*June 20, 2013*

Summary

All passive probes have some bandwidth specification which is generally in the range of a few hundred megahertz up to one gigahertz. This bandwidth is measured at the factory using a specialized test jig with a very specific ground inductance and source impedance. Depending on your connection scheme in the real world, the response and bandwidth of the probe can differ significantly. This application note will serve as a guide to predicting the performance of your probe for your specific test setup, as well as provide tips on getting the best performance out of your probe.

Introduction

The go-to oscilloscope probe for most engineers is the basic 10:1 passive probe that comes standard with most scopes. The majority of Teledyne LeCroy scopes come equipped with 500 MHz bandwidth probes that have an assortment of tips and ground connections. This application note will explore the implications of different ground connection schemes and device impedances.

The input resistance and capacitance for any passive probe are readily available from the data sheet. Typical values you will see for a 500 MHz bandwidth probe are C = 9.5 pF and R = 10 Mohm. One specification that is missing from the data sheet is the ground lead inductance. This is because there are a variety of ways which people choose to ground their scope probes. The most typical way is using the long ground lead with the alligator clip on the end. This might lead to a ground loop inductance larger than 200 nH, which can significantly compromise the performance of the probe. We can create an equivalent circuit model for such a probe as shown below.
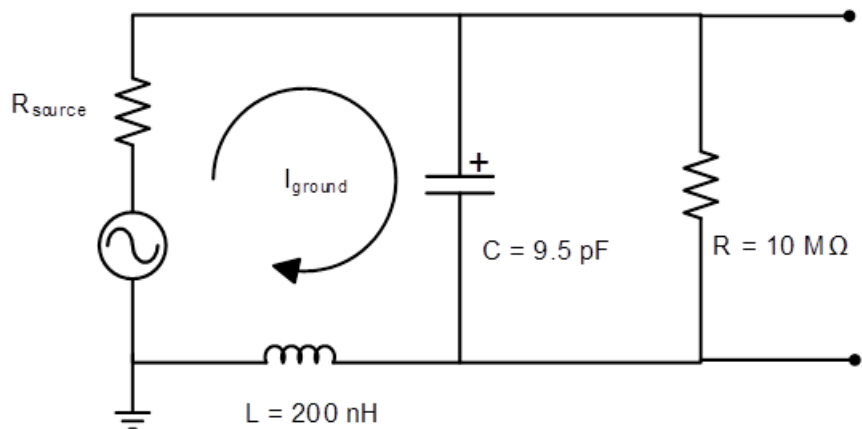
The input resistance of 10 Mohm is so large that we can ignore it for most cases. Let's look at the current loop, I_{ground}, and what effect different inductance values will have on the response of this circuit. The voltage across the capacitor is the value that is measured by the scope and the voltage represented by the AC source is the actual signal under test. To get an idea of how these two are going to differ we can look at the transfer function of this series RLC circuit, which is to say, the ratio of the voltage

across the capacitor, Vc, to the voltage source, Vs. The transfer function is given by the impedance of the capacitor divided by the sum of the all of the impedances.

Using the definitions

$$H = \frac{Z_C}{Z_C + Z_L + R}$$

$$Z_C = \frac{1}{j\omega C}$$

$$Z_L = j\omega L$$

We get the transfer function

$$H = \frac{1}{j\omega RC - \omega^2 LC + 1}$$

There are a variety of software tools available to help with plotting this function. Here is a snipit for plotting the magnitude of the transfer function in MATLAB.

```
C=9.5e-12;

L=12e-9;

R=45;


f=logspace(3,10,1000);

omega=2*pi*f;

H = 1./(i*omega*R*C-omega.^2*L*C+1);


gain=abs(H);

loglog(f,gain)
```

