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NETWORK

Why are oscilloscope probe amps at the tip?

Arthur PiniLawrence Jacobs, - August 22, 2014

Recently, an EDN reader asked "Why do oscilloscope manufacturers put amplifiers on their probe tips rather than in the oscilloscope?" Placing the amplifier in the probe minimizes signal losses in the probe and cable, but how? To understand how and why, you need a basic understanding of probes and input impedance.

An oscilloscope probe connects an oscilloscope's input to a voltage node that you want to measure. Traditionally, we have used three types of probes: high-impedance passive probes, low-capacitance transmission line probes, and active probes.

The most common probe type is the high-impedance passive probe. **Figure 1** shows a simplified schematic. This probe uses a compensated voltage divider (matched resistive and capacitive dividers) to drive the probe cable and oscilloscope input capacitances. These probes have a rated bandwidth of 500 MHz, but you should consider the limitations imposed by the input capacitance.

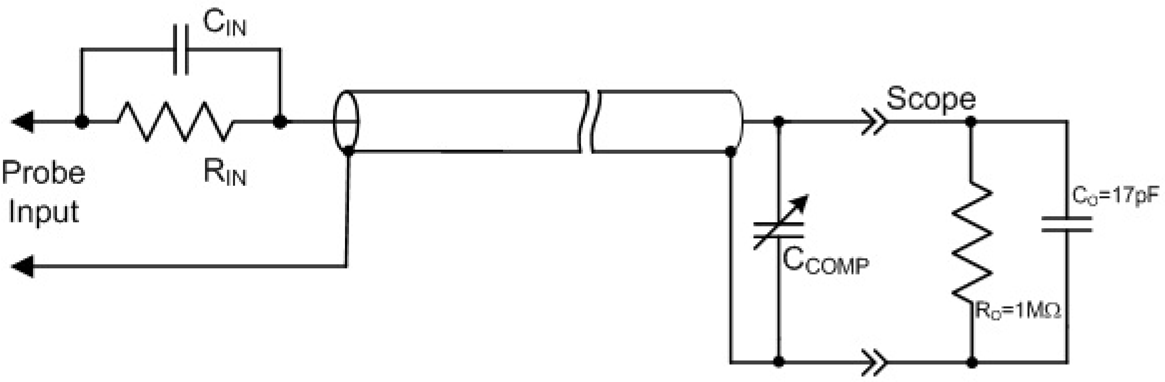

Figure 1. A high-impedance passive probe uses a matched capacitive and resistive divider.

An oscilloscope will have input capacitance of perhaps 15-25 pF. A coaxial cable would have capacitance of around 10 pf-30 pF per foot. The total capacitance might be about 80 pF. Thus, simply using a shielded cable to connect the oscilloscope to a DUT (device under test) would load the circuit with this capacitance. At 10 MHz, the impedance is about 200 Ω, which could significantly attenuate the voltage that you are trying to measure.

We can increase this input impedance by using a capacitively compensated voltage divider to divide the signal's amplitude by a factor of 10. Such a compensated divider would result in an input capacitance of 9 pF minimum at the probe tip with 10x attenuation, increasing the probe loading impedance by approximately 10x. Input capacitance could be further reduced by increasing the probe attenuation, but doing so would reduce the signal coming into the oscilloscope and make it difficult or impossible to measure small signals. In practice, a 10x attenuation represents a good compromise between signal amplitude and loading impedance.

At higher frequencies, however, even this lower value of probe capacitance can be too much. At 500 MHz, a 9-pF probe capacitance would be about 35Ω, which would load down the voltage of all but the lowest impedance circuits.

The input capacitance can be drastically reduced if you think of the coaxial cable as a transmission line. If the oscilloscope input is terminated with 50Ω, the impedance looking into the probe end of the cable would be a constant 50 Ω independent of frequency. This very low loading impedance can be increased using a voltage divider; a 450 Ω series resistor will divide the amplitude by 10x and result in a relatively constant loading impedance of 500 Ω. A low capacitance or transmission-line probe (Figure 2) utilizes a terminated transmission line.

