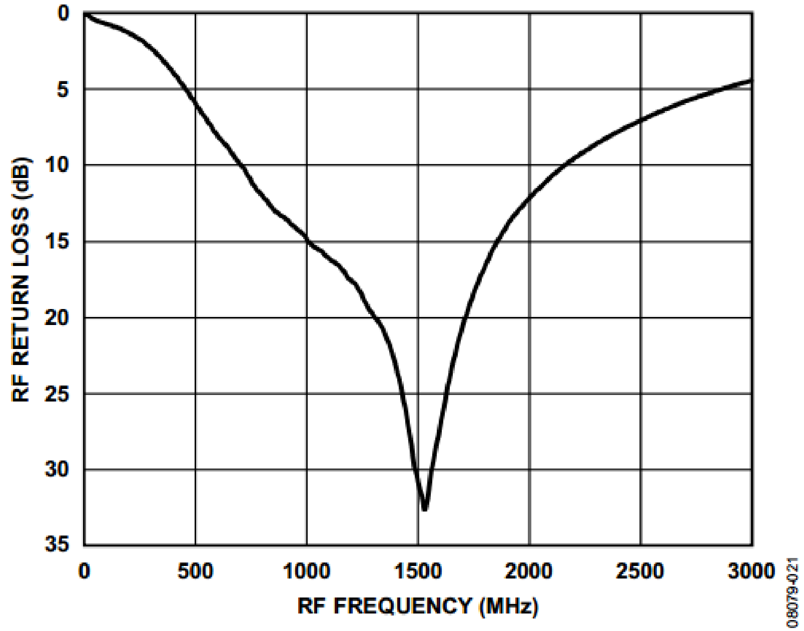
Figure 1.

