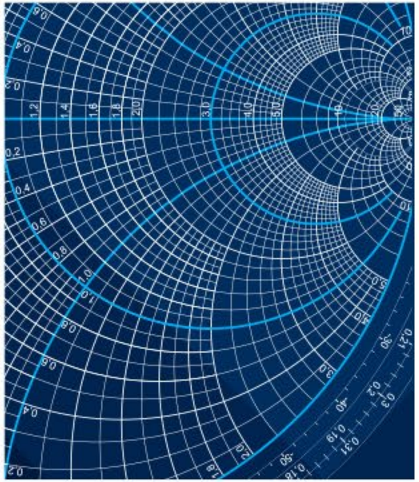
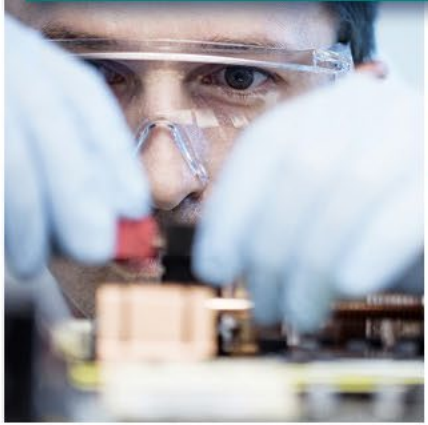


Measurement Techniques

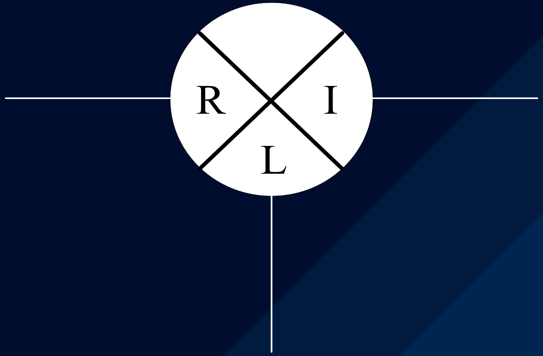
Design Verification & Evaluation

EVERYTHING TEST

Instrument Selection & Optimization



RF TEST:
Mixer and Frequency Converter Testing



Neil Jarvis, RF and Microwave Applications Engineer

ROHDE&SCHWARZ

Make ideas real

Mixers and Frequency Converters

Introduction to Mixers and Converters

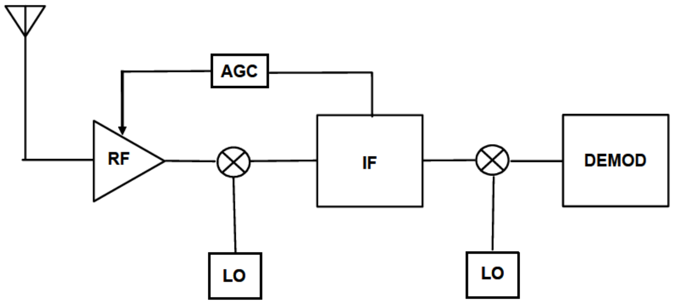
- Applications of Mixers
- Mixer Fundamentals
  - Transfer Characteristics
  - Images
  - Spurious M x N Analysis
- Demo
- Key Mixer Specifications
  - Conversion Loss
  - Port to Port Isolation
  - Input 1 dB Compression Point
  - Input Intercept Point
  - Noise Figure

Advanced Mixers/Converters

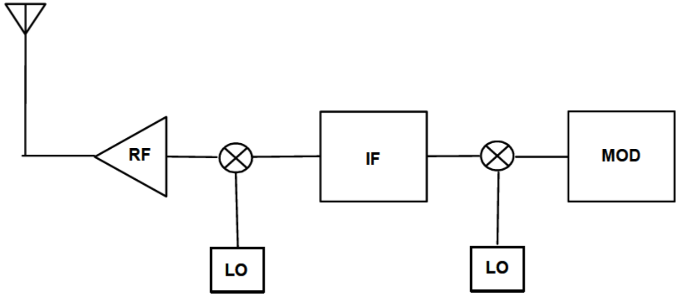
- Basic Converter Functionality
- Key Converter Characteristics
- Phase measurements
- Group delay
- Embedded LOs

Superheterodyne Receiver

► A receiver architecture that uses frequency mixing to convert a received signal to a lower intermediate frequency (IF) that is more easily processed that the original higher RF or carrier frequency. Virtually all modern radio receivers use the superheterodyne principle.



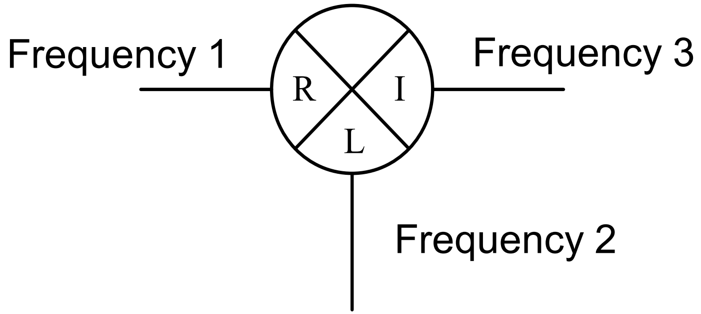
Receiver



Transmitter

Applications of mixers

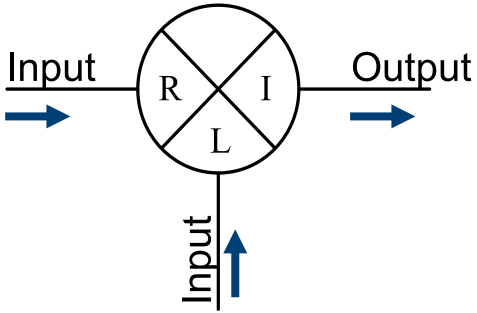
- Converters – Used to move a band or block of bands from one part of the spectrum to another
- Repeaters – Used to receive and retransmit an RF signal. Usually after filtering and amplifying
- Receivers – Used to receive an RF signal and translate it into information. Examples are audio, data, and video
- Tuner – Used to pass one radio frequency (RF) or band of frequencies while excluding others, with the use of filters and other devices.



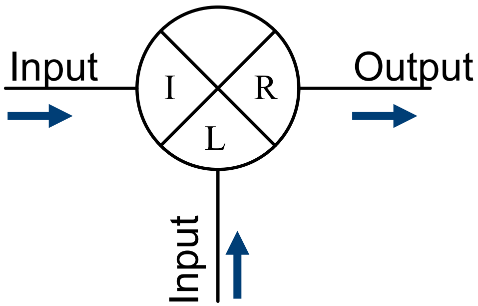
Mixer Fundamentals

- Receivers
  - Up or down conversion
  - Demodulation
- Transmitters
  - Up Conversion
  - Modulation

Downconversion Mixer



Upconversion Mixer



Mixer Fundamentals Continued

- Mixer
  - Mixer is the generic term used to describe a 3 port device which creates an output frequency from two input frequencies applied to it.

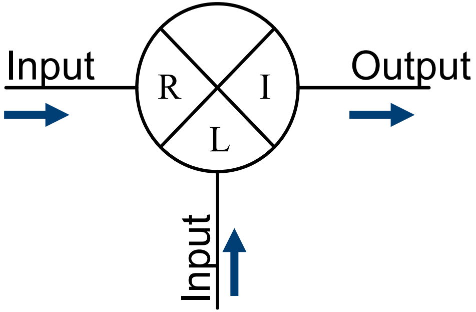
$$f_{\text{out}} = f_{in1} \text{ +/- } f_{in2}$$

- Wikipedia
  - A nonlinear electrical circuit that creates new frequencies from two signals applied to it. In its most common application, two signals are applied to a mixer, and it produces new signals at the sum and difference of the original frequencies. Other frequency components may also be produced in a practical frequency mixer.
  - Mixers are widely used to shift signals from one frequency range to another, a process known as heterodyning, for convenience in transmission or further signal processing. For example, a key component of a superheterodyne receiver is a mixer used to move received signals to a common intermediate frequency. Frequency mixers are also used to modulate a carrier signal in radio transmitters.

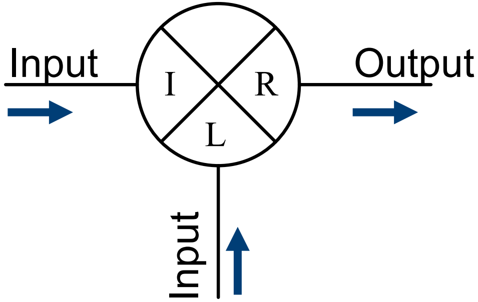
Mixer Fundamentals Continued

- **3 Ports**
  - **LO – Local Oscillator**
    - Typically sin wave or square wave
  - **RF – Radio Frequency**
    - Can be input or output usually higher frequency
  - **IF – Intermediate Frequency**
    - Is the opposite of the RF
    - RF input - > IF output
    - IF input - > RF output