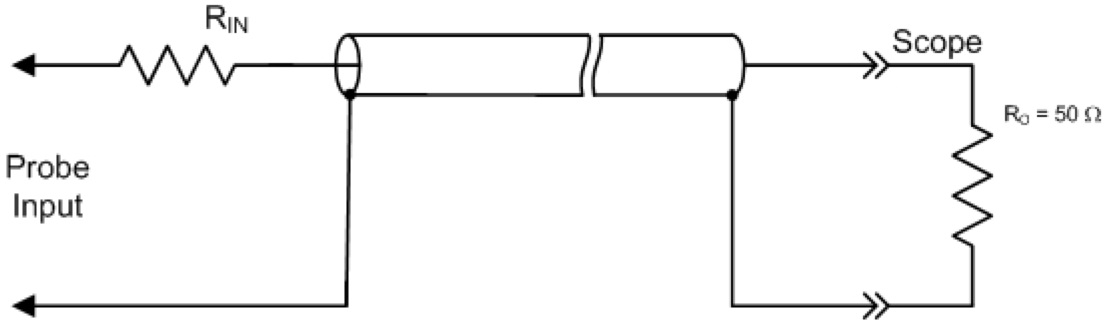

Figure 2. A transmission-line probe drastically reduces input capacitance, but it also reduces input resistance, thus reducing overall impedance.

The input capacitance of a terminated transmission-line probe is quite low, typically about a small fraction of a picoFarad. The limiting factor with this probe is the low input *resistance*. For a 10x probe, the input resistance is only 500 Ω, which can load circuits too heavily.

This brings us to active probes (Figure 3). The active probe uses a compensated voltage divider that drives an amplifier. The amplifier's buffered output in turn drives a coaxial cable terminated in its characteristic impedance, just like the transmission-line probe. The amplifier also isolates the probe from the capacitive loading of the cable and the input circuitry of the oscilloscope.

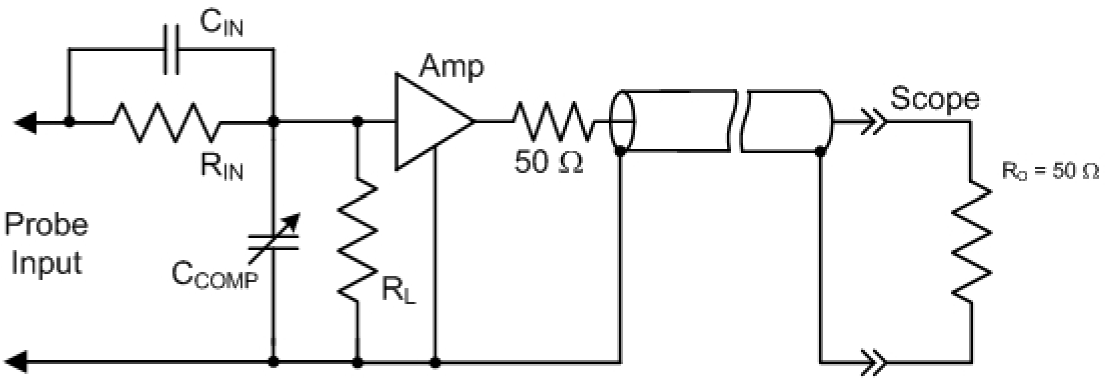

Figure 3. An active probe has a buffered input that drive a 50-Ω transmission line.

An active probe still needs a low input capacitance, but that is much easier to accomplish in the small geometry of a probe tip. A high impedance buffer amplifier can be designed to have in input capacitance of perhaps 4 pF. A compensated divider of 10x would further reduce input capacitance as well as to allow larger input voltage swing, yielding an input capacitance of about 0.4 pF. In reality, an amplifier needs input-protection devices and it adds the stray capacitance of the probe's tip metal, so an input capacitance of about 0.5 pF to 4 pF is more realistic.

