

Spectrum Analyzer and Spectrum Analysis

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Chapter 1

SPECTRUM ANALYZER AND SPECTRUM ANALYSIS

1.1 Objectives

Upon completion of the experiment the student will:

- Learn the basic concept of frequency domain measurements.
- Learn, and understand how to operate the spectrum analyzer.
- Understand the function of each block of the spectrum analyzer.
- Simulate and analysis electrical signals.

1.2 Necessary Background:

The student needs to have a basic understanding of Fourier series, and Fourier transform.

1.3 Prelab Exercise

1.3.1 Problem 1

1. **Fourier series of a real squarewave-** Suppose you need to measure a clock signal of 100 kHz, amplitude 1 volt, with 20ns edge speeds (10% to 90% rising time see Fig. 1). A frequently asked question, is what is the minimum bandwidth of an oscilloscope I need to perform a reliable measurement.

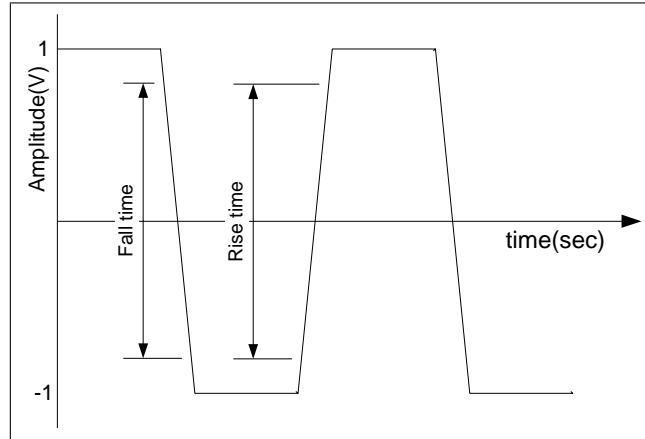


Fig. 1 Time domain of 100kHz, amplitude 1 volt, rise time 20nsec. squarewave

A 'rule of thumb' is to consider the fastest transition time of the signal, the rise time

$$BW = \frac{0.5}{T_r} \text{ within 20\% accuracy} \quad (1.1)$$

$$BW = \frac{0.65}{T_r} \text{ within 10\% accuracy} \quad (1.2)$$

$$BW = \frac{0.95}{T_r} \text{ within 3\% accuracy} \quad (1.3)$$

where T_r is the rise time of the signal,

1. (a) Find an analytic expression, for an ideal squarewave, frequency 100kHz, amplitude $1V_p$.
- (b) According to equation Eq. (3) , find the required bandwidth of the oscilloscope.
- (c) Find the number of odd harmonics, you need to reconstruct the real square-wave within 3% accuracy.
- (d) Using Matlab, draw a graph of the reconstructed squarewave, based on the sum of N odd harmonics. find the rise, and calculate the error in rise time.

1.3.2 Problem-2

Fourier transform of a squarewave- Using Matlab, draw a graph of repetitive 100kHz squarewave (10 periods) in time domain. Use FFT command to draw a frequency domain graph(magnitude only), use FFT shift command, and further adaptation to show a graph, similar to an analytic graph.

1. (a) Use the graph to indicate the amplitude (v) and frequency of the first, third, fifth, and seventh harmonics.

1.3.3 Problem-3

Block diagram of a Spectrum Analyzer-Draw a block diagram of a spectrum analyzer, and explain briefly each of the following blocks (Attenuator, amplifier, LPF, IF filter, envelope detector, video filter, display, LO, Ramp generator).

1.3.4 Problem-4

Shape factor of a Gaussian filter-The voltage of a gaussian shape filter is given by

$$V(f) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(f-f_0)^2}{2\sigma^2}\right) \quad (1.4)$$

where f_0 is the center frequency of the filter, and σ is the standard deviation. In probability theory σ is the standard deviation (About 68% of values drawn from a normal distribution are within one standard deviation, σ). Electrical engineering consider the envelope of the curve.

Assume that the the center frequency is 10MHz, and the -3dB bandwidth of the filter is 1MHz.

1. (a) Use Eq. (4) to find the standart deviation of the filter (-3dB is related to the power $V^2(f)$).
- (b) Use Eq. (4) to find the -60dB bandwidth of the filter, and the shape factor of the filter

$$\text{Shape factor} \equiv \frac{-60dB \text{ Bandwidth}}{-3dB \text{ Bandwidth}}$$

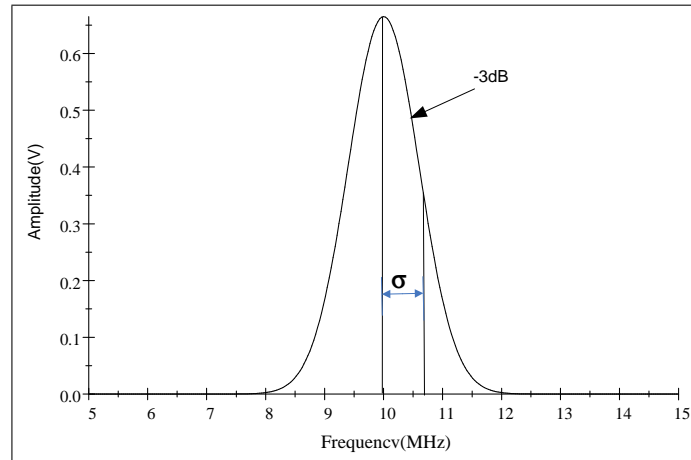


Figure problem 4

1.4 References

1. ROBERT A. WITTE "Spectrum and Network Measurements" . New Jersey , Prentice Hall,1991

2. CYDE F. COOMBS, Jr. "Electronic Instrument Handbook". McGraw-Hill, second edition 1995.

3. C. Rauscher: "Fundamental of Spectrum analysis" Rhode&Schwarz 2001.

4. Agilent Company: "Spectrum Analysis Basics". Application Note 150, January 2005.

1.5 Background Theory -Frequency and Time Domain

So what is a spectrum? Fourier series theory tells us that: " Any physical signal, is a collection of sine waves that, when combined properly, produce the time-domain signal under examination" Fourier transform add time and frequency domain, is two different representations, of the same signal.

