Spectrum Analysis and the Frequency Domain

Note: This lab manual has been created by modifying the original application note developed by Keysight (http://literature.cdn.keysight.com/litweb/pdf/5991-4703EN.pdf)

Introduction

Signals can be represented in either the time or frequency domain. Mathematically, the two representations are connected by either Fourier or Laplace transforms. Signals can be measured in the laboratory in either domain, but using different instruments. While the oscilloscope is the most common instrument for time domain measurements, the spectrum analyzer is the most common instrument for frequency domain measurements. Spectrum analyzers allow the frequency domain representation of a signal to be directly viewed, and network analyzers provide direct measurement of the transfer function in the frequency domain. In this laboratory, the spectrum analyzer will be introduced and its basic operation, functions, and measurements will be developed.

A quick overview of spectrum analysis

There are two fundamentally different ways to obtain the frequency domain representation of a signal. The first method is computational in which the signal is first acquired in the time domain and this time domain signal is then transformed into its corresponding frequency domain representation by means of a Fast-Fourier Transform or FFT algorithm. The second method is to directly measure the output amplitude as the signal is fed through a fairly narrow band pass filter which is swept across the frequency span of interest.

Oscilloscopes do not have the frequency capability to perform frequency domain signal analysis in the RF and microwave ranges. For this, traditionally, a swept frequency analyzer or swept filter analyzer (SFA) is used. A narrow band pass filter is swept across the frequency range of interest and the output from that filter is used to directly measure the frequency spectrum of the input signal. Although the center frequency of the filter may be quite high, the speed of the frequency sweep is much slower, and this allows the output from the swept filter to be sampled, digitized, stored, and displayed.

While it is possible to create exceptionally sharp band pass filters for signal analysis, it is extremely difficult to sweep them across a range of frequencies without significantly changing their band pass characteristics. A more practical approach is using an oscillator. It turns out that constructing an oscillator whose output frequency can be swept linearly over a range of frequencies is quite practical. A voltage-controlled oscillator or VCO is a sine wave oscillator whose frequency can be tuned by an applied DC voltage. Driving the VCO from a ramp or sweep generator produces an output which starts at one frequency, increases linearly with time up to another end point frequency, and then repeats. The combination of a VCO and a sweep generator is usually known as a sweeper for short. Sweeping an oscillator turns out to be significantly easier than sweeping a filter.

So how does that help solve the problem of spectrum analysis at RF frequencies? An important principle, expressible as a law of trigonometry, details the result of multiplying two sinusoids:

$$\cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}\cos((\omega_1 - \omega_2)t) + \frac{1}{2}\cos((\omega_1 + \omega_2)t)$$

The multiplication of two sinusoids of different frequencies ω_1 and ω_2 will produce an output which contains the difference and the sum of those frequencies, $\omega_1 - \omega_2$ and $\omega_1 + \omega_2$. A mixer is a nonlinear electronic device which can produce this desired multiplication of two signals. A mixer combined with a fixed oscillator input, often referred to as the local oscillator (LO) signal, can be used to move an input signal up or down in frequency by an amount equal to the frequency of the LO. Extracting only the sum or difference frequency by means of a filter is known as heterodyning and is a fundamental system concept to many types of radio receivers. Now, if the local oscillator is tuned to function as a swept oscillator, the output from the mixer will be the input signal spectrum moving up and down in frequency by an offset equal to the LO frequency. If a narrow band-pass filter is applied to the output of the mixer, then as the input signal spectrum is moved up and down through the frequency sweep, the band-pass filter will pick out only those components which align to its pass band, performing the same function as if the band-pass filter itself were being swept.

Figure 1 illustrates the essential blocks of an SFA. The conventional names for the signals are: RF, the radio frequency input; IF, the intermediate frequency output from the mixer; f_{IF}, the filtered IF whose strength represents the frequency content of the input signal at this frequency selected by the LO; LO, the local (voltage controlled) oscillator; and SWP, the voltage sweep signal, most commonly a ramp or saw tooth waveform from the sweep generator.