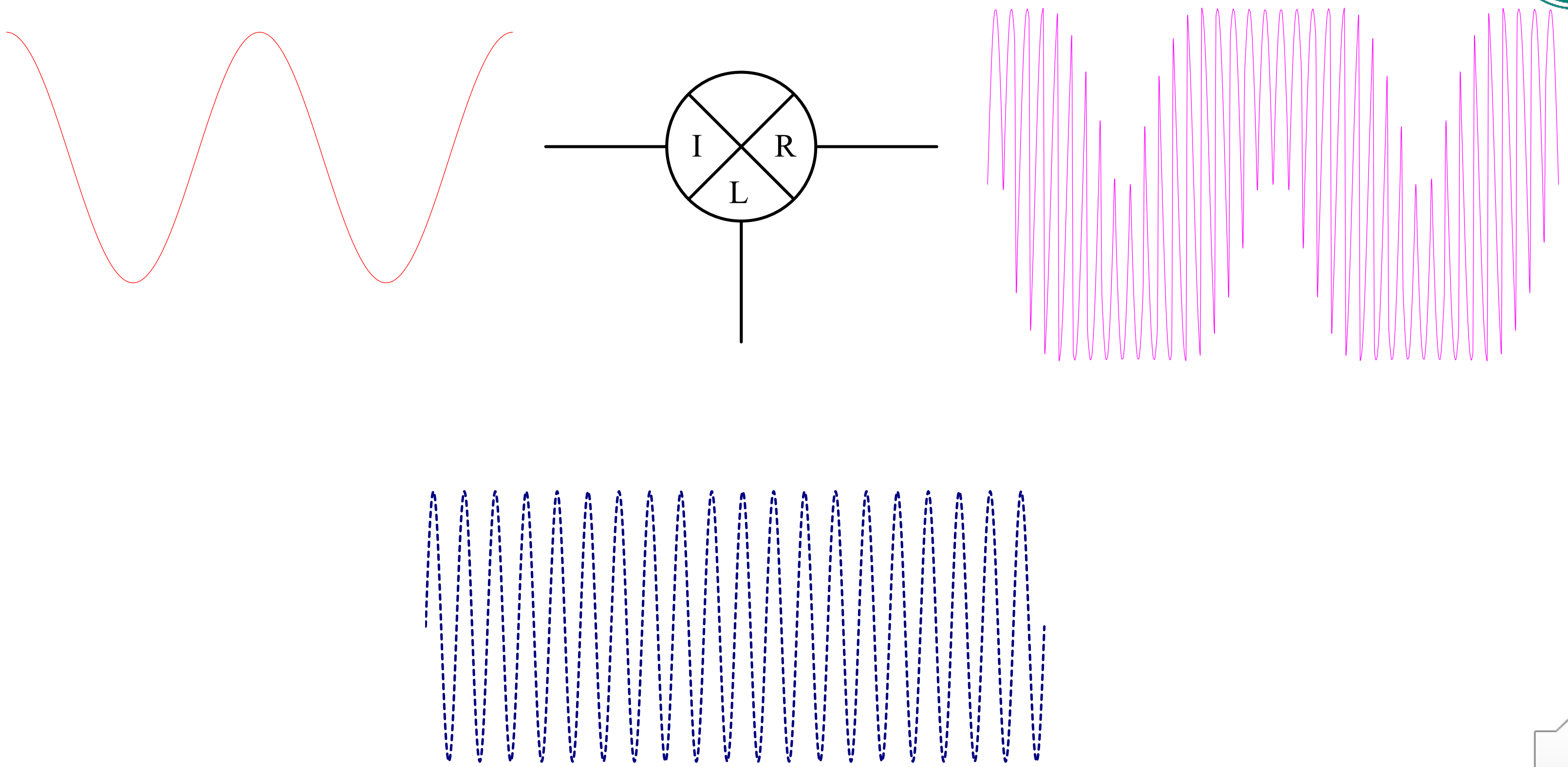
Downconversion Mixer



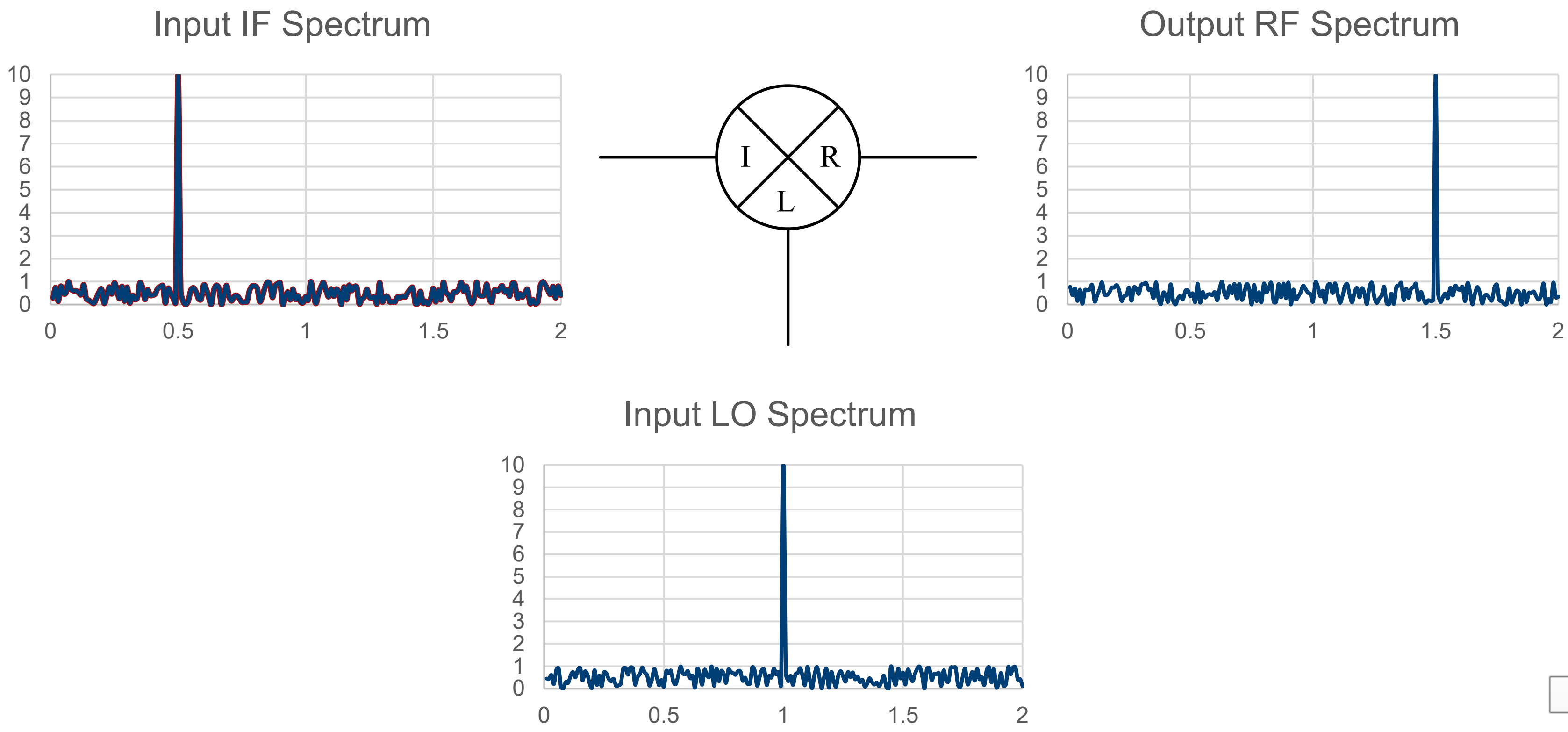
Upconversion Mixer



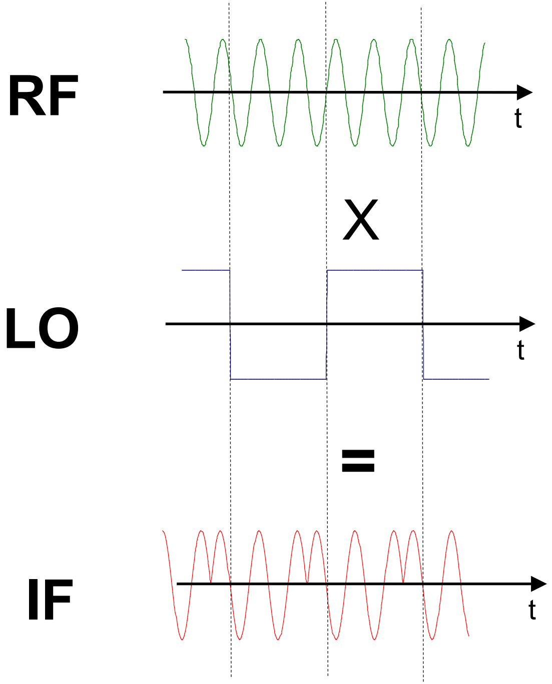
Mixer Fundamentals Continued - Time domain

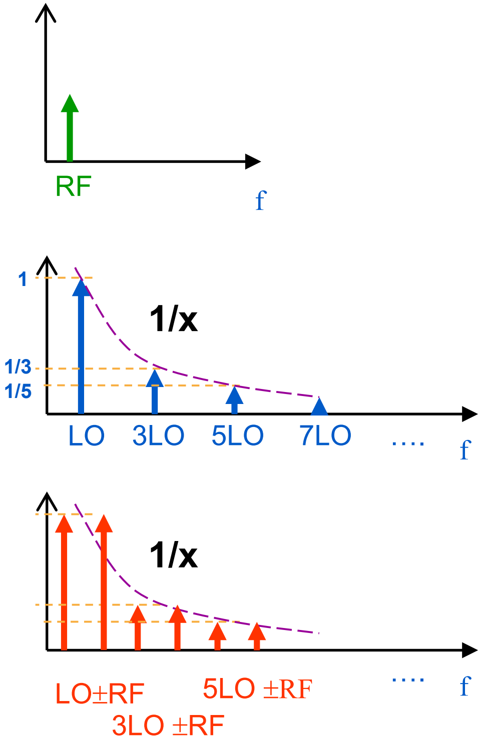


Mixer Fundamentals Continued - Frequency domain

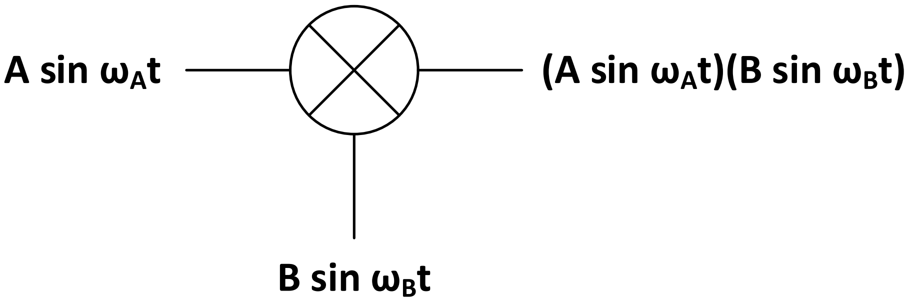


Mixer in Frequency Domain (Spectrum)



