Square Wave Testing for Frequency Response of Amplifiers

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Introduction

Square waves are rich in odd numbered harmonics and have a very simple shape that makes it easy to observe frequency response limitations in amplifiers. This note discusses how to use square waves to measure the approximate low and high cutoff frequencies of an amplifier. Amplifiers generally have AC coupled sections that limit the low frequency response and have shunt capacitances either parasitic or intentional that limit high frequency response. This not is divided into two sections – one section discusses the measurement of low frequency response and the other discusses the measurement of high frequency response. In each case we are looking for the low and high frequencies where the power transfer has dropped to one-half the mid-band value. These are known as the -3dB frequencies or cutoff frequencies.

Low Frequency Response

An AC coupled stage acts as a derivative network for frequencies below the series RC cutoff frequency. This will significantly modify a square wave passing through it. Figures 1 through 5 below illustrate the effect of AC coupling on a square wave. In Figures 1 and 2 the amplitude of the fundamental is reduced but that effect is insignificant for Figures 3 through 5 – although the wave shapes vary a human ear would not be able to distinguish between any of the wave forms and a perfect square wave.

The figures begin on the next page.

Square Wave Testing for Frequency Response of Amplifiers

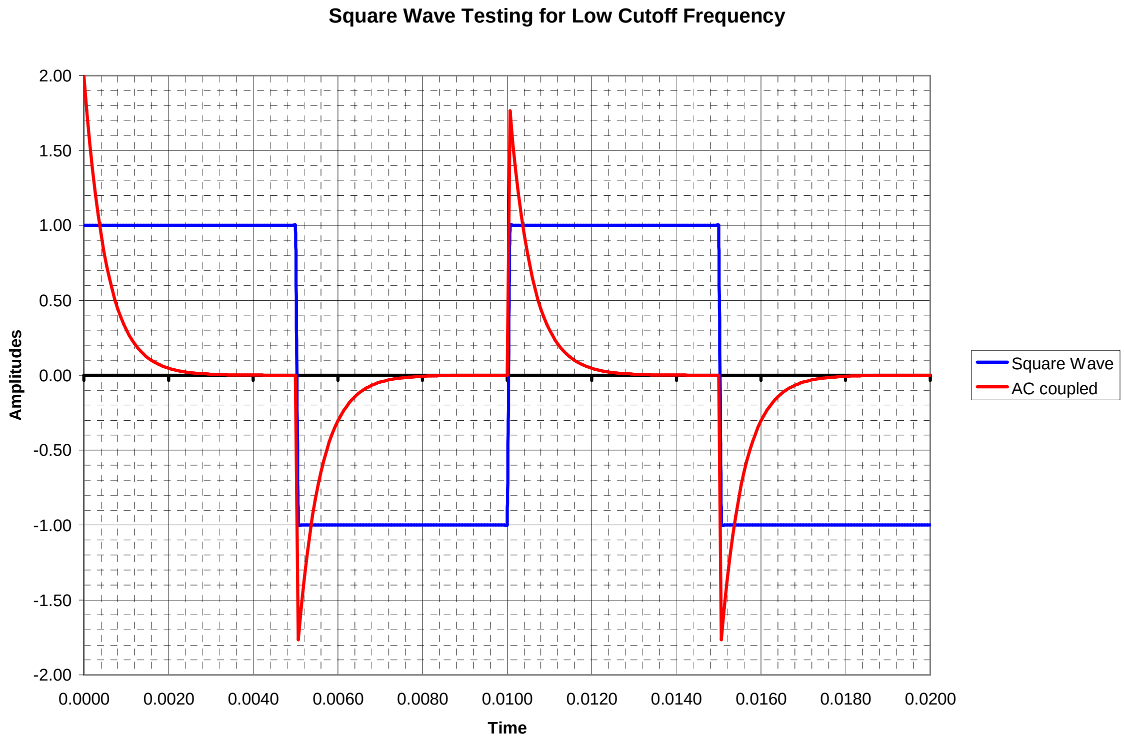

Figure 1: 100 Hz square wave through 300 Hz AC coupling

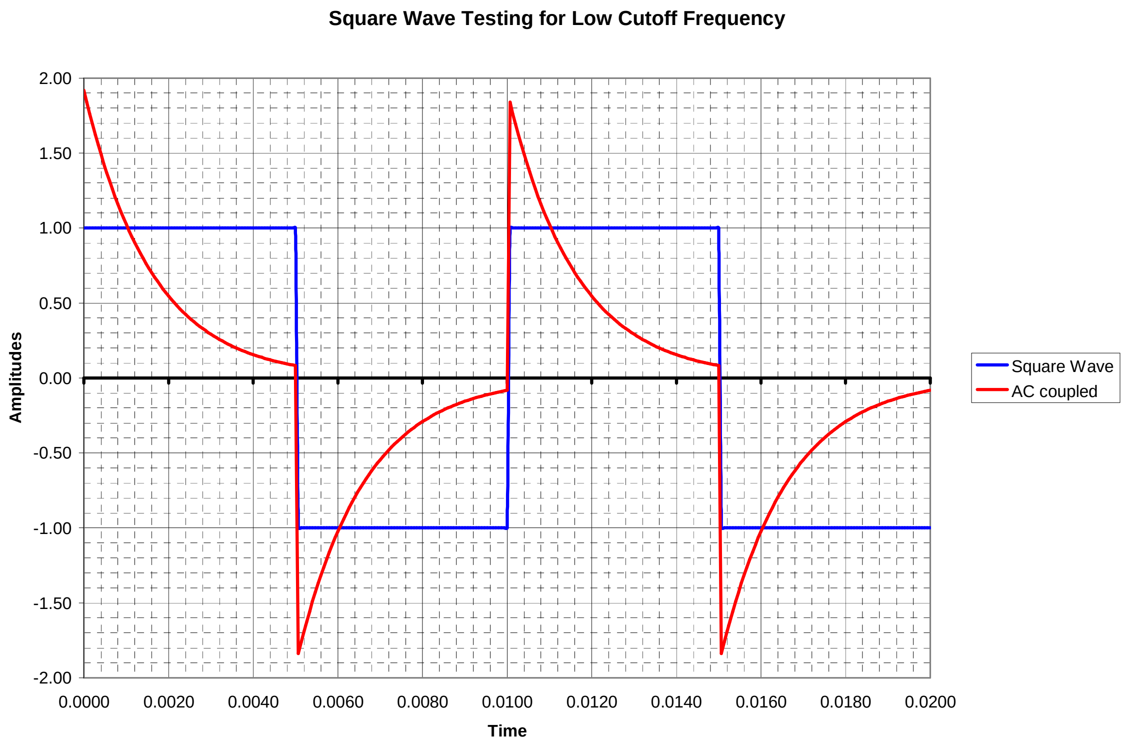

Figure 2: 100 Hz square wave through 100 Hz AC coupling

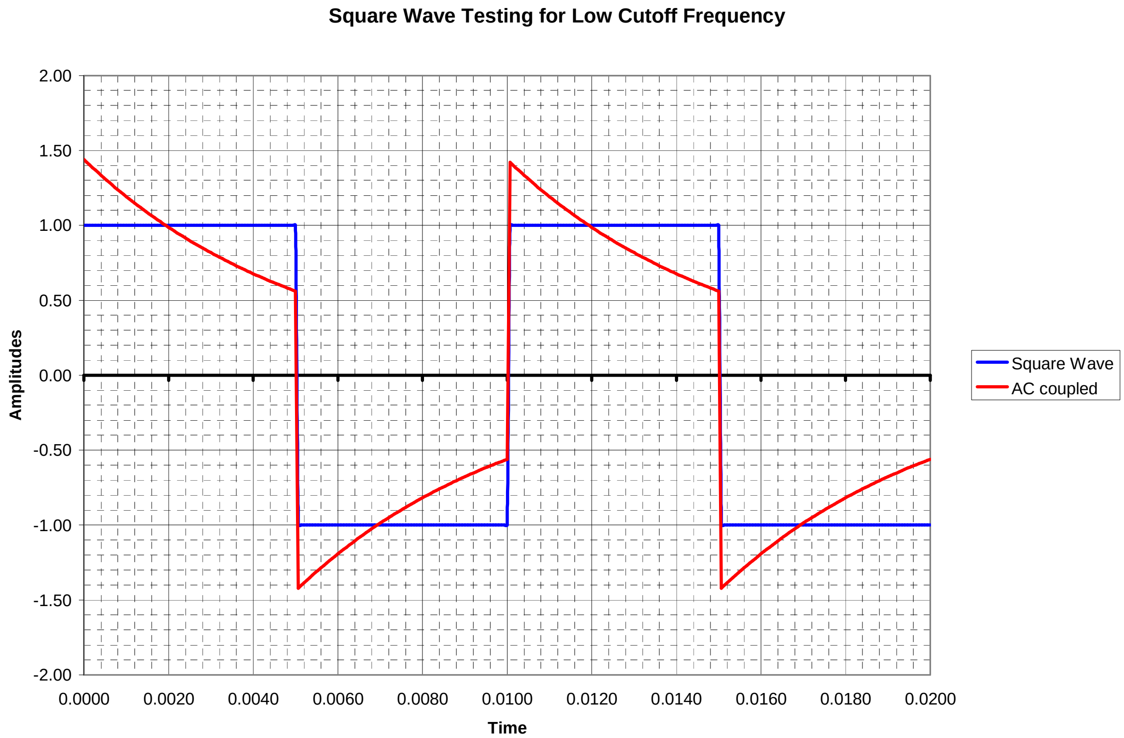

Figure 3: 100 Hz square wave through 30 Hz AC coupling

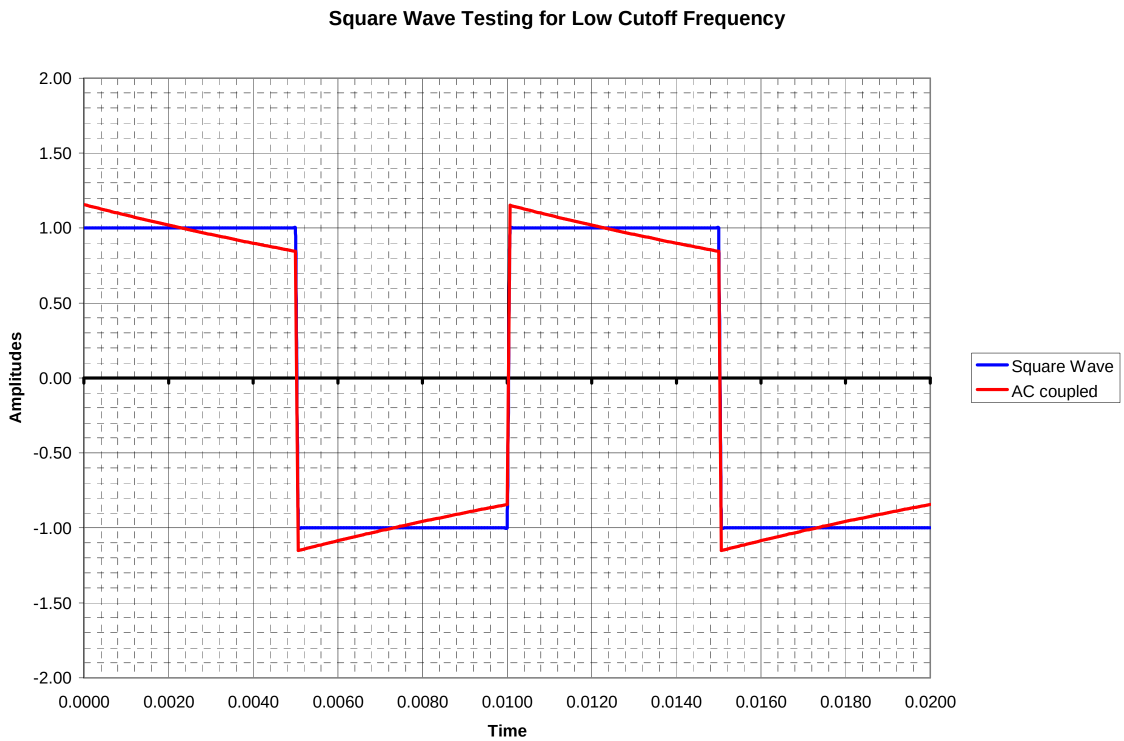

Figure 4: 100 Hz square wave through 10 Hz AC coupling

