Lab 3

Mixers and Amplitude Modulation

The underlying theme of this lab is amplitude modulation. Considerable up-front effort will be placed on the exploration of circuits that perform signal multiplication. Signal multiplication of baseband signals and radio frequency (RF) signals is quite challenging. In the co-requisite lecture course you have likely already been introduced to linear modulation. This lab will explore basic linear modulation and demodulation using the envelope detector.

Many more components of the RF Board will be utilized in this lab as well. There is now a center section of the ECE 4670 home page title RF Board Details dedicated to the board and the components on the board.

Linear Modulation

Signal multiplication is fundamental to the generation of linear modulation. Recall that in double sideband (DSB) modulation, the transmitted carrier $x_c(t)$ is created from message signal $m(t)$ via

$$x_c(t) = m(t) \times A_c \cos(2\pi f_c t + \phi) \tag{1}$$

where A_c is the carrier amplitude and f_c is the carrier frequency in Hz. For the special case of a sinusoidal message $m(t) = A_m \cos(2\pi f_m t)$, we have that

$$\begin{aligned} x_c(t) &= A_m \cos(2\pi f_m t) \times A_c \cos(2\pi f_c t + \phi) \\ &= \frac{A_m A_c}{2}\big[\cos(2\pi(f_c - f_m)t + \phi) + \cos(2\pi(f_c + f_m)t + \phi)\big] \end{aligned} \tag{2}$$

Frequency Mixers

If it existed, an ideal multiplier would perform the function

$$y(t) = x_1(t) \cdot x_2(t) \tag{3}$$

and have block diagram as shown in Figure 1.

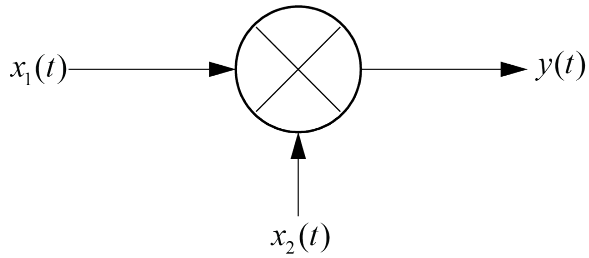


Figure 1: Ideal multiplier block diagram.

A circuit that comes close to being an analog multiplier is the Texas Instruments MPY–634, shown in Figure 2. This part has limited bandwidth and is rather expensive.

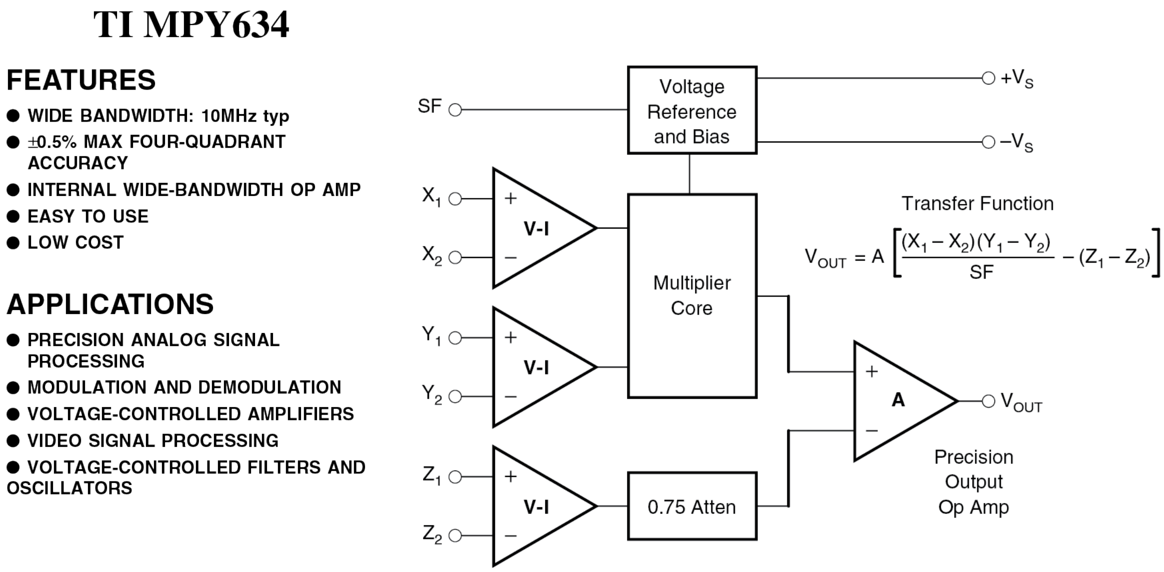


Figure 2: The MPY–634 analog IC multiplier [TI data sheet].

In practice, however we have to accept approximations that are available via various analog circuit designs. In the world of RF circuit design the term *mixer* is more appropriate, as an ideal multiplier is rarely available. Instead, active and passive circuits that approximate signal multiplication are utilized. The notion of *mixing* comes about from passing the sum of two signals through a nonlinearity, e.g.,

$$y(t) = [a_1 x_1(t) + a_2 x_2(t)]^2 + \text{linear} + \text{other higher-order terms} \tag{4}$$

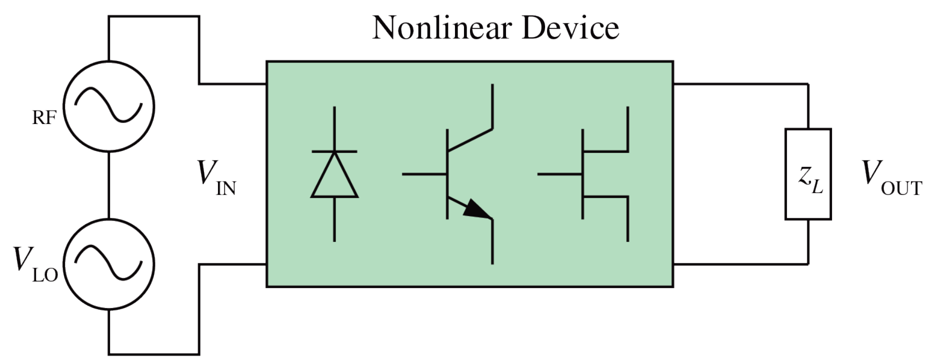
Expanding out just the square–law term yields

$$y_{\text{square-law}}(t) = a_1^2 x_1^2(t) + 2a_1 a_2 x_1(t) x_2(t) + a_2^2 x_2^2(t) \tag{5}$$

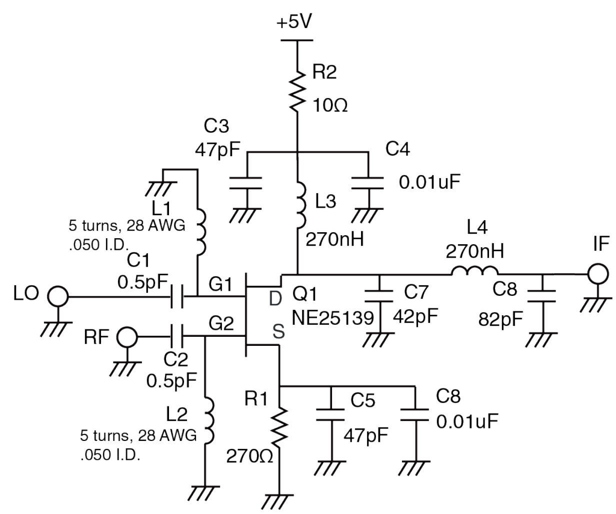
In this mixing application we are most interested in the center term

$$y_{\text{desired}}(t) = 2a_1 a_2 \big[x_1(t) \cdot x_2(t)\big] \tag{6}$$

Clearly this mixer produces unwanted terms (first and third), and in general may other terms, since the nonlinearity will have more than just a square-law input/output characteristic. A diode or active device can be used to form mixing products, and in particular we may consider a dual-gate MEtal Semiconductor FET (MESFET) mixer as shown in Figure 3a & b.



(a) Mixer concept



(b) Dual-Gate MESFET Active Mixer

Figure 3: Nonlinear device mixer: (a) Concept, (b) Device implementation.}

The double-balanced mixer (DBM), which can be constructed using a diode ring as shown in Figure 4, provides better isolation between the RF, LO, and IF ports.

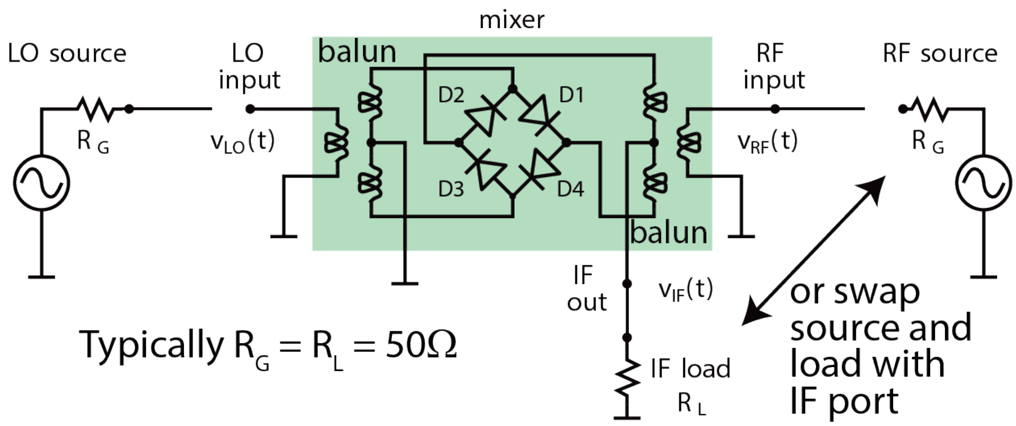


Figure 4: Passive DBM configured with inputs LO and RF and output IF; alternatively inputs at LO and IF produces an output at the RF post.

Much has been written about about this circuit configuration, see for example: 2, 3, 4. Typically the LO is driven at a high level so that the diode switching action is controlled by this port. Two *baluns* (balanced–to–unbalanced transformers) are required to make the diode ring act as a switch relative to the LO and RF ports. At frequencies up to a few GHz the baluns are wound on powdered iron cores. When properly balanced the DBM also allows even harmonics to be suppressed in the mixing operation. The DBM is also suitable for use as a *phase detector* in phase–locked loop applications.

In this lab you will using diode–ring based DBMs from Mini Circuits, specifically the ADE–R6+ and the ADEX–R10+, with partial data sheets shown in Figure 5 and Figure 6, respectively.

Surface Mount

High Reliability Mixer

ADE-R6+

Level 7 (LO Power +7 dBm) 0.15 to 250 MHz

CASE STYLE: CD637

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

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.

