# Digital Oscilloscopes: Powerful Tools for EET Laboratories

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## Introduction

The digital oscilloscope has gained in popularity as the laboratory measurement tool of choice in EET laboratories, and much has been written about integrating its use into existing courses.[1,2] This paper will present some innovative ways to use a digital oscilloscope that have proven to be easily accomplished and highly useful in baccalaureate undergraduate EET courses, from first year through fourth year.

Digital oscilloscopes are increasingly found in academe and in industry because of the many advantages they offer compared with analog oscilloscopes. These advantages include the digital oscilloscope's ability to:

- perform automated measurements of voltage (average, maximum & minimum, RMS, peak to peak), and time (period, frequency, rise time & fall time, duty cycle, pulse width, phase shift & time delay between channels 1 and 2)
- provide a reasonable display for most waveforms using the "autoscale" button
- print and/or store waveforms on disk
- store instrument settings to speed setup time for experiments
- store waveforms for comparison with live waveforms
- perform mathematical operations on channels: add, subtract, multiply, integrate, differentiate, fast Fourier transform (FFT)
- capture transient events and store them for analysis and/or viewing
- reduce noise on waveforms using digital averaging
- perform routine calibrations and diagnostic tests on itself
- turn on "infinite persistence" to store a record of waveform behavior
- show and record displays of very slow phenomena, with up to 50 seconds per horizontal division

Some of these advantages of digital oscilloscopes are less well known, and are not often utilized in undergraduate laboratories; it is these that will be illustrated in this paper. An Agilent 54621A oscilloscope was used for all examples shown; other manufacturers' oscilloscopes have similar features.



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**Infinite Persistence - Diode Volt-Amp Characteristics**

The infinite persistence feature can be used to produce a family of curves (e.g. volt-amp characteristics for a diode, or collector characteristics of a bipolar transistor), thus serving as a curve tracer. The circuit in Figure 1 below shows how to connect a digital oscilloscope to measure I vs. V for a diode.

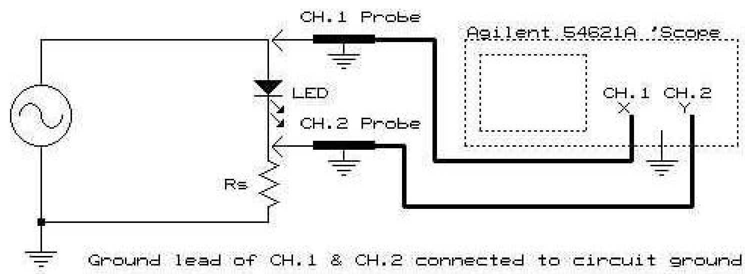



**Figure 1 Circuit to Produce Diode Volt-Amp Characteristics**

Rs is a 1.0 Ω, ½ watt sampling resistor which produces a voltage (in volts) equal to the diode current (in amps). In this way, the oscilloscope y-axis will be the diode current (the voltage across Rs with 5 mV/div = 5 mA/div), while the x-axis will be the voltage across the diode. The function generator should be set to produce a sine wave with a minimum voltage of 0 V, and a maximum voltage enough to turn on the diode being used (about 2.5 V for an LED). If the function generator is creating the sine wave at a very low frequency (perhaps 0.2 Hz) the display will be a dot that moves from lower left corner (the origin: 0 V, 0 mA) across horizontally (until the LED begins to conduct at about 1.8 volts), at which point the current rises steeply. The low frequency allows students to observe both the LED and the display, and notice that the LED begins to emit light when the dot is at or above 1.8 volts.

Turning on the "Infinite Persistence" function creates a continuous graph (as shown below in Figure 2) of the volt-amp characteristics of the LED; this graph can be saved to disk as a graphic image, which can then be inserted into a lab report.