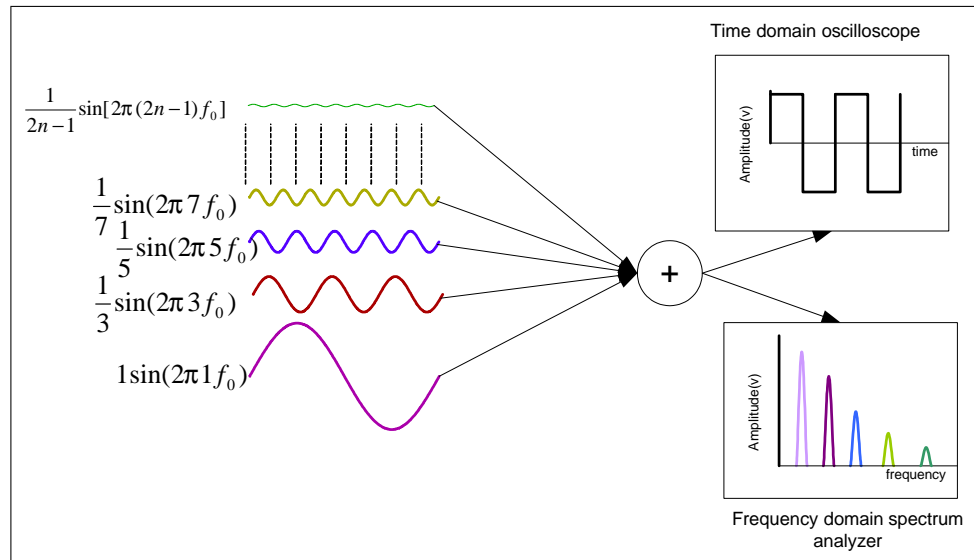


Figure 2 Time and frequency domain

Figure 2 shows a squarewave signal in both time and frequency domains. The frequency domain display plots the amplitude versus the frequency of each sine wave in the spectrum, while the time domain shows, true amplitude versus time. Does this mean we have no need to perform both domain measurements? Not at all. Some measurement can be made only in the time domain. For example, pulse rise and fall times, overshoot, and ringing, while other measurements like harmonics content, can be made only in frequency domain.

1.6 Spectrum Analyzer Block Diagram and Theory of Operation

Figure 3 is a simplified block diagram of a superheterodyne spectrum analyzer. Heterodyne means to mix; that is, to translate frequency. And super refers to super-audio frequencies. Referring to the block diagram in Figure 3, we see that an input signal passes through an attenuator, then through a low-pass filter to a mixer, where it

mixes with a signal from the local oscillator (LO). Because the mixer is a non-linear device, its output includes not only the two original signals, but also their harmonics and the sums and differences of the original frequencies and their harmonics. If any of the mixed signals falls within the passband of the intermediate-frequency (IF) filter, it is further processed. It is essentially rectified by the envelope detector, digitized, and displayed. A ramp generator creates the horizontal movement across the display from left to right. The ramp also tunes the LO so that its frequency change is in proportion to the ramp voltage.

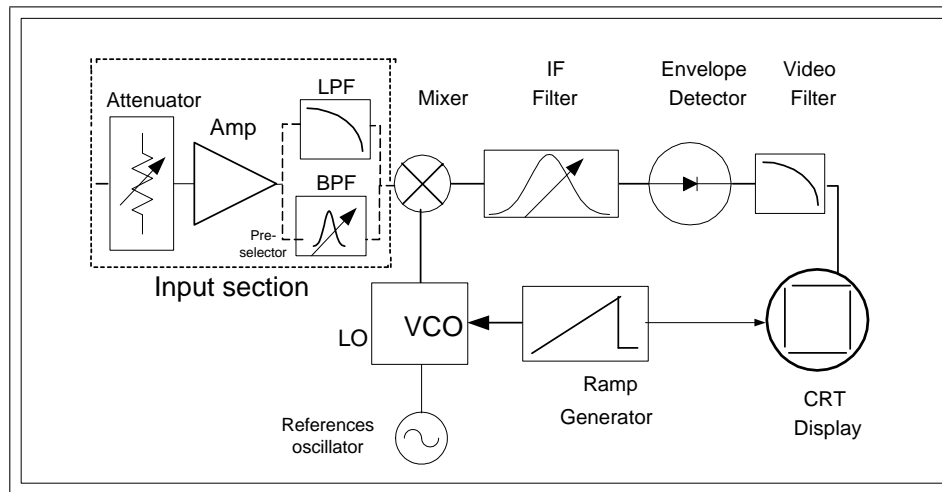


Figure 3 Simplified block diagram of Heterodyne spectrum analyzer

1.7 Input Section

The input to the spectrum analyzer block diagram has a step attenuator, followed by an amplifier. The purpose of this input section is to control the signal level applied to the rest of the instrument.

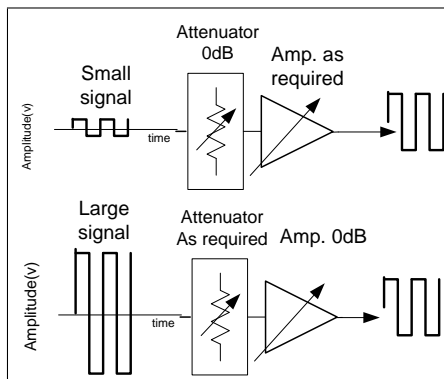


Figure 4 Signal controlling by input section

If the signal level is too large, the analyzer circuits will saturate the mixer and distort the signal, causing distortion products to appear along with the desired signal. If the

signal level is too small, the signal may be masked by noise present in the analyzer. Either problem tends to reduce the dynamic range of the measurement.

1.7.1 LPF or Preselector (Tunable BPF)

The low-pass filter blocks high frequency signals from reaching the mixer. This stage prevents out-of-band signals from mixing with the local oscillator and creating unwanted responses at the IF

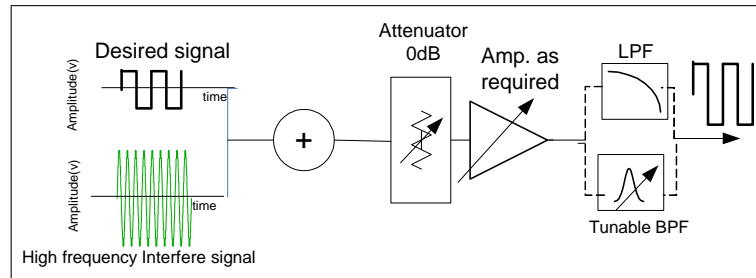


Figure 5 Interference rejection by LPF or preselector

Microwave spectrum analyzers replace the low-pass filter with a preselector, which is a tunable filter that rejects all frequencies except those that we currently wish to view.