Pin Connections

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

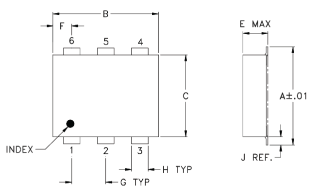
Features

- hermetically sealed ceramic quad
- low conversion loss, 4.6 dB typ.
- excellent L-R isolation, 55 dB typ.
- low profile package
- aqueous washable
- protected by US Patent 6,133,525

Applications

- cellular

Outline Drawing



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.
0.15-250	DC-200	4.6	0.05	7.0	7.5	70	50	55	40	42	28	65	45	45	27	32	18	10

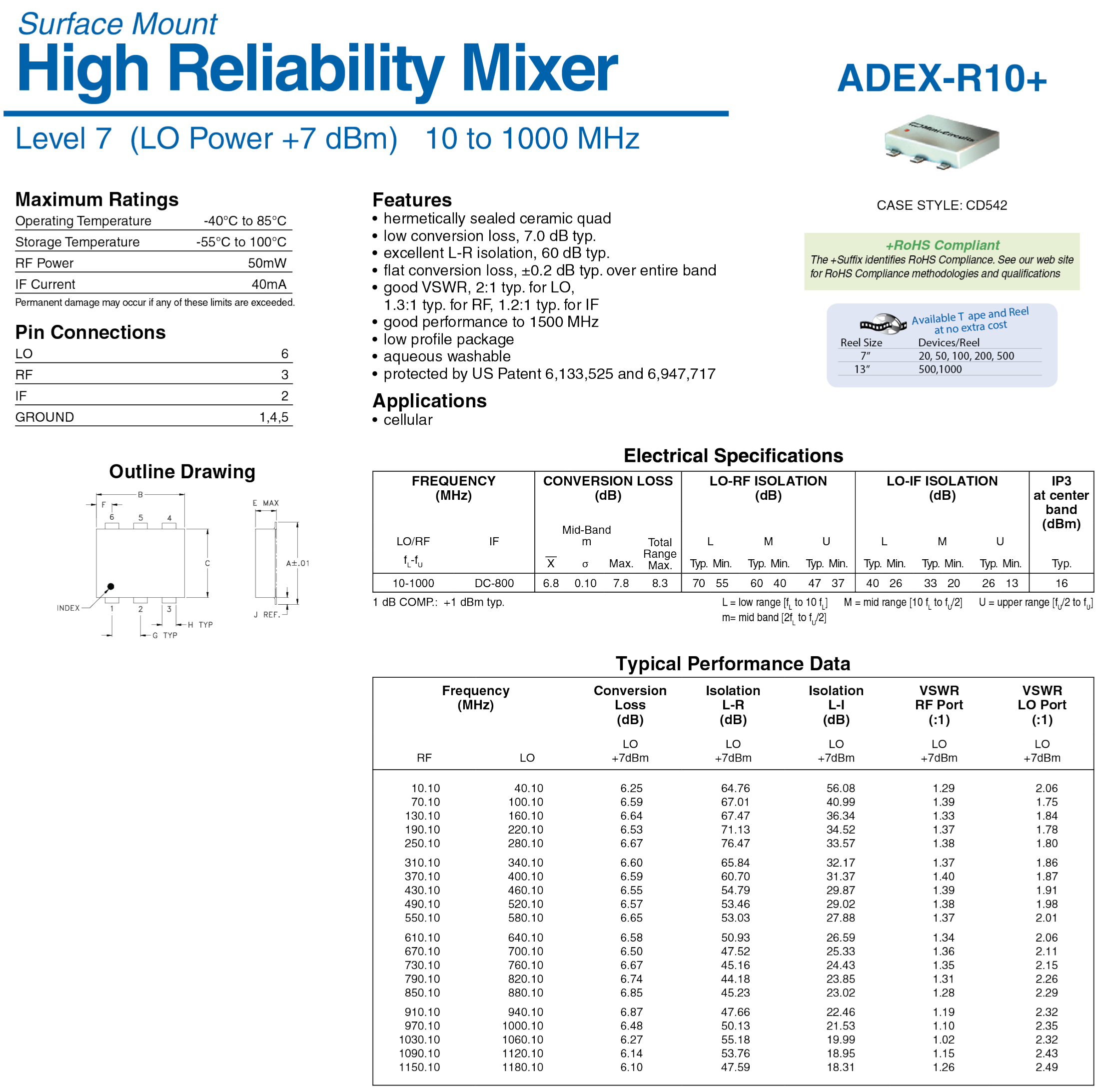
1 dB COMP.: +1 dBm typ.

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]

Typical Performance Data

Frequency (MHz)		Conversion Loss (dB)	Isolation L-R (dB)	Isolation L-I (dB)	VSWR RF Port (:1)	VSWR LO Port (:1)
RF	LO	LO +7dBm	LO +7dBm	LO +7dBm	LO +7dBm	LO +7dBm
0.15	30.10	4.77	67.20	56.68	1.23	2.57
0.20	30.20	4.76	67.02	56.62	1.21	2.57
0.50	30.50	4.74	66.81	56.59	1.21	2.57
1.00	31.00	4.71	67.12	56.34	1.22	2.56
5.00	35.00	4.65	65.59	54.88	1.22	2.56
10.00	40.00	4.64	64.80	53.73	1.22	2.54
22.00	52.00	4.65	62.28	50.03	1.21	2.56
42.00	72.00	4.71	59.58	45.36	1.17	2.55
52.00	82.00	4.75	58.11	43.75	1.17	2.54
72.00	102.00	4.80	53.23	40.96	1.14	2.52
92.00	122.00	4.76	60.22	37.63	1.08	2.57
102.00	132.00	4.86	55.06	37.74	1.10	2.64
120.00	150.00	5.03	47.68	37.44	1.12	2.70
140.00	170.00	5.03	42.60	35.88	1.14	2.66
160.00	190.00	5.13	41.55	32.76	1.16	2.67
180.00	210.00	5.32	41.37	31.05	1.05	2.88
200.00	230.00	5.71	40.03	29.83	1.16	3.05
220.00	250.00	5.76	38.44	28.28	1.30	3.05
240.00	270.00	5.80	36.97	26.07	1.42	2.87
250.00	280.00	5.85	35.69	24.46	1.48	2.78

Figure 5: Mini–Circuits `ADE-R6+`, a 0.15 to 250 MHz mixer, top level data sheet providing performance expectations.



Surface Mount

High Reliability Mixer

ADEX-R10+

Level 7 (LO Power +7 dBm) 10 to 1000 MHz

CASE STYLE: CD542

+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, 500
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.

Pin Connections

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

Features

- hermetically sealed ceramic quad
- low conversion loss, 7.0 dB typ.
- excellent L-R isolation, 60 dB typ.
- flat conversion loss, ±0.2 dB typ. over entire band
- good VSWR, 2:1 typ. for LO, 1.3:1 typ. for RF, 1.2:1 typ. for IF
- good performance to 1500 MHz
- low profile package
- aqueous washable
- protected by US Patent 6,133,525 and 6,947,717

Applications

- cellular

Outline Drawing

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.
10-1000	DC-800	6.8	0.10	7.8	8.3	70	55	60	40	47	37	40	26	33	20	26	13	16

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]

Typical Performance Data

Frequency (MHz) RF	Frequency (MHz) LO	Conversion Loss (dB) LO +7dBm	Isolation L-R (dB) LO +7dBm	Isolation L-I (dB) LO +7dBm	VSWR RF Port (:1) LO +7dBm	VSWR LO Port (:1) LO +7dBm
10.10	40.10	6.25	64.76	56.08	1.29	2.06
70.10	100.10	6.59	67.01	40.99	1.39	1.75
130.10	160.10	6.64	67.47	36.34	1.33	1.84
190.10	220.10	6.53	71.13	34.52	1.37	1.78
250.10	280.10	6.67	76.47	33.57	1.38	1.80
310.10	340.10	6.60	65.84	32.17	1.37	1.86
370.10	400.10	6.59	60.70	31.37	1.40	1.87
430.10	460.10	6.55	54.79	29.87	1.39	1.91
490.10	520.10	6.57	53.46	29.02	1.38	1.98
550.10	580.10	6.65	53.03	27.88	1.37	2.01
610.10	640.10	6.58	50.93	26.59	1.34	2.06
670.10	700.10	6.50	47.52	25.33	1.36	2.11
730.10	760.10	6.67	45.16	24.43	1.35	2.15
790.10	820.10	6.74	44.18	23.85	1.31	2.26
850.10	880.10	6.85	45.23	23.02	1.28	2.29
910.10	940.10	6.87	47.66	22.46	1.19	2.32
970.10	1000.10	6.48	50.13	21.53	1.10	2.35
1030.10	1060.10	6.27	55.18	19.99	1.02	2.32
1090.10	1120.10	6.14	53.76	18.95	1.15	2.43
1150.10	1180.10	6.10	47.59	18.31	1.26	2.49

Figure 6: Mini–Circuits `ADEX-R10+`, a 10 to 1000 MHz mixer, top level data sheet providing performance expectations.

A basic DBM property with sinusoidal inputs, say at $f_{\rm LO}$ and $f_{\rm IF}$, is that the output will contain frequencies

$$f_{\rm RF} = nf_{\rm LO},\ \ mf_{\rm IF},\ \text{and}\ |mf_{\rm IF} \pm nf_{\rm LO}|,\ \ n, m = 1, 2, \ldots, \tag{7}$$

but the balanced nature of the mixer means outputs with n and m even are generally suppressed as a result of the clipping symmetry imposed by the matched Schottky diodes of the ring. Also, when the drive level is strong on the LO port, e.g., +7 dBM for the above mixers and the IF level is small say −20 to −15 dBm, $m = 1$ or the fundamental of the IF dominates on the $n =$ odd terms and only small harmonics of the LO are found for $n =$ even at the RF output. The roles of IF in and RF can also be reversed, and a the behavior is similar, e.g.,

$$f_{\rm IF} = nf_{\rm LO},\ \ mf_{\rm RF},\ \text{and}\ |mf_{\rm RF} \pm nf_{\rm LO}|,\ \ n, m = 1, 2, \ldots \tag{8}$$

In general the LO port is driven with a strong signal to establish good switching action in the diode ring.

- For a transmitter or *frequency up converter* the second and weaker input is on the IF port. The output is on the RF port
- For a receiver or a frequency *down converter* the second and weaker input is on the RF port. The output is on the IF port
- Caution: The IF port is DC coupled to the diode ring, which is both good and bad. For transmitter and receivers alike the DC coupling is often needed. The downside is that if even a small DC is fed into the IF port, the Schottky diodes, with their low turn-on voltage (around 0.2V), can be biased into the active region and have enough current flow to destroy them. Be carefull!

Modeling the DBM

We now consider DBM models in both LTSpice and a Python *behavioral level model*.

LTSpice Model

Since we are dealing with a specific circuit configuration, it makes sense that we should first consider a pure circuit model simulation. A DBM model created in LTSpice using coupled inductors to form baluns and Schottky diodes for the diode ring, is given in Figure 7. The inductor coupling is set to 1.0 for each balun, which makes the circuit behave like an ideal transformer.

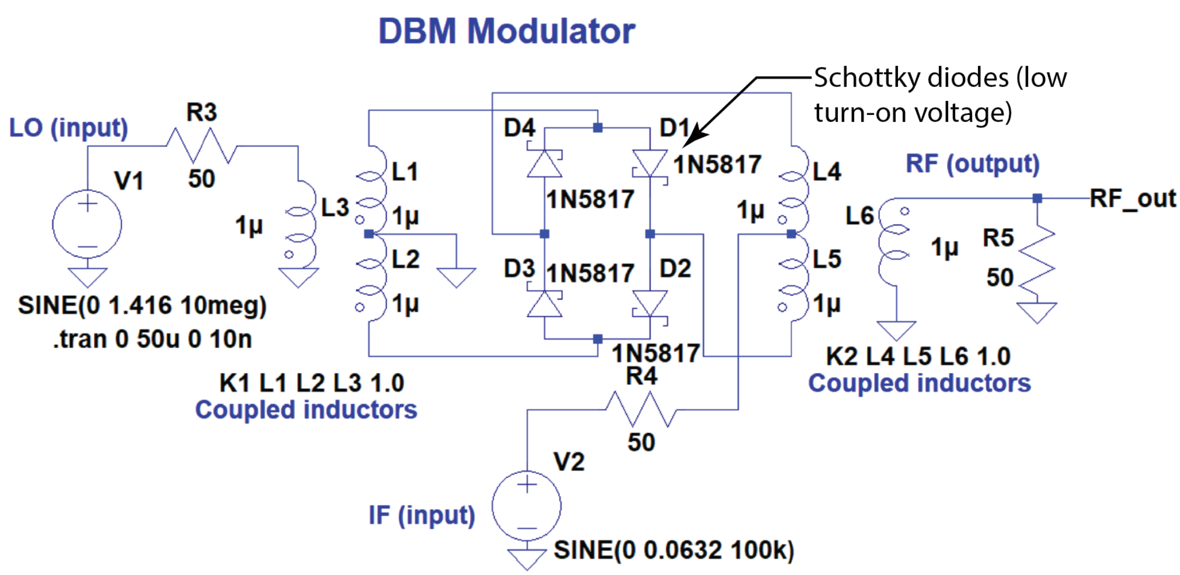


Figure 7: LTSpice model of a DBM configured as a transmitter with LO at 10 MHz and the IF signal at 100 kHz.

The LTSpice circuit file, `DBM_mod.asc` can be found in the [Lab 3 Jupyter notebook sample] ZIP package. When the simulation is run you can view a time domain plot and export the data to a `.txt` file and also view and FFT (spectrum) of the time domain data and export this data to a `.txt` file as well. Both data sets can be viewed in the Jupyter notebook. Examples are provided in the `Lab3_notebook_sample` ZIP package. Exports from LTSpice in general are best converted to `.csv` files using a utility I created called `LTSpice Data Export Reparser`, available under Lab 3 [LTSpice export app zip file]. This utility cleans up the LTSpice export files for seamless import into Jupyter. Examples of this are in the Lab 3 Jupyter notebook sample.