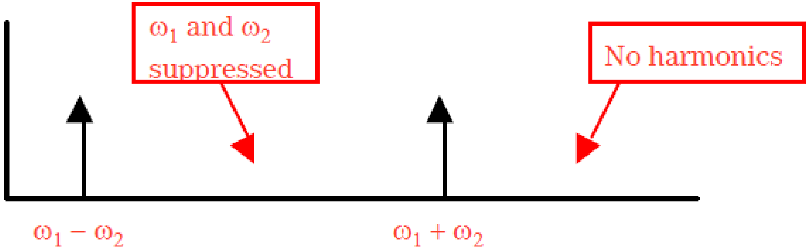


Mixer Fundamentals Continued - Trig



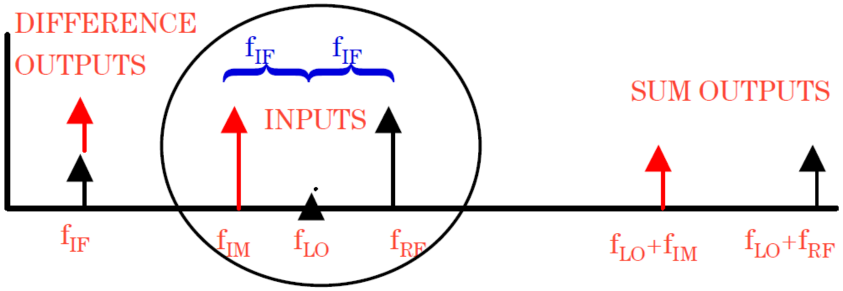
$$(A\sin\omega_1 t)(B\sin\omega_2 t)=\frac{AB}{2}\left[\cos(\omega_1-\omega_2)t-\cos(\omega_1+\omega_2)t\right]$$

Downconvert Upconvert



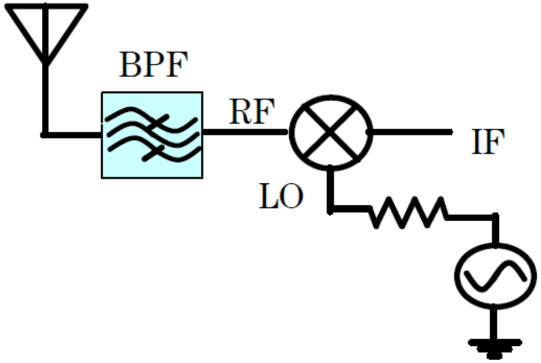
- Mixer doesn’t sum signals
- Mixer multiplies signals
- Notice that both the **SUM** and **DIFFERENCE** frequencies are generated
- Because of sum and difference frequencies, can be used for up and down conversion

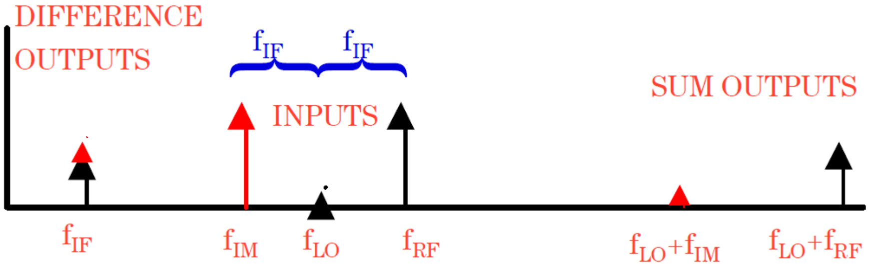
Mixer Fundamentals Continued - Images



- Output signal will also generate an image f_{IF} below the LO frequency f_{LO} denoted f_{IM}
- F_{RF} - F_{LO} = F_{LO} - F_{IM} = F_{IF}
- Both frequencies are valid, the design process entails selecting the image as the easier signal to filter
- Image frequency must be filtered out
- Frequency selection must be done very carefully particularly for multistage converters
- Image rejection ratio is the ratio of the desired to the undesired frequency

Mixer Fundamentals Continued - Image rejection





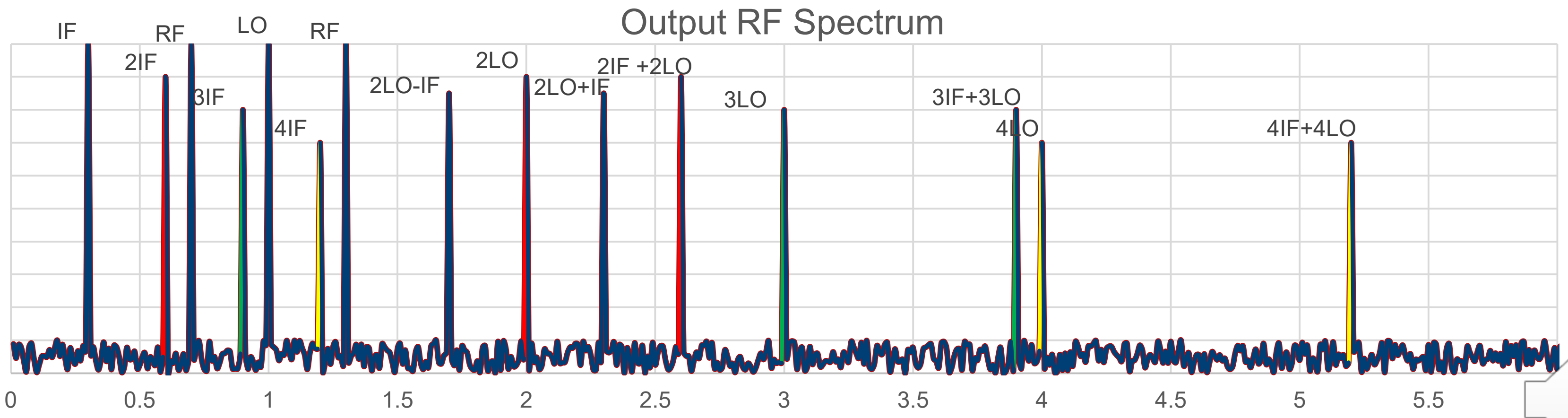
- Preselection filter is typically used to attenuate the image frequency
- Selecting IF and LO frequencies are chosen to optimize filtering of image
- F_{RF} - F_{LO} = F_{LO} - F_{IM} = F_{IF}
- Both frequencies are valid, the design process entails selecting the image as the easier signal to filter
- Image frequency must be filtered out
- Frequency selection must be done very carefully particularly for multistage converters
- Image rejection ratio is the ratio of the desired to the undesired frequency

Mixer Fundamentals Continued - Other higher order signals

- Unfortunately, or sometimes fortunately, many other higher order terms and frequencies will be generated
- Second, third, and higher order nonlinearities typically exist
- There are many other possibilities for using all these nonlinearities to generate much higher frequency signals all the way up to mm waves.
- The nonlinear mixer can be applicable at any frequency where the device presents a known nonlinearity. It is the only approach available at the upper mm-wave frequencies

Mixer Fundamentals Continued – output spectrum

- IF=300 MHz, LO=1 GHz for fundamental mixer we would like to only see outputs only at 1.3 GHZ and 700 MHz
- We can see that there are a lot of spurious outputs generated from higher order terms (not every term is included)
- These terms can take us up through much higher frequencies



Mixer Fundamentals Continued – spurious M x N

- IF=300 – 350 MHz, LO= 500 MHz for fundamental mixer desired output is at 800 – 850 MHz
- The spur calculator spreadsheet helps to determine all of the signals that are generated
- From this, we choose the terms we want so that undesired signals are removed by filtering
- This will be used also to specify the filters required

Difference Frequencies

LO ↓ / IF →

	0	1	2	3	4	5
0		300	600	900	1200	1500
1	500	200	0	400	700	1000
2	1000	700	400	0	200	500
3	1500	1200	900	600	300	0
4	2000	1700	1400	1100	800	500
5	2500	2200	1900	1600	1300	1000

Sum Frequencies

LO ↓

	1	2	3	4	5
1	800	1100	1400	1700	2000
2	1300	1600	1900	2200	2500
3	1800	2100	2400	2700	0
4	2300	2600	2900	0	0
5	2800	0	0	0	0

Key Specifications of A Mixer

- ► Conversion Loss
- ► Port to port Isolation
  - – LO – RF
  - – LO – IF
  - – RF – IF
- ► Frequency Response
- ► Return Loss
- ► Input 1 dB Compression Point
- ► Input 2 Tone TOI
- ► Noise Figure
- ► Higher Order Terms

Marki microwave

MICROLITHIC™ DOUBLE-BALANCED MIXER **ML1-0110SM**

The ML1-0110SM is a Surface Mount Microlithic™ double balanced mixer. As with all Microlithic™ mixers, it features excellent conversion loss, isolation, and spurious performance across a broad bandwidth and in a miniaturized form factor. Accurate, nonlinear software models are available for Microwave Office through the Marki Microwave PDK. The ML1-0110SM is a lead free, RoHS compliant package compatible with standard leaded and lead-free solder reflows. SMA connectorized evaluation packages are available. The ML1-0110SM is an excellent alternative to Marki Microwave M1 and M3 mixers packaged in surface mount packages such as the EZ package.

MICROLITHIC

Features

- Compact SMT Style Package (0.152" x 0.090"x0.045")
- CAD Optimized for Superior Isolation and Spurious Response
- Broadband Performance
- Excellent Unit-to-Unit Repeatability
- Fully nonlinear software models available with Marki PDK for Microwave Office
- RoHS Compliant

Mixer Line	Suitable Alternative for Models
M1	M1-0204, M1-0208, M1-0212, M1-0310, M1-0408, M1-0412
M3	M3-0309, M3-0312, M3-0408, M3-0412

Electrical Specifications - Specifications guaranteed from -55 to +100°C, measured in a 50Ω system.

Parameter	LO (GHz)	RF (GHz)	IF (GHz)	Min	Typ	Max	Diode Option[1] LO drive level (dBm)
Conversion Loss (dB)	1.5-10		DC-1 1-2		7 9	10 11	
Isolation (dB) LO-RF LO-IF RF-IF					See Plots		
Input 1 dB Compression (dBm)					+3 +9		L (+8 to +13) H (+16 to +20)
Input Two-Tone Third Order Intercept Point (dBm)					+12 +21		L (+8 to +13) H (+16 to +20)

[1]Contact factory for other diode options.

