Physics 623
Transmission Lines and Characteristic Impedance (including 3 prelab questions)

February 01, 2026

In this lab, we are going to build the circuit of Figure 1 to investigate propagation characteristics of transmission lines. From reflection measurements, we will determine the propagation speed of waves inside a transmission line, and measure its impedance. Noting Figure 1, consider a transmission line of length L, impedance Z_0. Let's denote the propagation speed of electromagnetic waves inside the line as u_0. We supply a voltage pulse with time duration of T at point C of the circuit. When the pulse hits point B, due to impedance mismatch, part of the wave is reflected. This reflected wave encounters a similar phenomenon when it reaches point A. As a result, multiple reflections can be observed at points **A** and **B**.

Prelab Q1. Assume that $T << L/u_0$, $Z_T = \infty$, and 5.6 k $>> Z_0$. Plot what you would expect to see on points **A** and **B** (if we look on a scope, for example).

Prelab Q2. Repeat (1), but now assume that $Z_T = 0$ (short circuit). What would you expect to see on points **A** and **B**?

Prelab Q3. Repeat (1), but now let's introduce some loss to our system (in reality every circuit is lossy). Let's assume that, while propagating from A to B, 10% of the wave is attenuated. What would you expect to see on points **A** and **B**?

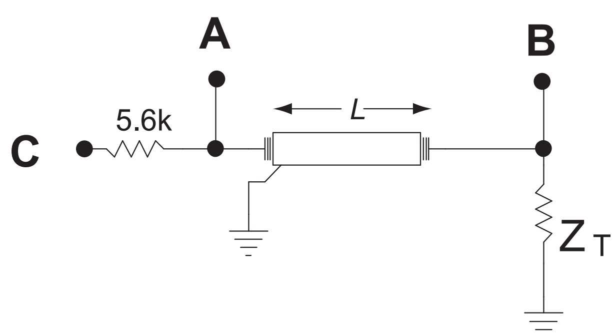


Figure 1:

1 Lab Instructions

1.1 Purpose

- To experimentally determine the speed of signal propagation and the characteristic impedance of transmission lines.
- To interpret these measurements in terms of the capacitance and inductance per unit length of the cable.
- To observe termination effects in cables and interpret them in terms of virtual running waves.
- To observe clipping, capacitive charging and resonance in cables and interpret the observations in terms of the previously measured characteristics.

1.2 Procedure

At low frequencies, we can approximate the wires and cables that are used to connect the separate elements of the circuit as ideal connectors which transmit voltage and current unchanged in magnitude. However, at high frequencies ($>\sim$ 100 MHz) and in pulse applications, this approximation breaks down and the cable itself must be considered an integral part of the circuit with its own characteristic properties using Maxwell's equations.

The line you will use for these measurements is a coil of coaxial cable (RG-58 or a similar RG-223/U which is a double-shielded version of the same Z_0 and u_0). The length of the cable L is indicated on the attached tag. Two of the measurable parameters associated with the line are: $\mathrm{Z_0}$ = Characteristic Impedance and $\mathrm{u_0}$ = Speed of Transmission.

To measure these quantities, you must use an extremely short timing pulse. First, use the coaxial cable to connect the Pulse Generator output to the scope input (to "CH 2").

1. Adjust the pulse generator to emit a pulse of approximate width4 about 10 to 30 ns (1 ns = 10^{-9} s).

2. You want (most of the time) to look at single pulses, so the pulses you put in should be spaced far enough apart that all the back and forth reflections have died out before another pulse is injected so you don't get confused. So make this time very large compared with the L/u_0 time by setting T_0 to 300 ms.