Internal LO amplifier allows a small LO input



All ports are differential

ADL5801 – Impedance Matching



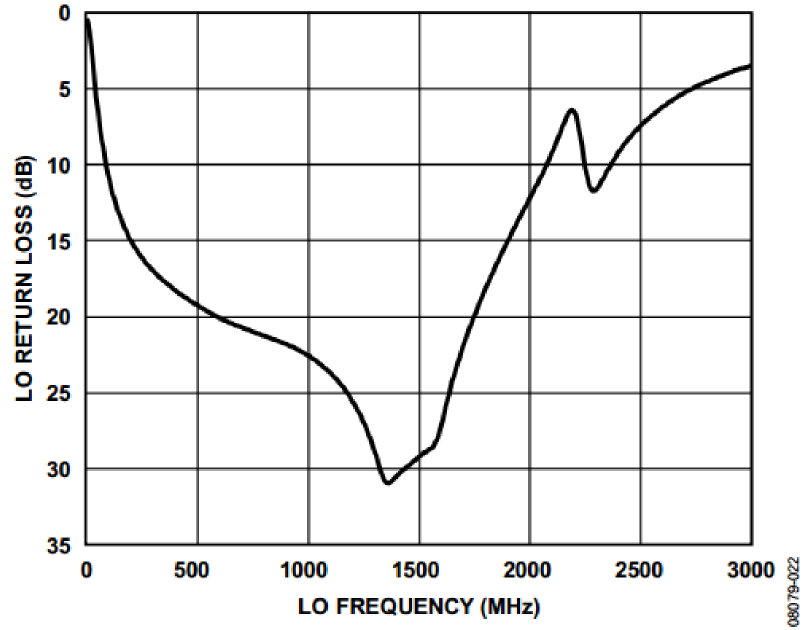
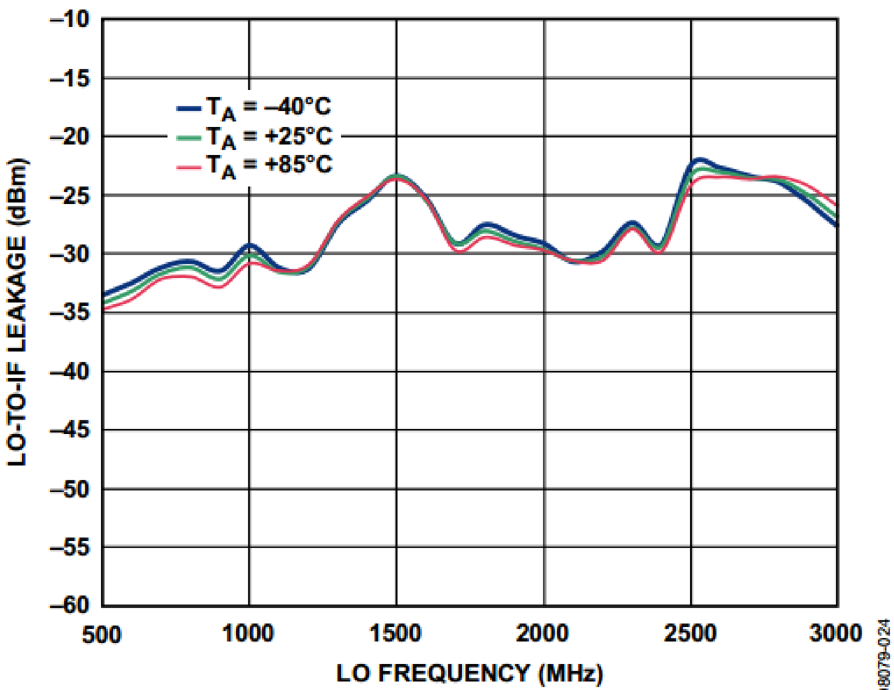
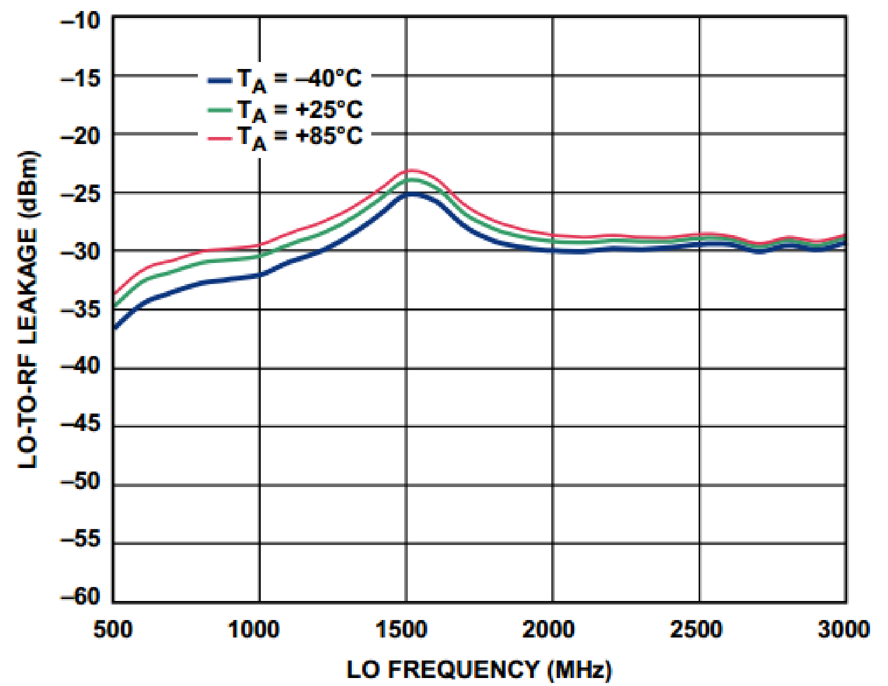