A screen shot of the data export reparse utility is shown in Figure 8. Versions for Mac and Linux can be found on the [ECE 3001 Web Site].

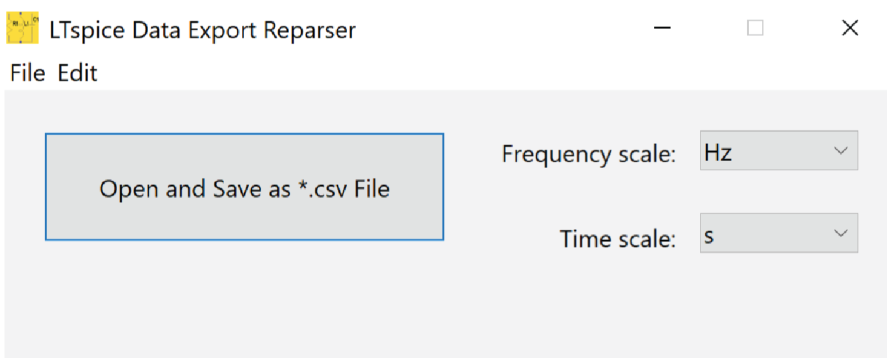


Figure 8: The LTSpice data export GUI tool.

The export reparse process is simple for both time domain (`.tran`) and frequency domain (`.ac` and FFT spectra). Select units for the frequency and time column in the `.csv` (using the default of Hz and s is fine in most cases), then select the `.txt` file of interest coming from LTSpice. When you click *Open* from the dialog box the `.csv` will be written to the same location as the original `.txt` file.

Example: $f_{\mathrm{LO}} = 10$ MHz at 7 dBm, $f_{\mathrm{IF}} = 100$ kHz at –20 dBm

Import LTSpice simulation results as described above and plot the results in the Jupyter notebook. Begin by importing time domain data exported from LTSpice to `.txt` and then reparsed to `.csv`. Note The time domain data is not uniformly sampled, this is the was Spice works, so we cannot directly estimate the spectrum in Jupyter.

```
# Skip the first 32 rows, then skip the last row that contains 'END'
t_spice, RF_out = loadtxt('DBM_mod_time.csv',delimiter=',',skiprows=1,
                          usecols=(0,1),unpack=True)
```

With the data imported into Jupyter we can now plot the waveform shown in Figure 9.

```python
plot(t_spice[:3200]*1e6,RF_out[:3200]*1e3)
title(r'LTSpice Simplified DBM Time Domain $x_{RF}(t)$')
ylabel(r'Amplitude (mV)')
xlabel(r'Time ($\mu$s)')
grid();
```

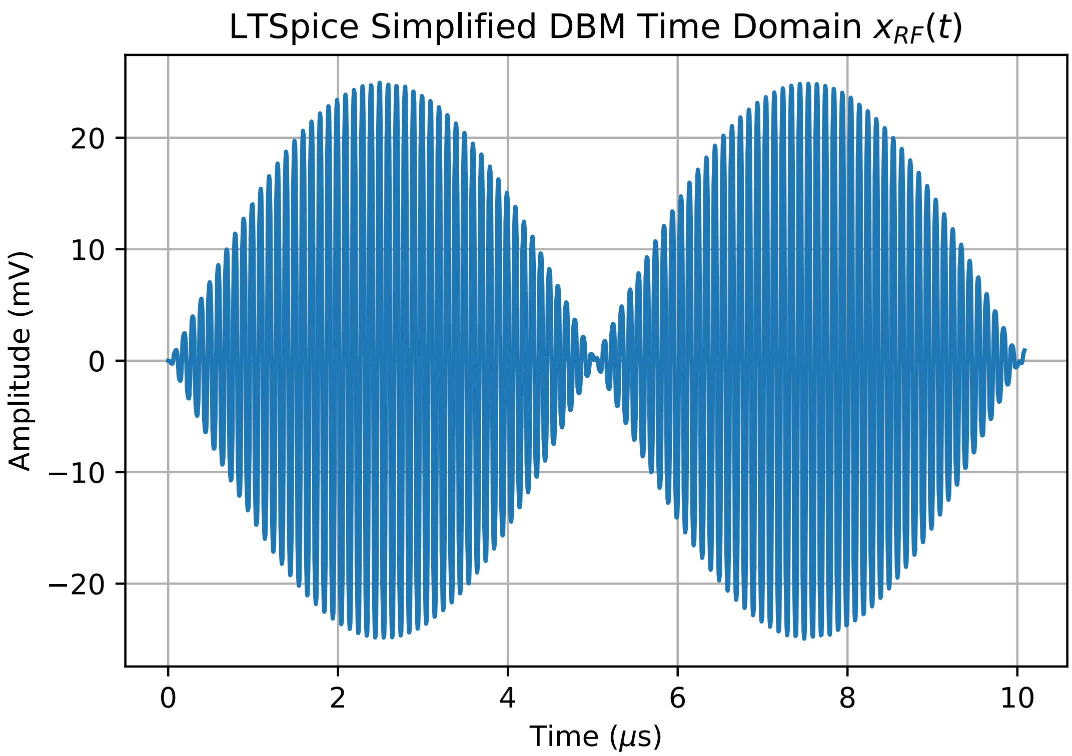


Figure 9: Time domain data corresponding to $x_{\mathrm{RF}}(t)$ from the LTSpice DBM simulation of 10 MHz mixed with 100 kHz.

New we import the FFT spectrum exported from LTSpice as a `.txt` file that is reparsed as a `.csv` file.

```python
# Skip the first 32 rows, then skip the last row that contains 'END'
f_spice, RF_out_psd = loadtxt('DBM_mod_spec.csv',delimiter=',',skiprows=1,
                usecols=(0,1),unpack=True)
```

With the spectrum imported into Jupyter we can now plot the spectrum magnitude in dB shown in Figure 10.

```
plot(f_spice/1e6,RF_out_psd)
title(r'LTSpice DBM Spectrum of $x_{RF}(t)$ at 10 MHz with 100 kHz Mix')
ylabel(r'Power Spectrum (dBm?)')
xlabel(r'Frequency (MHz)');
ylim([-110,-30])
xlim([5,80])
grid();
```

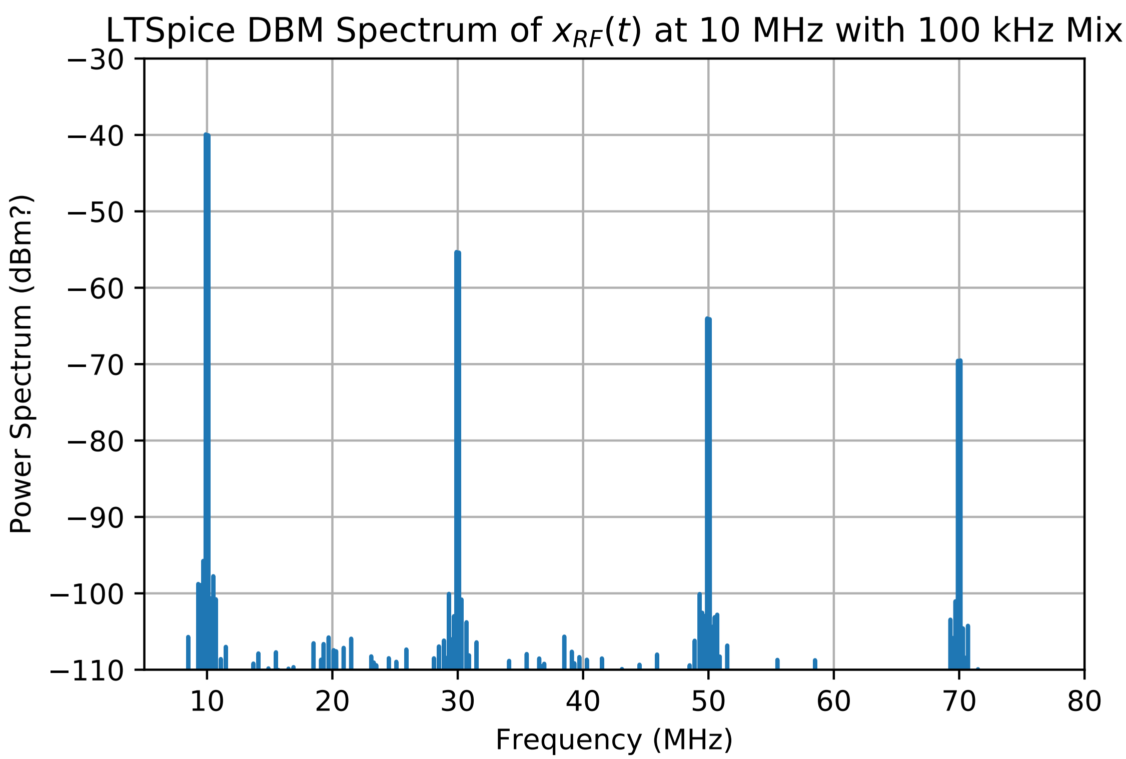


Figure: 10 Spectrum of $x_{\mathrm{RF}}(t)$ exported from the LTSpice DBM simulation of 10 MHz mixed with 100 kHz.

The spectrum results above are noisy as a result of the processing technique LTSpice uses to FFT non–uniformly space samples. The amplitude scaling is also not what it should be, although close. If we zoom in on the spectral lines centered any of the odd harmonics of f_{LO} we see that as expected there are actually two spectral lines separated by 200 kHz.

A Simulation Model in Python

It would be nice to have a pure mathematical model of the DBM, and in particular written in Python. The diode ring of the DBM acts as a switching element when the LO port is driven hard. The switching waveform is more like the that of a diode clipper as obtained from the LTSpice schematic of Figure 11.

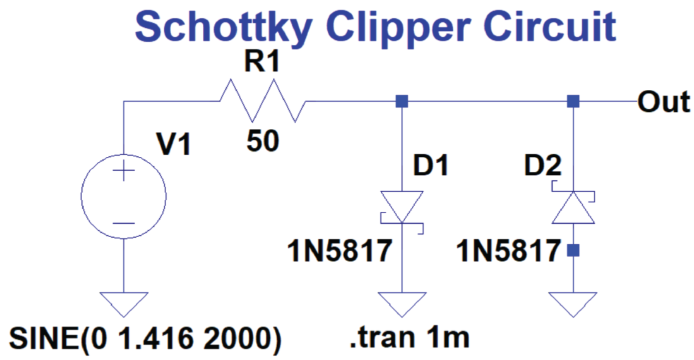


Figure 11: Schottky diode clipper circuit to model the DBM switching waveform.

To represent the output waveform in simple mathematical terms we use the $\arctan()$ function as a nonlinear input/output mapping. To make the nonlinearity adjustable we add scaling to the argument and normalize the output to unity

$$y = \frac{2}{\pi}\arctan(\alpha \cdot x) \tag{9}$$

The input/output characteristic is known as a *soft limiter* and response curves with α a parameter are shown in Figure 12.

