APPLICATION NOTE

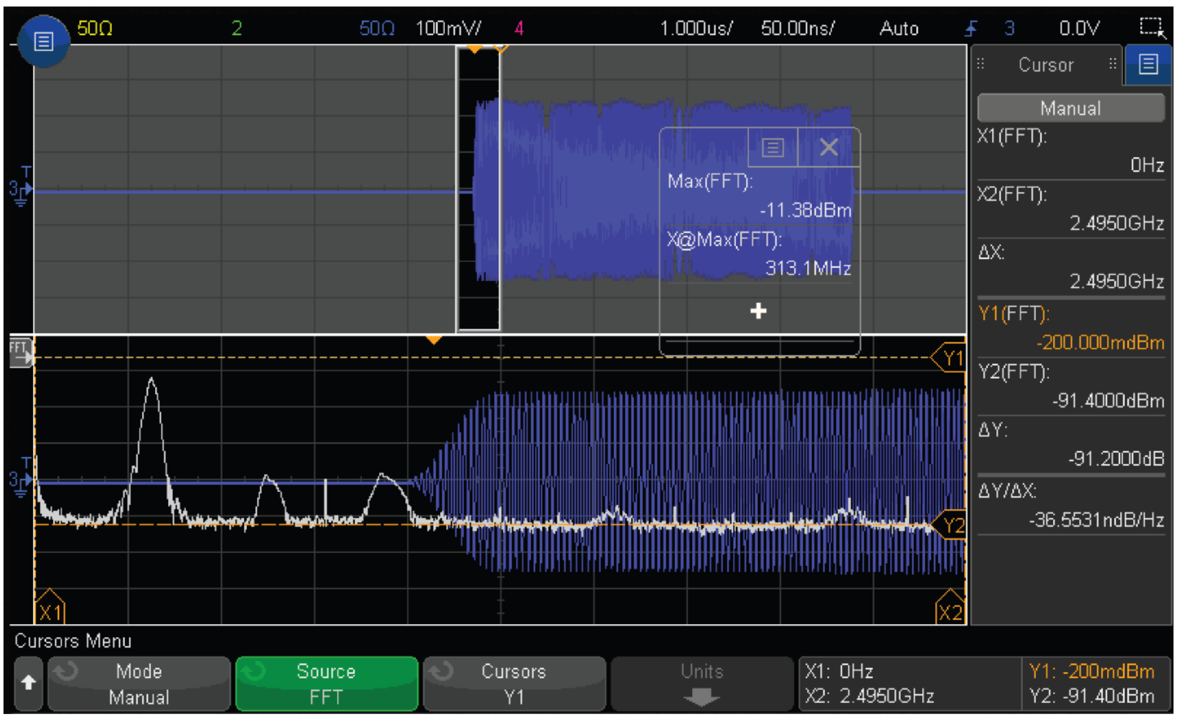
FFT Functions on Keysight 3000T Oscilloscopes

Introduction

The oscilloscope Fast Fourier Transform (FFT) function and other math functions are valuable when working with digital and RF designs. For example, the FFT function in an oscilloscope can quickly highlight the frequency content of signals coupled onto power supply rails. This, in turn, can help pinpoint the source of such noise signals. That's important because such signals can translate into noise in other parts of the design, cutting signal margins, and potentially preventing the design from moving beyond the prototype stage until the problem is fixed.

An FFT spectral view can also be helpful when looking at RF signals to verify if the proper pulse characteristics or modulation is happening. Time-gated FFTs even further evaluate spectral components of a signal, such as what frequency is present at certain points along RF pulses. Math functions such as a "Measurement Trend" on frequency measurements can quickly verify whether a classic modulation scheme is happening properly, like a linear frequency modulation chirp across RF pulses in a pulse train.

This Application Note will explore a number of these examples and look at practical considerations for making FFT measurements and pulsed RF measurements with an oscilloscope.



