Tektronix

Application Note

High-Speed Probing

High-speed digital circuitry requires unique probing considerations.

As clock speeds increase, digital signals begin to look more like analog signals. At high speeds, parasitic parameters that exist within the measurement system introduce significant aberrations into the measured waveform. Understanding how those parameters affect the measured waveform before a probe is attached to a high-speed device will significantly increase measurement accuracy.

System Bandwidth

Selecting the proper probe for your oscilloscope is the first step in accurately measuring high-speed signals. It's commonly assumed that the bandwidth of the oscilloscope and the probe should be equal in magnitude. However, the relationship between the oscilloscope bandwidth and the probe bandwidth is not trivial.

The oscilloscope and probe together form a measurement system, and the displayed output waveform of that system is a transient response. Since the transient response is a waveform, it's presented as a plot of voltage versus time, in contrast to a frequency response.

Theoretically, if an oscilloscope/probe system had infinite bandwidth, its transient response would be an exact duplicate of the input pulse. It's not possible for an oscilloscope or a probe to have infinite bandwidth, so the displayed transient response is always a distorted version of the input pulse. It's necessary for the measurement system to have a wide bandwidth in order for it to amplify a pulse or a square-wave signal with minimum distortion.

It's generally true for all electronic devices that the time required for the transient response to rise to a certain level is inversely proportional to bandwidth. Risetime is the time required for a waveform to change from 10% of its final value to 90% of its final value. For reasonable accuracy, the rise time of the oscilloscope/probe system should be 3 to 5 times faster than that of the pulse being measured. The equations used to approximate oscilloscope/probe system rise time and bandwidth for the Tektronix TDS 794D is as follows:

$$\text{System Risetime} \approx \sqrt{tr_{Scope}^2 + tr_{Probe}^2}$$

Where:

tr_{Scope} = Risetime of the oscilloscope

tr_{Probe} = Risetime of the probe

$$\text{System Bandwidth} \approx \frac{0.4}{\text{System Risetime}} \approx \frac{0.4}{\sqrt{tr_{Scope}^2 + tr_{Probe}^2}}$$

For example, the risetime of the TDS 794D oscilloscope is approximately 200 ps. The risetime of the P6158 Low Capacitance Probe is approximately 100 ps. When these values are entered into the above equations, the system risetime is calculated to be 224 ps, which is equivalent to a system bandwidth of 1.8 GHz. This tells the user that when the P6158 is attached to the TDS 794D, the system bandwidth at the probe tip will be approximately 1.8 GHz. For reasonable accuracy, the maximum risetime of the pulse being measured should be no greater than 672 ps (three times slower than the oscilloscope/probe system risetime). As the bandwidth of the source being measured approaches the bandwidth of the oscilloscope/probe system bandwidth, the measured waveform becomes significantly attenuated.

Table 1. Source Bandwidth vs. System Bandwidth

Ratio of Source Bandwidth to Probe/Scope System Bandwidth	Risetime Slowing Amplitude Attenuation
1:1	41%
1:2	12%
1:3	5%
1:5	2%

Table 2. Risetime of Selected Logic Families

Logic Family	Typical Risetime	Calculated Bandwidth[1]
TTL	5 ns	70 MHz
CMOS	1.5 ns	230 MHz
ECL	500 ps	700 MHz

[1] = $0.35/t_{rise}$.

Table 1 shows how this ratio can affect the amplitude attenuation of the measured waveform.

The risetimes of input signals vary with respect to the logic family. Table 2 outlines the typical signal risetimes of three logic families. The calculated bandwidth of the source should always be 3 to 5 times less than the scope/probe system bandwidth.

Source Impedance

Once the probe bandwidth is matched with the oscilloscope, the source impedance of the device-under-test (DUT) should be matched properly with the input impedance of the probe. Circuit boards with high-speed components have a wide variety of source impedances at different test points.

For example, when the P6158 Low Capacitance Probe, which has an input resistance of 1 kΩ is attached to a 10 kΩ load driven by a 5 V signal, the measured waveform is severely attenuated (see Figure 1). The measured waveform has an amplitude of 500 mV which represents approximately –20 dB of attenuation.