1.8 Mixer and Local oscillator.

A mixer (Fig-3) is a device that converts a signal from one frequency to another. It is therefore sometimes called a frequency converter device

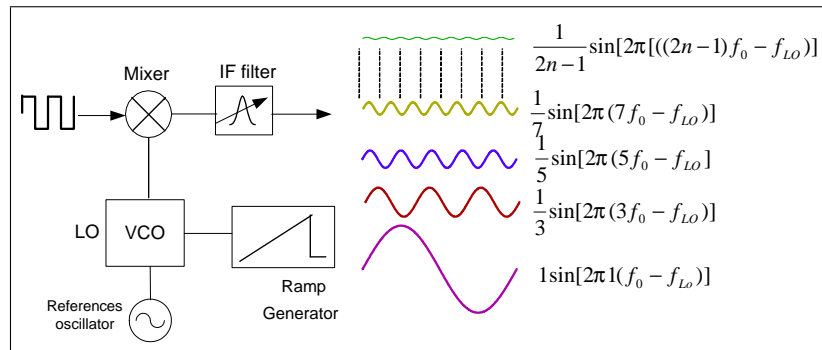


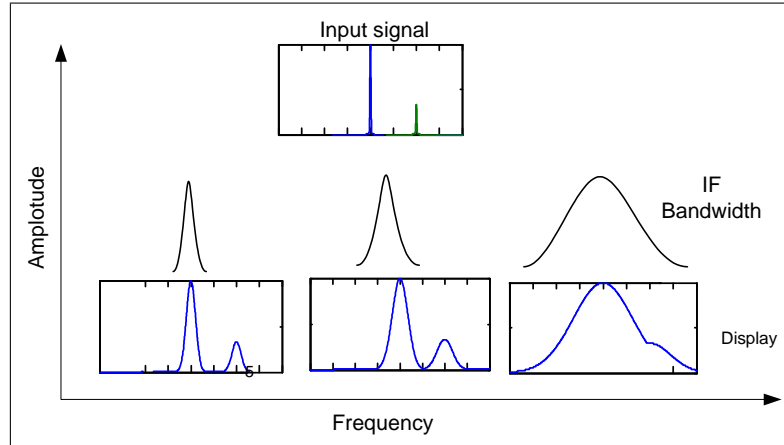
Figure 6 Mixing process, assume down conversion.

The main output of the mixer , consists of the two conversion signals $f\{LO\} + f\{RF\}$ and $f\{LO\} - f\{RF\}$. IF filter select the desired conversion (down conversion in our case), and stopped the other unwanted products. Reference oscillator, which is high quality quartz oscillator, stabilizes the VCO, which is unstable oscillator.

1.9 IF (Intermediate Frequency) Filter and Selectivity

The IF filter is a Band Pass Filter (BPF). IF filter could be implemented as analog or digital filter. This filter is used as the "window" for detecting signals. Its width is

also called a Resolution Bandwidth (RB, RBW) of the analyzer, and can be changed via the front panel of the analyzer. By giving you a broad range of variable resolution bandwidth settings, the instrument can be optimized for the sweep and signal conditions, letting you trade-off frequency selectivity (the ability to resolve signals), signal-to-noise ratio (SNR), and measurement speed.



One thing to note is that a signal cannot be displayed as an infinitely narrow line. It has some width associated with it. This shape is the analyzer's tracing of its own IF filter shape as it tuned. Thus, if we change the filter bandwidth, we change the resolution of the instrument.

1.10 Envelope detector

Spectrum analyzers typically convert the IF signal to video with an envelope detector. In its simplest form, an envelope detector consists of a diode, resistive load and low-pass filter, as shown in Figure 8.

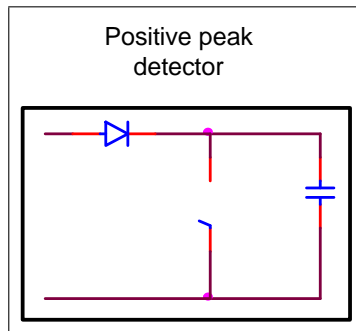


Figure 8 Peak detector, based on diode and RC LPF

1.11 Video Filter

Many modern spectrum analyzers have digital displays, which first digitize the video signal with an analog-to-digital converter (ADC). This allows for several different de-

tector modes that dramatically effect how the signal is displayed. Ordinary spectrum analyzer use peak-detection technic. Video Filter

The video filter is a low-pass filter that is located after the envelope detector and before the ADC. This filter determines the bandwidth of the video amplifier, and is used to average or smooth the trace seen on the screen as shown in figure . The spectrum analyzer displays signal-plus-noise so that the closer a signal is to the noise level, the more the noise makes the signal more difficult to read. By changing the video bandwidth setting, we can decrease the peak-to-peak variations of noise. This type of display smoothing can be used to help find signals that otherwise might be obscured in the noise

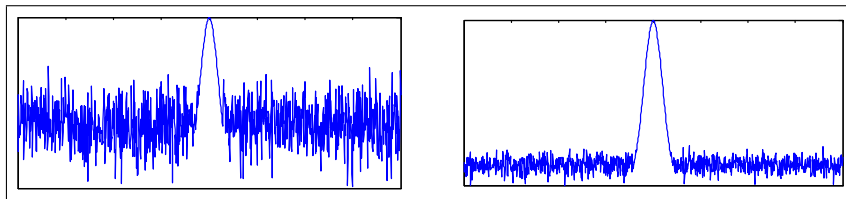


Figure 9 Effect of video filter on displayed noise

The VBW, however, does not effect the frequency resolution of the analyzer (as does the resolution bandwidth filter), and therefore changing the video filter does not improve sensitivity. It does, however, improve discernibly and repeatability of low signal-to-noise ratio measurements.