Simple Example FFT Measurement with an Input Sine Wave

The MSO-X 3104T oscilloscope with 1 GHz analog bandwidth and up to a 5 GSa/s sample rate is used for the various measurements. These are both important specifications that will tie into what kinds of measurement applications are possible. A first example measurement to be considered is the capture of a 600 MHz, 632 mV (p-p), 0 dBm, 1 mW sine wave signal into 50 ohms (orange) and resultant FFT (white) as shown in Figure 1.

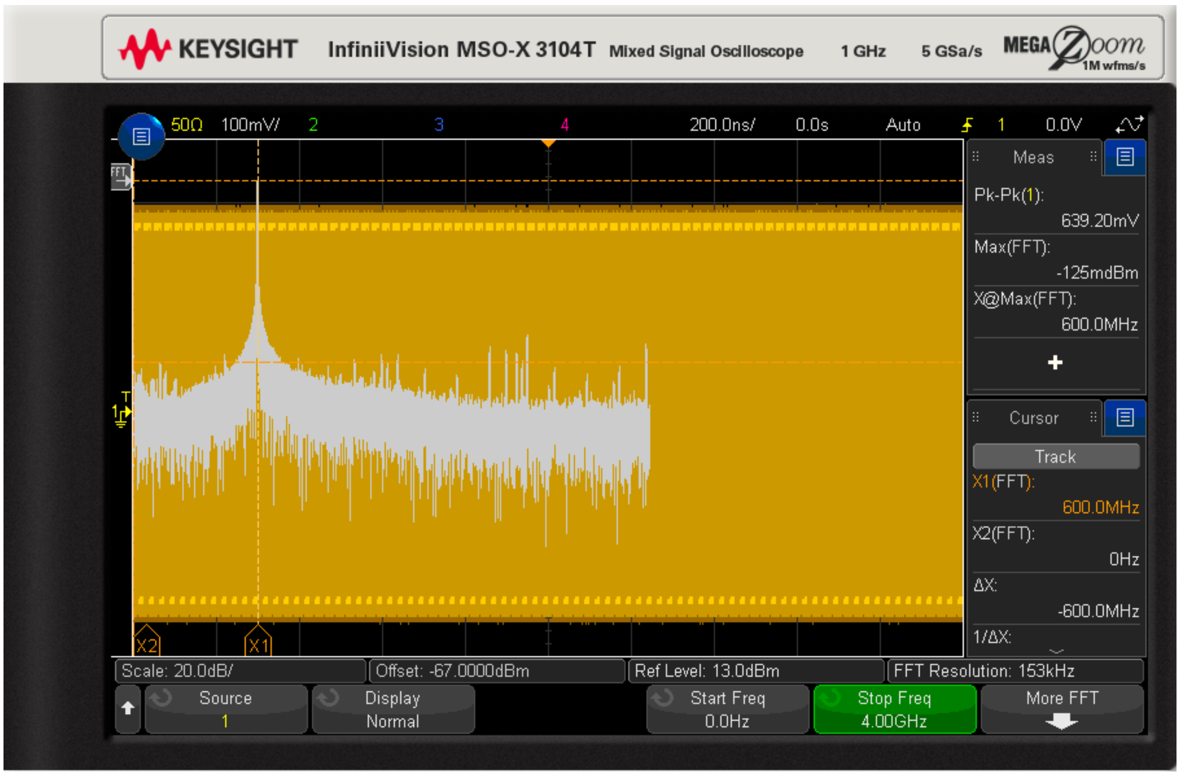


Figure 1. Time domain capture at 200 nsec/div and resultant FFT calculation with a 600 MHz sine wave input

Some Fundamentals about this FFT Spectral Measurement

There are a number of factors that all tie into being able to make such an FFT measurement with the accuracy and precision desired. These factors will now be considered.

It's important to understand how the oscilloscope sampling characteristics play into the quality of this FFT measurement. The oscilloscope analog bandwidth, sample rate, memory depth and related time capture period all can have a profound effect on the measurement result. This effect is heavily influenced by the characteristics of the signal under test, and how those signal characteristics are related to the oscilloscope capture performance.