As an example of how this works, suppose that the input signal was a sinusoidal carrier at 2.0 GHz with AM (amplitude) modulation of 100 MHz. This would give the frequency spectrum of the input a main carrier peak at 2.0 GHz with two smaller sidebands at 1.9 GHz and 2.1 GHz as a result of the modulation. The sweep generator produces a ramped voltage which controls the local oscillator and sweeps it over a range of 1.0 GHz to 2.0 GHz. The band-pass filter is a fixed filter centered at 500 MHz with a bandwidth of 10 MHz. When the sweep starts with the LO at 1.0 GHz, the mixer will produce sum and difference frequencies with the RF input. This will shift the 2.0 GHz RF carrier down to 1.0 GHz and also up to 3.0 GHz. The modulation sidebands will track along with the carrier.

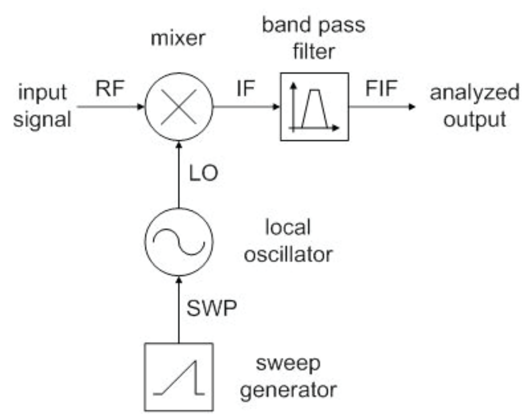

Figure 1

At this point, nothing lines up with the band-pass filter's selected range of 500 MHz so there is no output. At the other extreme, when the local oscillator has swept up to 2.0 GHz, this now shifts the 2.0 GHz RF carrier down to DC and also up to 4.0 GHz. Again, nothing appears at the 500 MHz window of the band-pass filter. However, when the sweep is midway with the local oscillator at 1.5 GHz, the 2.0 GHz RF carrier is shifted down to 500 MHz and up to 3.5 GHz. Now the down shifted RF carrier aligns with the 500 MHz selection of the band-pass filter which will output this IF frequency in proportion to the amplitude of the input RF carrier. This is illustrated in figure 2. When the local oscillator is at 1.4 GHz, the lower modulation sideband of the RF input is aligned with the band-pass filter, producing an output, and similarly, when the local oscillator is at 1.6 GHz, the upper sideband of the RF input is aligned with the band-pass filter, producing another output. Notice that as the local oscillator sweeps up, the band-pass filter in effect scans upward through the input RF signal spectrum.