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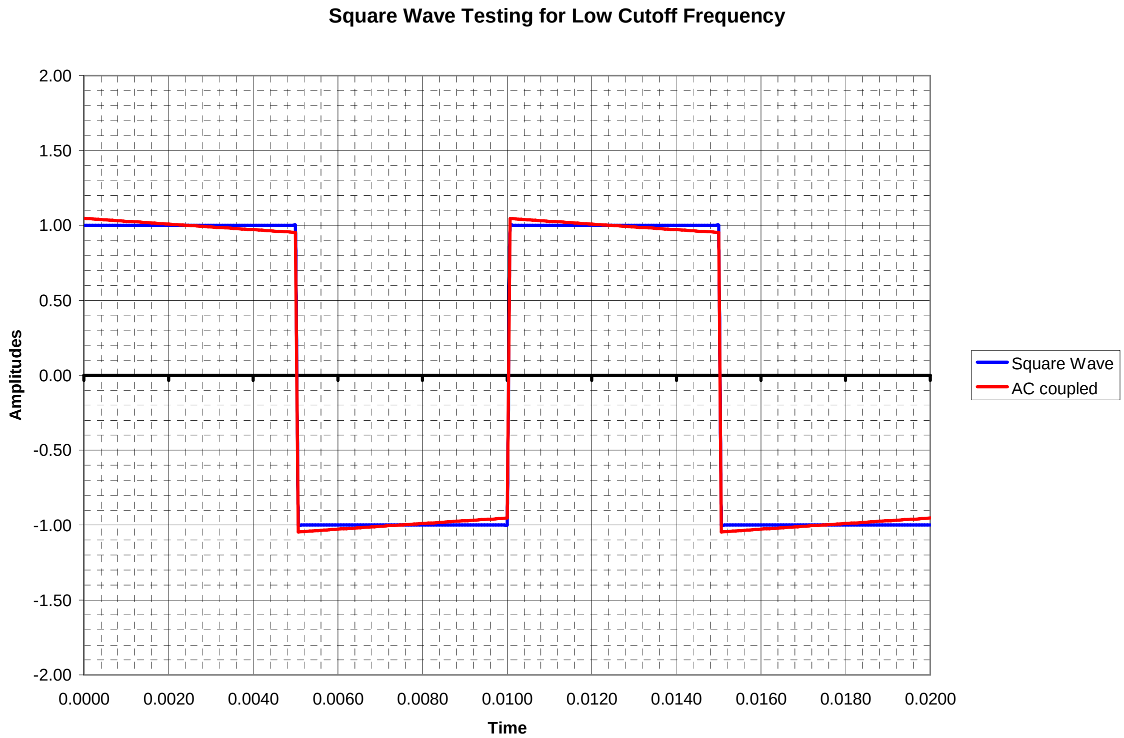

Figure 5: 100 Hz, square wave through 3 Hz AC coupling

A useful relation that gives the approximate low cutoff frequency based on the slope of the AC coupled square wave is as follows

$$Fcl = \frac{(Vmax\_pp - Vmin\_pp) * F}{Vmax\_pp * \pi} \qquad \text{Eq. 1}$$

Where:
Vmax_pp is the overall peak-peak value of the waveform
Vmin_pp is the peak-peak value of the low-points of the decaying slopes
F is the frequency in Hz of the square wave
π is 3.14159

Equation 1 is reasonably accurate providing the decaying slopes are fairly linear.