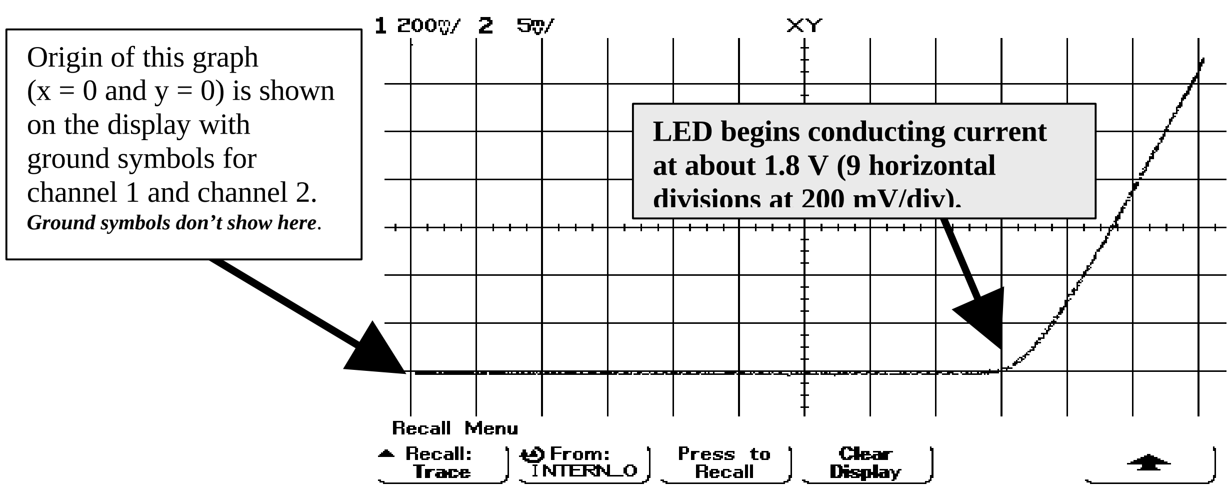



**Figure 2 Graph of I versus V for an LED (Volt-Amp Characteristics)**

**Infinite Persistence - Collector Characteristics of a Bipolar Junction Transistor**

The infinite persistence feature can be used to produce a family of curves, the collector characteristics of a bipolar transistor, thus making the oscilloscope serve as a curve tracer.

Figure 3 below is the circuit to which the digital oscilloscope is connected (Channel 2 = y-axis, Channel 1 = x-axis) to create a graph of emitter current versus collector-emitter voltage ($I_E$ vs. $V_{CE}$) for different values of base current IB. The source voltage, here shown as a 50 Hz. 10 Vpp sinusoid, sweeps the collector-emitter voltage from 0 V to 10 V.

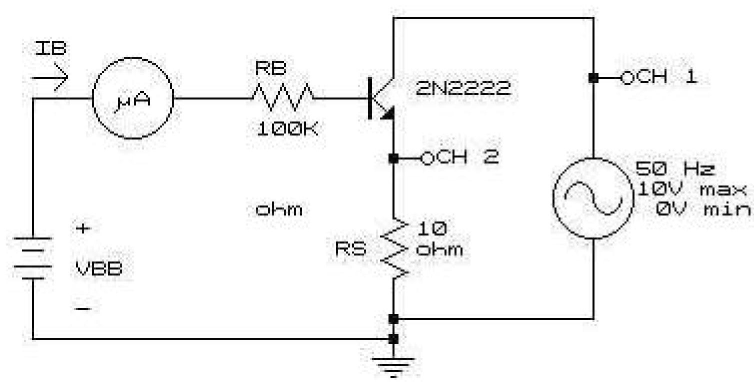


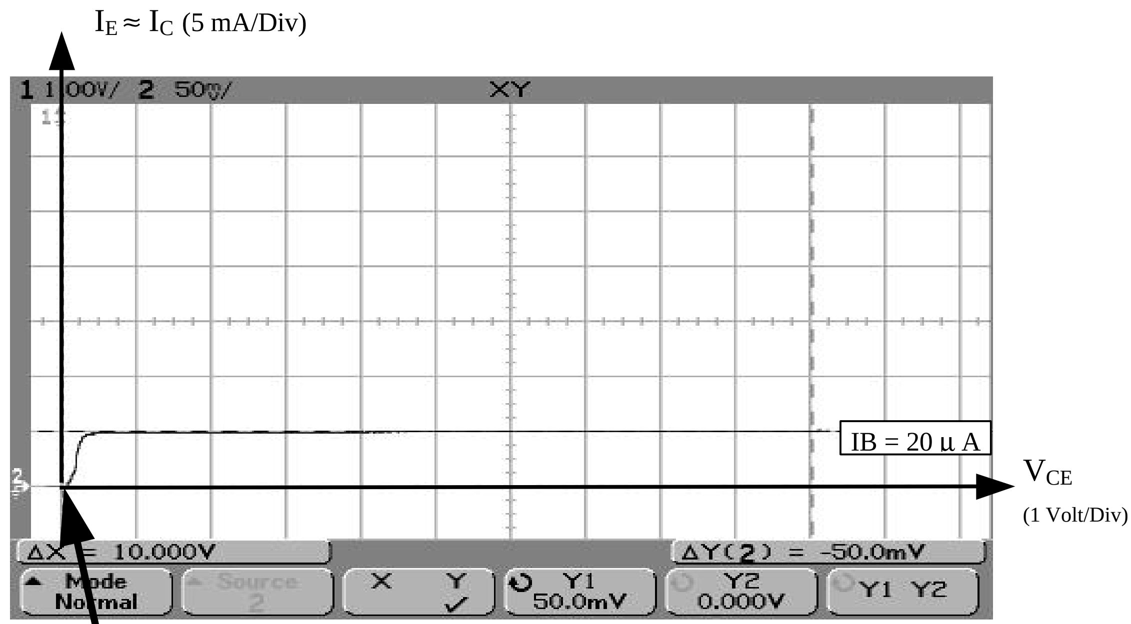

**Figure 3 Circuit to Produce Transistor Collector Characteristics**

RS is a 10 Ω ½-watt sampling resistor which produces a voltage (in volts) proportional to the emitter current (in amps). [50 mV/Div]/[10 Ω] = 5 mA/Div. The oscilloscope y-axis will be emitter current (the voltage across RS), while the x-axis will be the collector-emitter voltage of the transistor. For most transistors used in undergraduate laboratories, the DC current gain is high, so $I_C \approx I_E$. The function generator should be set to produce a sine wave with a minimum voltage of 0 V, and a maximum voltage large enough for the active region of the transistor being tested (about 10 volts for this example). Initially, the voltage source VBB is raised until base current = 20 μA.