A DC model can be used to demonstrate how the probe resistance loads the 10 kΩ source. The DC equivalent circuit is shown in Figure 2. By taking a current-flow approach, we find that at one point on the waveform the source voltage is 5 V; therefore, the load current can be calculated as follows:

$$\begin{aligned} I &= \frac{V}{R} \\ &= \frac{5\ \text{V}}{R_S + R_P + R_{Scope}} \\ &= \frac{5\ \text{V}}{11\ \text{k}\Omega} \\ &= 0.46\ \text{mA} \end{aligned}$$

Therefore, the voltage drop across the 10 kΩ source resistance (R_S) is:

$$\begin{aligned} V &= I \cdot R \\ &= 0.46\ \text{mA} \cdot 10\ \text{k}\Omega \\ &= 4.6\ \text{V} \end{aligned}$$

The measured pulse amplitude is:

$$5\ \text{V} - 4.6\ \text{V} = 400\ \text{mV}$$

Or, about –21.9 dB (92% attenuation) from its

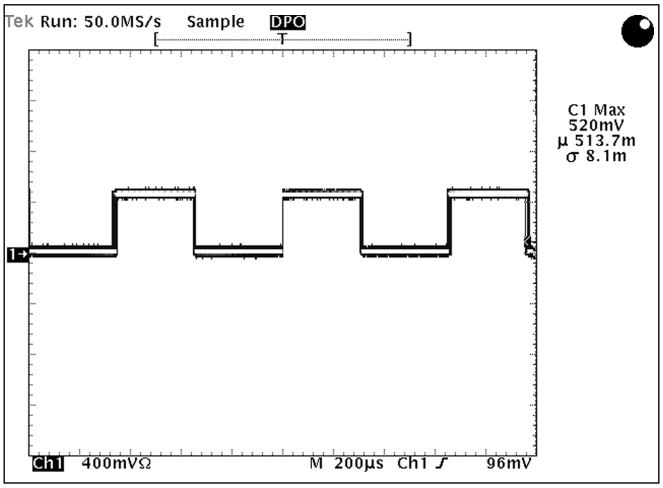

Figure 1. P6158 Low Capacitance Probe attached to a 10 kΩ load on a DPO.

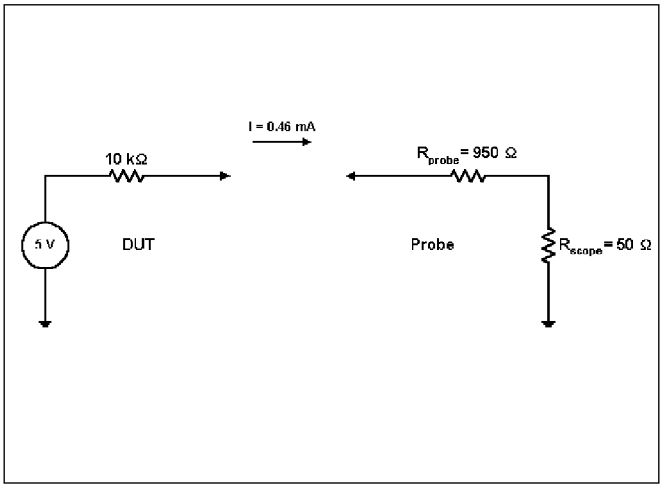

Figure 2. DC Equivalent circuit when P6158 is attached to a 10 kΩ load.

unloaded state. The calculated amplitude is slightly less than the actual amplitude because of capacitive effects.

If the same measurement is made with a P6339A Buffered Passive Probe which has an input resistance of 10 MΩ, the measured waveform has no visible attenuation (Figure 3).

The DC equivalent circuit is shown in Figure 4. The load current is:

$$I = \frac{V}{R}$$

$$= \frac{5\ \mathrm{V}}{R_S + R_P + R_{Scope}}$$

$$= \frac{5\ \mathrm{V}}{10\ \mathrm{M\Omega}}$$

$$= 0.5\ \mu\mathrm{A}$$

Therefore the voltage drop across the 10 kΩ source resistance (R_S) is:

$$V = I \cdot R$$

$$= 0.5\ \mu\mathrm{A} \cdot 10\ \mathrm{k\Omega}$$

$$= 5\ \mathrm{mV}$$

The measured pulse amplitude is:

$$5\ \mathrm{V} - 0.005\ \mathrm{V} = 4.995\ \mathrm{V}$$

Or, about –0.009 dB (0.1% attenuation) from its unloaded state. The calculated measured amplitude is consistent with the actual measured amplitude in Figure 3. The P6339A Buffered Passive Probe is more suitable for measuring a 10 kΩ source impedance than the P6158 Low Capacitance Probe.