Example calculations from the above figures:

Data from Figure 3
Vmax_pp = 2.82
Vmin_pp = 1.1
T = 0.005 seconds (half a period for 100 Hz)

Fc = (2.82 – 1.1) * 100 / (2.82 * 3.14) = 19.4 Hz

The actual cutoff frequency is 30 Hz. The error is because the slopes are not straight and have significant exponential curvature.

Data from Figure 4
Vmax_pp = 2.3
Vmin_pp = 1.7

Fc = (2.3 – 1.7) * 100 / (2.3 * 3.14) = 8.3 Hz

This is closer to the actual value of 10 Hz because the slopes are straighter.

Data from Figure 5
Vmax_pp = 2.1
Vmin_pp = 1.9

Fc = (2.1 – 1.9) * 100 / (2.1 * 3.14) = 3.0 Hz

This is very accurate as the slopes are very straight. The significance of this is that the square wave frequency should be greater than ten times the low frequency cutoff. In actual measurements if this factor turns out to be too small then the measurement should be repeated with a higher frequency.

It is left as an exercise for the student to derive Equation 1. Hint: derive it for the condition where the square wave period is a small fraction of the time constant.

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High Frequency Response

An RC roll-off acts as an integrator for signals above the RC cutoff frequency and this reduces the amplitude of signals roughly be the frequency is above the cutoff frequency. This is illustrated in Figures 6 though 9 below. In Figure 6 the fundamental and all harmonics are significantly reduced and the output waveform resembles a triangular wave which is what one would expect by integrating a square wave.