Part Number Options

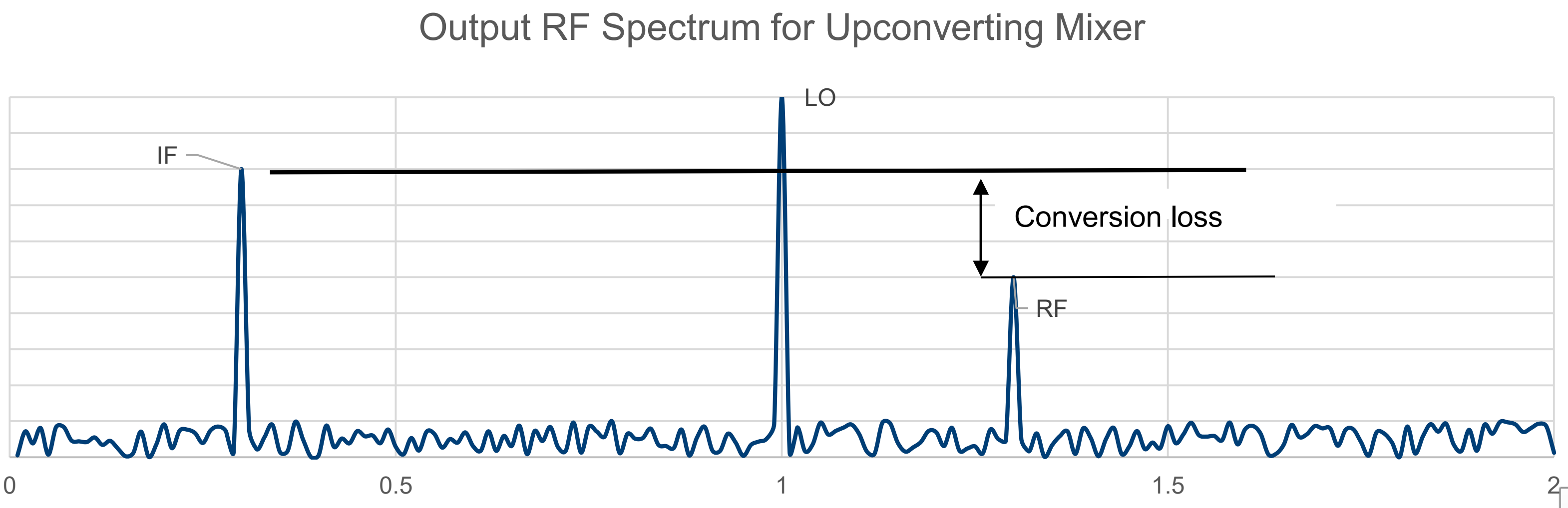
Model Number	Description
ML1-0110LSM-2, ML1-0110LSM-1 [1]	Surface Mount, L-Diode, I Port Configuration -2 or Configuration -
ML1-0110HSM-2, ML1-0110HSM-1 [1]	Surface Mount, H-Diode, I Port Configuration -2 or Config
EVAL-ML1-0110L	Connectorized Evaluation Fixture, L-Diode
EVAL-ML1-0110H	Connectorized Evaluation Fixture, H-Diode

[1]See -2 and -1 configuration options on page 4.

215 Vineyard Court, Morgan Hill, CA 95037 | Ph: 408.778.4200 | Fax 408.778.4300 | info@markimicrowave.com

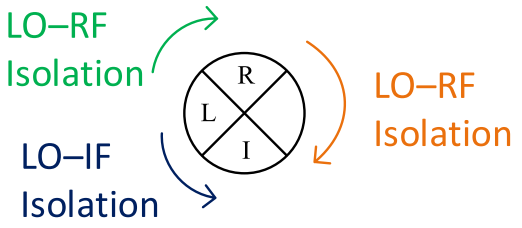
Key Mixer Characteristics - Conversion Loss

► Conversion Loss – Typically the most basic characteristic of mixers defined as the ratio of the output power to the available source power
  – Ratio of the RF output power to the available IF source power for upconverting mixer
  – Ratio of the IF output power to the available RF source power for downcoverting mixer



Key Mixer Characteristics – Port to port isolation

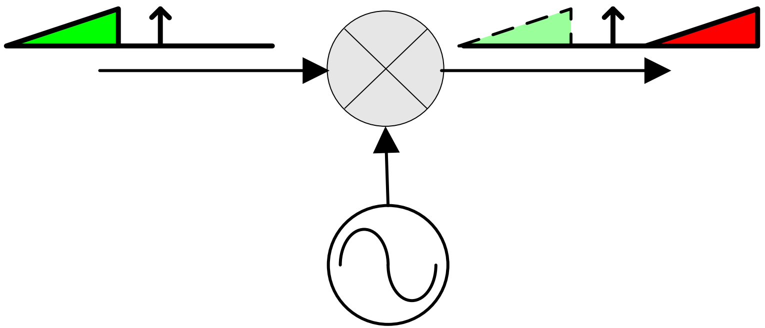
- Isolation is a measure of power leakage between the three ports of a mixer. A higher isolation value results in leakage between the pairs of ports



- **LO-RF Isolation:** Measure of LO signal attenuation from LO port to RF port at the LO frequency, typically the most significant term because the frequency is closer to the RF frequency and more challenging to filter and degrades the performance of the amplifiers
- **LO-IF Isolation:** measure of the LO signal attenuation from LO port to IF port at the LO frequency
- **RF-IF Isolation:** Measure of the RF signal attenuation from RF port to IF port at the RF frequency, this is usually much smaller than the IF signal power levels so less challenging to deal with

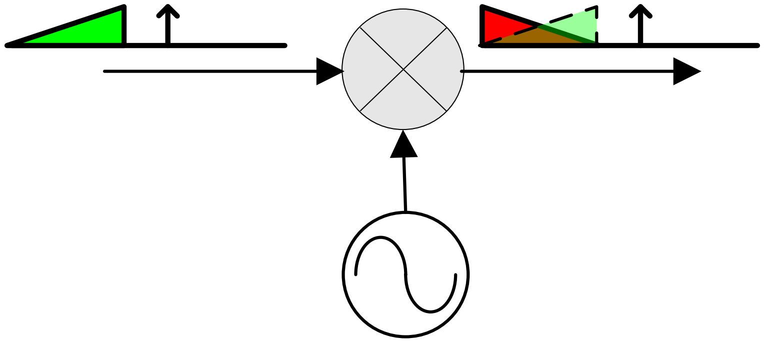
Mixer Responses

- Fixed LO, Swept RF, Swept IF; RF > LO
  - Most common measurement
  - RF to IF transfer function is well defined
  - No Phase/Frequency Inversion from RF to IF
  - Group Delay is well defined

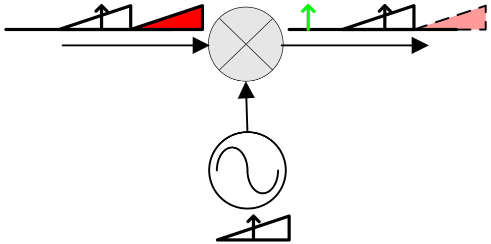


Mixer Responses

- Fixed LO, Swept RF, Swept IF; RF < LO
  - RF to IF transfer function is less well defined
  - Phase/Frequency Inversion from RF to IF
  - Group Delay is well less well defined
  - We call this the “Image Mixer” case, and the scattering matrix contains a conjugation term.



Mixer Responses



- Fixed IF, Swept RF, Swept LO
  - Commonly requested measurement
  - RF to IF transfer function is NOT well defined
  - Phase is NOT well defined
  - Group Delay is NOT defined
- Fixed IF, Swept RF, Swept LO: Issues
  - IF output is at a fixed frequency, phase doesn't change if delay is added at the output
  - Phase depends on LO, so adding delay to LO causes change of phase in the IF which is different for different RF inputs
  - In ALMOST ALL CASES: this requested measurement means instead "Swept RF, Swept IF (over a receiver channel), stepped LO (at many different channels).
  - Delay is d(Rf)/d(IF) at each LO step

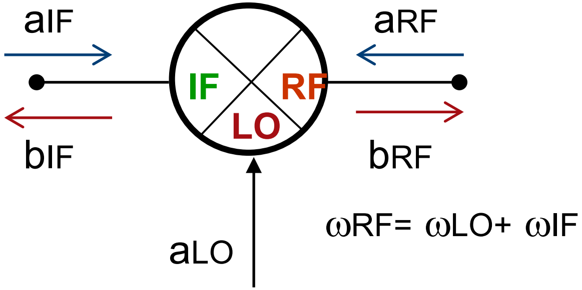
Key Mixer Characteristics – frequency response (RF>LO)

- Model of ideal mixer
- No impact on magnitude and phase
- No reflections at input or output

- Up-conversion $\omega RF = \omega IF + \omega LO$
- Down-conversion $\omega IF = \omega RF - \omega LO$

- $|aLO| = 1$

- LO shifts IF phase in forward direction
- Conjugate LO shifts RF phase in reverse direction



$$\begin{matrix} b_{IF} \\ b_{RF} \end{matrix} = \begin{bmatrix} 0 & a_{LO}^{*} \\ a_{LO} & 0 \end{bmatrix} * \begin{matrix} a_{IF} \\ a_{RF} \end{matrix}$$

Key Mixer Characteristics – frequency response (RF>LO)

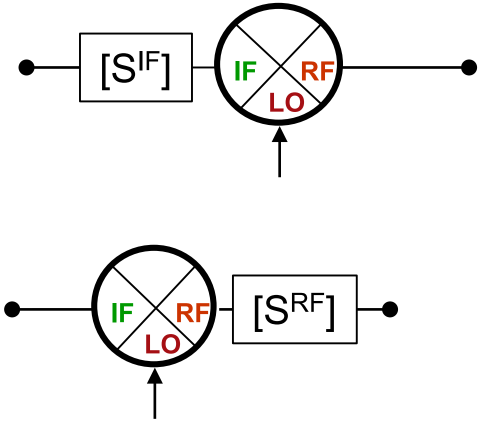
- Non ideal response added to the ideal mixer

- Either at input or at output side

$$\begin{matrix} b_{IF} \\ b_{RF} \end{matrix} = \begin{bmatrix} S_{11}^{IF} & a_{LO}^{*} \cdot S_{12}^{IF} \\ a_{LO} \cdot S_{21}^{IF} & S_{22}^{IF} \end{bmatrix} \cdot \begin{matrix} a_{IF} \\ a_{RF} \end{matrix} = [S^{IF}] \cdot \begin{matrix} a_{IF} \\ a_{RF} \end{matrix}$$

