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ECE320H1F: Fields and Waves
Laboratory 1: Waves On Transmission Lines

1 Objective

This is an investigation of the fundamental properties of travelling waves using a coaxial transmission line and a variable load.

2 References

[1] Your lecture notes.

[2] F. T. Ulaby and U. Ravaioli, *Fundamentals of Applied Electromagnetics*, 7th ed. Upper Saddle River, NJ: Pearson, 2015.

3 Experimental Procedure

Notation: In the following instructions, [Command] refers to a softkey on the oscilloscope front panel while *Command* refers to an option appearing on the buttons directly below the oscilloscope screen.

We will study the fundamental behaviour of travelling waves on a transmission line using the configuration of Fig. 1. The experiment has several test points where the voltage can be monitored, namely points A, B, C, D, E, and F. Test points A, B, C, and F are located on the test box (seen in Fig. 4), whereas test points D and E are located on the coaxial line. The terminating impedance of the line is controlled by the dial on the test box and determines the type of reflection seen at the load. There is also a "Source Switch" which is used to create reflections at the source; in the *Down* position, the signal passes through (no source reflection) while in the *Up* position, a $100\,\Omega$ resistor is added to the input of the line.

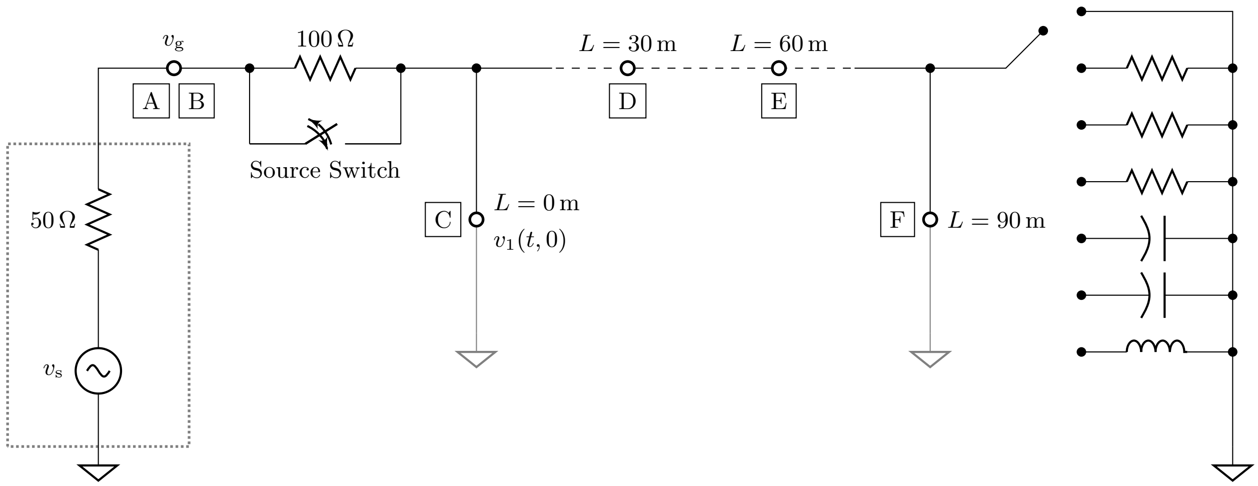


Figure 1 Circuit model for the experimental setup. Test points A, B, C, and F are located on the test box (seen in Fig. 4), whereas test points D and E are located on the coaxial line.

3.1 Instrumentation Background

The oscilloscope (also referred to as a 'scope') is a fundamental piece of instrumentation, providing a graph of a signal's voltage (on the y-axis) as a function of time (on the x-axis), also known as a *waveform*. Scopes generally measure the timing characteristics (such as frequency/period, duty cycle, and rise/fall times) as well as voltage characteristics (amplitude, maximum, minimum, mean, and average voltages) of waveforms. They can also be used to characterise some of the more complex behaviour in systems, such as e.g. noise.

The measured waveform will appear on the display at the front of the scope. The display is broken down, both horizontally and vertically, in a number of *divisions*. The divisions can be tuned to zoom in and out of a waveform to focus on traits of interest. There are two knobs for each of the vertical and horizontal controls. The first is controls the *position*, which allows the repositioning of the waveform in both time (left and right on the display) and voltage (up and down on the display). This way, an offset can be introduced in either time or voltage. In the case of two-channel scope, such as the one in the laboratory, the position can be adjusted to overlay the two channel measurements over each other for the sake of comparison. The second controls the *volts per division* and *time scale* in x and y, respectively. These allow zooming in and out of a waveform to focus on areas on interest.

