VISIBLE REFLECTIONS IN COAX CABLE

Sam Wetterlin

April 28, 2010

The purpose of this document is to demonstrate visible reflections in a coaxial cable, and relate them to the math of reflection coefficients. We will also show that the reflections can be used to measure the length of the cable, or to find the location of a cable defect.

The test setup requires a source of a clean square wave with 50-ohm output impedance. This square wave is run through a resistive splitter, one output of which goes to a coaxial cable terminated in a variety of possible ways, with the other output of the splitter going to the 50-ohm input of an oscilloscope. I used the 1 MHz square wave from my Calibration Source, because it provides a square wave with minimal over/undershoot and an excellent 50-ohm output impedance. The oscilloscope had a bandwidth of 400 MHz, but a smaller bandwidth could also work. Figure 1 illustrates the test setup.

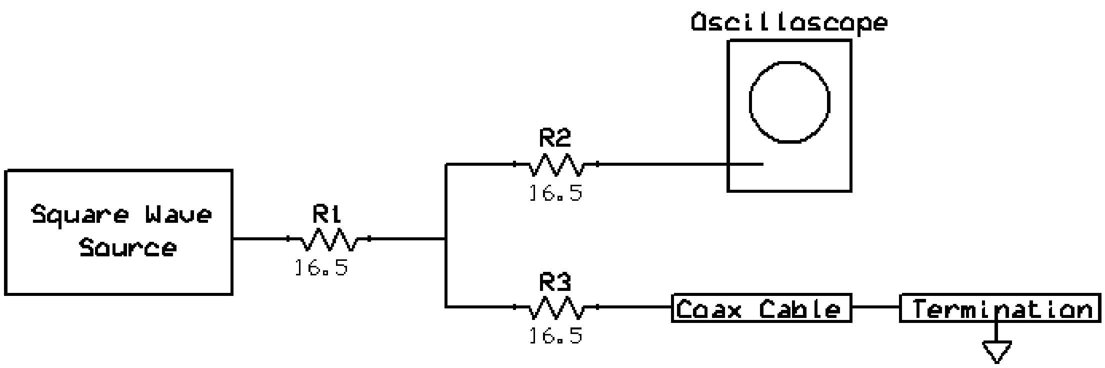

Figure 1—Test Setup

As we will see, the scope will show the amplitude of the square wave as it begins to travel down the coax cable, and will show any reflection that returns. It is important to keep in mind that the returning reflection gets split between the scope and the square wave source, with the result that the scope will show exactly half the actual amplitude of the reflection. The scope input needs to be set to 50 ohms, to minimize reflections from the scope.

Photo 1 shows the scope display with the coax cable terminated in 50 ohms. With that termination, there is no reflection and we simply see the amplitude of the square wave as it enters the cable.

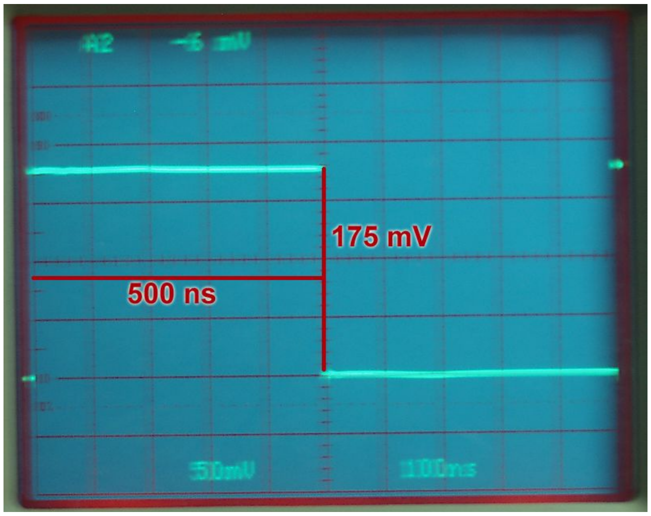

Photo 1—Cable terminated with 50-ohm load
(Subsequent photos are less fuzzy.)

Photo 1 shows one cycle of the 1 MHz square wave, whose "high" level is 175 mV and lasts 500 ns. This amplitude is the result of voltage division between the source's 50-ohm output impedance and the 50 ohm load presented by the cable plus termination. A very clean square wave is displayed, as there is no reflection from the 50-ohm load.

The Open

Photo 2 shows a similar display, with the cable now terminated with an open circuit—i.e., the 50-ohm termination was removed.