Turning on the "Infinite Persistence" function briefly for a base current of 20 μA "freezes" a single horizontal curve (as shown below in Figure 4) of emitter current versus collector-emitter voltage. Then "Infinite Persistence" is turned off.

Base current IB is then increased from 20 μA to 40 μA (which creates a new curve of emitter current versus collector-emitter voltage), and the "Infinite Persistence" function briefly turned on (and then off). This will result in two curves of emitter current versus collector-emitter voltage.

This process is repeated for increasingly higher values of base current, up to 120 μA, until a complete family of collector characteristics is obtained. These curves can be seen in Figure 5 below.




Origin of this graph (x = 0 and y = 0) is shown on the display; the ground symbols for channel 1 and channel 2 show where the origin is.

The X-axis, $V_{CE}$, is 1volt per division.
The Y-axis, IE, says 50 mV/division. But, since the Y-axis input is the voltage across the 10 Ω resistor between the emitter and ground, 50 mV/10Ω = 5 mA/division. And IC ≈ IE.

**Figure 4 $I_E$ vs. $V_{CE}$ for IB = 20 µA**

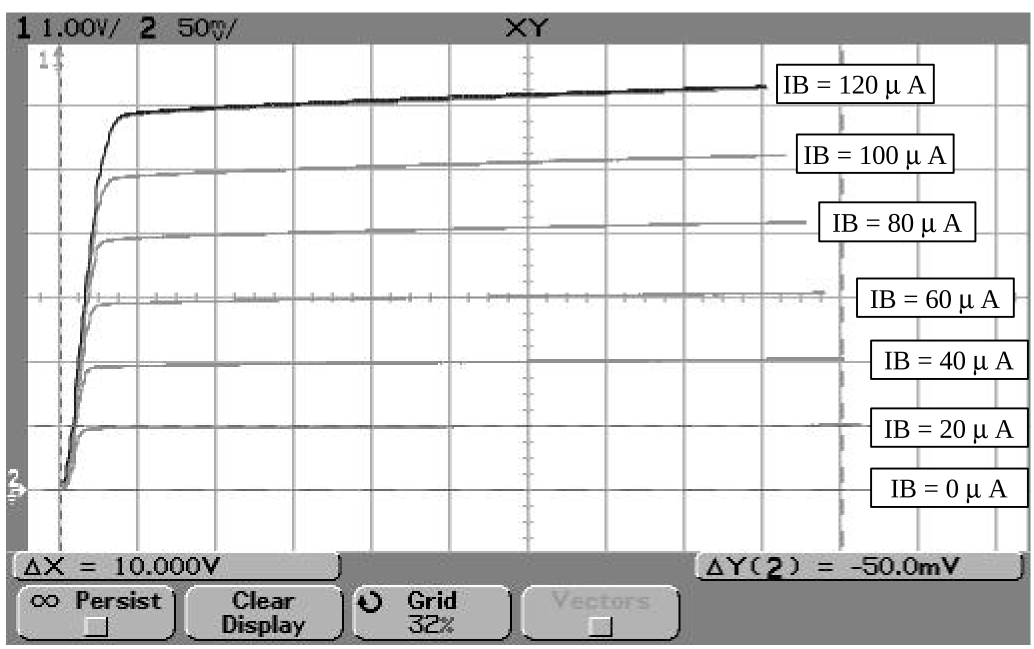



**Figure 5 Family of $I_E$ vs. $V_{CE}$ Curves for IB = 20, 40, 60, 80, 100 & 120 µA**

## Waveform Math: Multiplication of Channel 1 and Channel 2

Analog oscilloscopes can add or subtract waveforms, allowing differential measurements to be made. The digital oscilloscope allows us to multiply two waveforms as well. If one of those waveforms is voltage, and the other is current (i.e., a voltage proportional to current), then their product is the instantaneous power. This is a wonderful way to show students that reactive devices actually absorb power from a circuit in one half cycle of a sine wave, and then return that power during the other half of the sine wave. The circuit below (Figure 6) can be used to can be used to produce the current, voltage and power waveforms for a capacitor. The same circuit will work for a resistor and inductor as the device under test (D.U.T.), instead of the capacitor. Note that the resistance of the sampling resistor, Rs, should be much smaller than the impedance of the D.U.T.