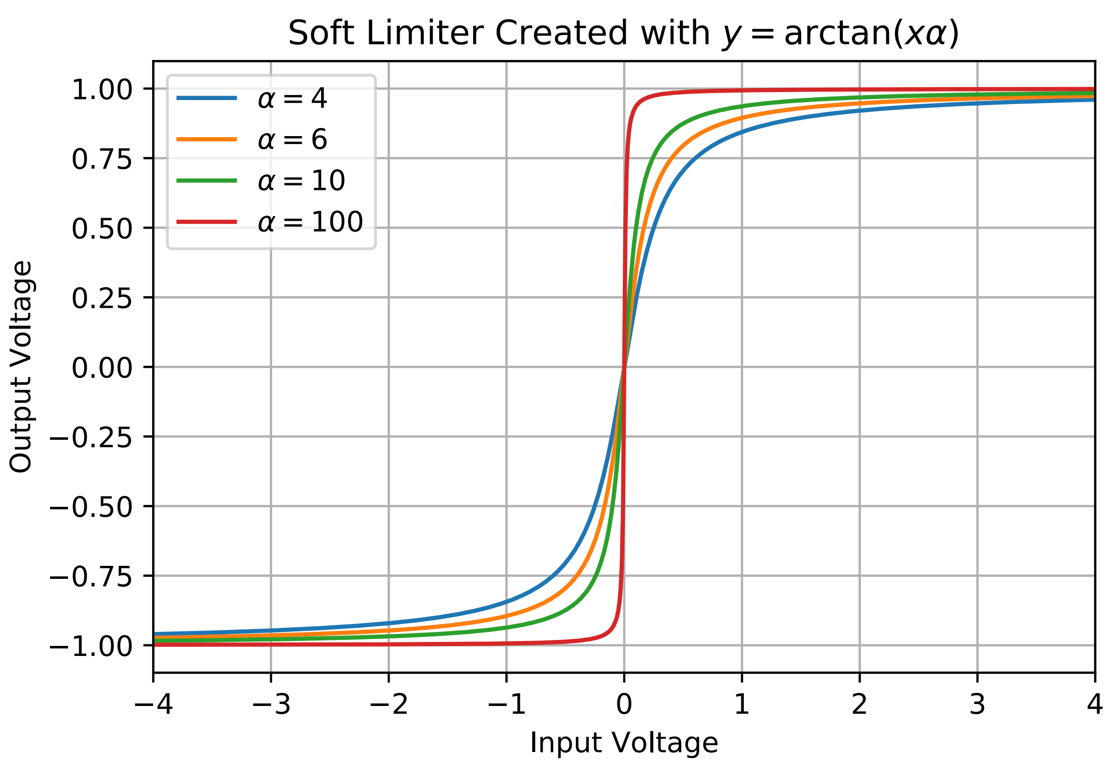


Figure 12: The soft limiter input/output characteristic curves.

To match the characteristic curves of Figure 12 with diode clipper we simulate a soft limited sinusoid in Python and overlay the response of the LTSpice circuit of Figure 11, for a sinusoid having amplitude corresponding tp +7 dBm into 50 ohms. A value of $\alpha = 4.0$ gives a good waveform match as shown in Figure 13.

```python
# Import clipper output from LTSpice
# Skip the first 32 rows, then skip the last row that contains 'END'
t_clip, clip_out = loadtxt('DiodeClipper.csv',delimiter=',',skiprows=1,
                usecols=(0,1),unpack=True)

# Behavioral level model using arctan as an amplitude limiter
t_behav = arange(0,1e-3,1e-5)
x_behav = 1.416*sin(2*pi*2000*t_behav)
# Choose alpha = 4.0
y_behav = arctan(x_behav*4.0)*2/pi
y_behavs = y_behav*max(clip_out)/max(y_behav)

# Overlay waveforms
plot(t_behav*1e3,y_behavs)
plot(t_clip[:-1]*1e3,clip_out[:-1])
title(r'Fitting the $\arctan()$ Model to the DBM Circuit')
ylabel(r'Amplitude (V)')
xlabel(r'Time ($\mu$s)')
legend((r'$\arctan$ Model',r'LTSpice Schottky Clipper'))
#ylim ([-.4,.4])
grid();
```

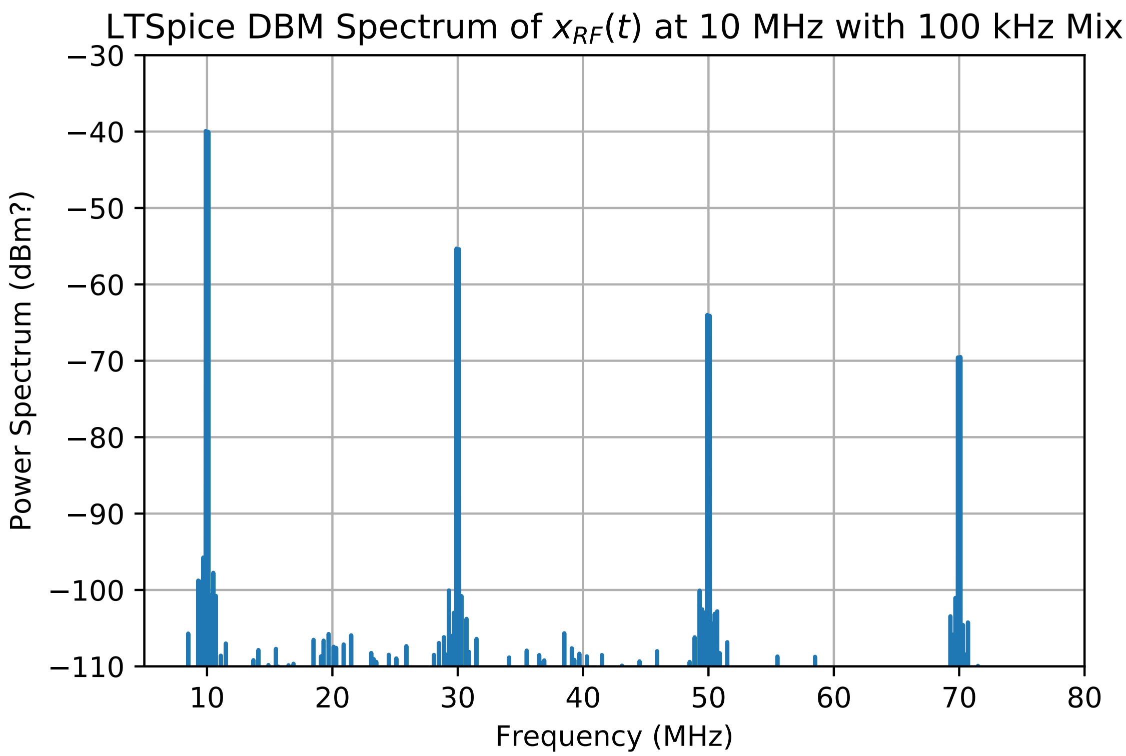


Figure 13: Establishing a realistic value for α in the soft limiter model of the DBM.

The results of Figure 3 and the block diagram of Figure 5 in 2 motivate the simple DBM behavioral model of Figure 14.

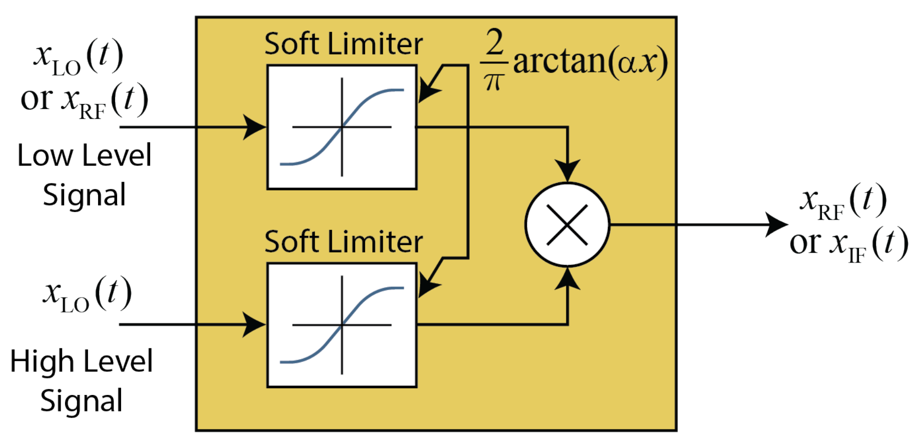


Figure 14: A simple DBM behavioral level model using soft limiters.

The term *behavioral level* applies to simplified math models used to represent the action of a true circuit model. A high level signal from the LO input creates string clipping action which in the diode ring circuit acts as a waveform multiplying the low level signal arriving via the IF or RF ports. The low level signal is also subject to a lesser degree of soft limiting. The Python function `DBM_model` wraps up the model by providing a default α value and also includes a conversion loss scale factor in dB. Conversion loss relates to the fact that the mixer outputs are not simply signals at $f_{\mathrm{LO}} \pm f_{\mathrm{IF}}$ due to the harmonic terms generated at the mixer out output. It is a passive device and the output signal power is spread to many different frequencies beyond those of the ideal multiplier.

```python
def DBM_model(x_LO,x_IF_RF,conv_loss_dB = 5.0, alpha = 4.0, ):
    """


    Mark Wickert February 2019
    """
    x_LO_clip = 10**(-conv_loss_dB/20)*arctan(x_LO*alpha)*2/pi
    x_IF_RF_clip = 10**(-conv_loss_dB/20)*arctan(x_IF_RF*alpha)*2/pi
    x_out = x_LO_clip*x_IF_RF_clip
    return x_out, x_LO_clip, x_IF_RF_clip
```

How well does the model work?

Example (continued)

Here we continue the earlier example with $f_{\mathrm{LO}} = 10$ MHz and $f_{\mathrm{IF}} = 100$ kHz. This time hardware measurement will be included using the `ADE-R6+` mixer. The system measurement block diagram is shown in Figure 15.

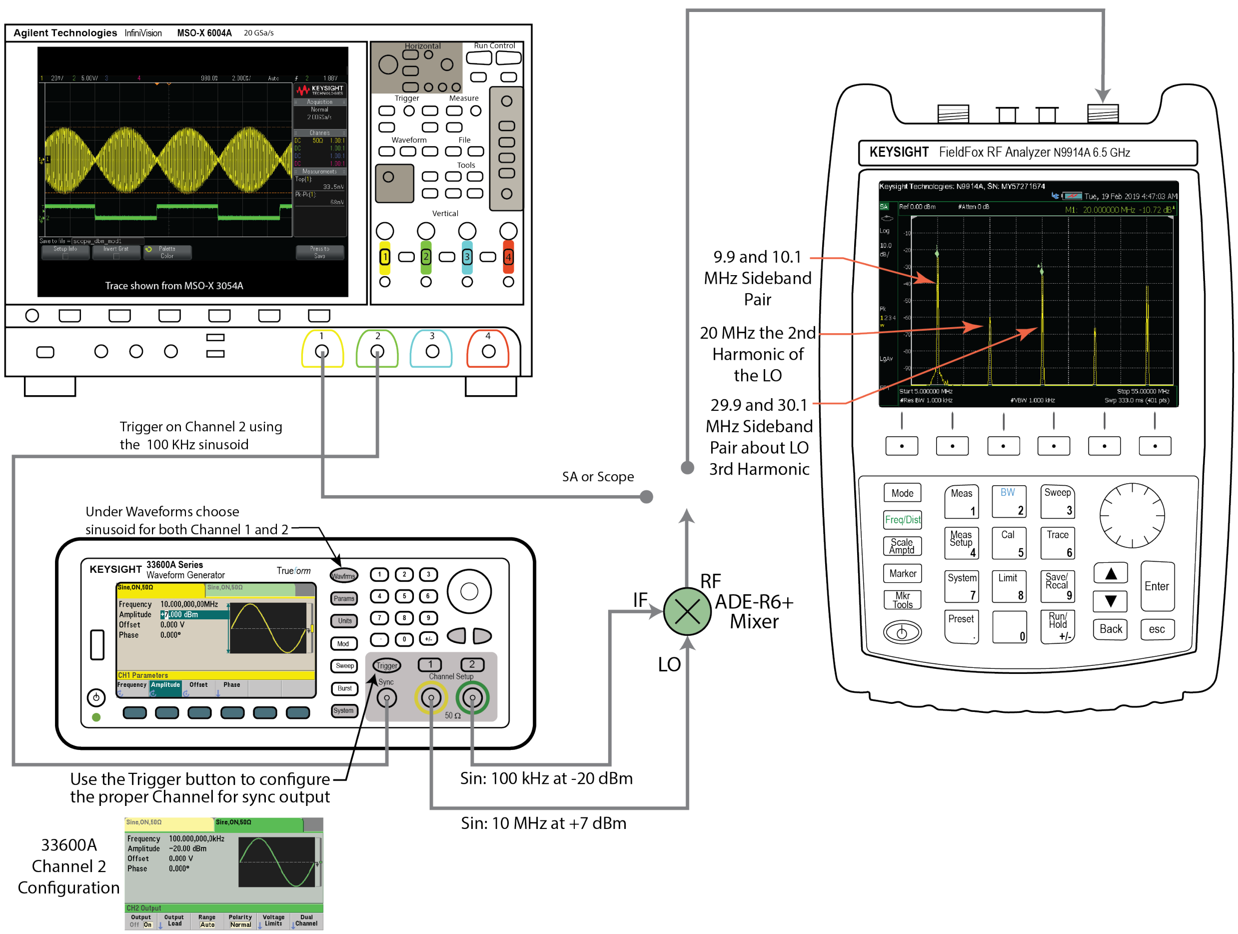


Figure 14: Test equipment configuration for the $f_{\text{LO}} = 10$ MHz and $f_{\text{IF}} = 100$ kHz example including embedded measurement results from instrument screenshots.