Figure 4 shows the probe input impedance (based on the specified input resistance and capacitance) as a function of frequency for the three probe types discussed. At the 500 MHz upper limit for the passive probe, the input impedance is only 34 Ω. At the same frequency the input impedance of the transmission line probe is 359 Ω for the active probe, 530 Ω. This capacitive impedance will load down the signal being measured.

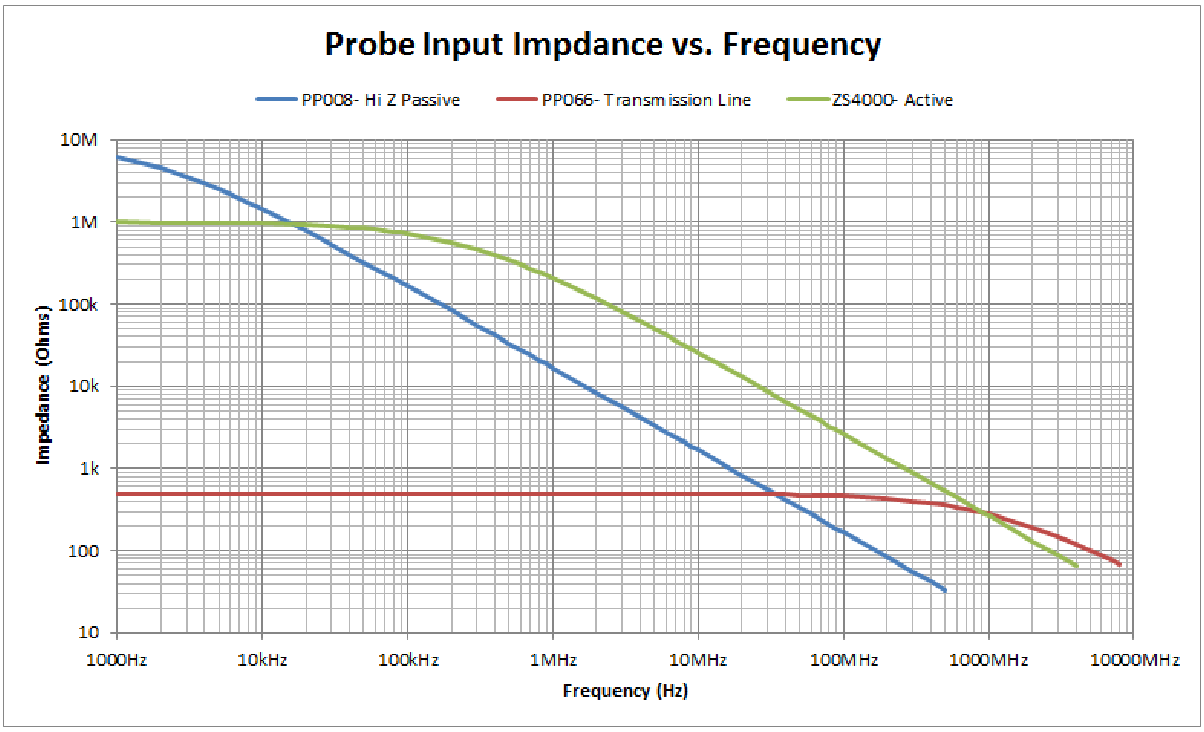

Figure 4. An active probe maximizes input impedance over the widest bandwidth compared to passive and transmission-line probles.

Examples of probing effects

The example in **Figure 5** shows a step waveform in a 25-Ω system (50-Ω source and load impedance). Even in such a low impedance environment, the effect of capacitive loading from a passive probe can easily be seen.