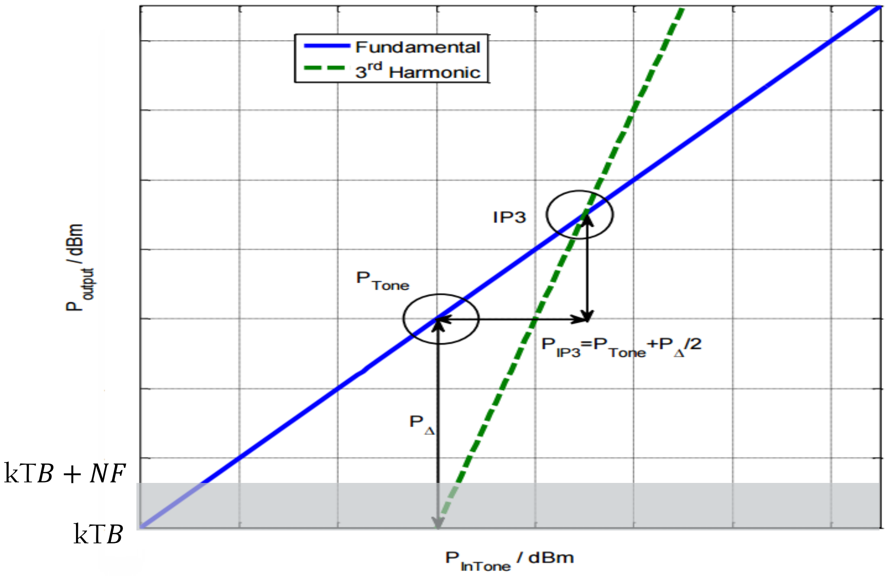
$$\begin{matrix} b_{IF} \\ b_{RF} \end{matrix} = \begin{bmatrix} S_{11}^{RF} & a_{LO}^{*} \cdot S_{12}^{RF} \\ a_{LO} \cdot S_{21}^{RF} & S_{22}^{RF} \end{bmatrix} \cdot \begin{matrix} a_{IF} \\ a_{RF} \end{matrix} = [S^{RF}] \cdot \begin{matrix} a_{IF} \\ a_{RF} \end{matrix}$$

- Conversion Losses
  - Down conversion bIF/aRF aIF = 0
  - Up conversion bRF/aIF aRF=0



ωRF= ωLO+ ωIF

Key mixer characteristics - dynamic range

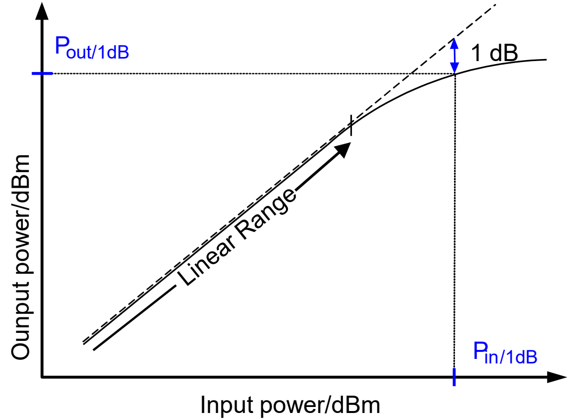


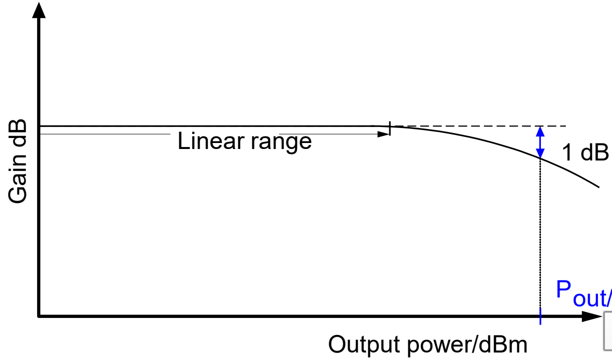
$$SFDR = \frac{2}{3}\left[\mathrm{IIP3} - \left(10\log \mathrm{kT}\Delta f + NF\right)\right]$$

- Dynamic range of a receiver is determined be the difference between the largest and smallest signals that can be processed error free without distortion
- Both 1 dB compression point and intercept point help determine the largest signal that can drive the mixer without distortion
- What determines the smallest signal that can be reliably be downconverter by a receiver? **Noise Figure**
- The resulting figure of merit for the system is the difference between the largest and smallest signals.

Key Mixer Characteristics – 1 dB Compression

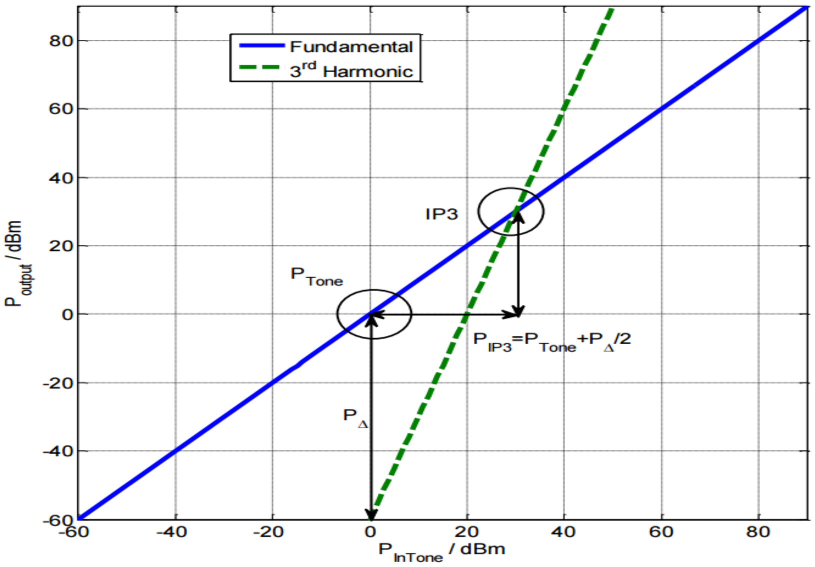
- Nominally mixer conversion loss is constant independent of input RF power
- In the nonlinear rage the output power does not linearily increase with input power i.e. the conversion loss will change
- The 1 dB Compression Point measures the linearity of the mixer defined as the RF input power required to increase the conversion loss by 1 dB
- Typically this is where the mixer is no longer operating “small signal
- When the RF power is within about 3 dB of the compression poinrt, the mixer will show increased levels of nonlinearities





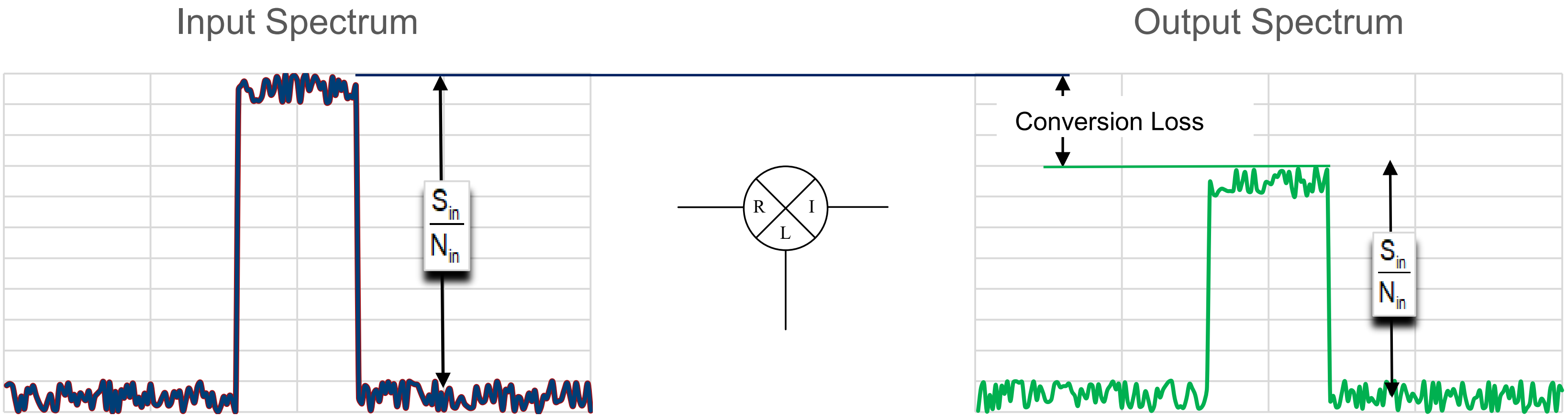
Key Mixer Characteristics – IMD / IP3

- Large-signal performance is often specified as intermodulation distortion or IP3 or IMD
- Intermodulation occurs when multiple signals are applied to input of the mixer
- The LO remains constant
- The two input signals interact with the mixer nonlinearities to generate unwanted IMD products
- These products are mixed down to IF IMD
- The IMD will be converter in both directions by the LO with the RF



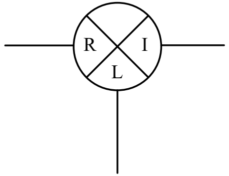
Key Mixer Characteristics – Noise Figure

- **Noise figure** (**NF**) and noise factor (F)
  - The degradation of the signal-to-**noise** ratio (SNR), caused by components in a radio frequency (RF) signal chain. It is a number by which the performance of an device can be specified, with lower values indicating better performance



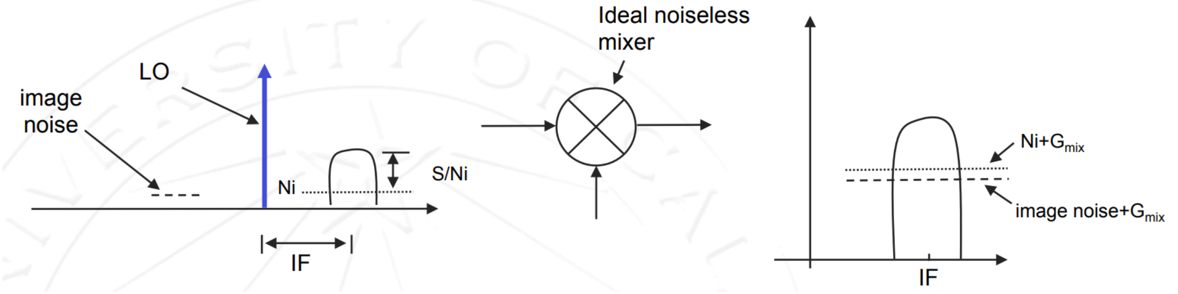
Key Mixer Characteristics – Noise Figure