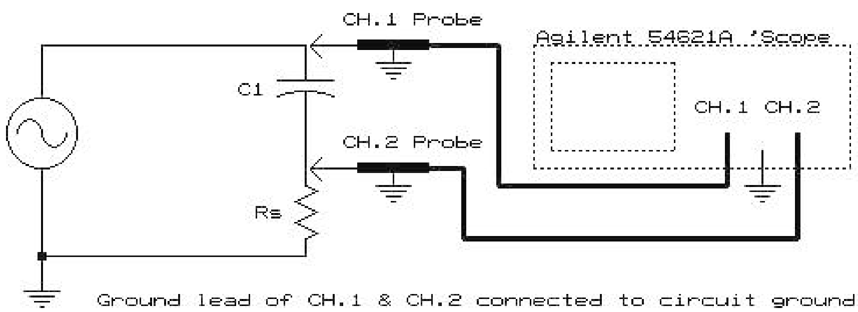



**Figure 6 Test Circuit for Displaying Voltage, Current and Power for a Capacitor**

Notice in the oscilloscope display below, Figure 7, that the waveform of capacitor current (Channel 2) leads the capacitor voltage waveform (Channel 1) by 90°. This display shows current and voltage, but does not show the instantaneous power.

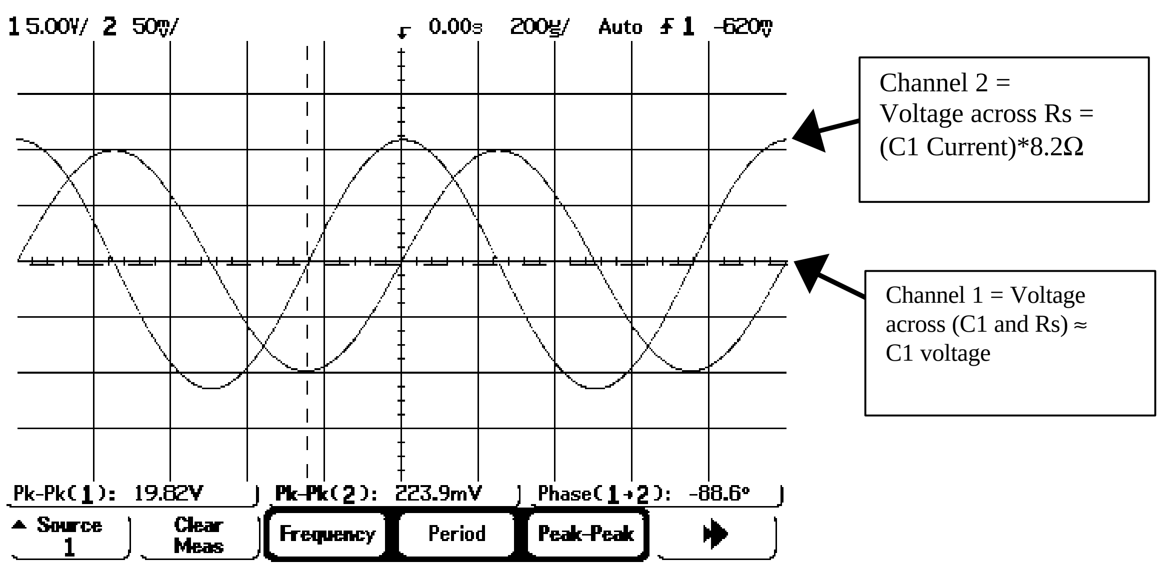
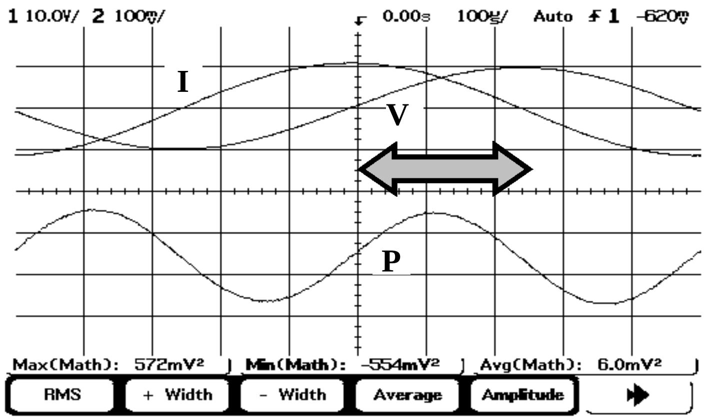