1.12 Sensitivity

One of the primary uses of a spectrum analyzer is to search out and measure low-level signals. The sensitivity of any receiver is an ability to detects small signals. A perfect receiver would add no additional noise to the natural amount of thermal noise present in all electronic systems, represented by

$$N = kTB$$

where N is the noise power, k is Boltzman's constant, T is a temperature in Kelvin degree, and B is the bandwidth of the system in Hz. In practice, all receivers, including spectrum analyzers, add some amount of internally generated noise.

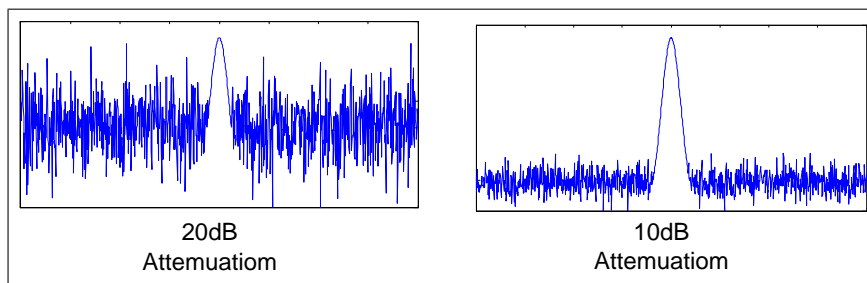


Figure 10 SNR decrease as input attenuation increase.

Spectrum analyzers usually characterize this by specifying the displayed average noise level in dBm, with the smallest RBW setting. An input signal below this noise level cannot be detected. Generally, sensitivity is on the order of -90 dBm to -150 dBm depending on quality of spectrum analyzer. It is important to know the sensitivity capability of your analyzer in order to determine if it will measure your low-level signals. One aspect of the analyzer's internal noise that is often overlooked is its effective level as a function of the RF input attenuator setting (Fig-7). Since the internal noise is generated after the mixer (primarily in the first active IF stage), the RF input attenuator has no effect on the actual noise level. (Refer to the block diagram Fig.-2). However, the RF input attenuator does affect the signal level at the input and therefore decreases the signal-to-noise ratio (SNR) of the analyzer. The best SNR is with the lowest possible RF input attenuation.

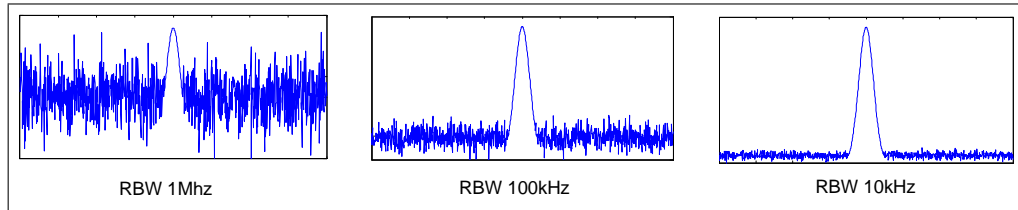


Figure 11 SNR increase as IF Bandwidth decrease

This internally generated noise in a spectrum analyzer is thermal in nature; that is, it is random and has no discrete spectral components. Also, its level is flat over a frequency range that is wide in comparison to the ranges of the RBWs. This means that the total noise reaching the detector (and displayed) is related to the Resolution bandwidth (Fig-8) selected. Since the noise is random, it is added on a power basis, so the relationship between displayed noise level and Resolution bandwidth is a ten log basis. In other words, if the Resolution bandwidth is increased (or decreased) by a factor of ten, times more (or less) noise energy hits the detector and the displayed average noise level increases (or decreases) by 10 dB. Spectrum analyzer noise is specified in a specific Resolution bandwidth. The spectrum analyzer's lowest noise level (thus slowest sweep time) is achieved with its narrowest Resolution bandwidth.

Chapter 2

EXPERIMENT PROCEDURE

2.1 Required Equipment

- Two Arbitrary Waveform Generator Agilent-33220A or equivalent.
 - Spectrum analyzer Agilent N9320
 - Signal generator Agilent N9310.
- LPF -1.9MHz. Mini Circuits BLP-1.9

2.2 Reading Amplitude and Frequency

This part of the experiment, deal with viewing the known sinusoidal signal, calibration signal, frequency 50MHz, amplitude -10dBm. The signal will be presented in frequency domain. begin with the measuring of the CAL OUT signal (calibration sinusoidal signal, frequency 50 MHz amplitude -10dBm).

1. Connect the spectrum analyzer **CAL OUT** BNC connector to **RF IN 50Ω,N** type connector, with an appropriate cable (see Fig-12).

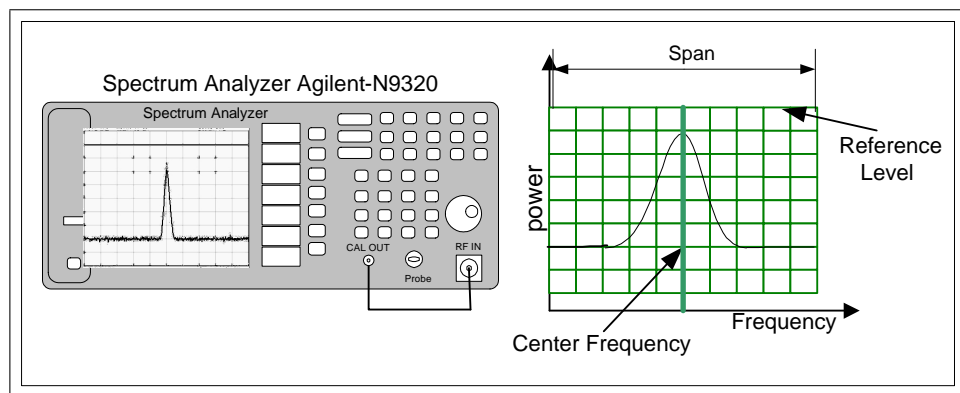


Figure-12 Frequency and amplitude setting

2. Turn on the spectrum analyzer by pressing on **ON** switch, Wait for the power-up process to complete.
3. Activate the calibration signal by pressing on **Preset System** button, **Alignment, Align, CAL OUT on**. The calibration signal will be appeared on the screen.