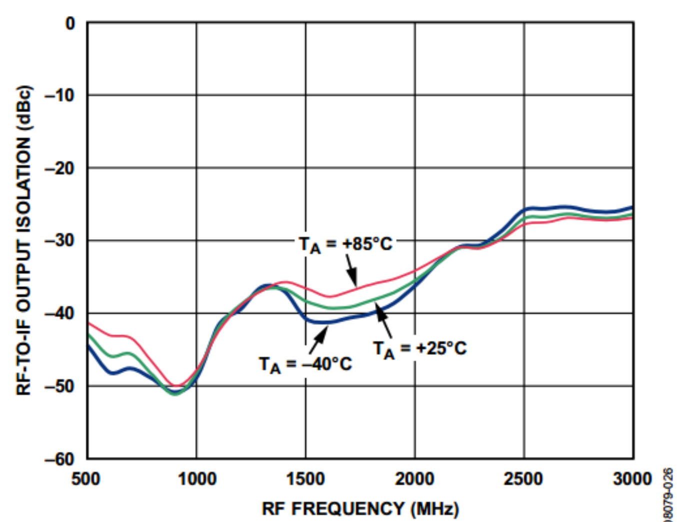
Table 1.

Parameter	Test Conditions	Min	Typ	Max	Unit
RF INPUT INTERFACE					
Return Loss	Tunable to >20 dB over a limited bandwidth		12		dB
Input Impedance			50		Ω
RF Frequency Range		10		6000	MHz
OUTPUT INTERFACE					
Output Impedance	Differential impedance, f = 200 MHz		230		Ω
IF Frequency Range	Can be matched externally to 3000 MHz	LF		600	MHz
DC Bias Voltage[2]	Externally generated	4.75	V_S	5.25	V
LO INTERFACE					
LO Power		−10	0	+10	dBm
Return Loss			15		dB
Input Impedance			50		Ω
LO Frequency Range		10		6000	MHz

ADL5801 – Isolation







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Mixer Example – MiniCircuits MAC-80H+

Ceramic, Hermetically Sealed

Frequency Mixer WIDE BAND

MAC-80H+

Level 17 (LO Power+17 dBm) 2800 to 8000 MHz

The level of a mixer is basically the required LO signal level

CASE STYLE: DZ1650
PRICE: $8.95 ea. QTY (10)

IF Current 40 mA
Permanent damage may occur if any of these limits are exceeded.

Features
- wide bandwidth, 2800 to 8000 MHz
- low conversion loss, 6.0 dB typ.
- high L-R isolation, 29 dB typ.
- LTCC double balanced mixer
- aqueous washable
- low cost
- low profile, 0.060"
- protected by US Patent 7,027,795
- *3-YEAR GUARANTEE -The Most Reliable Mixers*

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

Pin Connections

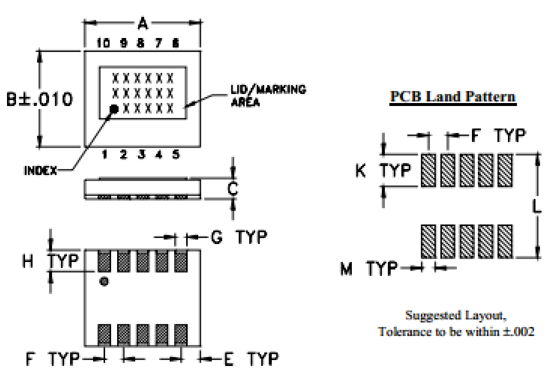
LO	10
RF	5
IF	3
GROUND	1,2,4,6,7,8,9

Available Tape and Reel at no extra cost

Reel Size	Devices/Reel
7"	10, 20, 50, 100, 200, 500
13"	1000

Applications
- satellite up and down converters
- line of sight links
- defense radar
- defense communications