Measure	P1:rise(C1)	P2:rise(M1)	P3:rise(M2)	P4:---	P5:rise(M3)	P6:rise(M4)	P7:---	P8:---
value	456 ps	501 ps	1.838 ns					
status	✓	✓	✓					

C1 AVG DC50 100 mV/div 0.00 mV
M1 100 mV/div 10.0 ns/div
M2 100 mV/div 10.0 ns/div
Timebase -10.0 ns 10.0 ns/div 250 S 2.5 GS/s
Trigger C1 DC Stop 0 mV Edge Positive
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Figure 5. Comparing the effects of capacitive loading of a passive probe (PP008) and an active probe (ZS4000). Click on the image to enlarge.

In Figure 5, the input step has a rise time of about 500 ps prior to the passive probe being placed on the signal. When the PP008 (input C=9.5 pF) is placed on the step, the rise time increases to 1.8 ns and there is considerable distortion on the leading edge. Using a ZS4000 active probe (input C=0.6 pF) results in no noticeable degradation in the signal fidelity.

The key to a low capacitance design is maintaining small geometry for all the conductors near the probe tip. This is also consistent with keeping the tip small so that it can physically interface with the components on our crowded circuit boards.

The capacitive loading of a probe tip has another effect beyond loading of the DUT. A single-ended probe requires a ground connection. This ground lead has inductance associated with its length. The inductance, in combination with the input capacitance of the probe, will cause ringing at the resonant frequency of the LC circuit **Figure 6**.

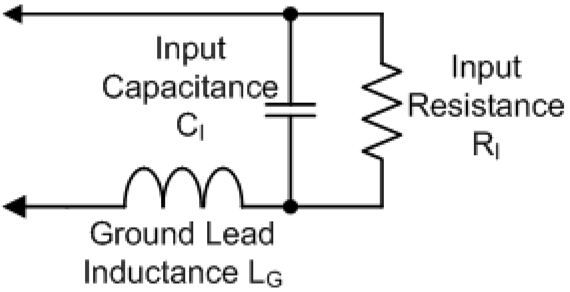

Figure 6. An oscilloscope's ground lead adds inductance to the circuit under test.

The frequency of this resonance can be estimated by using the rule-of-thumb of 20 nH/in. for the inductance of the ground lead. That inductance will resonate at a frequency (f_r) of:

$$f_r = \frac{1}{2\pi\sqrt{L_G C_I}}$$

To avoid distorting your measurement, the resonant frequency should be much higher than the signal that you are trying to measure. You can raise the resonant frequency by using a shorter ground lead, using a probe with lower input capacitance, or both.

As an example, we can make a measurement of a fast voltage step using a PP008 probe (input C = 9.5 pF) with a 6-in. ground lead (˜120 nH). With these values, the ring frequency will be about 150 MHz and can be easily seen on the measured waveform. The same ground lead was used with a ZS4000 probe that has only 0.6 pF input capacitance. This has a resonant frequency of almost 600 MHz and settles much faster, as can be seen in **Figure 7**.

Figure 7. Comparing the effect differing values of input capacitance have on ringing due to ground lead inductance. The active probe(ZS4000), with the lower capacitance settles much more quickly and has a higher frequency. Click on the image to enlarge.

Higher bandwidth probes come with short, fixed length ground leads. Using the shortest ground lead with the active probe from the above plot would let you measure the step voltage with virtually no ringing or rise time degradation. It is important not to try and extend these leads as the increase in inductance and capacitance will significantly affect the probes performance.

So getting back to our original question: "Why is the amplifier of an active probe in the tip of the probe and not in the oscilloscope?" The answer is that by placing the amplifier near the probe tip, oscilloscope manufacturers can employ a compensated voltage divider in the probe tip to increase the input impedance and the input voltage range of the probe. At the same time, an active probe can buffer the effects of the interconnecting cable from the probe. You can get a similar effect, without the amplifier, using a transmission line probe but you have to be able to live with the low input resistance.

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