As can be seen from Table 3, using a probe with a high input resistance is desirable for minimum amplitude error in the measured waveform.

Table 3. Source Resistance vs. Measured Accuracy

	Input Resistance of the Probe							
Source Resistance	**50 Ω**	**500 Ω**	**1 kΩ**	**5 kΩ**	**100 kΩ**	**1 MΩ**	**5 MΩ**	**10 MΩ**
	Measured Amplitude Accuracy							
1 Ω	98%	100%	100%	100%	100%	100%	100%	100%
10 Ω	83%	98%	100%	100%	100%	100%	100%	100%
50 Ω	50%	82%	95%	99%	100%	100%	100%	100%
100 Ω	33%	83%	91%	98%	100%	100%	100%	100%
10 kΩ	1%	5%	9%	33%	91%	99%	100%	100%

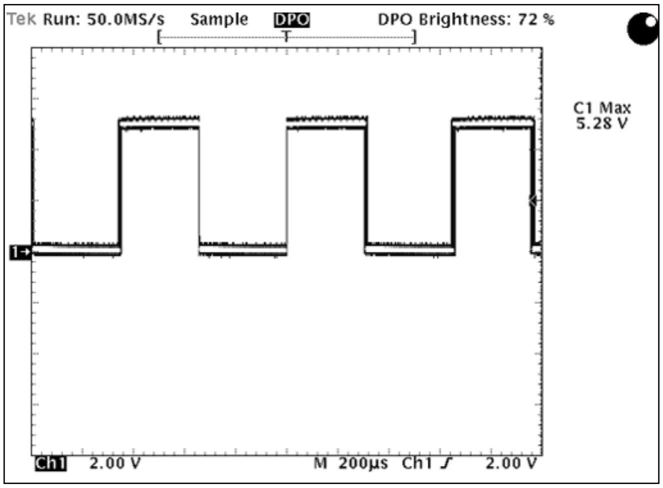

Figure 3. P6339A Buffered Passive Probe attached to a 10 kΩ load on a DPO.

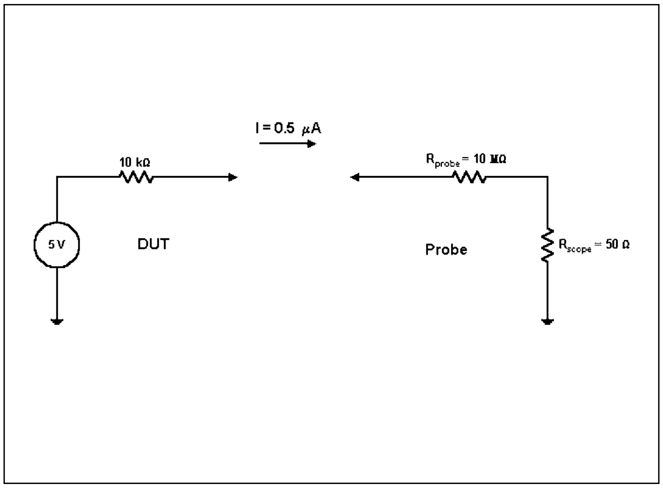

Figure 4. DC Equivalent circuit when P6339A is attached to a 10 kΩ load.

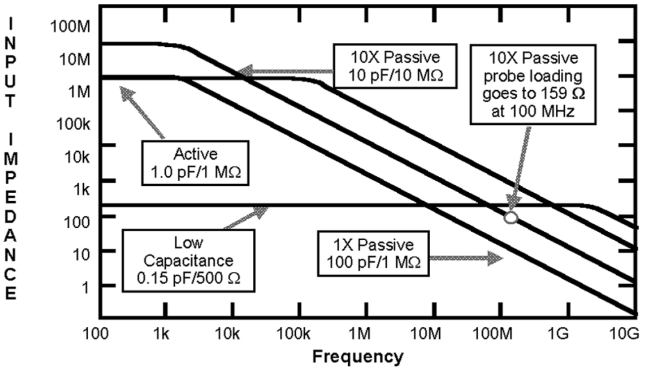

Figure 5. Probe input impedance vs. frequency.