Outline Drawing



Electrical Specifications at 25°C

Parameter	Condition (MHz)	Min.	Typ.	Max.	Units
Frequency Range, LO/RF			**2800 - 8000**		MHz
Frequency Range, IF			DC - 1250		MHz
Conversion Loss*	2800 - 5000 5000 - 8000	— —	6.0 6.5	9.1 8.9	dB
LO to RF Isolation	2800 - 5000 5000 - 8000	28 25	42 34	— —	dB
LO to IF Isolation	2800 - 5000 5000 - 8000	9 14	16 31	— —	dB
IP3	2800 - 5000 5000 - 8000	— —	23 21	— —	dBm
RF Input Power at 1 dB Compression	2800 - 8000		+14		dBm

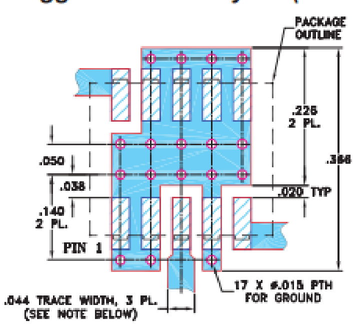
*Conversion Loss measured at 30 MHz IF.

Mixer Example – MiniCircuits MAC-80H+

Outline Dimensions (inch / mm)

A	B	C	D	E	F	G
.30	.250	.060	--	.050	.050	.030
7.62	6.35	1.52	--	1.27	1.27	0.76
H	**J**	**K**	**L**	**M**		**wt**
.056	--	.085	.270	.035		grams
1.42	--	2.16	6.86	0.89		0.29

Demo Board MCL P/N: TB-144
Suggested PCB Layout (PL-045)



NOTES: 1. TRACE WIDTH IS SHOWN FOR ROGERS RO4350B WITH DIELECTRIC THICKNESS .020" ± .0015"; COPPER: 1/2 OZ. EACH SIDE. FOR OTHER MATERIALS TRACE WIDTH MAY NEED TO BE MODIFIED.
2. BOTTOM SIDE OF THE PCB IS CONTINUOUS GROUND PLANE.

DENOTES PCB COPPER LAYOUT WITH SMOBC (SOLDER MASK OVER BARE COPPER)

DENOTES COPPER LAND PATTERN FREE OF SOLDER MASK

Typical Performance Data at 25°C and LO=+17dBm

Frequency (MHz) RF	Frequency (MHz) LO	Conversion Loss (dB) LO +17dBm	Isolation L-R (dB) LO +17dBm	Isolation L-I (dB) LO +17dBm	VSWR RF Port (:1) LO +17dBm	VSWR LO Port (:1) LO +17dBm
2800.1	2830.1	7.06	57.44	10.35	4.13	2.52
3100.1	3130.1	6.29	43.03	13.43	3.32	2.50
3400.1	3430.1	5.71	43.76	14.86	2.11	2.24
3700.1	3730.1	5.42	44.25	14.69	2.17	1.76
4000.1	4030.1	6.49	41.65	12.39	3.31	1.66
4400.1	4430.1	6.84	31.47	14.33	2.58	1.77
4600.1	4630.1	8.21	36.26	18.13	3.41	1.90
5000.1	5030.1	6.71	31.71	24.64	2.88	1.80
5200.1	5230.1	6.09	32.59	27.40	2.59	2.06
5400.1	5430.1	5.67	36.74	28.65	2.24	2.12
5800.1	5830.1	7.95	39.06	30.29	3.88	2.05
6000.1	6030.1	7.18	46.65	31.00	4.18	2.33
6400.1	6430.1	6.29	40.59	33.09	3.34	2.79
6600.1	6630.1	6.33	37.23	34.29	3.30	3.04
7000.1	7030.1	5.71	33.47	33.57	2.59	2.27
7200.1	7230.1	5.55	31.68	28.11	2.18	2.09
7400.1	7430.1	5.47	32.63	24.17	2.07	1.94
7600.1	7630.1	5.65	35.03	22.67	1.92	1.97
7800.1	7830.1	5.91	30.31	19.57	1.80	2.27
8000.1	8030.1	6.53	26.67	15.63	1.68	2.78

Electrical Schematic