2.2.1 Setting the Reference Level and Center Frequency.

1. Press **Amplitude, 10 dBm**, what happen to the reference level? Press again **0 dBm**.
2. Press **Frequency, 50 MHz**, what happen to the center frequency?

2.2.2 Setting the Frequency Span.

1. Press **SPAN, 50 MHz**, what is the displayed, start frequency, and stop frequency?

2.2.3 Using Marker to Read Frequency and Amplitude.

1. Press **Peak Search**, to place a marker (labeled-1) on the 50MHz signal peak. Note that the frequency and amplitude of the marker appear both in the active function block, and in the upper- right corner of the screen.

2.3 Resolving Two Signals of Equal Amplitude

In this example you explore the effect of resolution bandwidth filter (RBW), on the resolution of the spectrum analyzer, while measuring two signals of equal amplitude.

2.3.1 Simulation of Resolving Two Signals of Equal Amplitude

1. Simulate two function generators of equal amplitude connected to spectrum analyzer as indicated in Fig 13

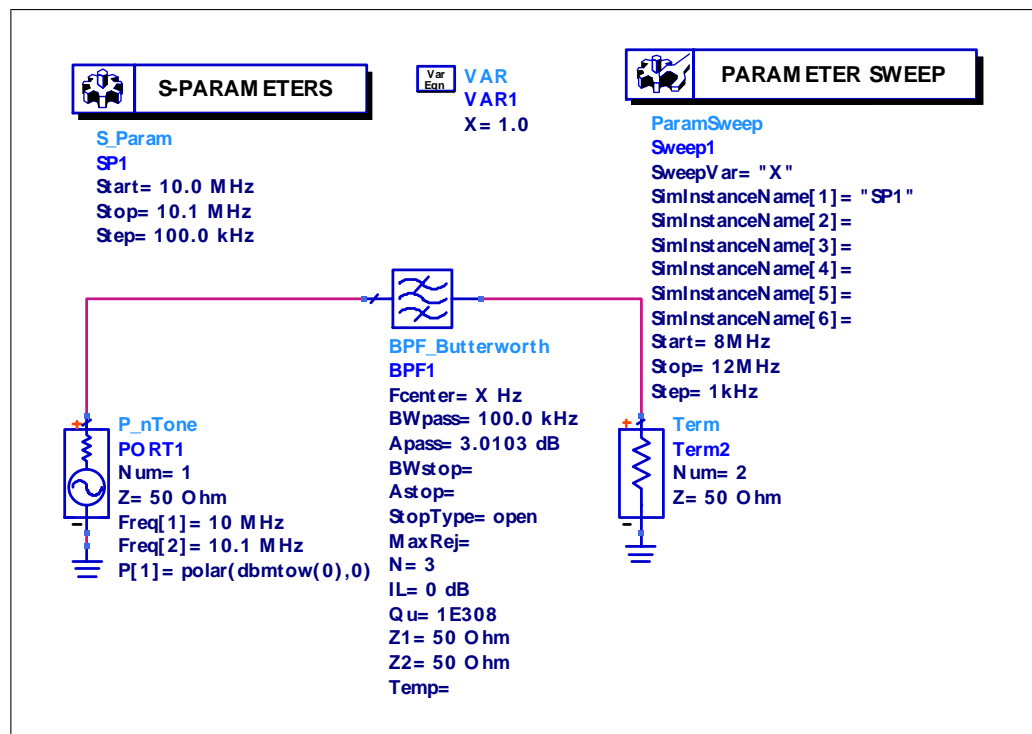


Figure. 13 Resolving two signal of equal amplitude.

2. Draw a graph of spectrum display, S_{21} versus variable X (center frequency), change the Y axis, to plot $_{vs}(dB(\max(S(2,1))), X)$, two signals are now visible.
3. Reduce BWpass of the filter to 10kHz and watch the display.
4. Increase BWpass of the filter to 300kHz and explain why one signals are now visible.
5. Explain if you change the order of the filter, you improve the ability of spectrum analyzer to resolve two signal of equal amplitude, prove your answer by simulation.

2.3.2 Measurement of Resolving Two Signals of Equal Amplitude

1. Connect the system as indicated in Fig 14.

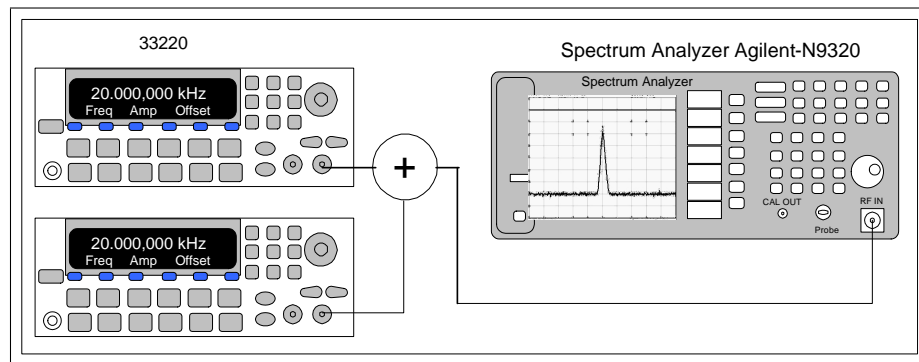


Figure. 14 Setup for resolving two equal amplitude signals

2. Set one function generator to frequency 10 MHz amplitude -20dBm. Set the second function generator to frequency 10.1 MHz amplitude -20dBm.
3. On the spectrum analyzer press **Preset System**. Set the center frequency to 10 MHz, the span to 3 MHz, and the resolution bandwidth to 300 kHz by pressing, **Frequency 10 MHz, SPAN 3 MHz, Then BW Avg to 300 kHz**. A single peak is visible.
4. Since the resolution bandwidth must be less than or equal to the frequency separation of the two signals, a resolution bandwidth of 100 kHz must be used. Change the resolution bandwidth to 100 kHz by pressing **BW/Avg 100 kHz**. Two signals are now visible as indicated Figure 15 **Save the data on magnetic media (CSV format)**. Use the knob or step keys to further reduce the resolution bandwidth and span to better resolve the signals **Save the data on magnetic media**.