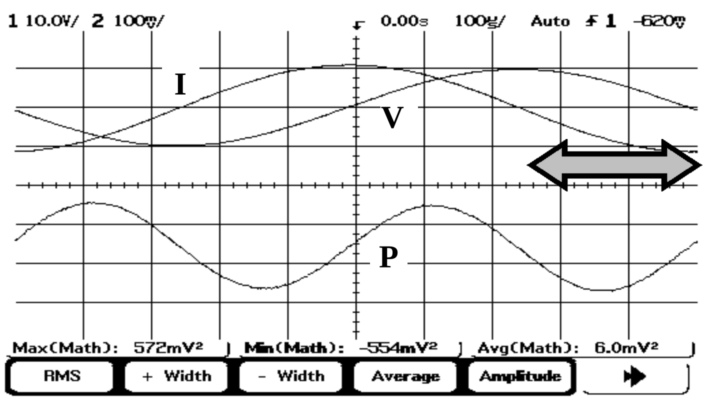

**Figure 7 Voltage and Current for a Capacitor**

In Figure 8, below, the "Math" function has been used to add the product of Channel 1 and Channel 2, producing a third display: the instantaneous power of the capacitor.  It is interesting to students to see that power delivered to the capacitor is both positive and negative over a full cycle, with an average value close to zero [6.0mV$^2$ from " Avg(Math): 6.0mV$^2$ "], and that the frequency of the power is twice that of the voltage or current.




During the time shown by the arrow (250 µs, or 1/4 of the period of the 1 kHz sine wave), the **voltage is positive**, the **current is positive**, and the power delivered to the capacitor (V*I) is also **positive**.

The sine generator is supplying power **to** the capacitor, which stores the energy in its electric field.



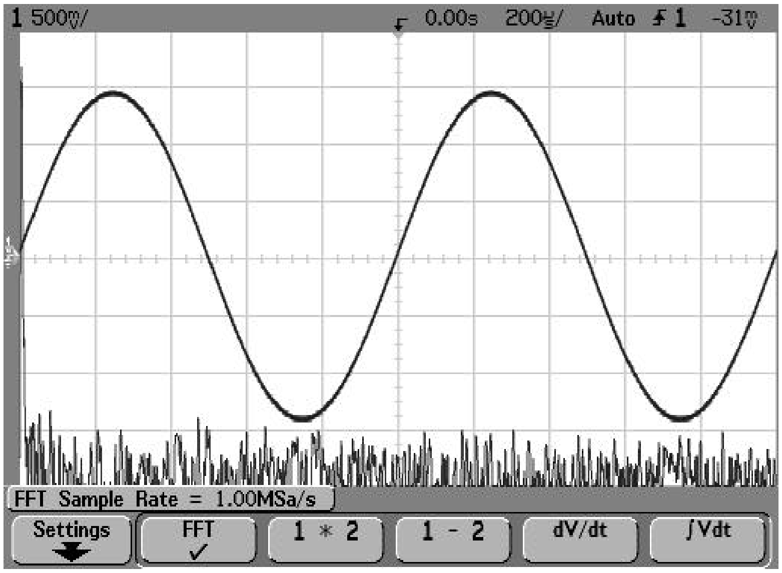

During the time shown by the arrow (250 µs, or 1/4 of the period of the 1 kHz sine wave), the **voltage is positive**, the **current is negative**, and the power delivered to the capacitor (V*I) is also **negative**.

The sine generator is receiving power **from** the capacitor, which gets the energy from its electric field.

**Figure 8  Voltage, Current and Instantaneous Power for a Capacitor**

## Waveform Math: Fast Fourier Transform (FFT)

Another powerful "Math" function of the digital oscilloscope is "FFT", Fast Fourier Transform. When applied to a time-domain signal the FFT display can show the frequencies present in many waveforms.  Perhaps the simplest case is to look at a sinusoid in both the time domain and the frequency domain.  Figure 9 below shows a 1 kHz sinusoid in the time domain (top graph); in the frequency domain (bottom graph) it's very hard to see the 1 kHz signal due to the large frequency span (500 kHz)  Each horizontal division is 50 kHz, and the 1 kHz frequency component is at the extreme left edge of the graticule, all but indistinguishable from the graticule itself.

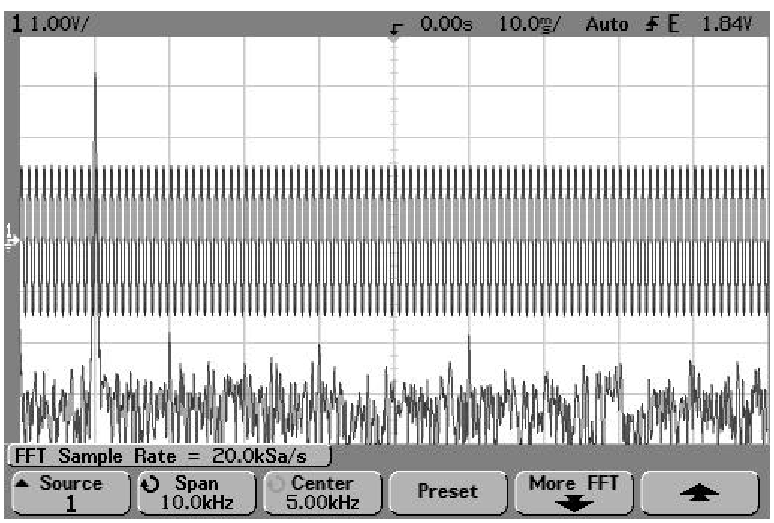



time/div = 200 µs
FFT sample rate = 1.00 MSa/s

Span = 500 kHz
Center = 250 kHz

**Figure 9 Sinusoidal Voltage in Time Domain and Frequency Domain**

In the display below, the time per division has been changed from 200 µs to 10 ms. As a result in the time domain display (upper graph) individual cycles of the sinusoid can not be seen. However, this has improved the frequency-domain display (lower graph) so that the frequency "window" now is 10 kHz wide, going from 0 Hz (D.C.) to 10 kHz. The 1 kHz component can clearly be seen in the bottom graph, one division from the left side of the graticule. The second and sixth harmonics (at 2 kHz and 6 kHz respectively) can barely be seen, approximately 50 dB below the 1 kHz fundamental.