Figure 14 also shows miniature screen shots from the instruments, but the main point is how the mixer inputs are configured and how to view the waveform on the scope using a waveform from the Channel 2 of the Keysight 33600A.

Measurement data is captured from both the scope and FieldFox as `.csv` files. The results are now compared to the behavioral model results in the sample Jupyter notebook. The key results in the time are provided in Figure 15 and Figure 16 for the Python simulation and actual measurement, respectively. The Jupyter Python code cells are also included.

Note: From the simulation results we will later calculate approximate Fourier series coefficients in order to plot a simulated power spectrum. With $f_{\text{LO}} = 10$ MHz and $f_{\text{IF}} = 100$ kHz, we know that `x_RF` will be periodic with period of 1/100kHz = 10 μs. In the following simulation we choose a sampling rate of 1 GHz to obtain a high fidelity waveform and with a period of exactly 10 μs.

```python
t = arange(0,10e-6,1e-9) # 10 us capture
x_LO = 1.416*cos(2*pi*10e6*t)
x_IF = 0.0632*sin(2*pi*100e3*t)
x_RF, x_LO_clip, x_IF_clip = DBM_model(x_LO, x_IF,conv_loss_dB=5.0)
```

```python
plot(t*1e6,x_RF*1e3)
#plot(t*1e6,x_LO_clip*1e3)
#xlim([0,1])
ylabel(r'Amplitude (mV)')
xlabel(r'Time ($\mu$s)')
grid();
```

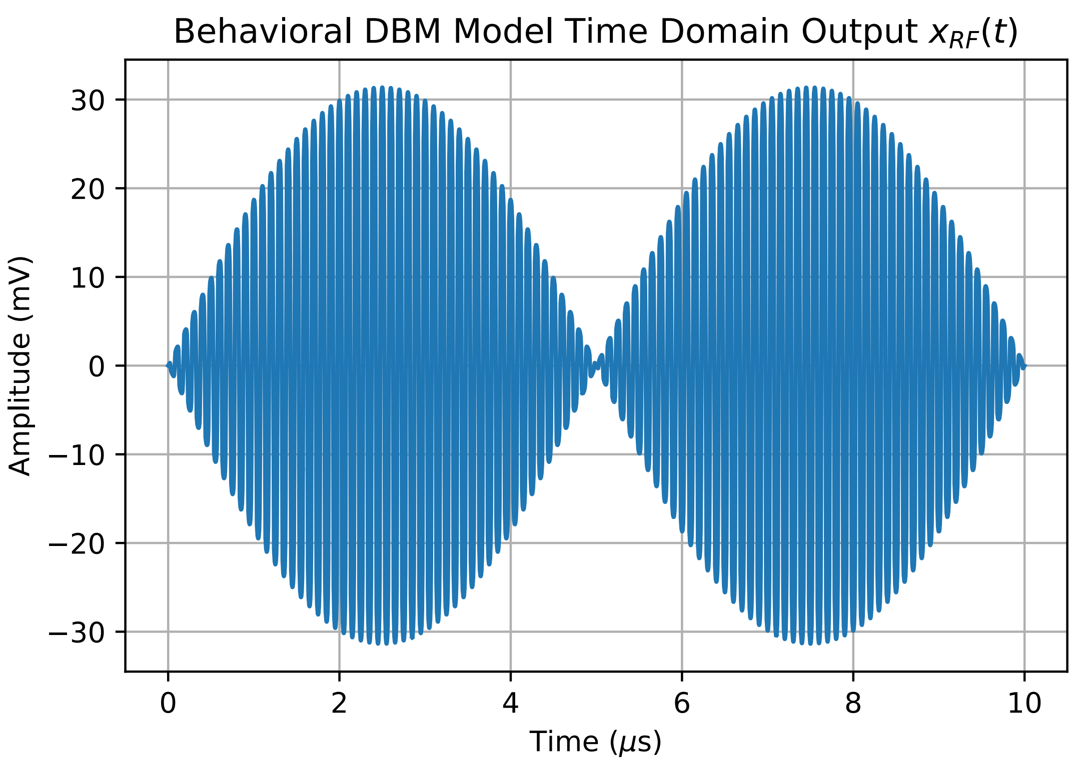


Figure 15: Time domain results from the Python simulation with the conversion loss increased to 6.5 dB to better match the measured results.

Next the corresponding scope capture `.csv` is imported so that time domain measurements of $x_{\mathrm{RF}}(t)$ can be compared.

```python
# Skip the first 32 rows, then skip the last row that contains 'END'
t_scope, scope_ch1, scope_ch2 = loadtxt('scope_dbm_mod.csv',delimiter=',',skiprows=2,
                usecols=(0,1,2),unpack=True)
```

```
plot(t_scope[:900]*1e6,scope_ch1[:900]*1e3)
title(r'Scope Measured Output $x_{RF}(t)$')
ylabel(r'Amplitude (mV)')
xlabel(r'Time ($\mu$s)')
grid();
```

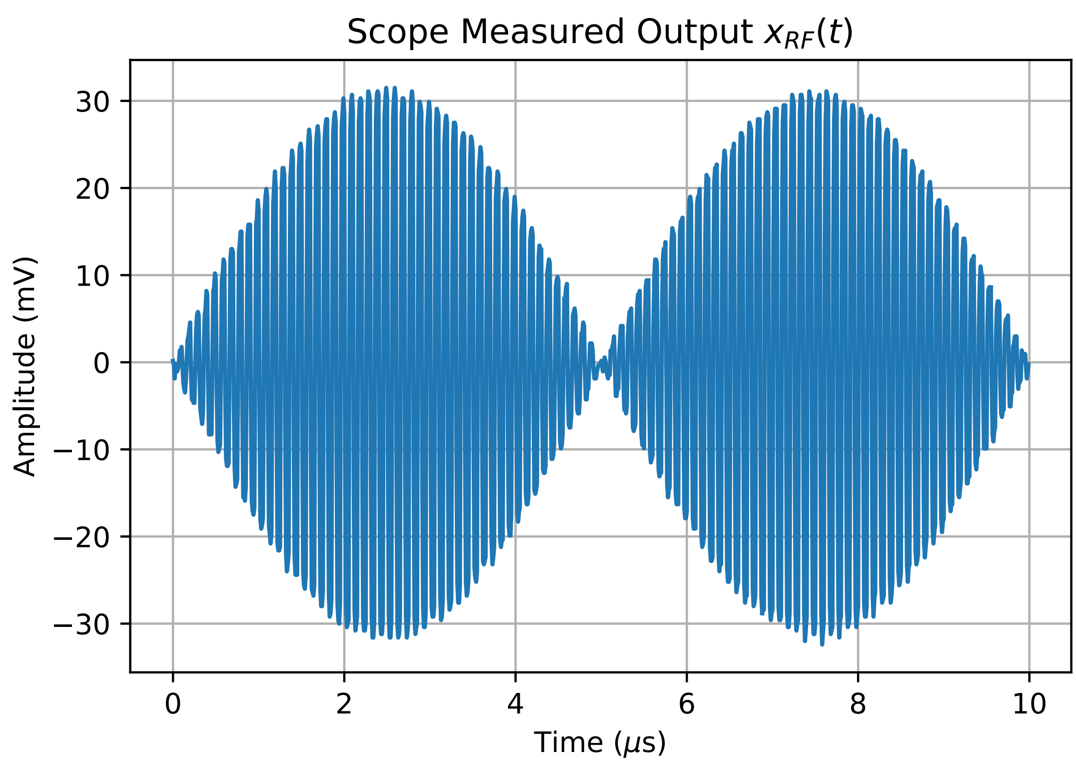


Figure 16: Actual measured results from the RF port of the `ADE-R6+` mixer.

The time domain results are comparable, but the spectrum analysis will reveal more detail.

Figures 17 and 18 move to the frequency domain to compare the power spectra from the behavioral model with the N9914A FieldFox measurements. We start by processing the 10μs simulation results. as shown in the following Python code.

```
Xk, fk = ss.fs_coeff(x_RF,550,100e3)
Xn_dBm = line_spectra_dBm(fk/1e6,Xk,-80,lwidth=1)
title(r'DBM Behavioral Model $x_{RF}(t)$ Line Spectrum')
xlabel(r'Frequency (MHz)');
ylim([-80,-10])
xlim([5,55]);
```

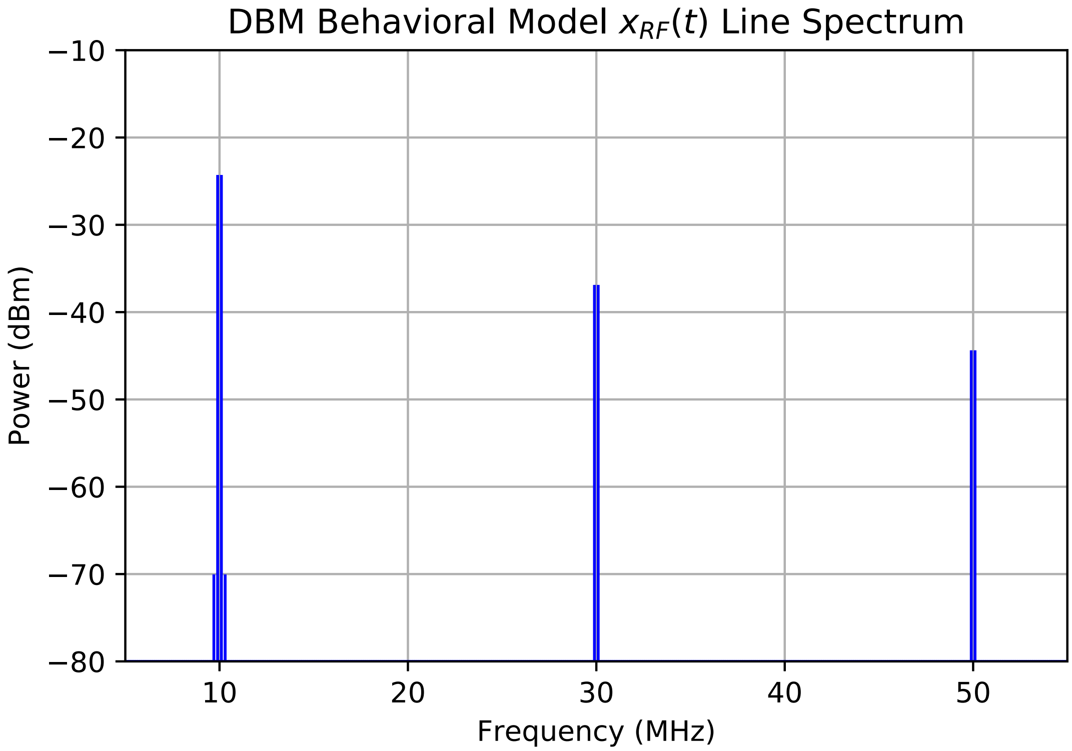


Figure 16: Power spectrum using the Python, with in particular the conversion loss set to 6.5 dB to better match the measured results shown in Figure 17.