3. Adjust the scope sensitivity, time/cm and trigger so you can verify the pulse width. Start out with auto trigger, 100 ns/cm, and $5V$/cm and the trigger point at the center until you find your pulses, since they won/t show up at higher sweep rates. (And to avoid cranking the trigger position knob on the scope forever, get it on center at a very low sweep rate and keep it there as you increase the sweep rate to 100 ns/cm)

4. Now make the circuit in Figure 1 to study the reflected pulses and measure the cable attributes.

   Remove the cable you have just used to set the pulse parameters and attach vertical "tees" to scope channels 2 and 4. Connect the far end of the long transmission line (point B on the schematic) to one leg of the channel 4 tee (leaving the other post open at this point is equivalent to having Z_T equal to Z_{in} of the scope), and the near end (point A) to the channel 2 tee. Attach a standard tee to the other post on this tee.

Attach the small shielded box which has within it a $\sim$ 5.6 k resistor ($\pm$ 10%) to one end of this tee using a double-male adapter and the other end of the box to the signal generator (point C) using a short cable. It is very important in constructing the circuit that the signals be shielded as much as possible and that the leads be as short as possible. This minimizes the noise pick-up and is a general rule to be observed at all times in the laboratory. (In this lab, it is important for all connections to avoid extraneous reflections from changes in impedance.)

Verify that your circuit is equivalent to the circuit in Figure 1.

5. The high impedance input at the scope and 5.6k resistor lead to repeated reflections of the pulses at the two ends of the cable with an inversion at each reflection.

   With the scope, examine the pulse on the near end with the far end open ($Z_T = \infty$) and shorted ($Z_T = 0$). In the open ended case, you may be interested in examining the signal at the far end on the second scope channel.

   Interpret your observations.

6. Measure, as carefully as you can, the length of time required for the signal to make 10-20 round trips on the cable. Using the length of the cable, calculate the speed of propagation u_0 of the signal. Remember that, between any repeated shape upon the scope, the signal must travel **twice** the length of the cable!

   Estimate and record your uncertainty in this velocity.

7. To measure Z_0, the characteristic impedance of the cable, connect a logarithmic potentiiometer (not wire wound) to the far end of your cable and vary it to minimize the reflections. *Because of stray capacitance, you may see a small differentiated signal. Try to minimize the algebraic average of the residual signal.* Then with the digital VOM, measure the value of the resistance by plugging the pot into you rDVM. Use a BNC adapter to avoid changing the resistance of the connections. The value you read is then an estimate of Z_0 .

   Estimating your uncertainty in this quantity is tricky. You can read the value from the DVM easily to 6 figures, but the limitation is how preicsely you could set the potentiometer ("pot" hereafter). Since you don't know the reading until after you've finished the setting, you don't have the usual problem of trying to reduce errors by making a large number of measurements. But the problem remains that the shape you decided is best is a personal decision and someone else might well have a different idea. You and your partner should each make a measurement.. You can take the difference as a reasonable lower limit to your uncertainty in Z_0, so record it with the measurement. If you have time, you could each make two measurements.

8. From these measurements determine the inductance per meter and the capacitance per

meter using the relations:

$$u_0 = \frac{1}{\sqrt{L_L C_L}}$$

and

$$Z_0 = \sqrt{\frac{L_L}{C_L}}$$

Propagate the uncertainties through from your estimates above. Use the shortcuts described in the appendix that was handed out (and is available on the website) It is not necessary to show any calculations.

9. Qualitatively describe the reflections obtained by varying the termination resistor from $R_T = 0$ to $R_T = \infty$.

10. Next set the pulse width to 250 ms and remove any termination from both ends of the line (so now 5.6 K at the near end and 1 Megohm at the far end. Observe the results at the near end. What you see is the sum of all the reflections coming back from the far end and summed as they are reflected back. All are positive because of the high termination resistance at both ends, but there is a loss in amplitude because the 5.6 K resistor is not infinite.. And each is delayed by a round trip time.