For example, in this simple illustration of measuring a single tone 600 MHz sine wave signal and wanting to see the basic spectral characteristics of that signal, the oscilloscope has to have enough analog bandwidth to not attenuate the amplitude of the signal. Since this oscilloscope has a maximum 1 GHz analog bandwidth, there is plenty of oscilloscope bandwidth to measure the 600 MHz tone. But it will turn out that the time/div setting is very important in order to maintain this bandwidth in a measurement.

In order to avoid aliasing in the digitizing process of the signal, sampling must occur at a rate at least twice the frequency of any appreciable frequencies present in the signal under test. In this simplest example of a sine wave, a 1.2 GHz sampling rate would be required for this 600 MHz sine wave signal. Clearly, if the scope is sampling at its maximum 5 GSa/s rate, that is more than sufficient. But to have at least a 1.2 GHz sampling rate, the time/div setting on the scope will have to be kept within a certain range.

What kind of quality is there in the FFT measurement made on the 600 MHz sine wave? Referring back to the oscilloscope FFT measurement in Figure 1, notice the main single frequency spike with a related measurement marker showing around a 600 MHz frequency and 0 dBm power. That matches expectations.

The spacing between actual frequency spectrum lines in the FFT driven by FFT data— sometimes referred to as the width of frequency "buckets" because of the signal energy apportioned to each—is called the "resolution bandwidth." The resolution bandwdith is based strictly on the time length of the acquired data and a factor for the FFT windowing type selected. A rectangular window is used here, with a factor of "1," so the resolution bandwidth is simply the inverse of the record time. In this example:

ResBW = 1 / (200 nsec/div x 10 divisions) = 500 kHz

So this FFT could distinguish frequency components in the signal spectrum as close as 500 kHz, but any components closer than 500 kHz apart would merge together and be indistinguishable. The FFT "resolution bandwidth" should not be confused with the "FFT Resolution" number displayed on screen (153 kHz). The latter describes the actual space between FFT points in the FFT data, but it doesn't account for the actual resolution bandwidth achieved given the time span.

How a reduced time on screen degrades the FFT response

To demonstrate the importance of the record time upon FFT results, if the time/div is zoomed to 1 nsec/div, with a new record time of 10 nsec across screen, the resolution bandwidth changes drastically to:

ResBW = 1 / (10 nsec) = 100 MHz

The significant change in the FFT result can be seen in Figure 2, with a much more coarse display of the 600 MHz frequency domain spike. A tradeoff is happening here. Now fewer time samples are being processed, the calculated FFT has fewer spectral lines and worse resolution bandwidth occurs, but the measurement runs much faster.