The spectral peaks from the Python simulation are also obtained:

```
for k, Xn_dBm_k in enumerate(Xn_dBm):
    if Xn_dBm_k > -50: # Threshold = -30 dBm
        print('Peak at %6.4f MHz of height %6.4f dBm'% (fk[k]/1e6,Xn_dBm[k]))
```

```
Peak at 9.9000 MHz of height -24.4337 dBm
Peak at 10.1000 MHz of height -24.4337 dBm
Peak at 29.9000 MHz of height -37.0275 dBm
Peak at 30.1000 MHz of height -37.0275 dBm
Peak at 49.9000 MHz of height -44.5158 dBm
Peak at 50.1000 MHz of height -44.5158 dBm
```

The FieldFox N9914A results load from a `.csv` file next. The Python for handling measurement data follows:

```
# Skip the first 32 rows, then skip the last row that contains 'END'
f_SA, Sx_DBM_mod_10M_100k = loadtxt('DBM_MOD_10M_100K.csv',delimiter=',',skiprows=32,
                                usecols=(0,1),comments='END',unpack=True)
```

```python
plot(f_SA/1e6,Sx_DBM_mod_10M_100k)
xlabel(r'Frequency (MHz)')
ylabel(r'Power Spectrum (dBm)')
title(r'FieldFox 10 MHz LO, +7dBm, 100 kHz IF, -20 dBm')
ylim([-70,-20])
xlim([5,35])
grid()
```

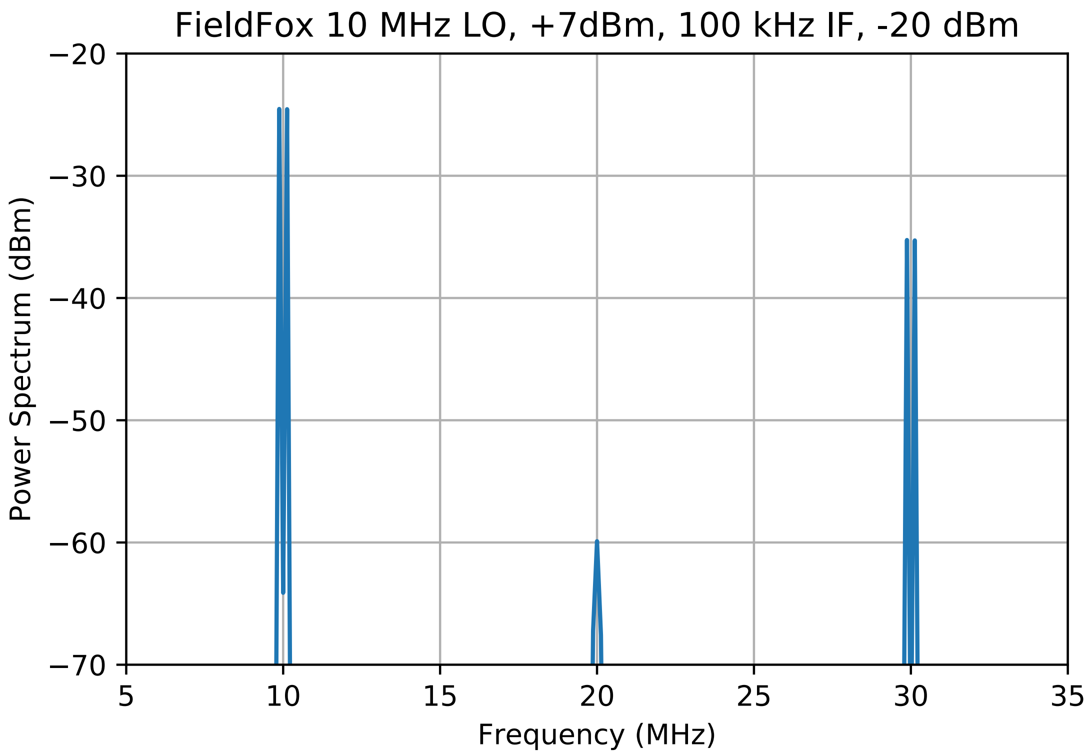


Figure 17: The power spectrum as captured from the FieldFox 9914A.

The spectral line at 10 and 30 MHz are comparable with the simulation. We also see a second harmonic term from the LO input. No sidebands are present at 20 MHz. The behavioral model does not produce this term. For even harmonics to be present the clipping action of the diodes has to have a small asymmetry. This is certainly possible and could be represented in the behavioral model.

The spectral peaks are displayed below:

```python
peak_idx = signal.find_peaks(Sx_DBM_mod_10M_100k,height=(-75,)) # peak threshold = -30 dBm
for k, k_idx in enumerate(peak_idx[0]):
    print('Peak at %6.4f MHz of height %6.4f dBm'%(f_SA[k_idx]/1e6,Sx_DBM_mod_10M_100k[k_idx]))
```

```
Peak at 9.8750 MHz of height -24.5360 dBm
Peak at 10.1250 MHz of height -24.5541 dBm
Peak at 20.0000 MHz of height -59.8962 dBm
Peak at 29.8750 MHz of height -35.2565 dBm
Peak at 30.1250 MHz of height -35.2895 dBm
Peak at 39.8750 MHz of height -66.5790 dBm
Peak at 40.1250 MHz of height -66.2963 dBm
Peak at 49.8750 MHz of height -41.4309 dBm
Peak at 50.1250 MHz of height -41.4799 dBm
```

More accurate frequency locations can be obtained via spectral zooming and/or a smaller resolution bandwidth.

Power Splitter and Combiner

At times an RF signal must be split into two paths for driving multiple devices or providing test points for say both the scope and spectrum analyzer. One such means for doing this, and maintaining an impedance match, is a reactive power splitter/combiner. The RF Board contains two power splitters. The Mini-Circuits `ADP-2-1+` is a 0.5 to 400 MHz passive splitter/combiner with portions of the data sheet shown in Figure 18.

Surface Mount

Power Splitter/Combiner

2 Way-0° 50Ω 0.5 to 400 MHz

ADP-2-1+

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"	10, 20, 50, 100, 200, 500
13"	500, 1000

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
Power Input (as a splitter)	0.5W max.
Internal Dissipation	0.125W max.

Permanent damage may occur if any of these limits are exceeded.

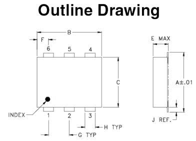
Features
- low insertion loss, 0.3 dB typ.
- excellent amplitude unbalance, 0.10 dB typ.
- very good phase unbalance, 0.5 deg. typ.
- aqueous washable
- protected under U.S. Patent 6,133,525

Applications
- instrumentation
- VHF/UHF

Pin Connections

SUM PORT	1
PORT 1	3
PORT 2	4
GROUND	6
Externally connect together & isolate	2,5

Outline Drawing



Electrical Specifications

FREQ. RANGE (MHz)	ISOLATION (dB)						INSERTION LOSS (dB) ABOVE 3.0 dB						PHASE UNBALANCE (Degrees)			AMPLITUDE UNBALANCE (dB)		
	L		M		U		L		M		U		L	M	U	L	M	U
f_L-f_U	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Max.	Typ.	Max.	Typ.	Max.	Max.	Max.	Max.	Max.	Max.	Max.
0.5-400	25	20	25	20	25	20	0.2	0.4	0.3	0.6	0.5	1.0	1.0	2.0	3.0	0.1	0.2	0.3

L = 0.5-5 MHz M = 5-200 MHz U = 200-400 MHz
See Notes below.

Typical Performance Data

Frequency (MHz)	Total Loss[1] (dB) S-1	Total Loss[1] (dB) S-2	Amplitude Unbalance (dB)	Isolation (dB)	Phase Unbalance (deg.)	VSWR S	VSWR 1	VSWR 2
0.50	3.13	3.13	0.00	30.12	0.03	1.06	1.08	1.08
10.00	3.13	3.13	0.00	34.46	0.05	1.03	1.01	1.01
30.00	3.16	3.16	0.00	33.18	0.04	1.03	1.01	1.01
60.00	3.18	3.19	0.01	31.23	0.04	1.04	1.01	1.01
90.00	3.21	3.21	0.00	29.53	0.11	1.05	1.01	1.01
120.00	3.21	3.22	0.01	28.15	0.07	1.06	1.02	1.02
160.00	3.26	3.25	0.01	26.67	0.12	1.08	1.02	1.02
200.00	3.28	3.27	0.01	25.63	0.08	1.09	1.03	1.03
240.00	3.29	3.27	0.01	24.87	0.14	1.09	1.04	1.04
280.00	3.34	3.35	0.00	24.45	0.19	1.09	1.05	1.05
320.00	3.33	3.32	0.00	24.36	0.26	1.08	1.07	1.07
340.00	3.37	3.37	0.01	24.50	0.29	1.07	1.08	1.08
360.00	3.38	3.37	0.00	24.69	0.24	1.07	1.09	1.09
380.00	3.42	3.42	0.00	24.97	0.28	1.05	1.10	1.10
400.00	3.41	3.41	0.00	25.39	0.37	1.04	1.11	1.12

1. Total Loss = Insertion Loss + 3dB splitter loss.

Figure 18: Mini-Circuits `ADP-2-1+`, a 0.5 to 400 MHz power splitter/combiner top level performance specifications.

Note a reactive power splitter/combiner introduces ~3 dB loss, which means that although a passive device, it is essentially lossless. When used as a power splitter the input power at the *sum port* is equally split to the outputs *port 1* and *port 2*. In the power combiner mode the output power on the sum port will be the sum of the two input powers, again in theory no insertion loss. Another nice feature of this devices is that it provides a degree of signal isolation between say ports 1 and 2. This means that when used as a combiner a signal input on port 1 will arrive at the sum port, but is ideally not present as an output on port 2. The opposite holds for an input on port 2.

The symbol for the power splitter used in the remainder of this lab document and beyond is given in Figure 19.

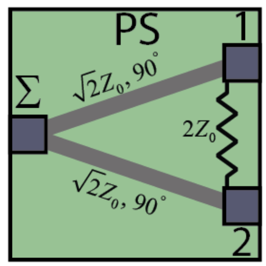


Figure 19: Power splitter/combiner block diagram symbol.

Laboratory Exercises

Characterizing the Power Splitter Combiner

Part a

Using the FieldFox network analyzer find the frequency response magnitude, $|S_{21}(f)|_{\text{dB}}$, of the power splitter signal path from the sum port to one of the output ports. Sweep frequency from at least 500 kHz to 400 MHz. Comment on how Well it compares to the `ADP-2-1+` data sheet. Make sure to 50 ohm terminate the unused power splitter port (just run a cable to the scope).

Part b

Using the FieldFox network analyzer find the frequency response magnitude, $|S_{21}(f)|_{\text{dB}}$, of the power splitter signal path from port 1 to port 2 and $|S_{\Sigma 1}(f)|_{\text{dB}}$ of the sum port Σ to port 1 or 2. This will be a measurement of the isolation between output ports and the transmission from the sum port to port1/2, respectively. Sweep frequency from at least 500 kHz to 400 MHz. Comment on how well it compares to the `ADP-2-1+` data sheet. Make sure to 50 ohm terminate the unused power splitter port (just run a cable to the scope). Import the `s2p` data into Jupyter for plotting.

Mixer Basics

Part a

To become familiar with the characteristics of a practical mixer apply sinusoids to the LO and IF inputs as shown in Figure 20. As a matter of practice one input is always a large signal and the other is always a small signal, in amplitude that is. Here make the LO signal be +7 dBm into 50 ohms at a frequency of 5 MHz. Set the IF input to initially be −20 dBm into 50 ohms at a frequency of 100 kHz. Observe the RF port output on the spectrum analyzer with a 50 ohm termination. Observe the output spectrum from 0 Hz up to 25 MHz and catalog the frequencies within 60 dB of the strongest signal. Categorize the signals into the three types of mixing products of

- nf_{LO}
- mf_{IF}
- $|mf_{\mathrm{IF}} \pm nf_{\mathrm{LO}}|$

where n and m are positive integers.

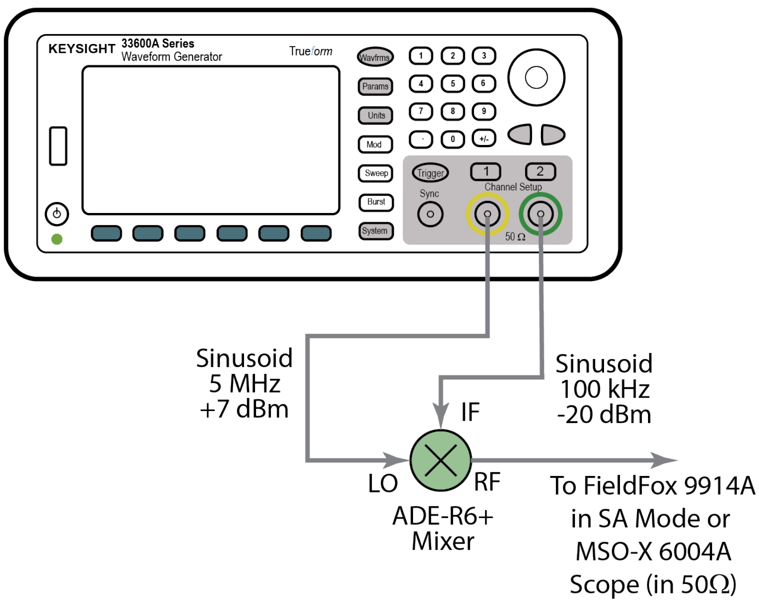


Figure 20: DBM basic test circuit.