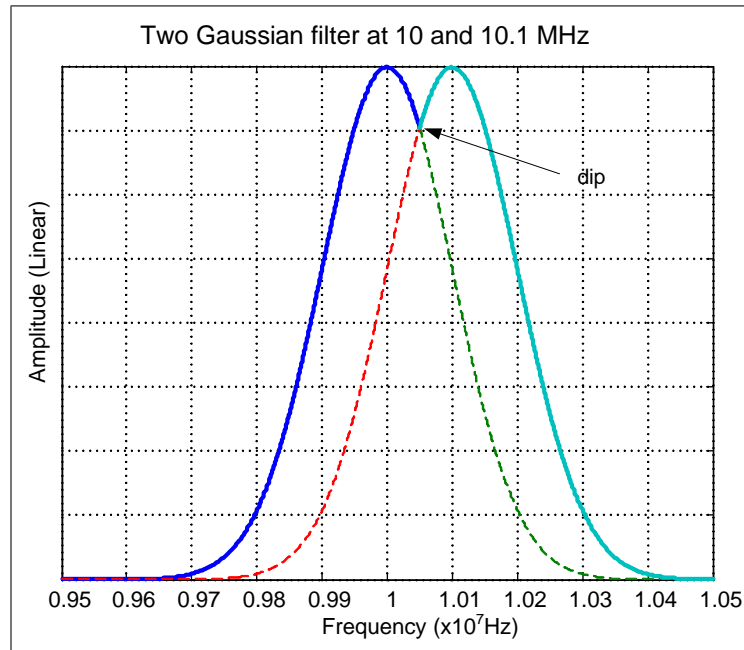


Figure 15 Measuring the depth of the 'dip'

2.3.3 Notice!

As the resolution bandwidth is decreased, resolution of the individual signals is improved and the sweep time is increased.

5. Set the **SPAN 1 MHz** Then **BW/Avg** to **100 kHz**.

6. Change the vertical scale to 3dB/division by pressing **AMPLITUDE, SCALE/DIV 3 dB**, set the trace near the top of the graticule by pressing **AMPLITUDE, Ref Level , -20 dBm**

7. Verify that the two signal have the same amplitude (change amplitude if necessary) Measure the depth of the 'dip' between the two signals, by using **PEAK SEARCH** and **MARKER, Delta On Save the data on magnetic media.**

2.4 Shape Factor

One quantitative way to measure how much the shape of the filter is close to an ideal filter, is the shape factor. Shape factor is defined by the width of the shape at -60dB points divided by the width at -3dB.

2.4.1 Simulation of Shape Factor- Butterworth Band Pass Filter.

1. Simulate Butterworth BPF, center frequency 10MHz, bandwidth100kHz, see Figure-16.

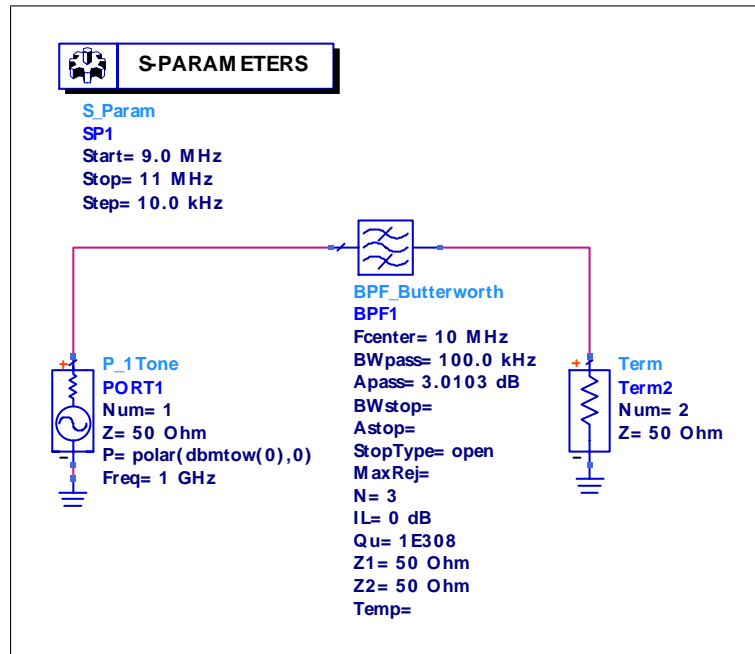


Figure 16 Shape factor of BPF

2. Draw a graph of Butterworth filter shape as displayed by the spectrum analyzer, S_{21} versus frequency, use markers to find the Shape Factor of the filter.

2.4.2 Measurement the Shape Factor of IF BPF

1. Connect the system as indicated in Figure 19.

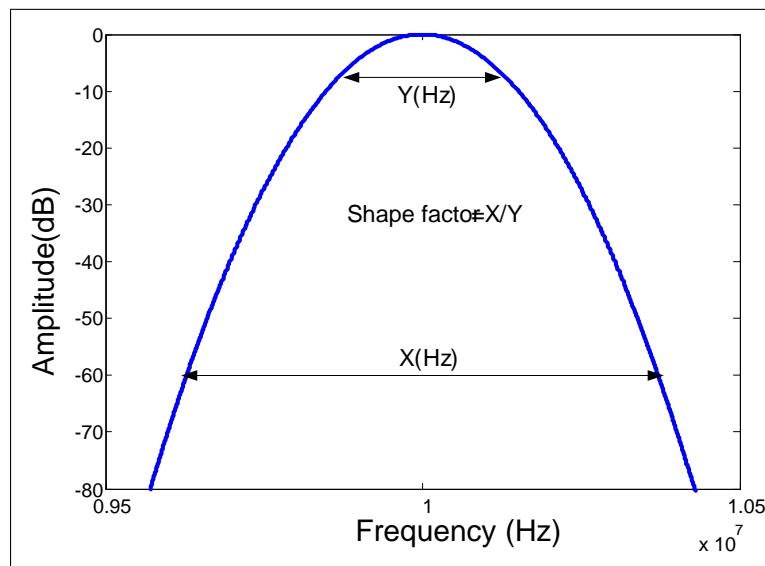


Figure 17 Measuring shape factor of IF filter

2. Set the function generator to **Frequency 10 MHz, Amplitude 0 dBm.**

3. Set the spectrum analyzer **Frequency 10 MHz, Span 3 MHz, BW 100 kHz**, use the **MARKER** or **MARKER Delta** function, to find and record the -3 dB bandwidth of IF filter.
4. Use the **MARKER Delta** function to measure the -60 dB bandwidth of the IF filter, using the data calculate the shape factor (-60dB/-3dB bandwidth) of the 100 kHz BW filter. **Save the data on magnetic media (CSV format).**

2.5 Measuring Signals using Logarithmic and Linear mode, Absolute and Relative Quantities.

In this part of the experiment you measure the amplitude and frequency of the harmonics of 1 MHz Squarewave. The measurement will be in Absolute and Relative mode.