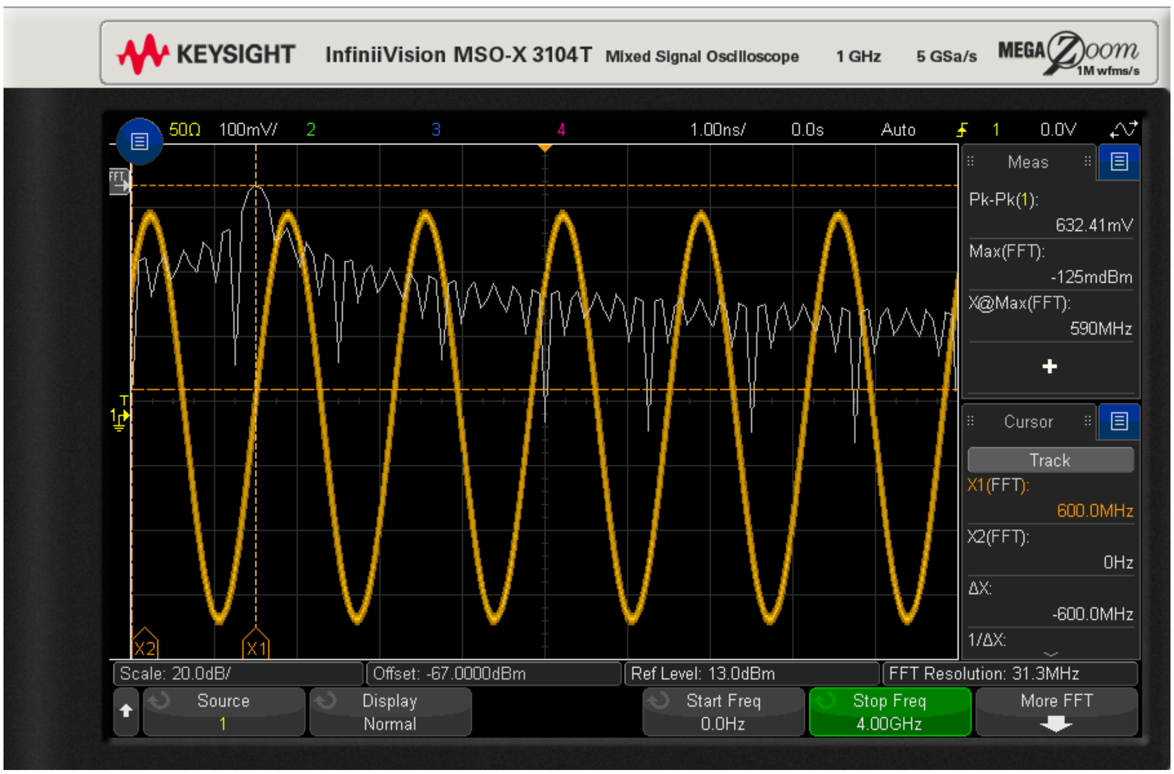


Figure 2. Time domain capture at 1 ns/div and resultant FFT calculation with a 600 MHz sine wave input

Time/Div Considerations

A time/div setting that results in too little time and too few time points being on screen can cause more than just degradation in an FFT measurement (example just shown). It turns out that a time/div setting that place too much time on screen can also be a problem because it can drive a reduced sample rate in order to keep up good throughput.

For example, the time/div setting can be panned up to 200 nsec/div, yielding 2 μsec across screen, and under that condition a 5 Gsa/sec sample rate and 1 GHz analog bandwidth is maintained. But at a 330 nsec/div setting and higher, the sample rate drops, and the oscilloscope bandwidth is reduced, thus affecting the FFT result.

Use of Start Frequency, Stop Frequency, Center Frequency and Span controls

An important capability in the FFT calculation and resultant view is to be able to zoom into an area of interest for analysis. The first example shown had a wide frequency span from 0 Hz to 2.5 GHz, so it was difficult to see any detail around the 600 MHz carrier. Suppose there was suspected noise around the 600 MHz carrier frequency and a desire to inspect that. The FFT controls can set a Center Frequency at 600 MHz and a desired span, such as 100 MHz around the 600 MHz carrier. A Start Frequency of 550 MHz and Stop Frequency of 650 MHz could also have been selected with the same result. Such an FFT measurement, with these parameters, can be seen in Figure 3.