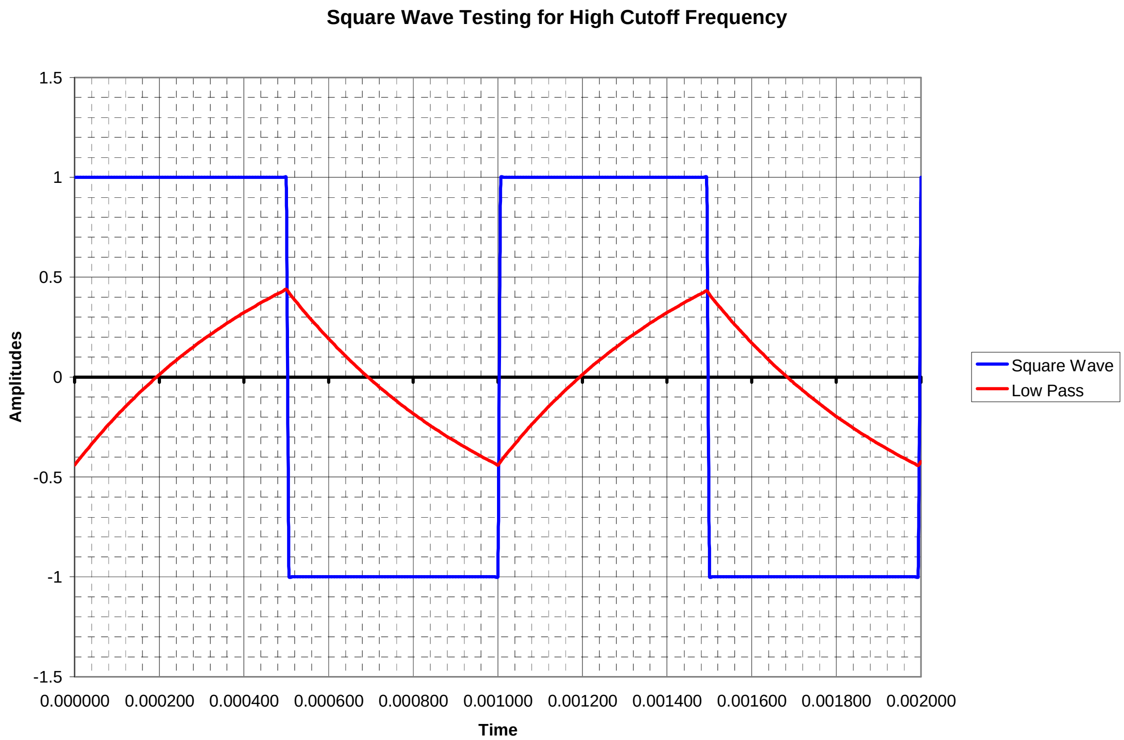

Figure 6: 1 kHz square wave with 300 Hz low-pass roll-off

In Figure 7 the cutoff frequency is higher but the fundamental and harmonics are still significantly attenuated. Figure 8 shows the effect of the cutoff frequency being three times the fundamental. Many people consider this to be the minimum bandwidth to pass a square wave. Figure 9 shows a higher cutoff frequency that only barely modifies the square wave.