- First order approximation - mixer noise figure (NF) is equal to its conversion loss
- Good for a first order estimate but with an uncertainty of approximately +/-0.5 dB
- NF of a perfectly matched passive device is equal to its insertion loss if its physical temperature is the same as that of the system.
- Mismatch with a measurable VSWR will affect the mixer NF
- Example
  - RF port VSWR = 2:1 or a Return Loss of 9.5 dB
  - This results in a mismatch loss from the standing waves of approximately 0.5 dB
  - This is the common rule of thumb for NF uncertainty - +/-0.5 dB



Key Mixer Characteristics – double Sideband Noise Figure

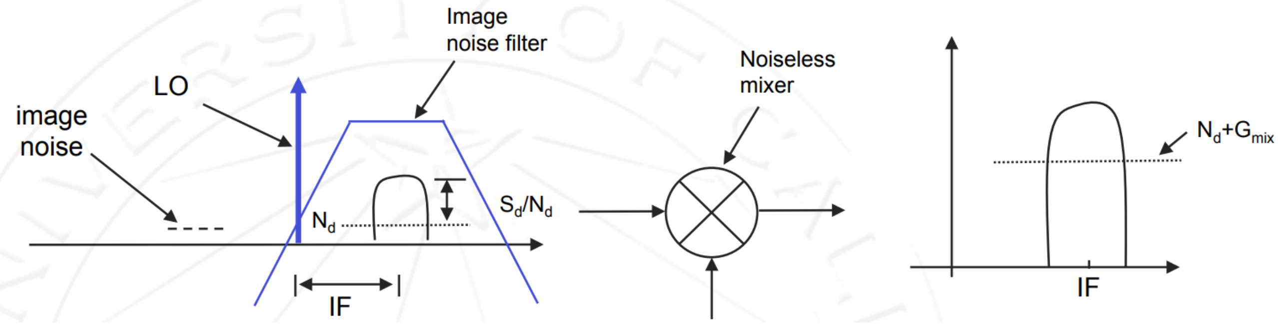
- ► Remember the Image?



- ► There are two definitions used for noise figure with mixers
  - – SSB NF assumes signal input from only one sideband noise inputs from both sidebands
  - – DSB NF includes both signal and noise inputs from both sidebands. Appropriate for direct conversion architectures.
- ► Without image rejection, a receive mixer downconverts the desired IF as well as the image
- ► The image noise is added to the IF noise at the desired IF
- ► Therefore, the total noise at IF includes: the desired RF band noise, the RF image noise, and the inherent noise of the mixer including noise from the LO all downconverted to baseband

Key Mixer Characteristics – Single Sideband Noise Figure

- ► Remember the Image?



- ► The single-side band NF definition assumes that there is no signal at the image frequency except the source noise
- ► Measuring SSB noise figure is relevant for superheterodyne receiver
- ► This definition is useful in finite IF architectures, where the image signal is suppressed by an image filter before reaching the mixer
- ► For a noiseless the mixer SSB NF is 3dB because of the image noise folding although has changed this definition

Phase…. First, a little background

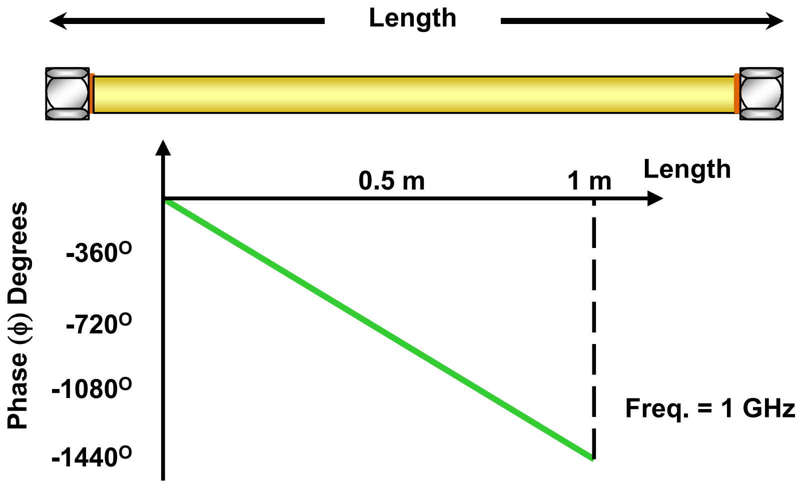
- When measuring phase, we need to understand the concept of a wave – a wave is a periodic variation of a physical quantity over time and space
  - The speed the wave travels is called the speed of propagation ν
  - The distance one complete wave oscillation travels at ν is called the wavelength λ
  - The time to travel one wavelength is called the period T

  Directly measuring phase is not typically useful

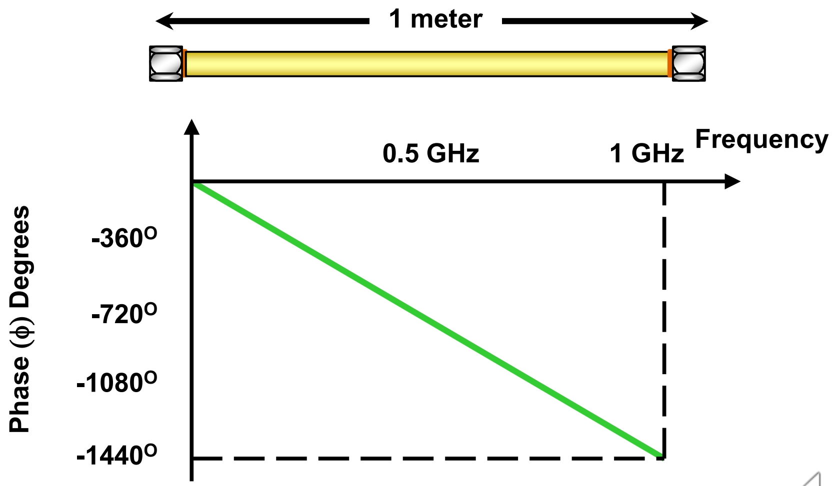
- The slope of the phase response often requires a large scale factor in order to see the complete trace on the display
- To measure the deviation from linear phase, the large scale factor must be removed
- The analyzer can mathematically remove the linear part of the device's electrical delay now referred to as group delay

A little background - Phase

- Phase as a Function of Device Length
- At a Fixed Frequency, the Phase is a function of Device Length

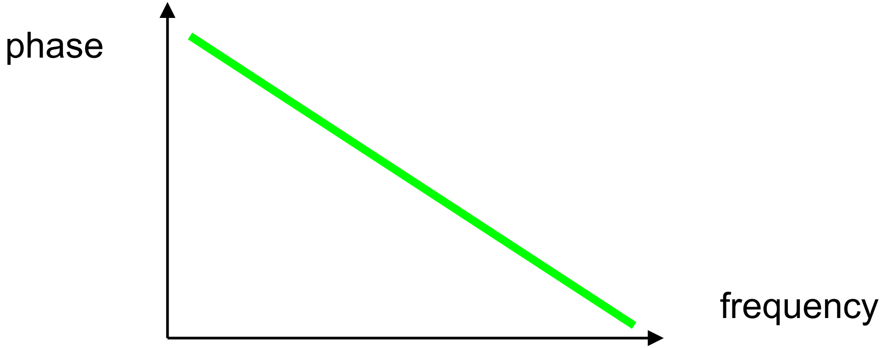


- Phase as a Function of Device Length
- For a Fixed Device Length, the Phase is a function of Frequency



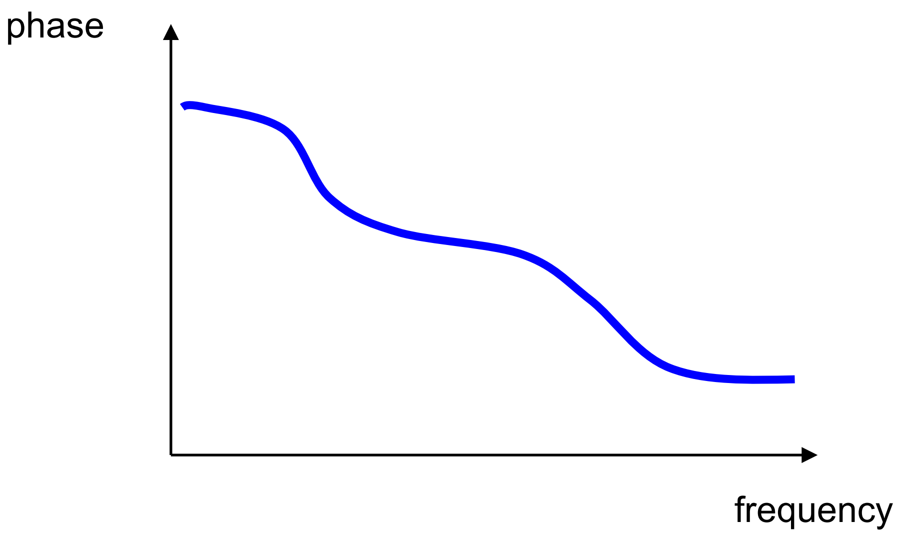
A little background - Phase Distortion & Deviation from Linear Phase

- What makes this confusing?
  - A linear phase response results in a sloping line.
  - The amount of slope depends on the DUT's insertion delay
  - Any slope is ok, as long as it is a "straight" line
  - So to measure phase distortion, we need to know how straight the line really is
- So we measure the "deviation" from straight line, or deviation from linear phase in order to quantify phase distortion.