Hand picking some optimal values for R and L we can see the 500 MHz bandwidth that this probe can achieve.
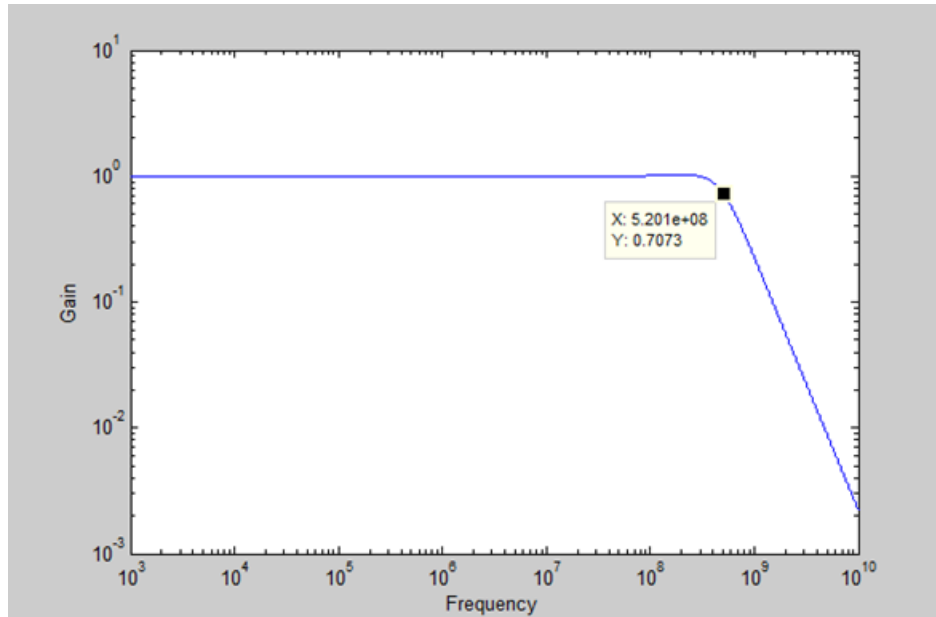
Something close to this performance can be achieved with the Teledyne LeCroy ground blade or ground spring accessories which may have an inductance of 10-20 nH. It is also important to consider the whole ground loop and connect to a nearby low inductance ground point on the device under test. Using copper foil can help to provide a nearby ground connection so that the length and inductance of the ground connection can remain small.
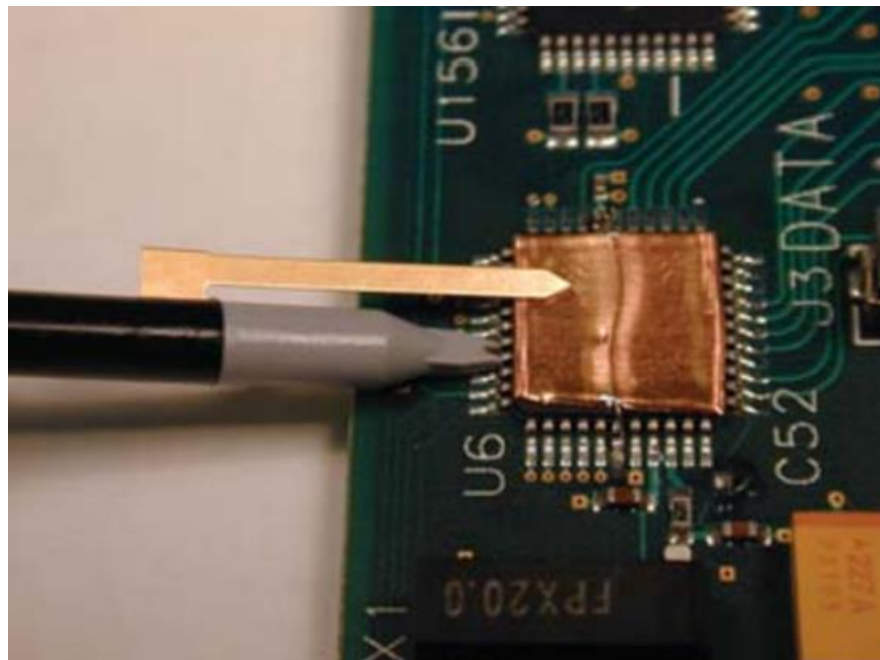
More often than not, the connection of choice is the long alligator lead. Let's investigate what effect using this ground lead has on the bandwidth and frequency response of the probe. Using this ground lead, the ground loop will have a length of at least 10 inches. Using 20 nH per inch as a rule of thumb we can calculate the inductance

at roughly 200 nH. As an example we'll look at the output of the Teledyne LeCroy ArbStudio function generator which has a source impedance of 50 Ohms. Plugging these two values into the transfer function we get the following plot.
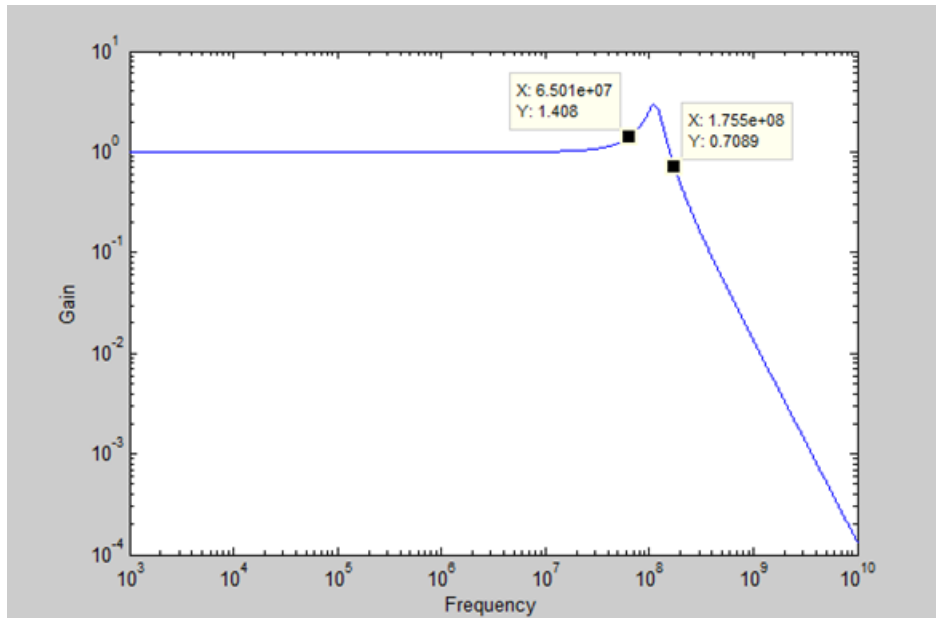