2.5.1 Simulation of a Squarewave in Frequency Domain

1. Simulate a 1MHz squarewave, see Figure 18

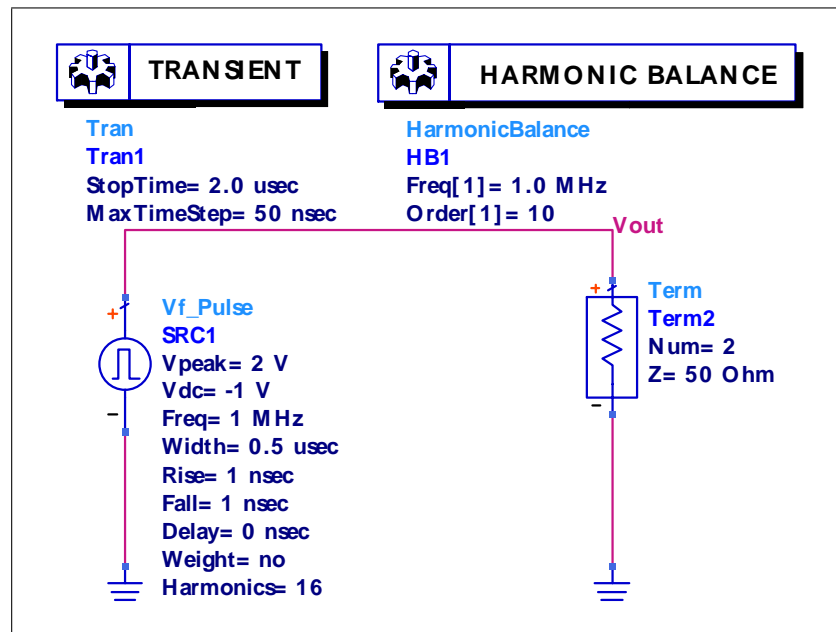


Figure 18 Simulation of squarewave in frequency domain

2. Draw a frequency domain, logarithmic graph of harmonics, a linear graph of harmonics magnitude, a time domain signal using Harmonic Balance simulator, and time domain signal using Transient simulator, and answer the following questions:

(a) Fill Table-1, and explain why the even harmonics disappear in linear mode

Absolute Measurement			
Harmonics	Frequency(MHz)	Amplitude(dBm)	Amplitude(mv)
First			
Second			
Third			

Table -1

(b) Explain why the time domain squarewave graphs of the two simulator are not identical?

2.5.2 Squarerave Measurement

1. Connect the equipment as shown in Fig-19

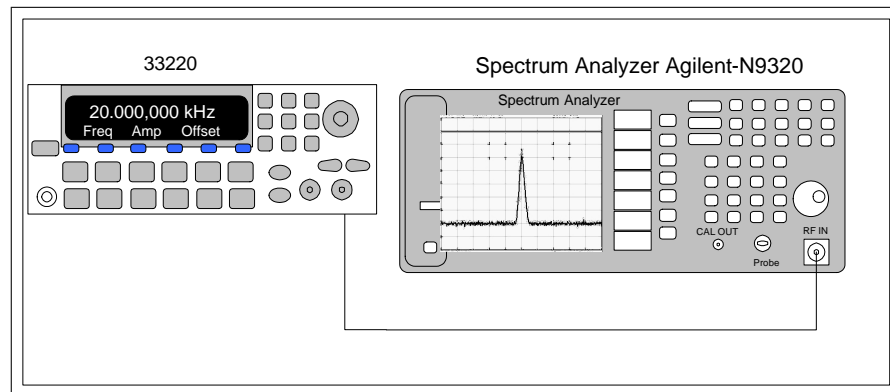


Figure 19 Setup for measuring signals, logarithmic and linear mode, and Minimum and Maximum hold measurement

- Set the Function Generator to **Square wave** Frequency 1 MHz Amp 1 Vpp.
- Set the Spectrum Analyzer to center frequency **1 MHz** and **Span to 10 MHz**. By pressing **FREQUENCY 1 MHz**, then **SPAN 10MHz**.
- Use the Marker function to identify the frequency and amplitude of the first five harmonics, by pressing **.PEAK SEARCH**, Start with first harmonics, +1MHz and fill Table-2.

Absolute Measurement			
Harmonics	Frequency(MHz)	Amplitude(dBm)	Amplitude(mv)
First			
Second			
Third			
Fourth			
Fifth			

Table -2

5. Measure the relative Amplitude and Frequency difference between the odd harmonics, and fill the relevant columns of Table -3. Compare the result to simulation. **Save the data on magnetic media**

Relative Measurement				
Harmonics (No)	Frequency difference (MHz)	Amplitude difference(dB)	Amplitude difference(%)	Matlab Simulation Result
First-Third				
Third-Fifth				

Table -3

2.6 Measuring Frequency Response of LPF

The maximum hold function, can be powerful tool, while measuring frequency response of passive elements, such as LPF.