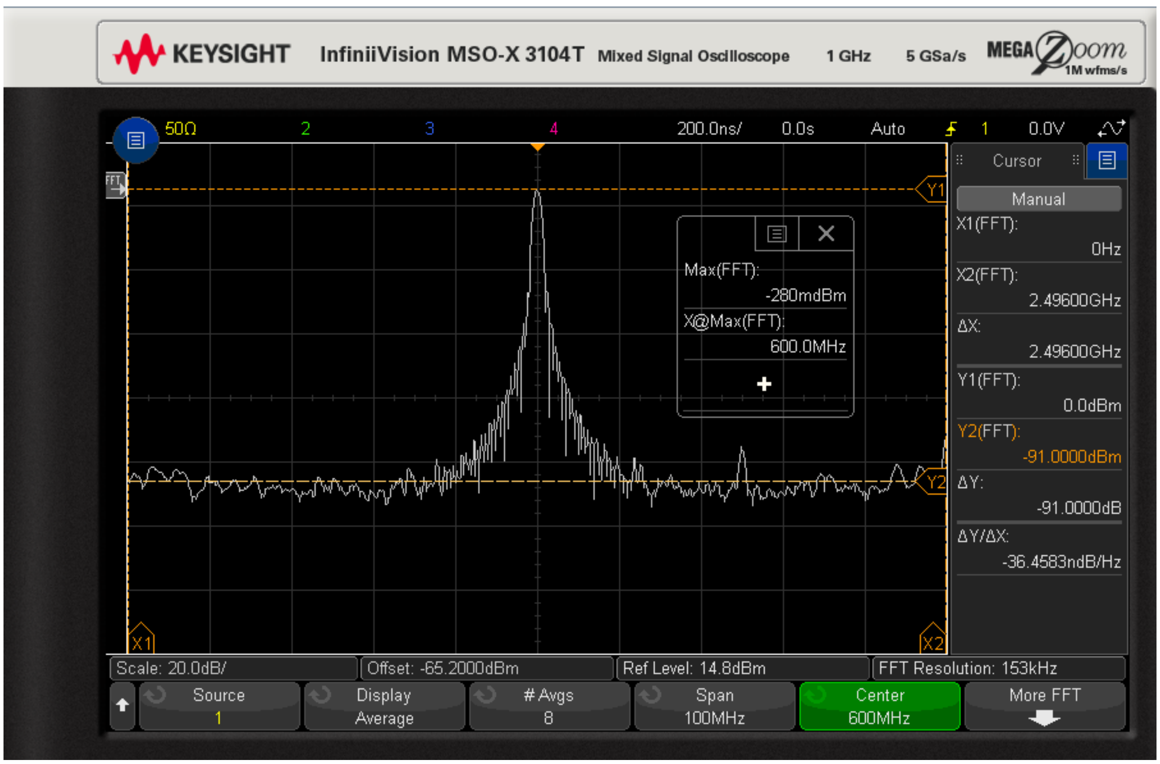


Figure 3. FFT of 600 MHz sine wave input when FFT controls set for a 600 MHz Center Frequency and 100 MHz Span

Wideband FFT Analysis

An increasing number of today's signals have modulation present that can increase the spectral width to hundreds of MHz or even multiple GHz. If spectral widths of signals are beyond around 500 MHz, then spectrum analyzers or vector signal analyzers available today do not have enough analysis bandwidth to make meaningful measurements. In such cases, an oscilloscope or digitizer is required that has enough analysis bandwidth for the application. The carrier frequency of a signal of interest is also important. The carrier frequency of the signal under test plus half the spectral width of that signal must be less than or equal to the oscilloscope bandwidth in order for the oscilloscope to be used on its own for the measurement.

A wideband signal frequency domain measurement will now be considered. The signal under test is a 600 MHz RF pulse train, with 4 µsec wide RF pulses repeating every 20 µsec. There is a 600 MHz-wide, linear frequency modulation of the signal that chirps the carrier frequency from 300 MHz at the start of the RF pulse envelope to 900 MHz at the end of the pulse envelope.

In order to make a basic FFT measurement of the RF pulse, a first step is to get a clean time domain capture of a pulse from the signal on screen. Trigger Holdoff is used to ensure that a trigger doesn't happen mid-pulse, since that would create instability in the captured trace. The Trigger Holdoff is set to something slightly longer than the width of the RF pulse. The RF pulse is 4 µsec wide so a trigger holdoff of 5 µsec works well.

The easiest way to get to the Trigger Holdoff definition is by pressing the "Mode/ Coupling" key in the Trigger section of the front panel, and then selecting a Trigger Holdoff time of 5 µsec.

Next the "FFT" button is pressed to calculate a spectral view of the RF pulse train from the time domain digitized signal on screen. There are FFT controls for Start and Stop Frequency, or Center Frequency and Span. A wide span is first chosen, with a Start Frequency of 0 Hz and a Stop Frequency of 2.5 GHz. A Rectangular Window is chosen for the FFT calculation since the data on screen starts with only noise and ends with noise and the entire RF pulse is within the screen window. FFT averaging, with a count of 8, also helps optimize the measurement result. The FFT response that results is shown in Figure 4.