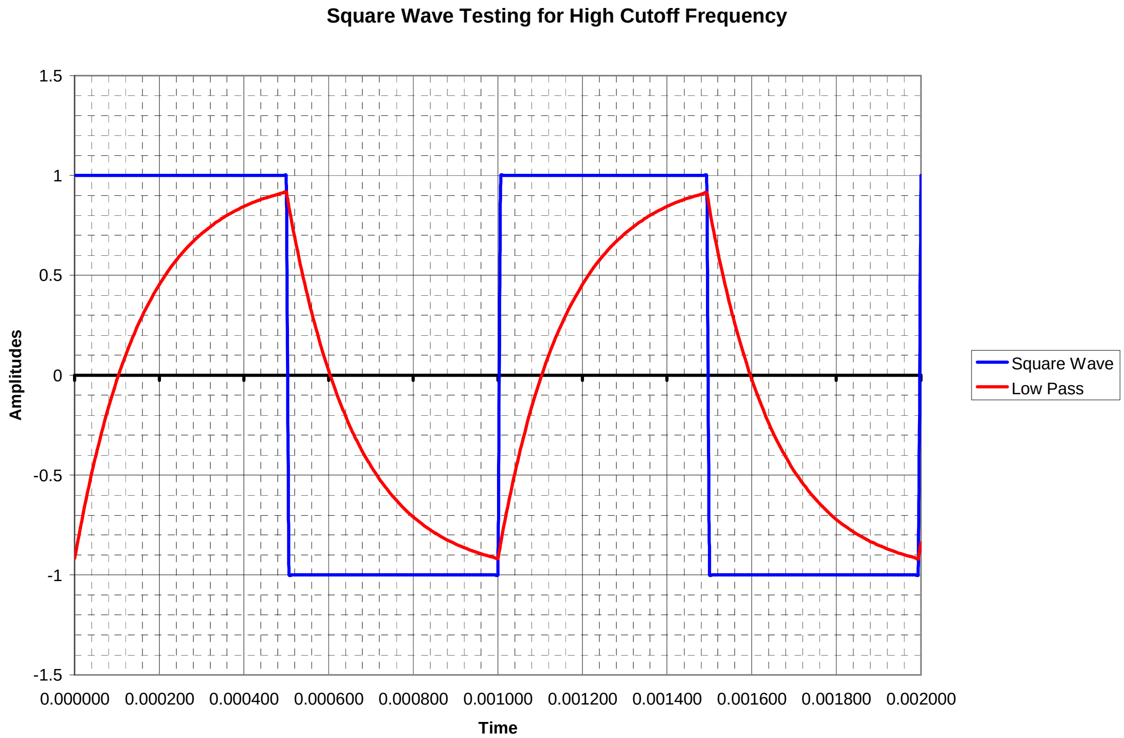

Figure 7: 1 kHz square wave with 1 kHz low-pass roll-off

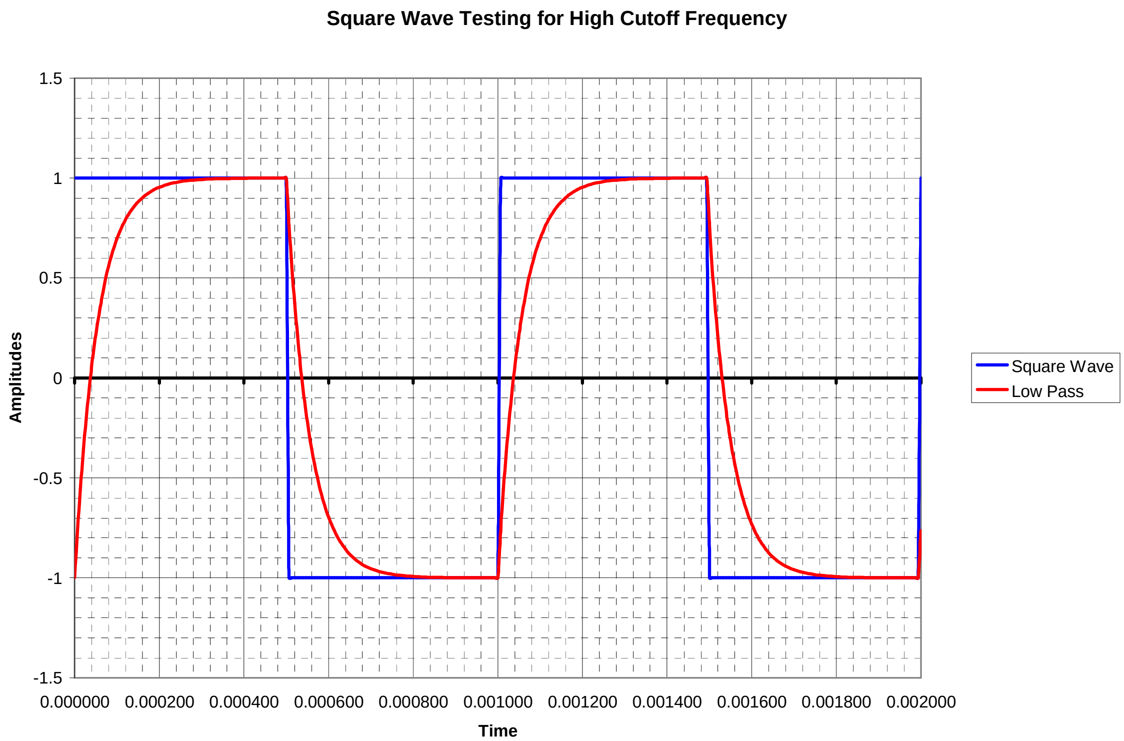

Figure 8: 1 kHz square wave with 3 kHz low-pass roll-off

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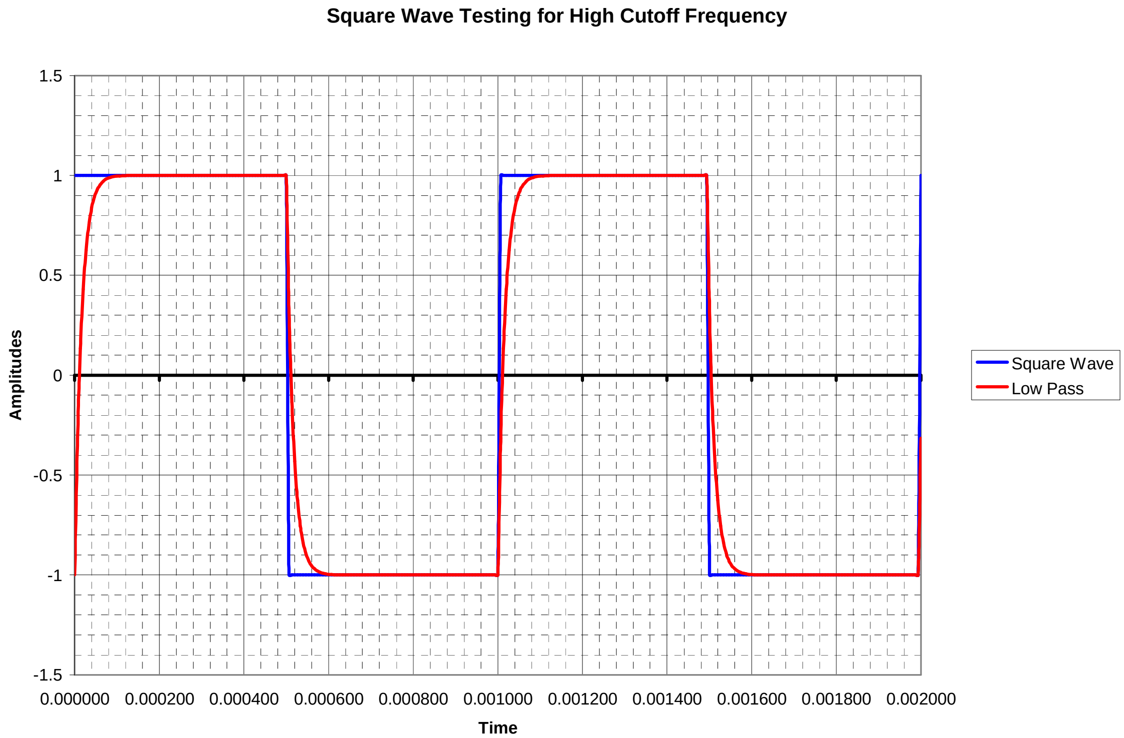

Figure 9: 1 kHz square wave with 10 kHz low-pass roll-off

A useful relation that gives the approximate high frequency bandwidth is derived from the time it takes the square wave to go from one state to the other. Since it is usually difficult to pick the starting point and a fully settled point, an alternative is to measure the time, $T_{10\text{-}90}$, required to move from the ten percent point to the 90 percent point. For a first order section the high frequency bandwidth, Fc, is:

$$Fc = 0.35 / T_{10\text{-}90} \qquad \text{Eq. 2}$$

Equation 2 also gives good results when there are multiple low-pass sections. For Equation 2 to be valid the square wave must fully settle as in Figures 8 and 9. As an example the 10 to 90 percent rise time in Figure 8 is approximately 113 µs which infers a bandwidth of 3.1 kHz – fairly close to the actual bandwidth of 3 kHz.

In application using an oscilloscope you adjust the frequency of the square wave to be low enough so that complete settling exists. The exact frequency does not matter. Then you set the amplitude on the scope display to make it easy to pick out the 10 and 90 percent time points. A good choice is five major vertical divisions peak-peak. Once the amplitudes are set then you should expand the horizontal display such that the rise portion is generally centered on the screen and occupies most of the horizontal width. Then visually note (probably using a cursor on a digital scope) the point at which the wave has risen one-half division. Visually note again (probably using a second cursor on a digital scope) the point at which the waveform passes though the upper last half division. Then measure the time between these points (if the cursors are in relative time mode that will be easy) and apply Equation 2.

It is left as an exercise for the student to derive Equation 2. It is not hard – just derive an exponential equation for the 10 and 90 percent points and relate the time difference to the cutoff frequency of the exponential which is one divided by two pi times the exponential time constant.