time/div = 10 ms
FFT sample rate = 20 kSa/s
Span = 10.0 kHz
Center = 5.00 kHz

There are two (2) graphs shown here: voltage vs. time (over a 100 ms interval) and voltage vs. ***frequency*** (in a “window” 10 kHz wide).

**Figure 10 1 kHz Sinusoidal Voltage in the Time Domain and Frequency Domain**



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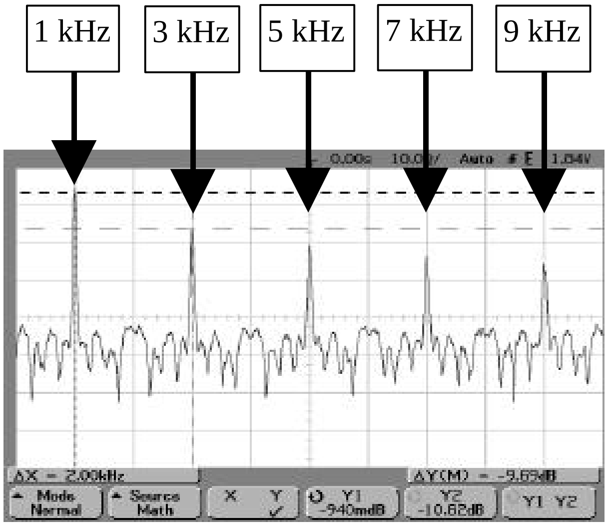
If the 1 kHz sine wave is changed to a square wave of the same frequency, the odd harmonics at 1 kHz, 3 kHz, 5 kHz, etc. can be seen, and their amplitudes measured, in the frequency-domain display. Figure 11 below shows only the frequency-domain graph.



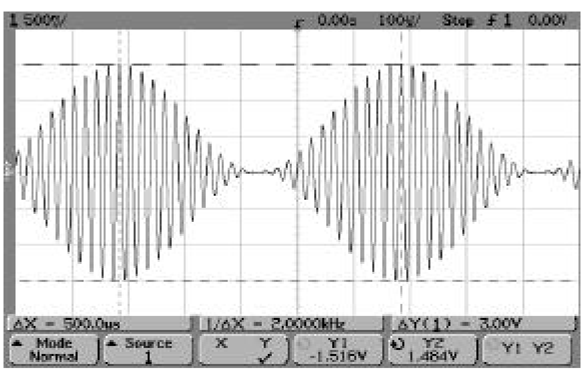

Frequency components can now be seen at 1 kHz, 3 kHz, 5 kHz, 7 kHz and 9 kHz. That is characteristic of a square wave with a 50% duty cycle: only odd harmonics (integer multiples of the fundamental frequency) will be present in its frequency spectrum.

**Note that both X and Y cursors have been used.** The two X cursors are placed on the 1 kHz and 3 kHz components, and the ΔX = 2.00 kHz is the difference between 3 kHz and 1 kHz.

The two Y cursors show the amplitudes of the 1 kHz and 3 kHz components, and the ΔY of –9.69 dB shows that the 3rd harmonic amplitude is 9.69 dB below the 1st harmonic amplitude.

**Figure 11 1 kHz. Squarewave Voltage in the Frequency Domain**

Another application of the FFT function is to examine the frequencies present in a double-sideband full-carrier (DSB-FC) signal. The time-domain display below shows this classic waveform with 100% modulation, and a carrier frequency low enough for students to be able to see individual cycles of the carrier within the "envelope" of the RF signal.




50 kHz RF Carrier, with 2 kHz **100% Modulation**
Sweep speed = 500 µs/division

Modulated carrier peak-peak amplitude is 3.00 Vpp at modulation peaks. Envelope period = 500 µs.

Modulating freq. = 1/T = 1/Δx = 1/(500 µs) = 2 kHz

**Figure 12 Amplitude Modulation of a Carrier in the Time Domain**

As was the case with the pure sinusoid (Figures 9 & 10), a better frequency-domain display results from using a slower sweep speed (a larger time per division) in the time-domain display. In Figure 12 above, the sweep speed is 100 µs/division, while in Figure 13 below it has been slowed to 500 µs/division, and the FFT function has been turned on.