The added inductance has moved the -3dB bandwidth of the probe from >500 MHz to 175 MHz. Additionally the resonant frequency has been pushed well inside the bandwidth of the probe to 115 MHz. At 65 MHz we can still see an error of 40%, in fact, to keep the error under 10% we need to limit the frequency to 35 MHz!

Let's look at a practical example to see how this model holds up in the real world. This example compares the same signal probed with a low inductance test jig and with the standard sprung hook tip and alligator ground lead. The signal is output from the Teledyne LeCroy ArbStudio and split to each probe via a BNC Tee.

First let's look at a sine wave at a frequency near the resonant frequency, 65 MHz in this case. The upper yellow channel 1 trace is the probe with the test jig and the lower red channel 2 trace is the probe with the long ground lead.
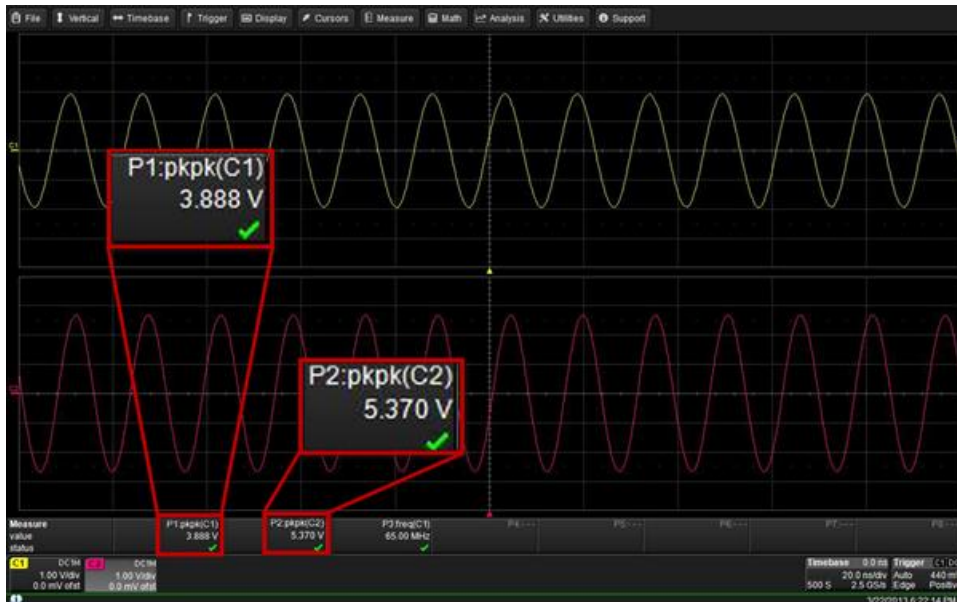
This is a 40% error in peak to peak voltage which is what is predicted by the MATLAB plot.

These effects can show up on much lower frequency signals as well. Many pulse shaped waveforms like serial data signals may have a very low frequency or bit rate but actually have very fast rise times. This means that even though your signal might be 125 kbit/s it could have frequency content high enough to exhibit the peaking effect. This peaking will show up on a square wave or any fast edge as ringing. How the ringing is damped will depend on the source impedance. Here is an example with the same setup as above but with a 5 MHz square wave.

Summary

Passive oscilloscope probes are very sensitive to ground lead inductance and source impedance. It is critical to take these factors into account when determining the connection scheme for probing your signal. By estimating values for ground lead inductance and source impedance you can easily plot the transfer function to get a good idea of what performance you can expect from your probe. Pay special attention to devices under test with very high source impedance, this will essentially turn you're your probe into an RC filter. For a source impedance of 10k Ohms the bandwidth will be reduced to 1.67 MHz. By understanding the effects of these different variables you can use your passive probe with confidence in a wide variety of environments.