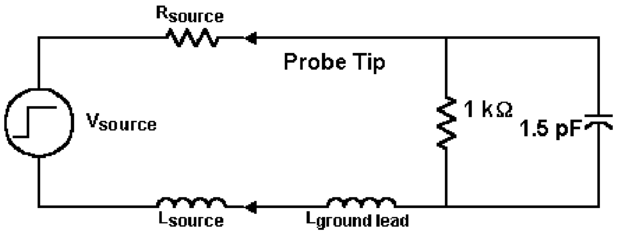

Figure 6. Equivalent circuit, ground lead inductance (excess inductance).

Capacitive Effects

As bandwidths increase, the impedance of the probe decreases because of capacitive effects. Figure 5 shows how different types of voltage probes maintain input impedance with respect to bandwidth. It's clear that trade-offs must be made when selecting the type of probe to measure a high-speed signal. Active probes such as the P6217 are excellent for maintaining high input impedance over a wide bandwidth. However, for low source impedance measurements, low capacitance probes such as the P6158 maintain their impedance over a much greater bandwidth.

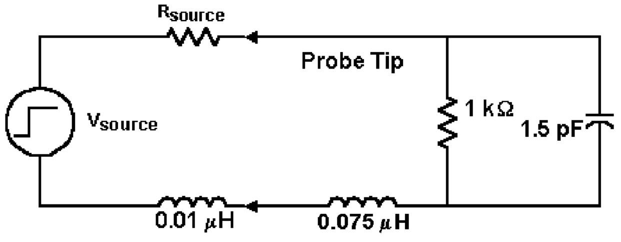

Figure 7. DC equivalent circuit of the P6158 probe with a 3-in. ground lead where:

$L_{source} = 0.01\ \mu H$

$L_{ground\ lead} = 0.075\ \mu H$

$L = 0.01\ \mu H + 0.075\ \mu H$

$= 0.085\ \mu H$

C = Input Capacitance of the Probe = 1.5 pF

The Effect of Ground Lead Length

When measuring high-speed signals, poor grounding can cause ringing and aberrations in the measured waveform. Engineers and technicians who work in industries where bandwidths are relatively low will not see any significant difference in a measured waveform when using a long ground lead or no ground lead attached to their probe. However, when measuring high-speed signals, the length of the probe ground lead can severely affect the waveform displayed on the oscilloscope. As a general rule of thumb, probe ground leads must be kept as short as possible when measuring high-speed systems.

When a ground lead is attached to a probe, lead inductance is added to the return path of the signal as shown in Figure 6. This causes ringing and aberrations in the waveform. As the frequency increases, the impedance of the lead inductance increases, which reduces the ring frequency and increases the chance for ringing to exist within the measured pulse. One way to increase the ring frequency is to shorten the length of the ground lead, thus reducing the inductance.

This phenomenon is clearly demonstrated by the following equation for ring frequency:

$$f_{ring} = \frac{1}{2\pi \sqrt{LC}}$$

The total inductance in the signal return path of a probe ground is equal to the sum of the source inductance of the DUT and the inductance of the probe ground lead:

$$L = L_{source} + L_{ground}$$

As the inductance decreases, the ring frequency increases. The easiest way to reduce the inductive loading for any measured waveform is to use a shorter probe ground lead. Generally, probe ground leads introduce as much as 25 nH of inductance per inch (2.54 cm), into the return path of the signal. For example, if you are measuring the output of a source using a P6158 Low Capacitance Probe with a three-inch ground lead (see Figure 7), the ring frequency is calculated as follows:

$$f_{ring} = \frac{1}{2\pi \sqrt{0.1 \times 10^{-6}\ H \cdot 1.5 \times 10^{-12}\ F}}$$

$$= 410\ MHz$$

If the actual bandwidth of the input pulse were 500 MHz, the 410 MHz ring would clearly be visible in the measured waveform.

However, if the Spring Ground Contact included with the P6158 Low Capacitance Probe is used instead of the three-inch ground lead (see Figure 8), the ground inductance is significantly reduced, resulting in a higher ring frequency. The length of the Spring Ground Contact is approximately 0.2 in. (0.5 cm) which translates to an inductance of 0.005 µH.