Part b

Starting from the part a configuration increase the IF input power from −20 dBm to −10 dBm. What is the most significant change in the output spectrum at the RF port?

Part c

Return to the Part a configuration but now move the LO to 70 MHz. Observe the spectrum at the mixer RF port with and without the RF Board 70 MHz RF filter as shown in Figure 21.

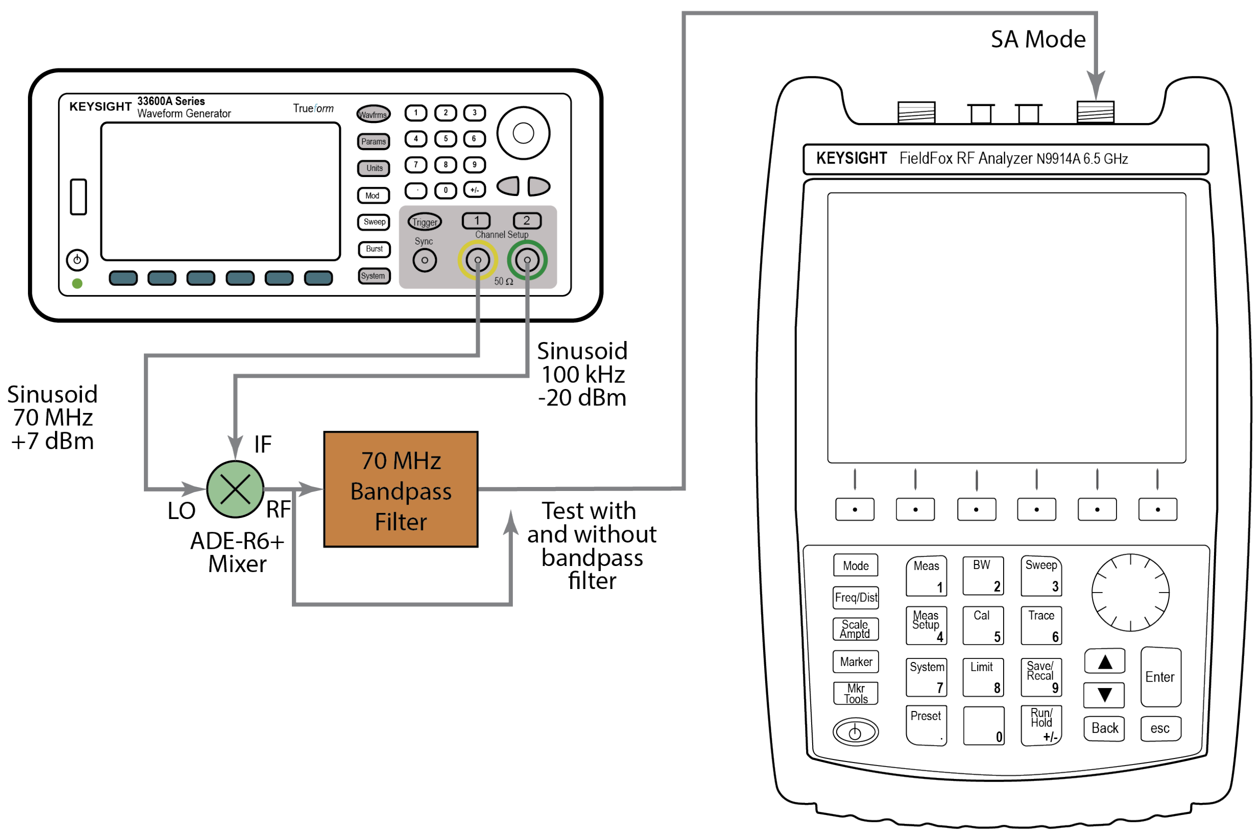


Figure 21: Shifting f_{LO} to 70 MHz and seeing the impact of the RF Board 70 MHz BPF.

The frequency span should be adequate to see that mixing products outside the vicinity of 70 MHz disappear after the filter is inserted. Verify however that the upper and lower sidebands at 69.1 and 70.1 MHz indeed present. Feel free to shift the 70 MHz LO up or down in frequency to best match the actual center frequency of the RF Board ~70 MHz BPF. The main intent of this exercise is to see how the BPF cleans up the unwanted mixer outputs.

Double Sideband Modulation and Demodulation

Part a

With the basic characterization complete, you will now build a DSB modulator cascaded with a demodulator, using a coherent carrier in the demodulator. The block diagram is shown in Figure 21. Configure this circuit using the RF interface elements described in the background section. Observe on the spectrum analyzer that the original message signal appears at the output (IF port) of the second mixer. How important is it that the demodulation carrier source be phase coherent with the transmitted carrier source?

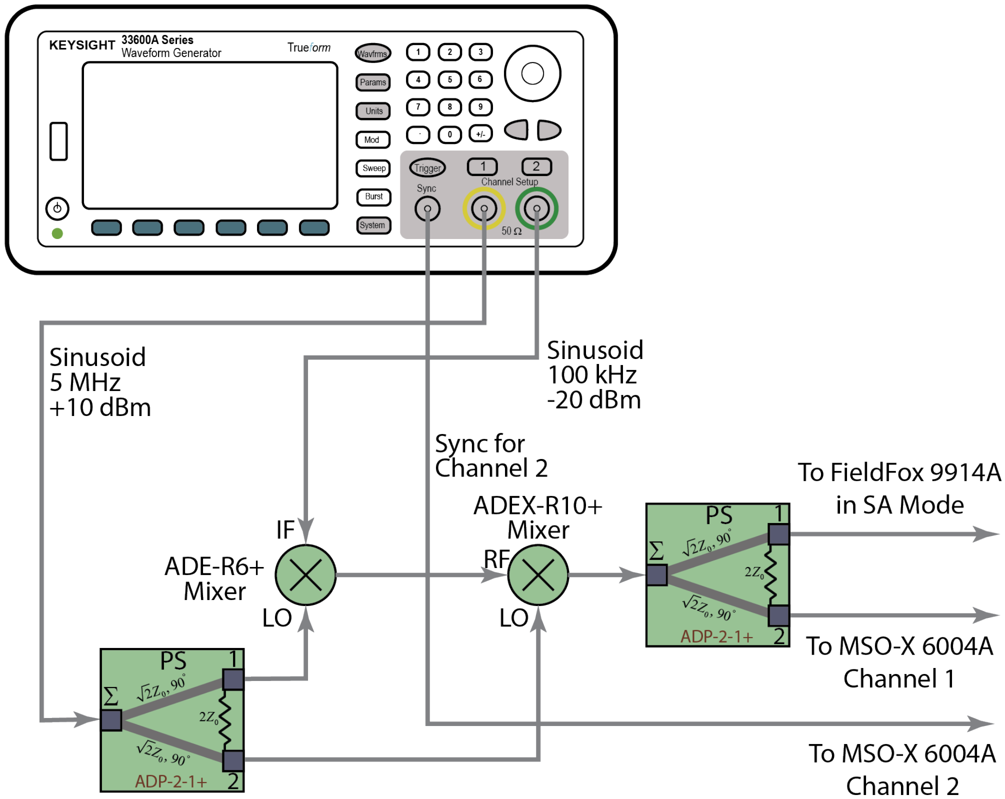


Figure 21: DSB modulator followed by a coherent demodulator.

Part b

Observe the output waveform on the scope to verify that among the various signal components that are now super imposed, the desired message signal is indeed present. How can we recover the message signal?

Part c

Attempt to recover the message signal, the 100 kHz sinusoid using the RF Board 1 MHz lowpass filter. Is this reasonable? Capture the time domain results on the scope. Make note of any strong interference signals that you see via the spectrum analyzer.

Part d

Compare your results with a Python behavioral simulation as described in the simulation modeling section of this document. For the 1 MHz lowpass filter use use a behavioral model, which means treat the filter as a digital filter designed using `scipy.signal.cheby1()`.

Filter design:

```
fs = 100e6 # sampling rate
fc = 1e6 # cutoff frequency
b, a = signal.cheby1(5, 1, 2*fc/fs) # digital filter design
```

Simulation code, in part:

```
fc = 5e6
fm = 100e3
t = arange(0,2/(100e3),1/100e6) # Two cycles of 100 kHz with fs = 100 MHz
# Create the modulated DSB
x_LO = 1.416*cos(2*pi*fc*t)
x_IF = 0.0632*sin(2*pi*fm*t)
x_RF, x_LO_clip, x_IF_clip = DBM_model(x_LO, x_IF,conv_loss_dB=5.0)
# Create the coherently demodulated DSB
# Write code here
...
x_demod = ....
# Filter with 1 MHz LPF
y_demod = signal.lfilter(...)
plot(t/1e3,y_demod*1e3) # t in ms and V in mV
```

Part e

In this part you will explore noncoherent demodulation starting from the setup of Part c. The Agilent 33250 generator will be used as a non-coherent reference in the demodulator as shown in Figure 22.

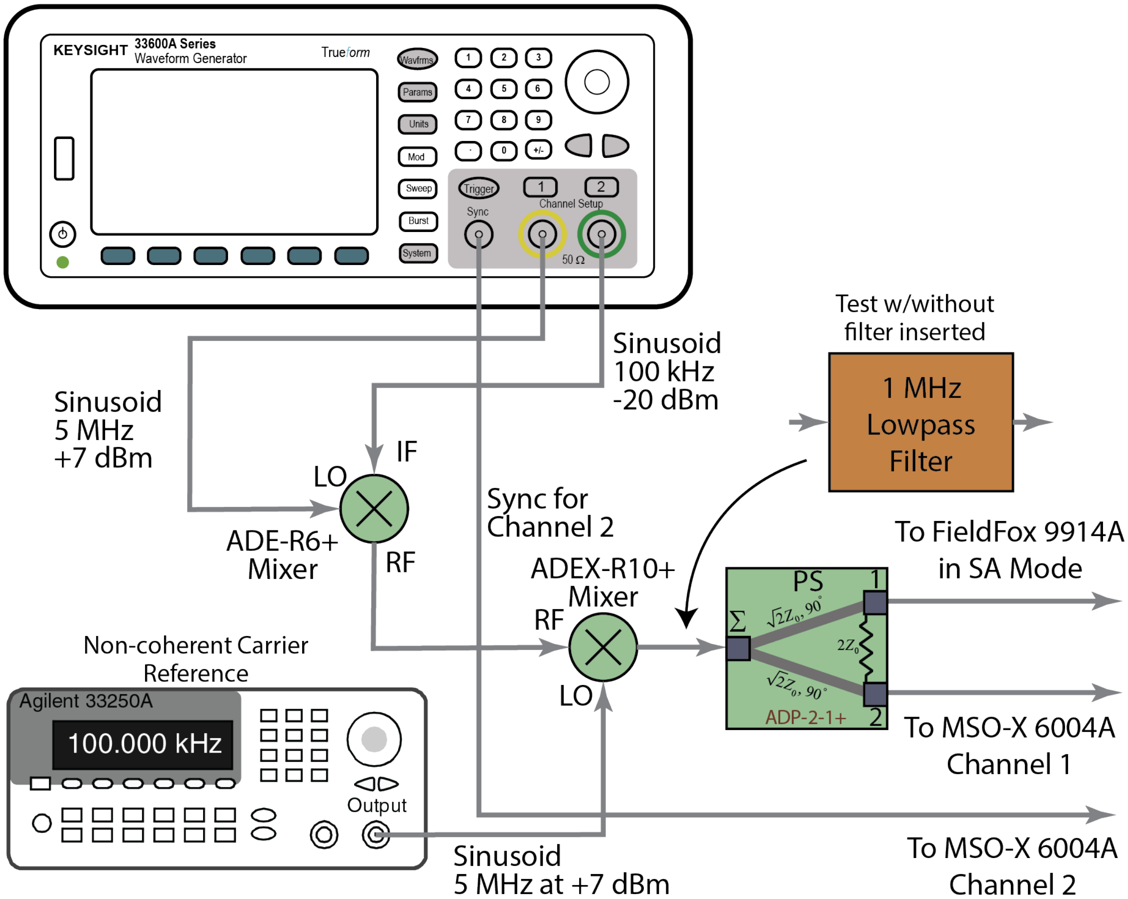


Figure 22: DSB modulation with noncoherent demodulation using the Agilent 33250 generator.