    The result is that you see a "stairstep" pattern at the near end which corresponds to the capacitive charging of your transmission line. It is clear that the effective capacitance is $C_{eff} = LC_L$, where L is the length of the cable. Note that the R in your lumped-circuit's RC is the 5.6 K resistor in the box (plus the 50 ohm output impedance of the pulse generator). Draw the low frequency equivalent circuit showing component values and calculate the RC time constant of the exponential charging.

    Set the sweep rate to $\sim \tau$/div and the trigger point 2 div from the left end. Record the digital reading of this trigger point. Increase the vertical scale until there are about 3 steps/div, set the trigger level in the middle of the first step, and record the actual trigger level in your notebook. At this sweep rate on the scope, you are in the "transmission line" domain and can't use our "lumped circuit" approximations. Get a screen shot of this in your notebook.

    Now slow down the sweep rate by a factor of 10^3 or so while increasing the volts/div to keep the entire sweep on the screen. Each time you change V/div you will need to reset the trigger level to the voltage you recorded above. You will want to start using single-sweep at this point, and may need to switch to normal trigger (remember scope lab!). When your display shows the entire charging curve in the left 1/4 of the screen turn on horizontal cursors and put one on the fully-charged voltage at the far right of the screen. If it still seems to be going up with any detectable slope, reduce the seep rate and take another sweep. Set one cursor using many points on the flat end at the upper right and the other cursor on the flat part before the trigger. Record both voltages.

    Now calculate the voltage of the $V_{\text{high}} * (1 - e^{-1/RC})$ point and speed up the sweep rate to the fastest scale where this point is still on the screen. The quantity RC has dimensions of time and is called the time constant. If you close a switch at $t = 0$ to connect a capacitor C to a voltage supply at V_{high} through a resistor R with the other end of C connected to ground, as you have seen (or will see soon in lecture) this expression gives the voltage after one time constant ($t = RC$). Your bottom cursor *is* at ground, so if it shows a non-zero voltage, this should be added to *both* cursor voltages and added to your predicted value of $V(t = RC)$. Move the upper cursor to your calculated value (minus the offset) and switch to the vertical cursors. Move the left one to the exact time of the trigger point you recorded above. Set the right cursor on the intersection of the scope trace with the top cursor, eyeball averaging the local slope over nearby points. Read this time off the vertical cursor position and record in your notebook. Now switch to the horizontal cursors and do the same thing moving the *lower* cursor to the intersection point and record its voltage, correcting for any offset. Get rid of the cursor displays but keep all four cursors on the screen with the horizontal ones selected. Get a screen shot of this. There is no sign of steps at this resolution, but you know they are there. This shows that the E&M solution is alway correct, and the transition to where we can use lumped circuit approximations depends on how long the wires are compared to the amplitude and time precision we need. If the wires are randomly laid out we'll have wildly varying impedances of the length and a terrible mess of reflections, but still limited to their length over something close to the speed of light.

Solve your equation for $V(t)$ for RC and plug in your measured values for V_{high} and the time you measured for your calculated value of $V(RC)$. The accuracy of this comparison is probably limited by the accuracy of your measured values used to calculate C_{L}, dominated by those of. $Z_{mathrm0}$.

11. Set your pulse generator back to making $\sim 40ns$ pulses and replace the terminator at the entrance end of the transmission line. Then try the experiment on the last page of these instructions. This is just intended to give you some insight and you don't have to report anything - just tape a copy of that page into your notebook to indicate you did it. If you have lots of time, you could annotate this page with your observations or include some screen shots, but you should prioritize the next item.

12. Terminate the far end with a capacitor of C $\sim$ 500 pf and iset the pulse width to a little less than half the round trip time. You should only look at the near end and first reflection, the rest are much to confused after reflecting multiple times from the capacitor.

    For the capacitor termination determine which features of the pulse are related by Fourier transformation to high and low frequencies and analyze how these extreme frequencies "see" the capacitor. (Or think of the impedance of the capacitor when the voltage across it is changing rapidly or slowly.)