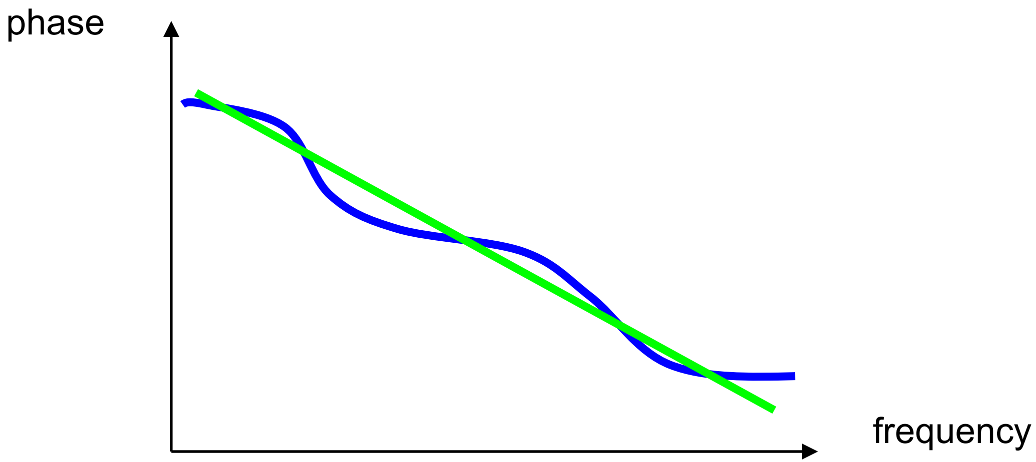
A little background - Phase Distortion & Deviation from Linear Phase

► Consider this phase response vs. frequency



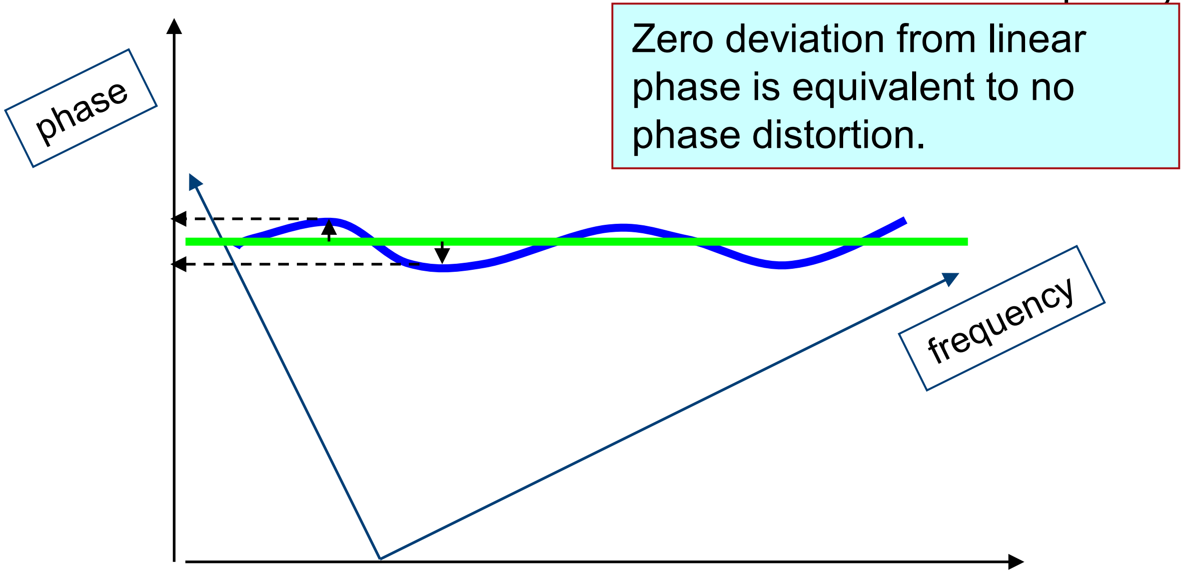
A little background - Phase Distortion & Deviation from Linear Phase

► Draw a straight line that represents no phase distortion.



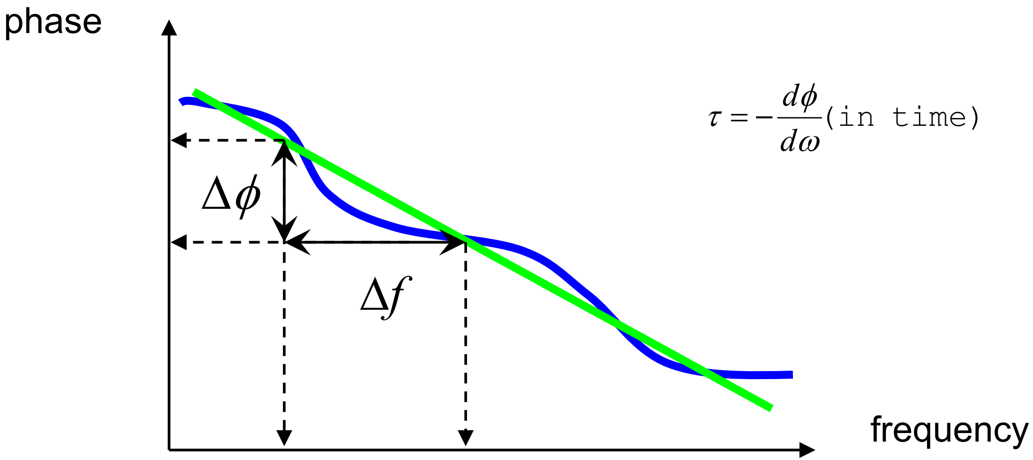
A little background - Phase Distortion & Deviation from Linear Phase

- To measure deviation from linear phase, we first "tilt" the response until it most closely fits a horizontal line.
- Then we consider how much it deviates from this horizontal line at each frequency.



A little background - Phase Distortion & Group Delay

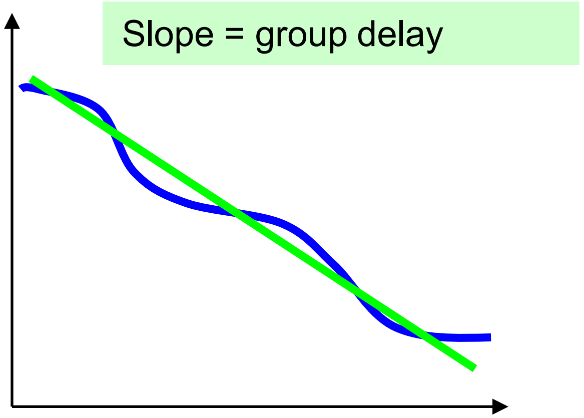
- Group Delay is defined as

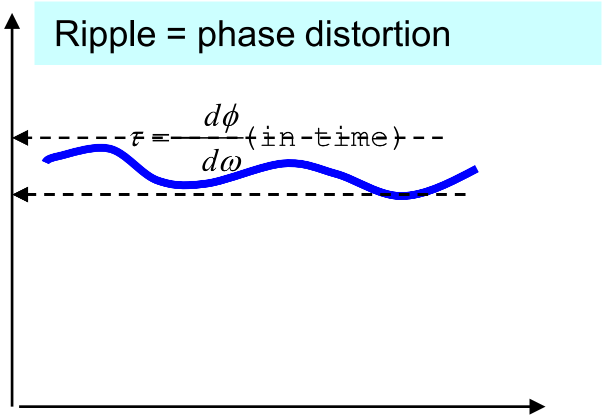


$$\tau = -\frac{d\phi}{d\omega} \text{(in time)}$$

A little background - Phase Distortion & Deviation from Linear Phase

- The slope of the green "curve fitted" line represents our nominal group delay over this frequency range.
- The deviation from linear phase is our phase distortion.



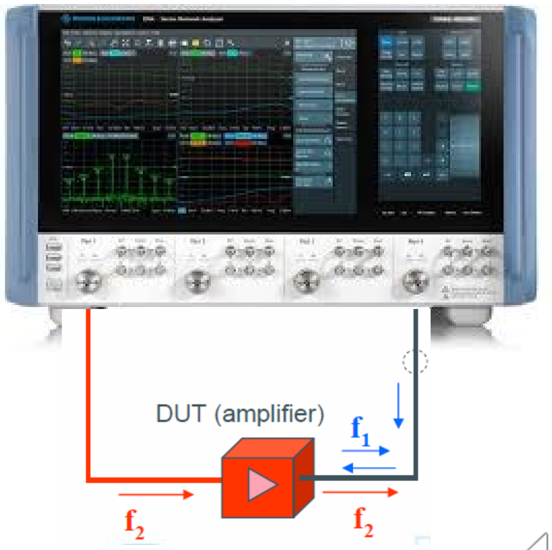


A little background - Phase Distortion and Group Delay

- Group delay is sometimes a measure of how long it takes for a signal's information to propagate through a channel or device under test.
- So there are times when we also care about group delay even when we do not care about phase distortion…
- Example: Gaming on our cell phone…

Vector Network Analyzer

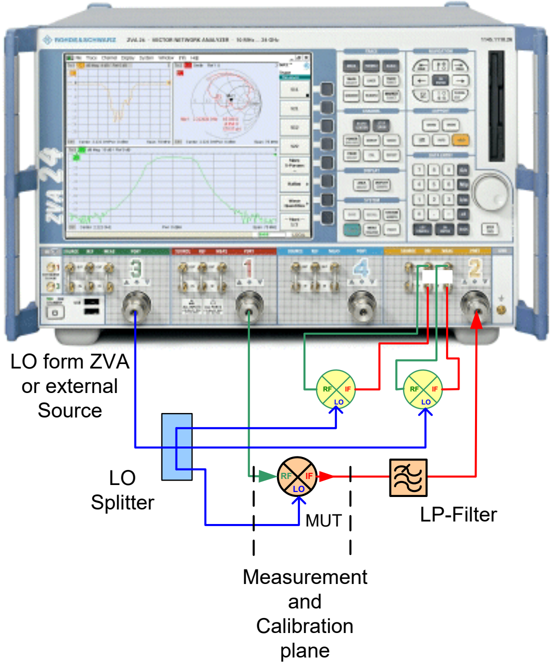
- Traditionally:
  - A Vector Network Analyzer is an ideal instrument for making magnitude and phase measurements.
  - It can easily make swept group delay measurements.
  - It is optimized for speed.
  - Offers full error correction.
  - Fully characterize DUT's
- Frequency converters require modification to standard VNA measurements