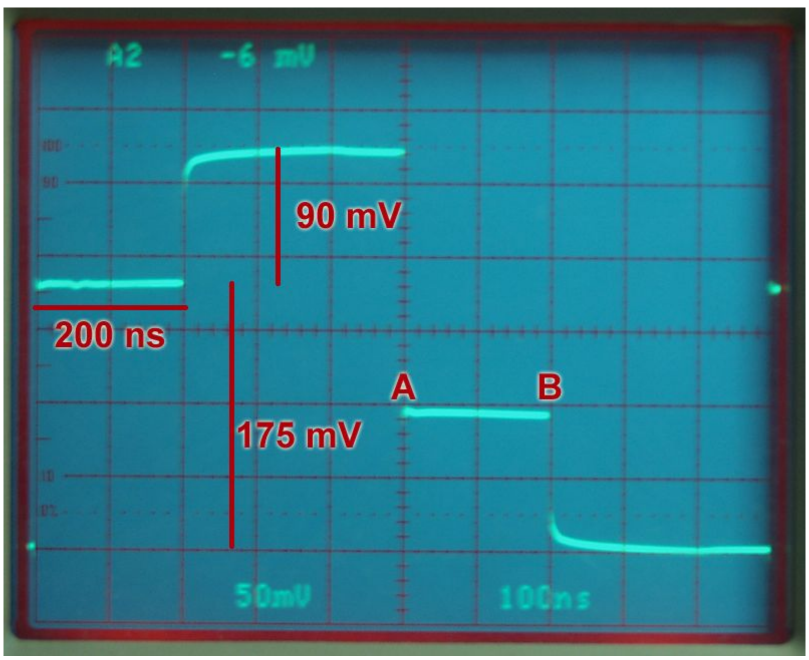

Photo 2—Cable terminated with an open circuit
The 90 mV jump represents half the reflection

Photo 2 can be confusing unless you read it in pieces from left to right. At the left side, the square wave goes high, at the same 175 mV amplitude shown in Photo 1. This is because the coax cable has characteristic impedance of 50 ohms. At this point, the square wave does not "know" what is at the end of the cable, and the current/voltage relationship is based on the cable's characteristic impedance.

After 200 ns (the time scale is 100 ns/division), the voltage goes up by another 90 mV. This is because the square wave has traveled to the end of the cable, reflected off the open circuit, and returned to the beginning of the cable. The reflection occurs because the current arriving at the end of the cable has nowhere to go, other than to return to the beginning of the cable. Recall that the resistive splitter in the test setup causes the scope to show half the actual reflection amplitude. This means the reflection is 180 mV equals the original signal amplitude (at least to the accuracy we can read). This in turn means that the reflection coefficient, which is the reflected voltage divided by the incident voltage, equals 1, which is well established for open circuits.

Therefore, the first voltage step in Photo 2 shows the incident voltage, and the second step shows the incident voltage plus reflected voltage. If you view the first step as a new reference level, the change from that level to the level of the reflection step equals the reflection.

We have only looked at the first half of the display in Photo 2. Normally that is all we need to do. But we will look at the second half for the open circuit. At point A, the voltage suddenly drops. This is because the "high" section of the incident square wave has reached its end, so the level drops by about 175 mV. 200 ns later at point B, the reflected square wave makes its transition from high to low, and the voltage is back to where it started at the left of the display, before the original low-to-high transition.

The useful information in Photo 2 is (1) the 200 ns time delay for the reflection to appear, and (2) the fact that the level of the reflection is 100% of the incident voltage, for a reflection coefficient of 1. That reflection coefficient shows that the cable is terminated with an open circuit, and the 200 ns time delay shows that the cable length is approximately 70 feet. That length is determined by using the rule of thumb that a signal travels 1 ft/ns at the speed of light. For this coax cable, the velocity factor is about 0.70 (i.e. the propagation velocity is about 70% of the speed of light), so the signal travels 0.7 ft/ns. Finally, the 200 ns delay represents a round trip in the cable, so the one-way travel distance is half that, or 100 ns. The cable length is thus

Cable length = 0.7 ft/ns x 100 ns = 70 feet

If, instead of having a cable purposely terminated with an open circuit, we had a long cable with a break in it, we would have determined that the break is approximately 70 feet from the beginning of the cable.

The Reflection Coefficient Formula

The formula for determining the reflection coefficient is well known, but what does it really mean? First of all, here it is:

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} \qquad \text{(Equation 1)}$$

Γ (gamma), the reflection coefficient, is a complex value calculated from the impedance (in our case, the impedance terminating the cable) and the reference impedance (in our case, the characteristic impedance of the cable). For an open circuit, Z is infinite and Γ is one.