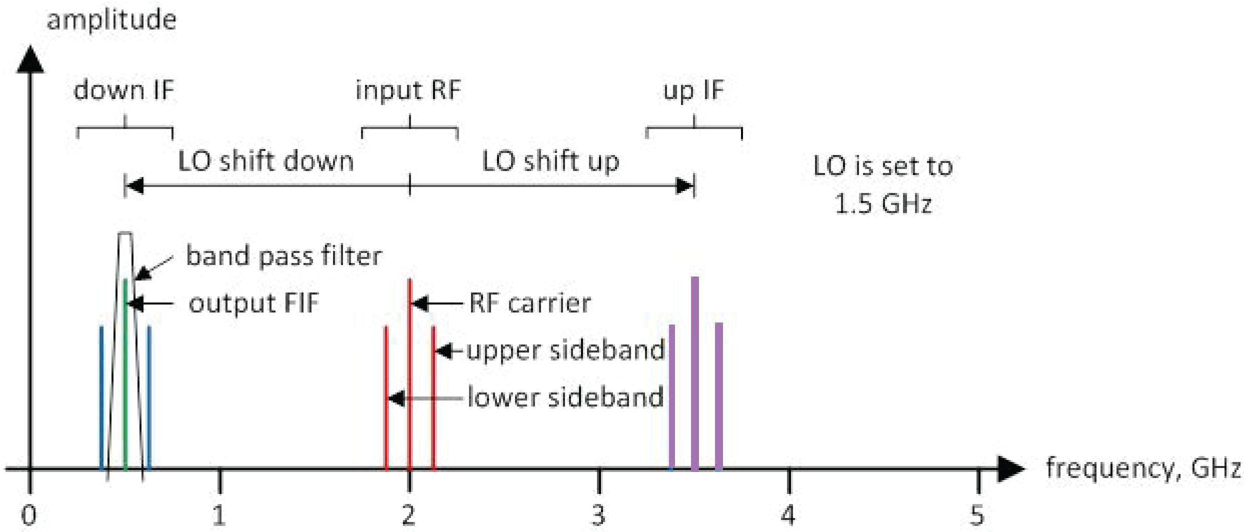

Figure 2

The amplitude of the 500 MHz f_{IF} output must be converted to a lower frequency voltage level. This is accomplished by an envelope (peak) detector, a diode in its simplest form, which is followed by a low-pass filter. Two important concepts for spectrum analyzers are the resolution bandwidth (RBW) and the video bandwidth (VBW). The resolution bandwidth is effectively the frequency width of the IF band-pass filter, and this determines how closely two input signal peaks can be spaced and have the spectrum analyzer resolve the difference between them. The video bandwidth is the bandwidth of the low-pass filter that follows the envelope detector, and this determines how fast the sweep can go for the data acquisition and display to accurately follow it. Both of these will be examined in more detail later on.

First spectrum measurements

The Keysight FieldFox RF analyzer contains a spectrum analyzer (SA) application which implements essentially the RF system described above. In this laboratory the Keysight 33611A 80 MHz arbitrary waveform generator will be used to provide an input signal for the FieldFox to analyze. It can create sine, square, triangle, and pulse wave shapes, with various types of applied modulation.

1. Set up the FieldFox so that it is running off of the AC power supply.
2. Power up the FieldFox, and wait for the CAT application to load and launch.
3. Press the Mode button to bring up the application selection. Press the SA soft key to load and launch the spectrum analyzer application. Note that the spectrum analyzer input needs to go into port 2, and that the spectrum analyzer will start up with the full span sweep of 0 Hz to 4 GHz.
   Note: Before applying any external signal to an analyzer, regardless of the type, the RF power levels must be considered so that the delicate and expensive front-end amplifier of the analyzer does not get destroyed from excessive power dissipation or over-voltage. The FieldFox inputs can handle a maximum of +27 dBm, with a maximum DC offset of 50V. The maximum output from the 33611A signal generator is +24 dBm (10 V_{pp}), with maximum DC offset of 5 V. So, in this case, there is no chance for the signal generator to destroy the FieldFox – all is well. But never simply assume this is the case; always check the power levels before running the risk of damaging an expensive instrument.