$$f_{ring} = \frac{1}{2\pi\sqrt{0.015 \times 10^{-6}\ H \cdot 1.5 \times 10^{-12}\ F}}$$

$$= 1\ GHz$$

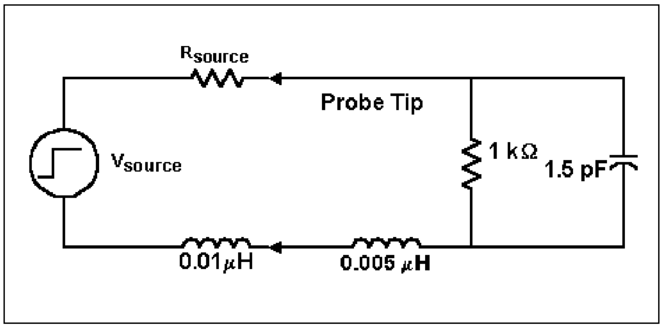

Figure 8. DC equivalent circuit of the P6158 with Spring Ground Contact where:

$L_{source} = 0.01\ \mu H$

$L_{ground\ lead} = 0.005\ \mu H$

$L = 0.01\ \mu H + 0.005\ \mu H$

$= 0.015\ \mu H$

C = Input Capacitance of the Probe = 1.5 pF

The Spring Ground Contact causes a 1 GHz ring which extends beyond the bandwidth of the 500 MHz input pulse. As a result, there will not be any ringing visible in the measured waveform.

In all cases, the shortest ground lead should be used, consistent with the need for probe mobility. If possible, use 3-in. or shorter ground leads, such as the Spring Ground Contact. These are supplied as standard accessories with the Tektronix P6158 Low Capacitance and P6217 Active Probes.

A TDS 794D 2 GHz DPO was used to access a 200 ps (fall time) pulse using the P6158 Low Capacitance Probe, with a 3-in. ground lead. The observed signal has serious problems with ringing and aberrations, caused by incorrect grounding techniques (see Figure 9). The measured waveform reveals 132 mV of ringing.

The same measurement was made with the Spring Ground Contact attached to the P6158, as opposed to the 3-in. ground lead. Figure 10 shows significantly less ringing present in the waveform. The ringing has decreased by more than 50%.

Shorter ground leads must be used when making high-speed measurements. Using shorter ground leads improves ringing and reduces risetime.

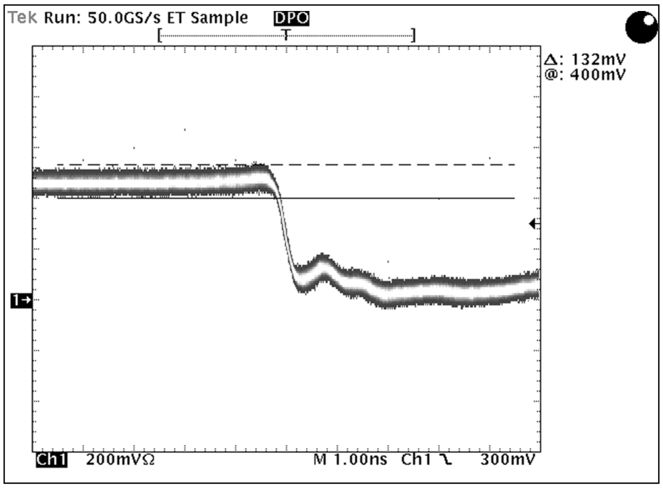

Figure 9. The TDS 794D connected to a P6158 Low Capacitance Probe with 3-in. ground lead reveals significant ringing in the waveform.

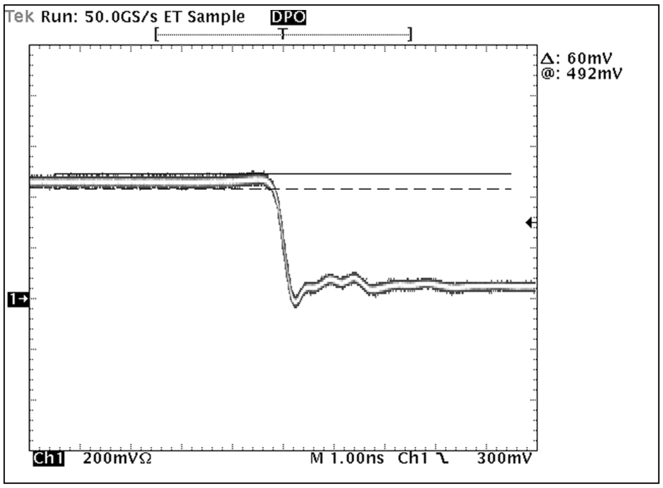

Figure 10. The same input signal as shown in Figure 9, but accessed by a TDS 794D DPO and P6158 with the Spring Contact Ground Lead.