Looking back at Photo 2, the initial voltage at the cable entrance was 175 mV. This represented what the 50-ohm source could produce in a 50-ohm load (the cable), and was the result of the voltage divider formed by the source and load impedances. However, in the longer view it turned out that the ultimate load was infinite (open). The voltage the source could produce with an infinite load is twice that which it could produce in a 50-ohm load. After 200 ns, it became clear that the ultimate load was actually infinite, and the voltage at the cable entrance jumped up to what it would be for an infinite load. The amount of that jump is what we have labeled as the reflection (though in our test setup the jump is only half the reflection amplitude). This illustrates a very basic point about reflections: **the reflection of a Device Under Test (DUT) is the voltage that the source can produce in the DUT impedance, minus the voltage the source would produce in a 50-ohm load (that subtracted amount being the "incident voltage"). The reflection coefficient is that reflection divided by the incident voltage.** We won't go through the algebra here, which is simply a matter of calculating a couple of voltage divider outputs, but it leads directly to Equation 1.

In Photo 2, the incident voltage is the initial level of the square wave, and the reflected voltage is twice the amount of the jump that occurs when the reflection returns at 200 ns (keeping in mind that Photo 2 shows only half the actual jump). The reflection coefficient is the ratio of the reflected voltage to the incident voltage.

We have devoted a lot of space to examining the reflection produced by an open circuit. We will now examine some other terminations, a bit less exhaustively.

The Short
Photo 3 shows the scope display with the coax cable terminated in a short circuit.

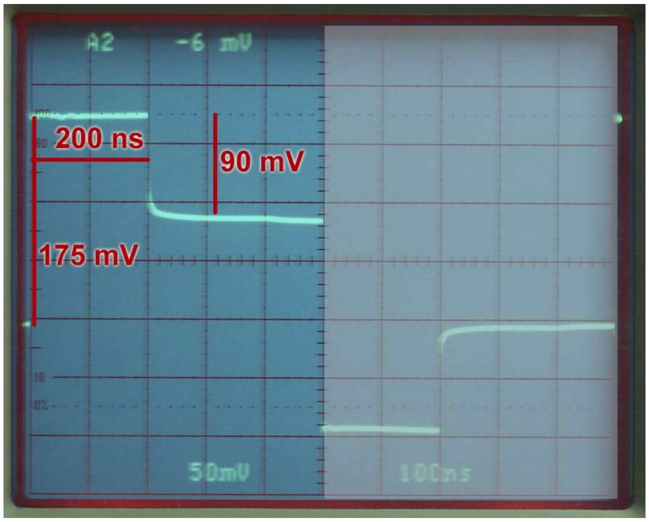

Photo 3—Cable terminated with short circuit
The 90 mV drop represents half the negative reflection.

The right half of Photo 3 is faded to facilitate focusing on the left half, which has all the information we need. Again, the initial signal level is 175 mV, but this time after 200 ns the voltage level drops, rather than increasing. The drop represents half the reflection, so the reflection from the short circuit is 100% but negative, for a reflection coefficient of negative 1. This is also the value that would be produced in Equation 1 with Z=0.

Capacitance
Photo 4 shows what happens if we terminate the cable with a capacitor (0.001 uF or 100 pF—I don't recall).

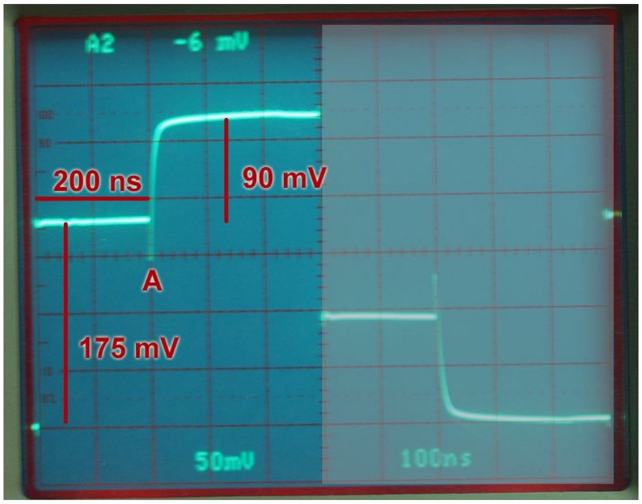

Photo 4—Cable terminated small capacitor

The cable terminated with a small capacitor looks much like the cable terminated with an open circuit, except for the “glitch” at point A in Photo 4. When the square wave reaches the capacitor, there is initially an unrestricted current flow into the capacitor, as with the short circuit. But as the capacitor becomes charged, the current is reduced. When it is fully charged, no more current can flow, and the capacitor looks like an open circuit. Thus, the response looks briefly like a short, with a negative reflection. Soon after, the response looks like an open circuit, with a positive reflection. A larger capacitor would spend more time looking like a short before transitioning to the open response.