4. Configure the 33611A signal generator to output a 50 MHz sine wave at a power level of −20 dBm (about 60 mV peak-to-peak – practice converting between dBm and Volt units).
5. Attach a Type-N to BNC adapter to port 2 of the FieldFox if one is not already present. Then use BNC coaxial cable to connect the output of the signal generator to the input on port 2 of the FieldFox.
6. Press the Freq/Dist button, and use the soft keys to set the spectrum analyzer to sweep from 40 to 120 MHz.
7. Press the BW button, and use the soft keys to manually set the Resolution BandWidth to 20 kHz.
8. The FieldFox should now show a prominent single peak at 50 MHz on its display whose peak shows a power level of −20 dBm. A single sharp peak in the frequency domain should indicate a perfect sine wave in the time domain, but the FieldFox can reveal quite a bit more detailed information about the signal generator.
9. Increase the output power from the signal generator to 0.0 dBm, or 0.63 V peak-to-peak. Observe that the main peak displayed on the FieldFox also increases in amplitude. As the power level is increased, a secondary peak should start to appear to the right of the main peak. The signal generator output can be toggled to verify that this secondary peak is indeed coming from the signal generator. On some signal generators, the power level may have to be increased beyond 0 dBm to see the secondary peak. If the increase in signal generator power results in an "ADC Over Range" message on the FieldFox, increase the RF attenuation on the FieldFox by pressing the Scale/Amptd key and then RF Atten soft key, and setting that to 20 dB.
10. The marker function can be used to get some quantitative numbers for these two peaks. Press the Marker button on the FieldFox to bring up the marker menu and turn on the first marker point. The coordinates of the first marker will appear in green letters in the upper right of the display, and the display will also show a solid green diamond at the current marker position. The easiest way to move the marker to the main peak is to simply press the soft key labeled Peak. The marker will jump to the largest peak in the display, and in this case it should have coordinates close to 50 MHz and 0 dBm. Record the specific values of this main peak.
11. Use the dial on the FieldFox to move the marker to the top of the secondary peak. The coordinates for this should be around 100.000 MHz and −45 dBm. Similarly, record the values of this secondary peak. The high frequency accuracy of the spectrum analyzer shows that the frequency of the secondary peak is exactly twice that of the primary peak; hence, this is the second harmonic of the first peak. Instead of creating a perfect sine wave, the signal generator is producing one with just a little bit of second harmonic distortion. As the power level of the signal generator is varied, it should have been observed that the amplitude of the secondary peak tracks that of the first. Rather than giving the secondary peak an absolute power level, it makes more sense to specify its power level relative to the main carrier peak. From the previous measurements, the secondary peak remains at a level of about 45 dB below that of the carrier. The second harmonic peak could then be stated to have an amplitude of −45 dBc, which simply means 45 dB below the carrier. Compute the signal level of the second harmonic from the previously recorded readings, and express this in dBc. 45 dB is a factor of 31,600 in power, or 177 in voltage, so the second harmonic is actually quite small in comparison to the carrier. The figure of −45 dBc second harmonic distortion is actually pretty good for a signal generator. The wide dynamic range of the FieldFox spectrum analyzer is what allows this measurement to be made. This same measurement would be nearly impossible to make in the time domain using an oscilloscope. Notice that the output of the signal generator needed to be increased to 0.00 dBm in order to get the second harmonic peak to emerge from the noise level.
12. <u>Perform measurements with the FieldFox that monitor the signal strength of the 50 MHz peak, and the amount of second harmonic distortion you measure, in dBc units, as function of signal</u>

<u>generator output. Is the increase in second harmonic signal linear with the 50 MHz signal strength?</u>

13. Next the effects of frequency span and resolution bandwidth on the displayed noise level will be examined. Adjust the FieldFox frequency sweep to a center frequency of 50 MHz with a frequency span of 50 MHz. At the bottom of the FieldFox display it should indicate a resolution bandwidth (Res BW or RBW) of 20 kHz and video bandwidth (VBW) of also 20 kHz. The sweep time should show about 55 ms for the 401 display points, indicating about a 18 Hz refresh rate on the spectrum analyzer display. Recall that the resolution bandwidth is set by the IF band-pass filter and the video bandwidth is set by the low-pass filter that follows the envelope detector. When the frequency span of the FieldFox is changed, the control software (known as firmware) automatically determines the best RBW and VBW filter cut offs to use, unless these values are changed manually. At the current span of 50 MHz, the displayed average noise level (DANL) should be seen to be around −85 dBm. At the full frequency span of 30 kHz – 4 GHz, roughly a factor of 100 wider, the DANL was around −65 dBm.
14. Change the BW setting back to automatic (300 kHz).
15. Change the span of the spectrum analyzer sweep to 500 kHz. The carrier peak should look about the same, but the DANL should have fallen to about −90 dBm. The RBW and VBW should also have been reduced to 3.0 kHz. At this span of 500 kHz, the 401 points in the display gives 1.25 kHz between points. Comparing that to the 3 kHz RBW means that the display is almost three times oversampled. Generally speaking, reducing the RBW reduces the amount of noise that can contribute to the amplitude displayed at each frequency, so the DANL is decreased.
16. Amplitude modulation (AM). Return the FieldFox to a center frequency of 50 MHz and a span of 50 MHz.
17. Return the 33611A signal generator to a carrier of 50 MHz with an amplitude of −20 dBm. Set the signal generator to to AM modulation, with a modulation rate to 20 kHz, and set the modulation depth to a value of 10%.
18. One may have been expecting to see some change in the FieldFox display when the modulation was turned on; however, the display remains unchanged. The reason is that the AM modulation of 20 kHz would only introduce sidebands of 20 kHz away from the carrier, and the current span setting of 50 MHz produces a resolution bandwidth of 300 kHz – too wide to pick up these AM sidebands. Thus, this particular span and sweep setting cannot resolve the AM the carrier peak.
19. Reduce the span further to 100 kHz, and the two AM sidebands should now become quite distinct, each located exactly two divisions to either side of the carrier peak. Notice that the AM sideband peaks are also rather small in amplitude in comparison to the carrier.
20. <u>Capture the screen of the FieldFox and be prepared to answer questions about the peaks you observe.</u>
21. Frequency modulation (FM). Turn the AM modulation off and set FM mode, with an FM deviation to 10 kHz, and FM frequency to 5 kHz.
22. On the FieldFox, set the center frequency to 50 MHz and the span to 50 kHz. There should now appear many peaks in the display.
23. Use the knob on the signal generator to change the FM modulation frequency from 5 kHz to 10 kHz in 1 kHz increments. Notice that the separation between the adjacent peaks is again equal to this modulation rate, just as in the case of AM.
24. Return the FM modulation frequency back to 5 kHz. Use the knob on the signal generator to change the FM deviation from 1 kHz up to 100 kHz in 1 kHz increments. Change the FieldFox span to 500 kHz in order to observe the full spectrum of the output.
25. <u>Capture the screen of the FieldFox and be prepared to answer questions about the peaks you observe.</u>