Probing SMT Devices

As bandwidths increase, surface mount packages become increasingly smaller. It's very difficult to probe individual pins of a fine pitch IC without accidentally shorting the adjacent pin with the probe tip. The SureFoot™ adapters are designed to facilitate the connection of the probe tip to a surface mount lead on a device under test (see Figure 11). The SureFoot uses the pins of the IC to guide the probe tip to the desired pin. The sizes of the SureFoot adapters are 0.65 mm (EIAJ), 25 mil (JEDEC), and 0.5 mm. The small size of the lead doesn't introduce significant inductance into the measured waveform. Using short ground leads is equally important when using the SureFoot adapters.

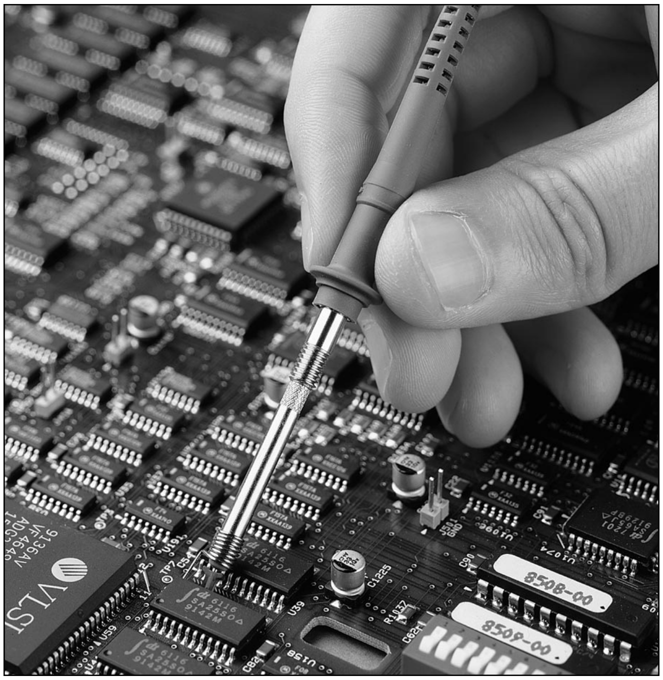

Figure 11. SureFoot adapter attaches conveniently to the tip of the P6158 and can be used with short ground leads.

Board Design Considerations

It's not uncommon for probing to be an afterthought when designing a Circuit Board. However, when working with high-speed signals, it's extremely important to note the signals of interest before the board is laid out. This is especially true when a board design includes IC packages such as Ball Grid Array (BGA). Incorporating test points into a board design will help insure that probe ground leads are kept to a minimum length. The Probe Tip to Circuit Board Adapter can be incorporated into a board design and mounted directly onto the board.

When a probe is connected to the device under test via a Probe Tip to Circuit Board Adapter, and to the circuit board ground plane (or device ground), ringing caused by long ground leads is significantly reduced.

Figure 12 shows a typical Probe Tip to Circuit Board Adapter (test point) installation. These test points are available in three sizes to accept miniature, compact, or sub-miniature series probes.

If there are probe mobility needs, then ground leads should be used in place of a Probe Tip to Circuit Board Adapter. When using ground leads, it's important to include ground pads in the layout of the board. (Adequate ground pads suggest the use of a ground plane.) The ground pads must be close enough to the signal of interest to use a short ground lead such as the Spring Ground Contact.

Induced Noise in Probe Ground Leads

Noise currents caused by sources other than the signal being measured can flow from ground into the DUT at a point where the probe is connected through the probe ground lead and onto the probe cable shield. The source of this noise current can be internal to the DUT or external, such as a nearby electrostatic discharge event. The magnitudes of the errors generated by this noise current can easily exceed those of the signals being measured. Figure 13 shows a typical measurement configuration and the path that the noise current takes into the measured waveform. At high frequencies of a few MHz or more, potential differences between the oscilloscope chassis and the local ground in the DUT causes a high fre-

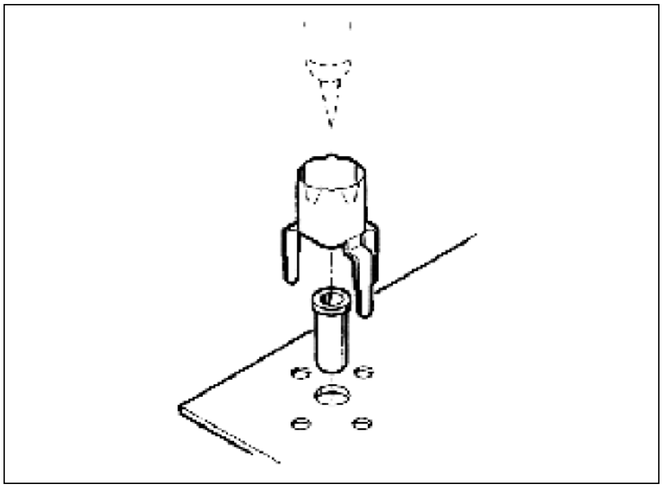

Figure 12. Typical Probe Tip to Circuit Board Adapter installation.