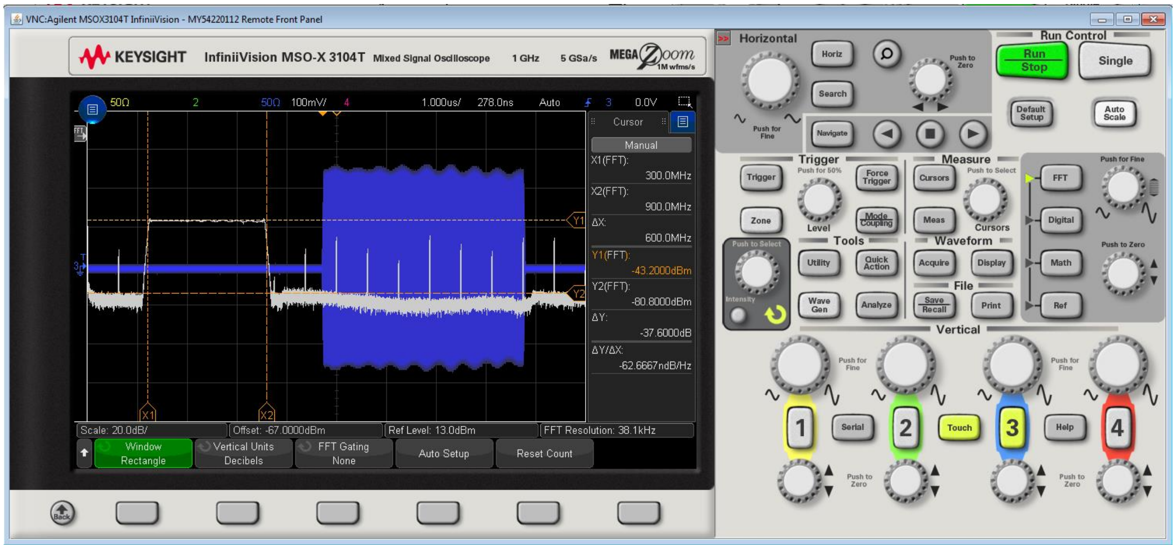


Figure 4. FFT of 4 µsec wide, 20 µsec repeating linear FM chirp

Markers are placed on the FFT response and it can be seen that this RF pulse does have a wide spectral width, from 300 MHz to 900 MHz, or 600 MHz wide. What's not yet proven is that the frequency of the carrier shifts from 300 MHz to 900 MHz, linearly, from the left side of the pulse, across to the right side of the pulse.

The Gated FFT Math Function

One way to quickly see some carrier frequency values across the pulse is to use the gated FFT function. This is achieved by turning on the normal time-domain trace time-gating function. Once turned on, there is a normal trace view at the top half of screen, and then a magnified view at the bottom of the screen. Whatever portion of the waveform present in this window shows up in the lower trace but magnified.

An interesting measurement results from creating a small time-width window function and then moving it to the very beginning of the pulse. The FFT is calculated from the data contained within the gated time window as shown in Figure 5.