Measurement assignment

Because of their wide dynamic range and superb frequency accuracy, spectrum analyzers are the premier instrument for electronic snooping of radio signals and other wireless transmissions. Because of its portability, FieldFox is an exceptionally able instrument for signal snooping.

1) Examine the commercial FM broadcast band of 87.5 MHz – 108.0 MHz. For this, a suitable antenna must be connected to port 2 of the FieldFox. Disconnect the FieldFox from the signal generator. Connect a telescopic whip antenna to the BNC connector and extend the antenna to its full length of about 19 inches. Set up the FieldFox for its spectrum analyzer application and set the frequency sweep to run from 90 MHz to 110 MHz. At this point, several peaks should be visible in the display, typically at power levels of around −70 dBm to −30 dBm. These are the local commercial FM radio stations. Due to the electrical isolation of the lab, you will not likely see these. Instead, take the FieldFox with you around the 3rd floor of the Bergeron Building to find FM stations. To do this, disconnect the power adapter from the FieldFox and mount the shoulder strap. **Ensure the shoulder strap is firmly connected to the FieldFox before taking it off the bench.** Adjust the RBW so that the peaks from the FM stations are displayed to your satisfaction. Capture the screen of the FieldFox and label the peaks you detect with the name of the respective FM stations.

2) From the frequency sweep menu, press Measure. Next, press the Tune & Listen soft key, and then the FM Wide soft key. This turns on the wide deviation FM demodulator and routes the output to the built-in audio subsystem and speaker on the FieldFox. A white vertical marker bar should appear on the display. Press the Tune Freq soft key and use the dial to move the white marker bar on to one of the signal peaks. The FM radio station should be able to be heard through the FieldFox speaker. The default listen time is fairly short at 2.5 seconds, so press the Listen Time soft key and rotate the dial to increase this to a larger value to keep the sound from being segmented. Volume can similarly be controlled using the Volume soft key. What is the minimum power detected from a radio station for an acceptable sound quality? What is the minimum power level you detect from a radio station?

3) Go back to the lab, and use the FieldFox to scan through the entire frequency range available, we are broadcasting a signal for you to detect. Use the FieldFox to isolate the frequency, capture the screen and describe what you have detected. Is the signal modulated? If so, AM or FM? Can you demodulate it and listen to it?

Grading Scheme

This lab is out of 15 marks.

- 5 marks for answering questions from the First Spectrum Measurements section
- 7 marks for performing the Measurement Assignment.
- 3 marks for INDIVIDUALLY answering additional questions about this lab found on eClass.

All questions can also be found on eClass, where you will enter your answers. Note that all group members may have similar answers, EXCEPT for the questions indicated that are to be answered INDIVIDUALLY, where each group member is expected to have their own answer.