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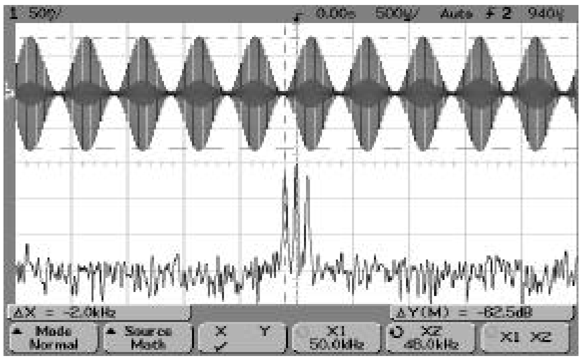
The frequency-domain display (lower graph in Figure 13 below) shows the three frequency components of an RF carrier amplitude modulated by a pure sine wave: the carrier, sandwiched between the lower and upper side frequencies. In this display, while the three frequencies can be seen, it is difficult to obtain precise frequency and amplitude information about them.

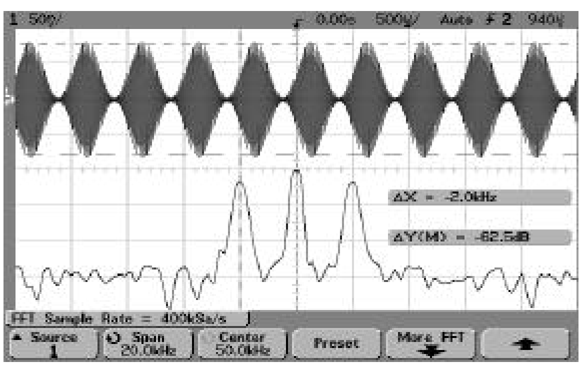



50 kHz RF Carrier, with 2 kHz **100% Modulation**
Sweep speed = 500 µs/division

FFT turned ON: Span Freq. = 100 kHz,
Center Freq. = 50 kHz, Vertical Scale = 20 dB/div
The carrier can be seen at 50 kHz, with upper and lower side frequencies seen at 52 kHz and 48 kHz respectively.

**Figure 13 Amplitude Modulated Carrier in the Time & Frequency Domains**

Without changing the sweep speed, in Figure 14 the frequency-domain display has been changed by narrowing the frequency span to 20 kHz, with the same center frequency of 50 kHz. In this way the frequency axis has been expanded, and the separation between carrier and both side frequencies can be seen clearly as one division or 2 kHz (20 kHz/10 divisions).




50 kHz RF Carrier, with 2 kHz **100% Modulation**

FFT turned ON: Span Freq. = 20 kHz,
Center Freq. = 50 kHz, Vertical Scale = 20 dB/div
The carrier can be seen at 50 kHz, with upper and lower side frequencies seen at 52 kHz and 48 kHz respectively.

**Figure 14 Amplitude Modulated Carrier in the Time & Frequency Domains**

## Waveform Math: Integration and Differentiation

The digital oscilloscope has the ability to perform integration and differentiation of waveforms displayed on channels 1 and 2. This feature can be put to good use in the classroom (and laboratory) to reinforce mathematics concepts, and is useful in courses where op-amp integrators and differentiators are studied.

In Figure 15 below, a 4 Vpp squarewave with an average value of 0 volts (upper graph) is integrated, and the resulting triangle waveform is shown on the lower graph. Note the ground symbol for channel 1 on the left side of the graticule, showing that the squarewave is indeed bipolar.

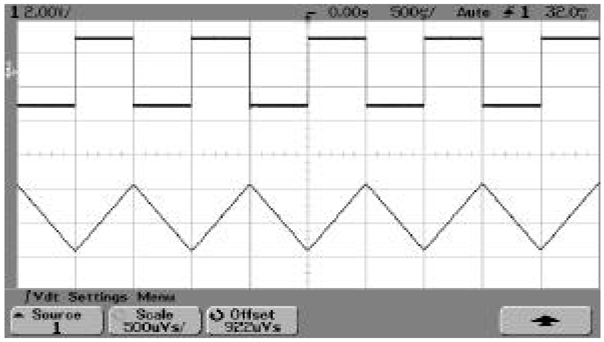



**Figure 15 Integration of a Bipolar Squarewave Producing a Triangle Waveform**

In Figure 16 below, a 2 volt DC offset has been added to the squarewave so that it is unipolar: the low level is 0 volts, and the high level is 4 volts. The resulting "staircase" confirms for students that integral of zero is zero (plus a constant), and the integral of a non-zero constant is a ramp.