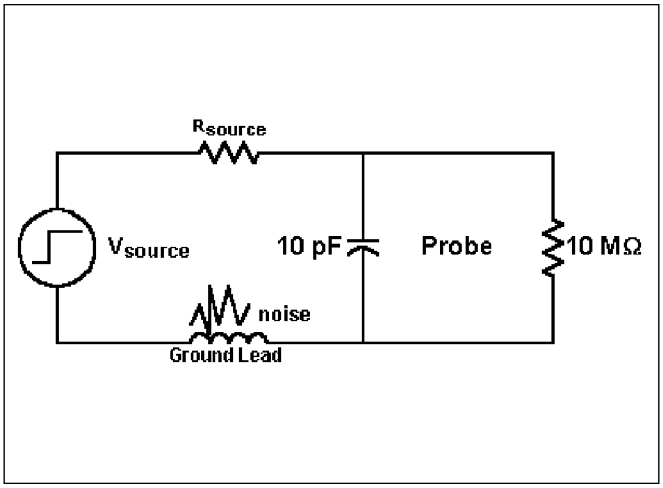

Figure 13. Equivalent circuit, ground lead inductance noise.

quency noise current to flow from the DUT ground on the oscilloscope probe ground lead and onto the shield of the probe cable. Some of the current is radiated from the probe shield as an antenna and some is conducted into the oscilloscope chassis.

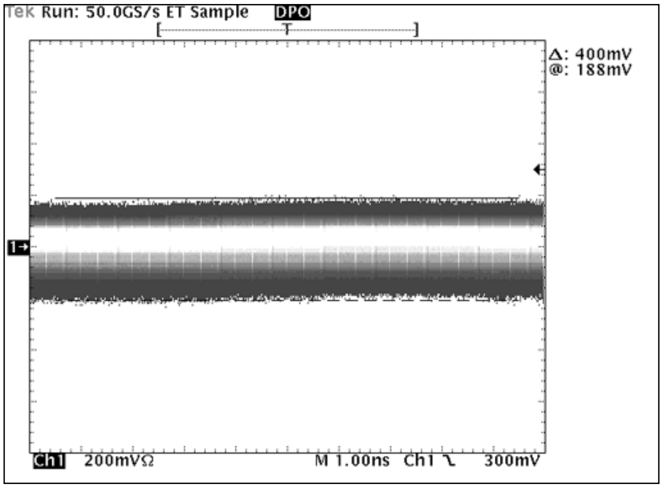

Figure 14. Induced noise in the probe ground loop (tip shorted to the ground clip).

Identifying Radiated Noise

If the probe ground lead is positioned too close to certain areas on a circuit board, a loop antenna is formed and the probe tip signal can pick up noise. Moving the probe ground lead around will help identify the problem. If the noise level changes, you have a ground lead induced noise problem. A more positive way of identification is to disconnect the probe from the signal source and clip the ground lead to the probe tip.

Now use the probe/ground lead as a loop antenna and search the board for radiated noise. Figure 14 shows what can be found on a logic board, when the probe tip is shorted to the ground lead. The 400 mV of radiated noise is induced in the signal-turn loop and fed into the probe tip. Noise at this level can cause significant aberrations in the measured waveform.

The significance of any induced or injected noise increases with reduced working signal levels, because the signal-to-noise ratio will be degraded. This is especially true with ECL, where signal levels are 1 V or less.

If possible, use a Probe Tip to Circuit Board Adapter (test point). If not, use a short ground lead such as the Spring Ground Contact.

Conclusion

As speeds continue to increase in electronic devices, there will continue to be probing challenges. However, the greater the understanding of system bandwidth, loading effects, and physical connection to the DUT, the greater the accuracy when probing high-speed signals.

References

ABCs of Probes, see www.tek.com.

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