Inductance
Photo 5 shows what happens if we terminate the cable with an inductor (roughly 300 nH).

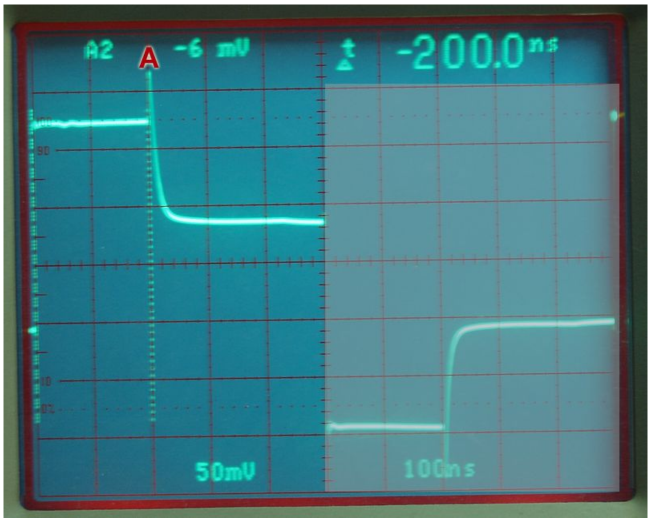

Photo 5—Cable terminated small inductor

The cable terminated with a small inductor looks much like the cable terminated with a short circuit, except for the “glitch” at point A in Photo 5. When the square wave reaches the inductor, there is initially strong resistance to current flow into the inductor, as with the open circuit. But the inductor gradually accommodates the current flow, eventually becoming just like an open circuit. Thus, the response looks briefly like an open, with a positive reflection. Soon after, the response looks like a short circuit, with a negative reflection. A larger inductor would spend more time looking like an open before transitioning to the short response.

Photo 5 also illustrates a facility provided by some oscilloscopes. Cursors are place at the beginning of the square wave and at the beginning of the reflection, and the time interval is automatically displayed as 200 ns. This can significantly increase the accuracy of time measurements when the start and end points don’t align with division markers.

Multiple Reflections
We have assumed that once the reflection returns to the beginning of the coax cable, it gets absorbed and we have no more reflections to look at. This is why it is important in Figure 1 that the square wave source has a 50-ohm output impedance, and the scope has a 50-ohm input impedance. Otherwise, some of the returning reflection will be re-reflected, confusing the simplicity of the oscilloscope display.

There is another possible source of confusion. If the cable contains a defect somewhere in its midsection that causes a partial reflection, then our scope display will show a small reflection from that defect, followed by whatever reflection results from the cable termination. But the reflection from the cable termination, when it returns to the backside of the defect, will be partially transmitted and partially reflected. The part that is reflected will return to the cable termination and create some additional reflection. Thus, analyzing the reflections that occur after the very first one can become very involved.

For the simple case of a coax cable that is expected to be properly terminated in 50 ohms, the first reflection shown on the scope will show the location and nature of the first defect in the cable. Subsequent reflections can be analyzed, but they can quickly become complicated if there are several sources of reflections. With our 1 MHz square waves, confusion is especially likely for any reflections that arrive after 500 ns, when the incident signal makes its high-to-low transition. For our terminated cable, this in turn means the cable should not be longer than about 175 feet, or even the first reflection will not occur in the first 500 ns.

Time Domain Reflectometry

The analysis we have been performing is a simplified version of "time domain reflectometry" (TDR), which typically involves sending very short pulses at varying intervals, and watching the reflections that return. It is basically radar inside a wire. In our case, the reflection ended up superimposed on top of the test signal (a square wave), but in pure TDR the test pulse is short enough that the test pulse is complete before the first reflection returns. For example, if the pulses were only 100 ps wide, we could examine multiple reflections from features that were very close together with each signal displayed on its own, without being combined with another signal. Of course, such narrow pulses cannot even be displayed on inexpensive oscilloscopes.

Conclusion

We have shown how reflected square waves can be viewed and even measured on an oscilloscope. The purpose is in part educational, to demonstrate the nature of reflections in coax cable. But the timing and amplitude of the reflected signal can also be used to learns something about the cable termination, the length of the cable, and the existence and location of defects in the cable.