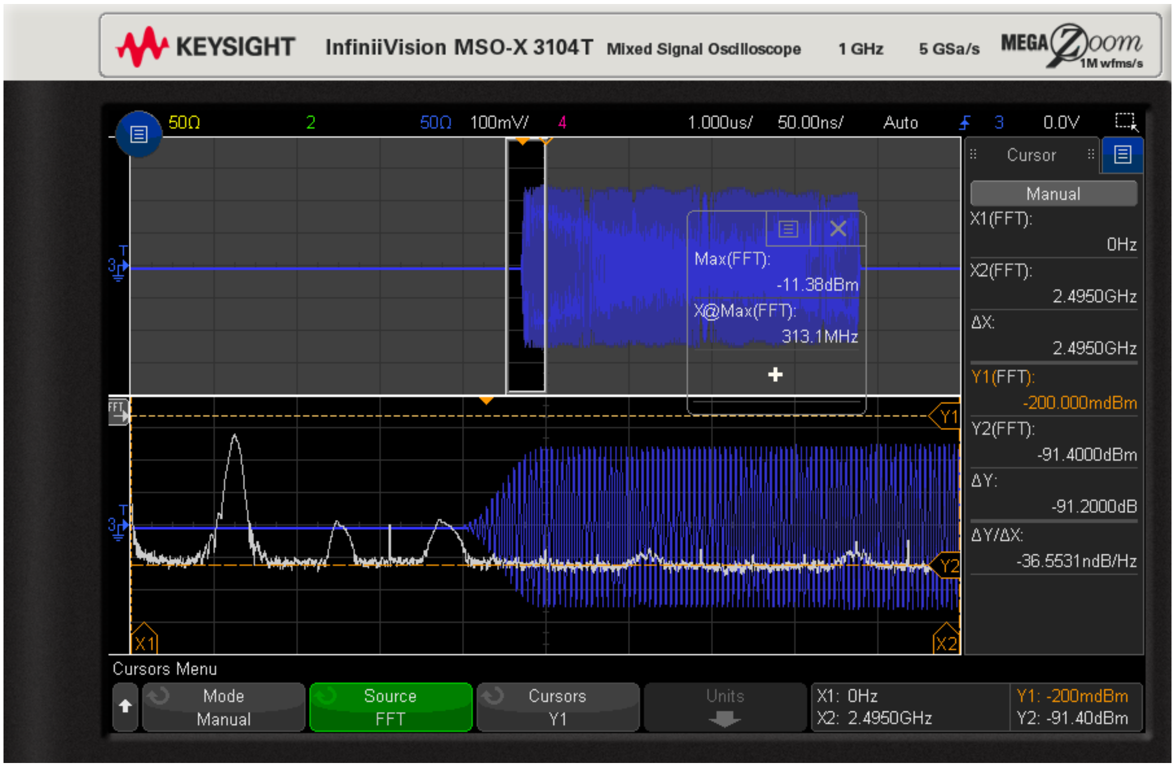


Figure 5. Time gated FFT function observing the carrier at the beginning of the RF pulse

The FFT measurement of the peak value amplitude and frequency of the spike shows that the RF pulse begins with a carrier frequency around 300 MHz. If the time gate window is moved to the center of the RF pulse, the frequency is seen to be around 600 MHz. And it is 900 MHz at the end of the RF pulse. This appears to be a linear frequency-modulated chirp as desired.

Frequency Measurement and "Measurement Trend" Math Function

In some cases a "Measurement Trend" math function can give a helpful view of the frequency chirp profile. In a similar signal example, a pulse train with 700 nsec wide RF pulses, repeating every 20 µsec, needs to be verified as chirping between 300 MHz to 900 MHz in a linear fashion. The FFT function is now turned off, and purely time domain measurements are made.

First, the acquisition mode of the oscilloscope is changed from "Normal" capture to "High Resolution" capture mode. Second, a frequency measurement is selected from the list of possible measurements. A middle threshold for carrier zero crossing detection is set to 30 mV. Then the "Math" key is pressed, and a math function called "Measurement Trend" is chosen. Markers are assigned to have their source be the math function result. An interesting view of frequency measurements taken across the RF pulse can be seen in Figure 6.