Observe on both the scope and the spectrum analyzer what happens when you make the 33250 frequency close to 5 MHz. You should see the 100 kHz message sinusoid break into two sinusoids. To see this more clearly insert the 1 MHz lowpass filter between the second mixer and the power splitter.

AM Modulation and Demodulation

Part a

AM modulation can be demodulated using envelope detection. This simplicity is the basis for AM radio broadcasting over carrier frequencies from 540 kHz to 1600 kHz. Here you will generate an AM modulated carrier at 5 MHz using the built-in modulation capability of the Agilent 33600A. The block diagram is shown in Figure 23.

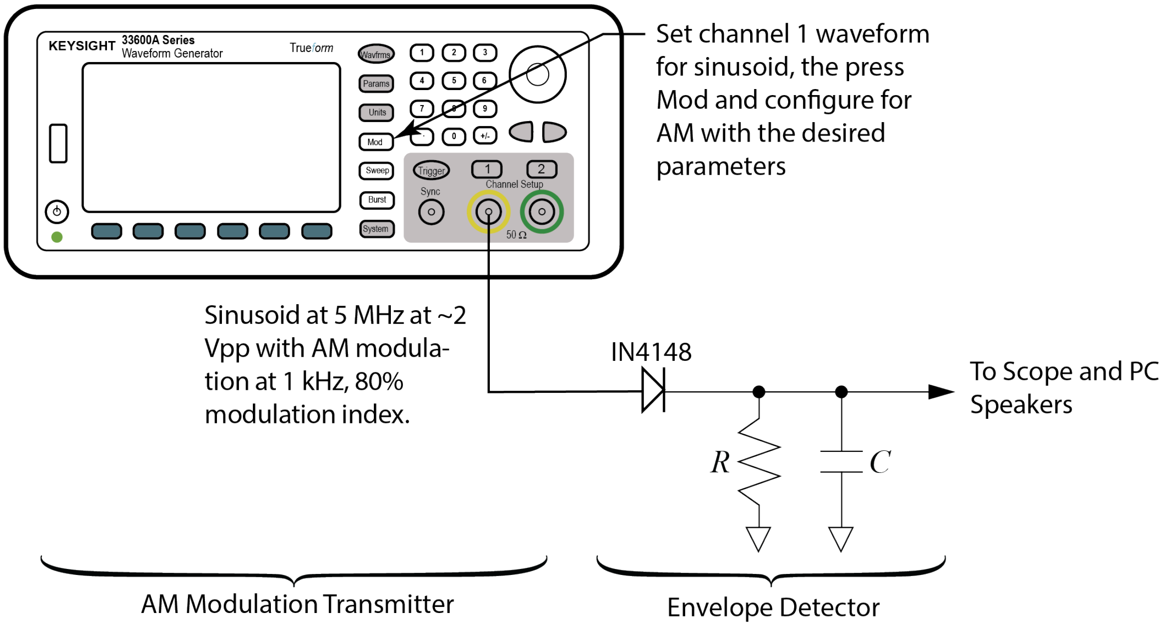


Figure 23: AM message recovery using an envelope detector.

Configure the Agilent 33600A to generate a 5 MHz AM carrier with a message signal initially at 1 kHz and a modulation index of 80%. You may need to refer to the Agilent 33600 to learn how configure the generator for AM modulation.The generator need to drive an envelope detector which consists of a 1N4148 silicon diode followed by an RC filtering circuit. Note that this is a nonlinear circuit.

Adjust the drive level to the diode envelope detector to be sufficient to overcome the diode turn–on voltage of roughly 0.7 v. Initially include only the R value so you can better see that the diode is indeed halfwave rectifying the AM signal.

Choose a value for C so that the RC filtering action allows recovery of sinusoidal message signals up to 5 kHz. There is a trade–off involved here, as you will see when you observe the waveform on the scope. We have capacitor substitution boxes in the lab which may be useful in the optimization process. Listen to the demodulated sinusoidal tone using the powered PC speakers found at each lab station.

Part b

Starting from the configuration of Part a apply custom modulation from an music source. On the rear of the Agilent 33600A there is a connector that allows an external modulation signal to be applied. Configure a music source, PC radio, phone/iPod, etc. as a source that can drive this rear connector. The modulation index will no longer be calibrated, so you will have to manually adjust the input audio level to keep the modulation index roughly below 100%. Comment on the quality of the recovered AM modulation using the PC speakers.

Frequency Translation and Super–Heterodyne

Frequency translation and the super–heterodyne principle, are fundamental to the design of radio receivers. For efficient signal processing, it is best if we can design the receiver to have high gain and good frequency selectivity, at a fixed frequency. Translated a range of carrier frequencies to a common *intermediate frequency* (IF) using a *local oscillator* (LO) is what is usually done. In AM radio broadcasting, where the carrier frequency ranges from 540 to 1600 kHz, a popular IF frequency is 455 kHz. Here we consider the simple frequency translation system of Figure 24 for converting a 10 MHz AM radio signal to a 250 kHz IF. The LO may use low–side or high–side tuning.

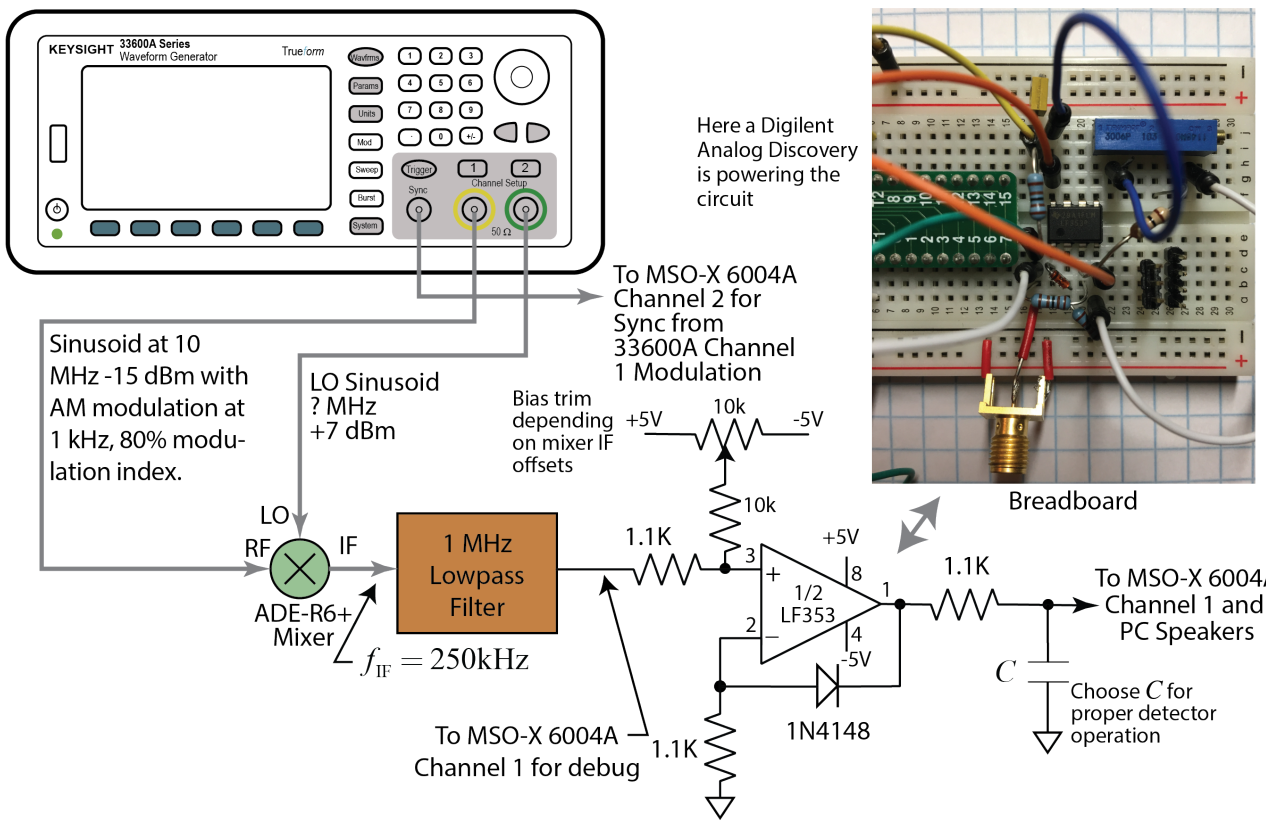


Figure 24: Frequency translation of a 10 MHz AM signal to a 250 KHz IF, followed by the 1 MHz LPF on the RF Board.

Part a

What are the two possible values for f_{LO}? What are the *image frequencies* associated with these LO frequencies, respectively.

Part b

In practice we want the IF filter to be a bandpass filter, but here we find it convenient to use the RF Board lowpass filter. Do you see any problems with doing this?

Part c

To complete the receiver build up the op-amp based envelope detector shown in Figure Superhet. Set up the RC filter at the output of the envelope detector to allow recovery of up to 5 kHz message signals.

Initially Listen and observe the output with a 1 kHz message signal. As you vary/tune the LO what you see and hear should be like tuning an AM radio. Confirm this behavior and compare it with an LTSpice simulation, supplied in the Jupyter notebook sample ZIP. The LTSpice simulation schematic is shown in Figure 25. Bring the scope data and the LTSpice data together in the Jupyter notebook.

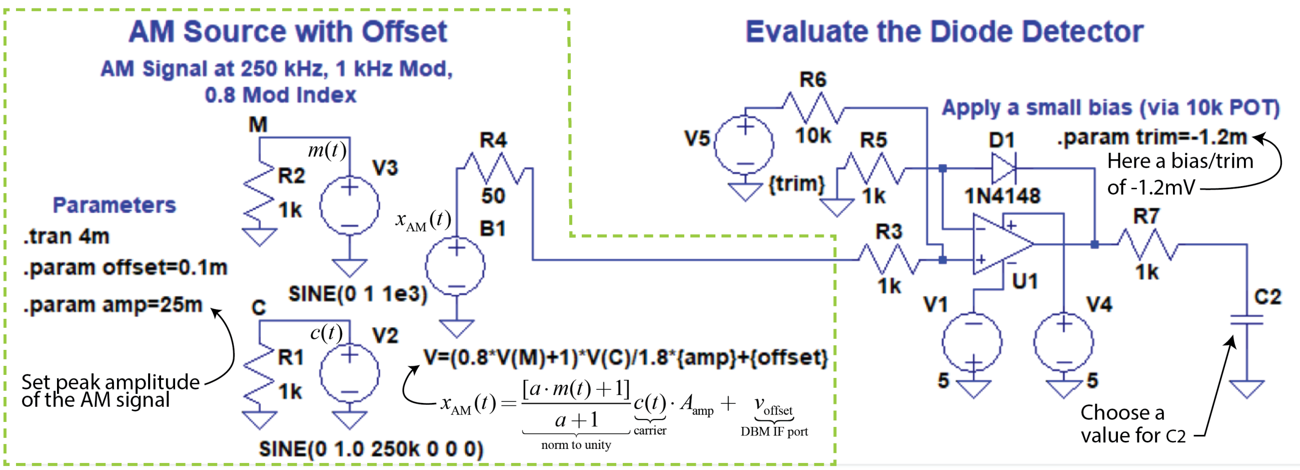


Figure 25: LTSpice envelope detector schematic with an AM source created using Spice behavoral model capabilities, e.g., variables and equations.

Part d

Lastly repeat above using a music source via the external AM modulation input.

References

1. Rodger Ziemer and William Tranter, Principles of Communications, 8th edition, Wiley, 2014.
2. Enrico Rubiola, "Tutorial on the double balanced mixer." https://arxiv.org/pdf/physics/0608211.pdf
3. Gary Breed, "The Mathematics of Mixers: Basic Principles," *High Frequency Electronics*, January 2011. https://www.highfrequencyelectronics.com/Jan11/HFE0111_Tutorial.pdf

4. Ferenc Marki & Christopher Marki, Ph.D., "Mixer Basics Primer," https://www.markimicrowave.com/assets/appnotes/mixer_basics_primer.PDF

Appendix: Improved DBM Behavioral Level Model

TBD