13. If you have time, replace the long transmission line with two or three meters of coax. Short the far end and terminate the near end with Z_0. This illustrates the use of "shorting stubs" in pulse shaping. For input pulses of any width we get an output pulse of width $2L/u_0$ where L is the length of the shorted cable, which can be chosen

at will. The negative going portion of the wave can be removed in practical situations with a diode clamp.

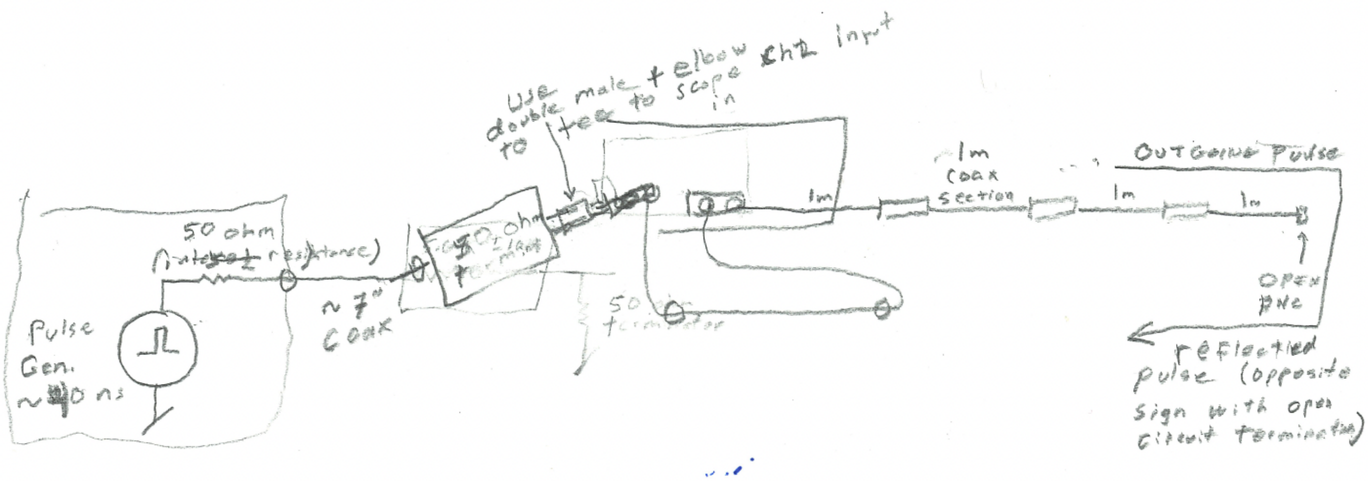
Physics 623 - Transmission Lines lab: Experiment add-on

This add-on is not required, but may be quite helpful in visualizing what is going on at the ends of the cable with various terminations. So it is recommended you at least try these observations. It isn't required that you put them in your notebook, but since your grade is in part based on convincing the instructor that you understand what you were doing, it can't hurt to have a couple of sketches or scope shots with a short note on what is happening.

So one question that comes up is why with open termination all the pulses except the first outgoing one are twice the height they should be. The answer of course is that at the ends of the cable you are always seeing the incoming and reflected pulse superimposed, so the voltages add.

So if you were to look near the end of the cable instead, you should see first the outgoing pulse, then shortly thereafter the returning one from the reflection from the open end. And both should be the correct height (half what you see at the end).

It's hard to tap into your long coax line, but you can achieve the same effect by adding some extra after the point where you are looking:



So use BNC "barrels" to splice together three or four of your 1 m lengths of coax (you can use tee's if we run out of barrels), connect this to a tee that goes to the scope and the far end of your long coax, and move your termination (short or open) out to the end of your extension.

Try this with both short and open terminations, and see if you can explain what you see. You can shorten your added length 1 m at a time until the outgoing and return pulses partially overlap and see what this looks like. (You can get a similar effect just by making the pulse wider at the pulse generator.)