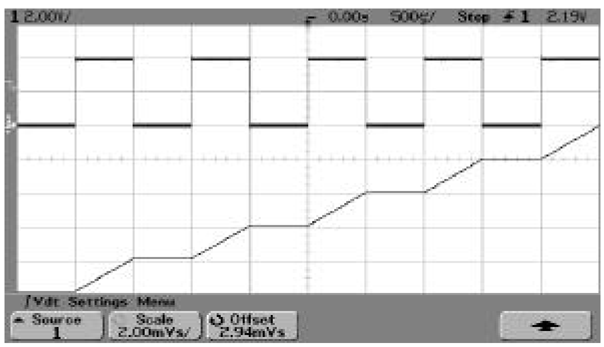



**Figure 16 Integration of a Unipolar Squarewave Producing a Staircase Waveform**

Selecting differentiation as the math function with a squarewave input results in the short "spikes" seen below in Figure 17. These spikes correspond to the transitions of the squarewave between levels. A good thought question to ask students is what the effect will be of making the squarewave input to the differentiator unipolar, and then having them test their hypothesis by doing it. This helps reinforce the concept that the derivative of a constant is zero.

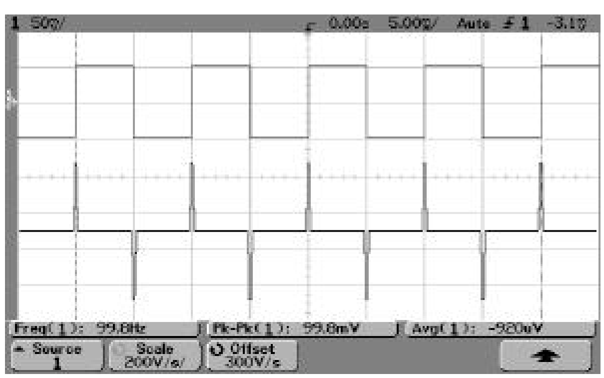



**Figure 17 Differentiation of a Bipolar Squarewave Producing Spikes**

## Noise Reduction by Averaging

College electronics laboratories have always had noticeable noise visible when small signals (tens of millivolts) were viewed on an oscilloscope. With the increasing presence of noise, both power line conducted and radiated from the myriad digital tools in our buildings, viewing and measuring low-level signals has become a real challenge. For many types of noise, the ability of the digital oscilloscope to average successive sweeps reduces the effects of noise dramatically, and can allow students to see, and measure, signals that are all but invisible.

Figure 18 below shows a 1 kHz sinewave with a considerable amount of noise present. As a result, in addition to the signal being unpleasant to view, the automatic measurement of the signal's peak-to-peak amplitude is grossly in error. Students often will trust the oscilloscope's value of amplitude (shown here as 98.8 mVpp), and don't notice the horizontal cursor lines which show that the amplitude displayed includes the noise.

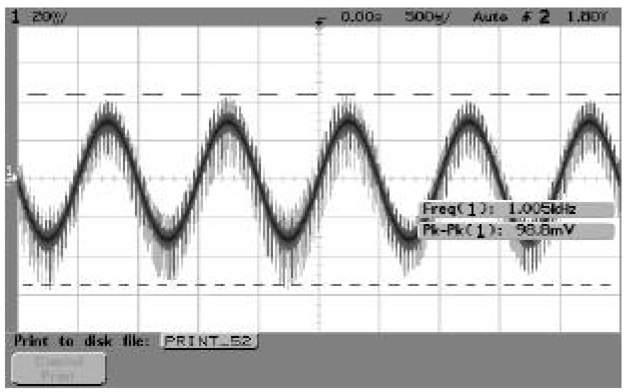



**Figure 18 A 1 kHz Sinewave with Noise Present**

Turning on the "averaging" feature results in the noise being reduced so that it is invisible visually. In Figure 19 the display is seen to be much cleaner, and the automatic measurement of amplitude (61.2 mVpp) is very close to the actual value (60.0 mVpp).

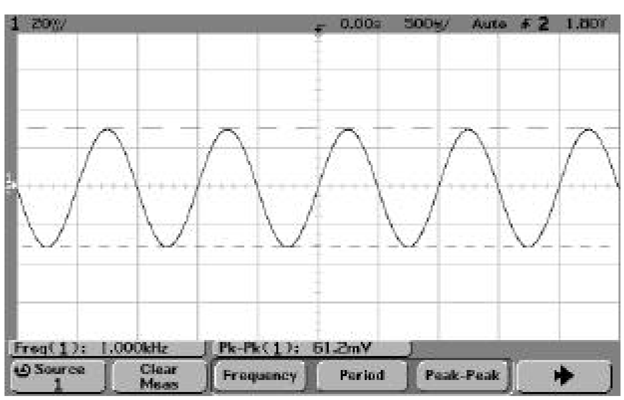



**Figure 19 A 1 kHz Sinewave with Noise Reduced by Averaging References**

## References

1. Bellando, J. & Nevin, J., "Multimedia Oscilloscope Training Program," 2000 ASEE Annual Conference Proceedings. June 2000, Albuquerque, NM. http://www.asee.org/conferences/search/20434.pdf
2. Ganago, A., "Lab Lecture Experiments as a Principle of Teaching," 2002 ASEE Annual Conference Proceedings. June 2002, Montreal, Quebec, Canada. http://www.asee.org/conferences/caps/document2/2002-946_Paper.pdf

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