Vector Network Analyzer

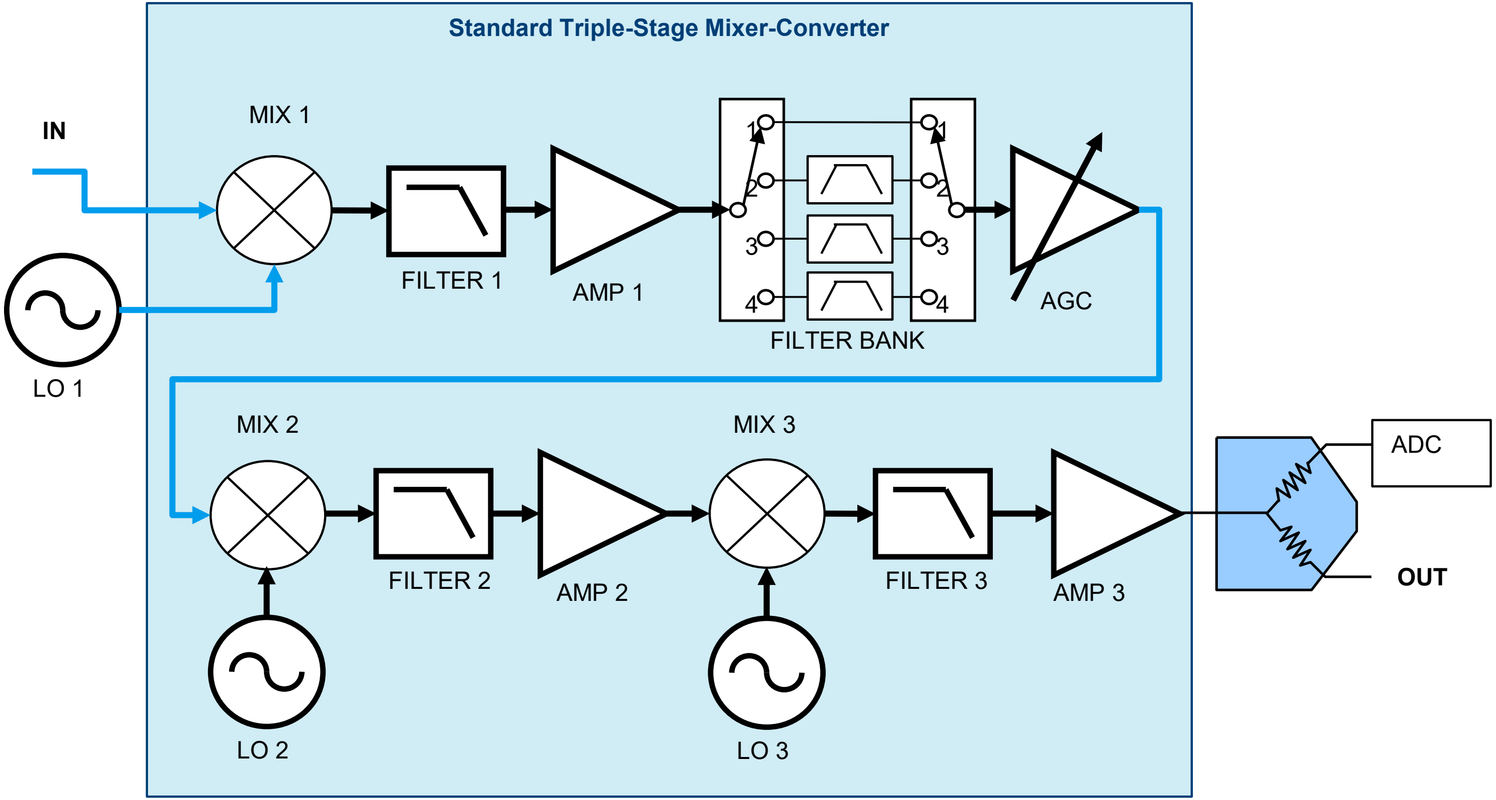
- So what is the drawback?
  - Traditionally Input and output frequency to the DUT have to be the same.
  - Traditionally doesn't work with mixers, amplifier harmonics, doublers, prescalers
- So far every other method we discussed was able to handle frequency translation…
  - But they did not offer full error correction.
- Of course we want to combine frequency conversion with full error correction.
- Rohde and Schwarz ZNA Network Analyzer has the ability to measure phase and group delay at different frequencies due to the coherent nature of its source

ZNA MIXER

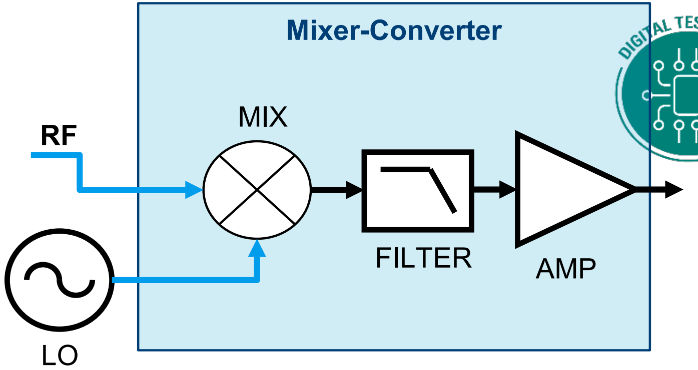

LO form ZVA
or external
Source
LO
Splitter
MUT
LP-Filter
Measurement
and
Calibration
plane


RF
IF
LO

Frequency Converters

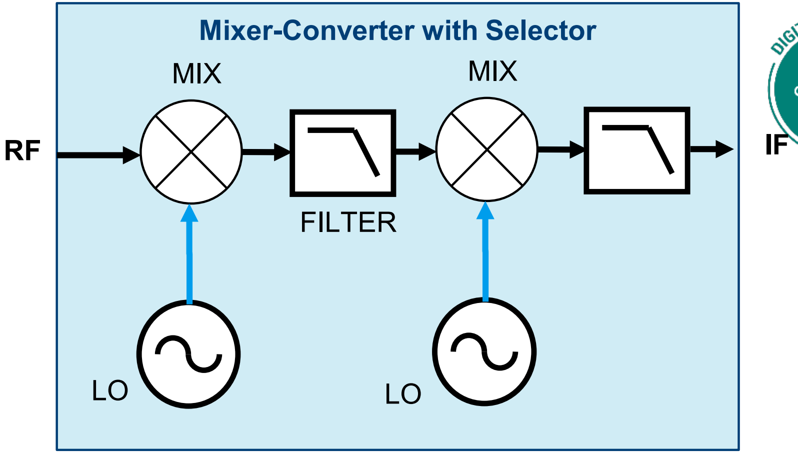


Single Stage Converter



- Summary
  - Simplest case converter
  - 1 LO external or embedded
  - Non reciprocal device
  - DUT Filtering not required
  - M x N spectral analysis may be required to verify spurious performance
  - Spectral Inversion must be considered
  - Typically can use same filter as the one in the DUT
- Issues
  - DUT is no longer reciprocal can't use as cal or reference device
  - Filtering of reference and cal mixer is required to suppress unwanted signals
  - If LO is tuned, a VMC cal set is required for each LO value
  - Measuring with a VNA requires reference and cal mixer and filter

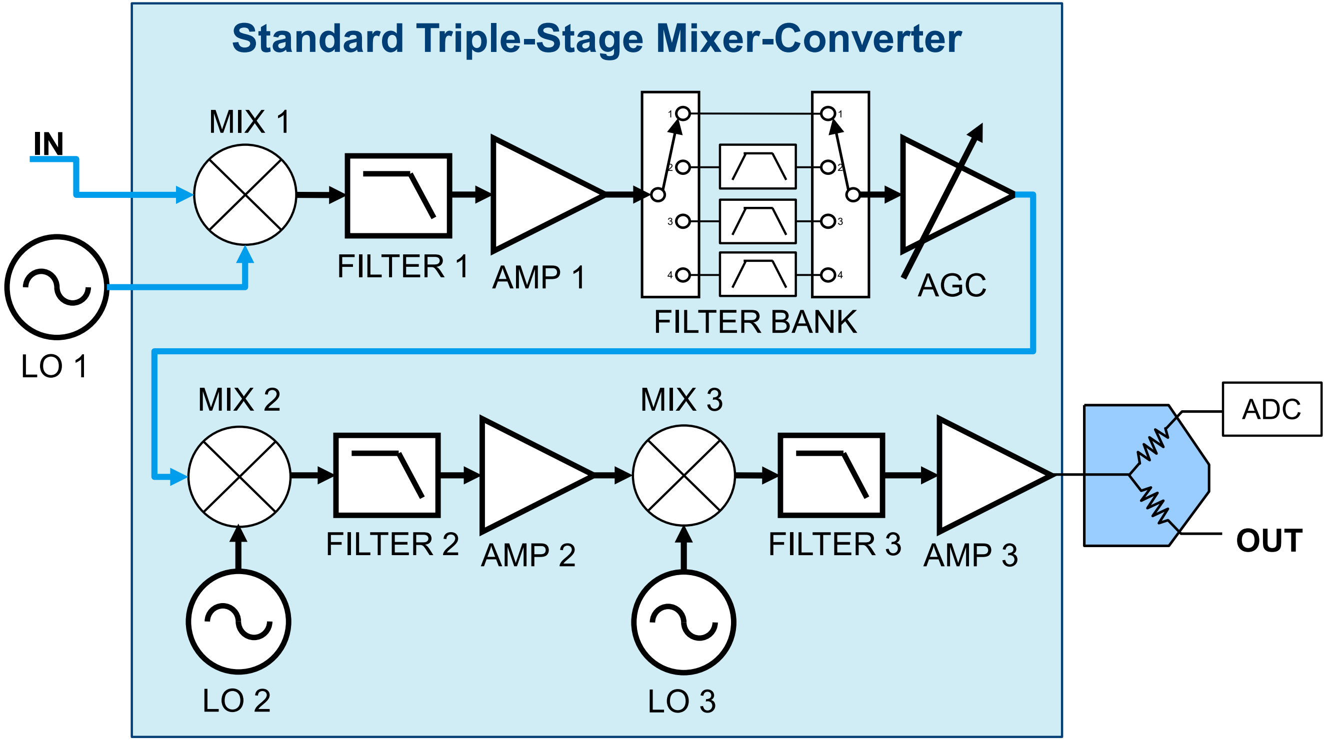
Dual Stage Converter



- Summary
  - Similar analysis to Single Stage Converter
  - Still need calibration and reference mixer
  - Requires multiple similar measurements to verify each path

- Issues
  - Need same cal and ref mixer and filter
  - Similar analysis to Single Stage Converter
  - Need to be able to control inputs of DUT and remeasure as applicable
  - If pass/Fail, each setting potentially has new specification

N Stage Converter



SUMMARY / Q&A

- Mixer are critical components in communications systems.
- An understanding of how a mixer works and the associated math must be understood
- Critical Specifications of mixers include:
  - Conversion Loss
  - Port to port Isolation
  - Frequency Response
  - Return Loss
  - Compression Point and TOI
  - Noise Figure
- Converters and receivers include mixers and required thorough analysis to avoid unwanted noise


Measurement Techniques
Design Verification & Evaluation
EVERYTHING TEST
Instrument Selection & Optimization