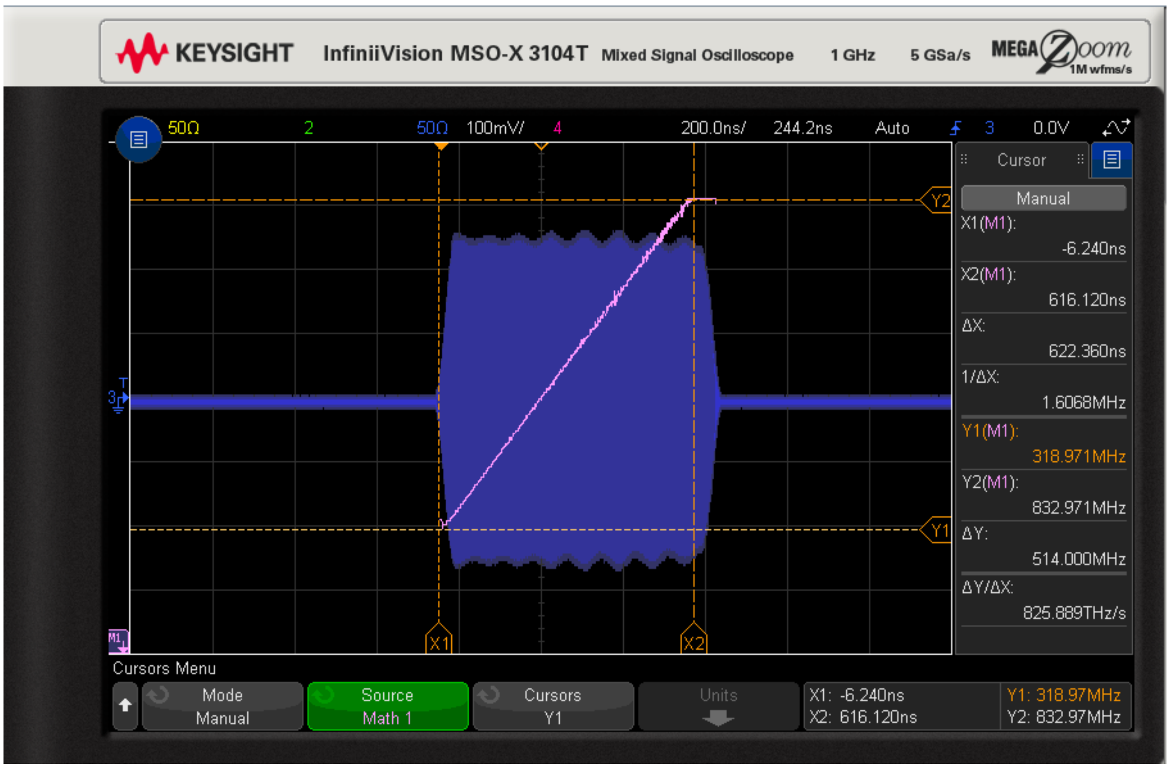


Figure 6. Measurement trend math function on "Frequency" measurements across the pulse

Clearly, the pulse carrier is shifting in a linear fashion across the pulse, from left to right, as designed. The vertical markers show a start frequency of around 320 MHz and a stop frequency of around 830 MHz, and the horizontal markers show this occurring over around a 600 nsec time. That computes to be a 0.85 MHz/nsec chirp rate. The expected chirp rate would have covered 600 MHz over a 700 nsec-wide pulse (including envelope rise and fall time), or 0.86 MHz/nsec. The measured chirp rate matches that of what was expected.

Notice that the linear ramp display is not going across the entire width of the RF pulse but hits a limit in value before the end of the pulse. This is because a 1000 measurement limit in the trend calculation has been reached. What's important is that a portion of the pulse FM function can be seen, and it is linear. For the frequency measurements across the pulse to have enough precision, it was imperative that the "High Resolution" acquisition mode was selected.

To select the "High Resolution" mode, press the "Acquire" key, in the "Waveform" section of the front panel, and then select "High Resolution".

If the carrier had been chirping over a higher range of frequencies across the pulse, for example twice the range (900 MHz to 1.8 GHz), then the linear ramp would have only been seen across half the pulse width. For applications at higher frequency ranges, such as common radar systems, then the Infiniium S-Series, V-Series or Z-Series oscilloscopes could be used instead, where there is not the same 1000 measurement limitation for a measurement trend.

Summary

FFTs in oscilloscopes are a valuable tool to give a frequency domain view of a signal. This can ultimately be done with very wide bandwidth, enabling measurements not possible with a narrower band vector signal analyzer. Example FFT measurements were able to verify that a linear FM chirp signal was shifting the carrier frequency as it should. There was also a place for other math functions, namely the measurement trend function. In this example, such a calculation allowed for a very simple verification of a linear FM chirp, within a certain frequency range.

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