2.6.1 Simulation of LPF

1. Simulate a Butterworth 1.9MHz LPF see Figure 20.

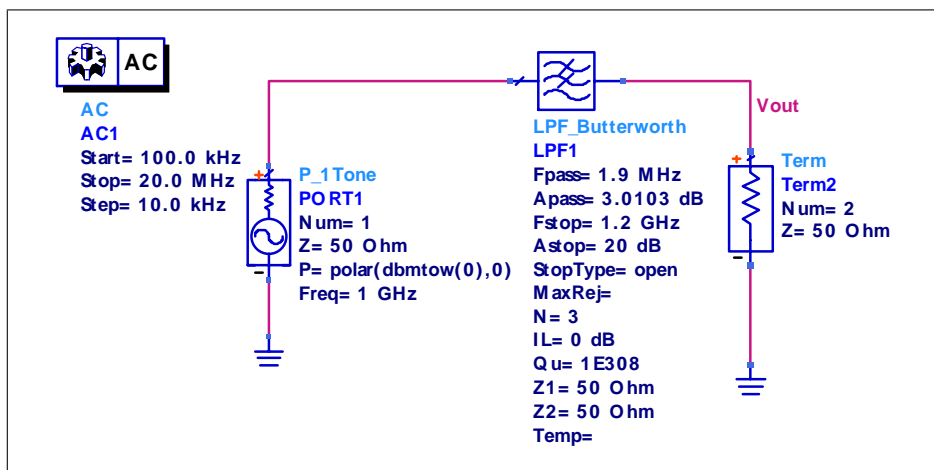


Figure 20 Simulation of LPF response, by Spectrum Analyzer

2. Draw a graph of the filter response, use marker delta function, to find the stopband slope of the filter, dB/octave and dB/decade.
3. Explain if you increase the order of the filter to $N=5$, the stopband slope of the filter, dB/octave, decrease or increase? prove your answer by simulation.

2.6.2 Measurement of LPF

1. Add 1.9MHz Elliptic LPF to the input of the Spectrum Analyzer and connect the equipment as shown in Figure 19.
2. Set the function generator to sweeper by setting, sweep mode, start frequency 100Hz and stop frequency 10MHz. Press **Sweep, Start 100Hz, Stop 10MHZ**.

2.6.3 Setting the spectrum analyzer

In order to measure the frequency response of the LPF, we will use the maximum hold function, while the source is swept, and spectrum analyzer set to maximum hold the trace.

1. Press **Preset, Frequency, Center Freq, 1MHz, Span 10MHz, View/Trace, Max Hold**.
2. Press **VIEW/TRACE** then **MAX HOLD** . now you see the maximum of the measured signal (see Fig.-17).
3. The negative frequency is a false display of the spectrum analyzer(due to the spectrum structure), refer only to the positive frequency.

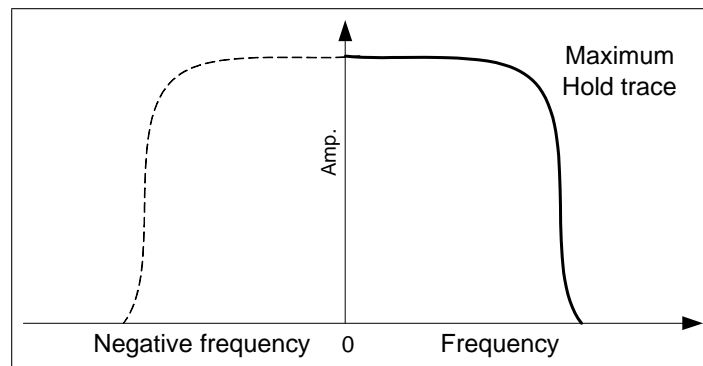


Figure 17 Measuring frequency response of LPF using Maximum hold function

4. Use marker delta function, to measure the stopband slope (dB/octave).

2.7 Measuring Signal To Noise Ratio of Low-Level Signal.

1. Connect the equipment as shown in Fig-16.
2. Set the function Generator to Sinewave, **frequency 10 MHz, Output off.**
3. Set the spectrum analyzer to 10 MHz Span 1 MHz. , by pressing **Frequency, Center Freq, 10 MHz, Span 1 MHz.** Can you explain why you see a signal while the output is off? .
4. Press **BW/Avg** , and **Average On 50**, to activate the trace average. Explain why the noise is changed under average, while the signal remain constant?
5. Measure the level of the signal (dBm), measure the level of the noise , and calculate signal to noise ratio SNR, use marker delta to verify your calculation. **Save the data on magnetic media**
6. Increase the attenuation by 10dB, what happen to the SNR
7. Reduce the attenuation by 10dB, use marker to measure the level of the noise (under average). Decrease the **BW**, by factor 10, from 10kHz to 1 kHz and measure the level of the noise> Calculate the factor of noise level change.

2.8 Measuring a Signal Very Close to the Noise Floor

Spectrum analyzer sensitivity is the ability to measure low-level signals. It is limited by the noise generated inside the spectrum analyzer. The spectrum analyzer input attenuator, and bandwidth settings affect the sensitivity, by changing the signal-to-noise ratio. The attenuator affects the level of a signal passing through the instrument, whereas the bandwidth affects the level of internal noise without affecting the signal. If, after adjusting the attenuation and resolution bandwidth, a signal is still near the noise, visibility can be improved by using the video-bandwidth and video-averaging functions.

1. Connect the equipment as shown in Fig-18.

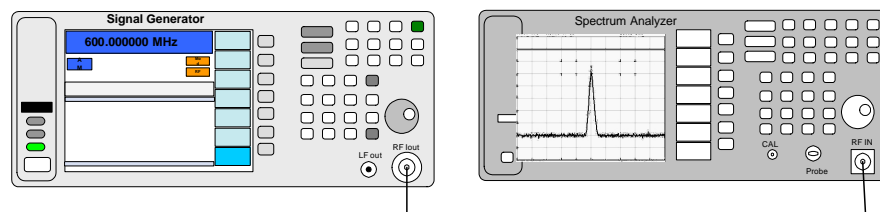


Figure 18 Setup for low level signal measurement

2. Set the Signal Generator to frequency 100 MHz, amplitude -100dBm.
3. Try to achieve maximum signal to noise ratio, place a marker on the low-level signal. and try to obtain maximum SNR. measure the level of the noise and **Save the data on magnetic media.**

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1. Using the data of the "Resolving signals of equal amplitude" draw a graph of the two signals, and find the depth of the 'dip' between the two signals, compare it to your measurement.
2. Draw a graph of the 1 MHz IF filter, use the record data of the filter, find the Shape factor of the IF filter. compare the calculated and measured Shape factor.
3. Using the Measurement result of "Measuring Signal Very Close to the Noise Floor", paragraph find the noise figure of the spectrum analyzer

$$\text{Noise Floor(dBm)} = kTB \text{ (dBm)} + NF \text{ (dB)}$$