Finally, the *trigger* system allows the scope to stabilize and focus on a signal. The *trigger level* sets the scope to "trigger" when the signal voltage reaches a certain threshold, aligning the waveform horizontally, resulting in a static display. The trigger can also be fine-tuned to focus on rising or falling signal edges. The effect of the trigger can be appreciated by raising the trigger level beyond the maximum voltage in the signal. This will result in a spinning and/or sweeping waveform on the display. Set the trigger level back down slowly, and the display will stabilize when the level reaches the maximum voltage of the signal.

3.2 Determination of the Characteristic Impedance Z_0

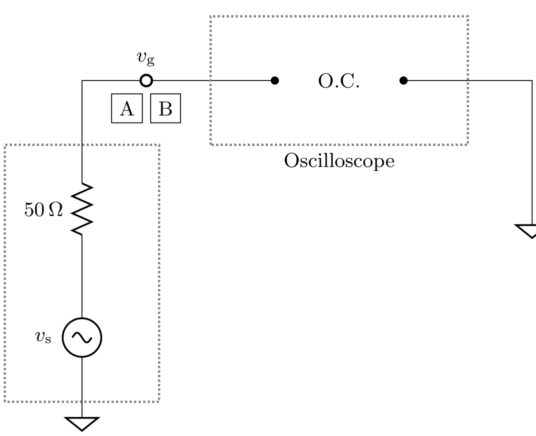
Set up a *Pulse* excitation on the voltage generator with the parameters listed in Table 1.

Table 1 Votage Generator Settings

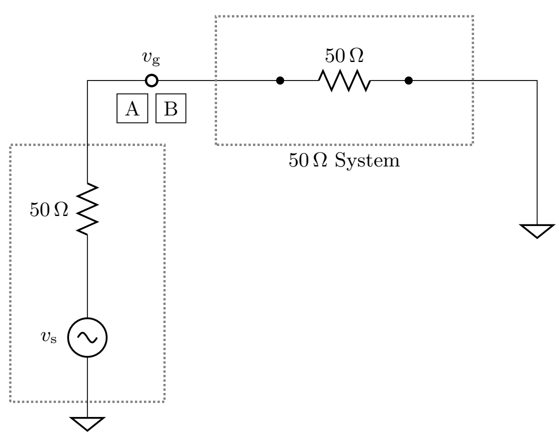
Parameter	Value
Amplitude	100 mV
Frequency	100 kHz
Pulse Width	200 ns

Connect the signal generator directly to the oscilloscope's *Channel 1* port to verify the output waveform and push the *Output* button on the generator. Verify the trigger settings ([Trigger] → Type "Edge" → Source "1" → Slope "Rising") and use the [Vertical] and [Horizontal] adjustment knobs on the oscilloscope to set the axes to 50 mV/div and 200 ns/div, respectively, to view the signal. The properties of the waveform can be measured using the on-screen cursors: press [Cursors] → Cursors.

Note that the measured peak-to-peak voltage will be double (i.e., 200 mV) of that specified on the generator. This is so since the generator assumes a 50 Ω load will be connected in series with its internal 50 Ω source resistance and thus the generator must actually supply twice the voltage specified by the user (apply voltage division to the equivalent circuit to see this result). The very large (effectively infinite) internal impedance presented by the oscilloscope 'load' means the full generator's voltage (i.e., double that specified on-screen) will appear across its output. This is illustrated schematically in Fig. 2.



(a)



(b)

Figure 2 Signal generator: (a) when connected to an oscilloscope with a very high internal impedance, and (b) connected to a 50 Ω system. The signal generator assumes it will be connected to a matched system, and hence generates exactly twice the voltage requested.

Connect the lab equipment as shown in Fig. 1 and ensure the "Source" switch is in the *Down* position. The signal generator is connected to port A on the test box ("Source Input"), channel 1 of the oscilloscope is connected to port B ("Source Monitor"), and channel 2 of the oscilloscope is connected to the port C ("Line Input"). **Ensure that the short-circuit knob is not connected on the test box, otherwise all loads associated with the dial will be shorted out.**

When the terminating resistance is equal to the characteristic impedance of the line there will be no reflection at the far end. The waveform at the input of the line (at point C) will be the same as the generator waveform except for a change in amplitude. Vary the terminating resistance and find the value for which the signal at point C shows no reflection. This is the characteristic impedance of the line and will be used for the remainder of the experiment. With this termination only one travelling wave will be excited.

3.3 Determination of Characteristic Impedance Using $v_1(t,0)/i_1(t,0)$

For a wave in the $+z$ direction $v_1(t,z)/i_1(t,z) = Z_0$. The voltage $v_1(t,0)$ can be observed directly in the experimental set-up at point C. To determine $i_1(t,0)$, put the source switch in the *Up* position, observe the generator voltage $V_g(t)$ at point B on the box, and note the value of the series resistor R ($100\,\Omega$). Simple application of Ohm's law gives Z_0 which should be the same as that of part A. A simple circuit model of the above can be seen in Fig. 3.

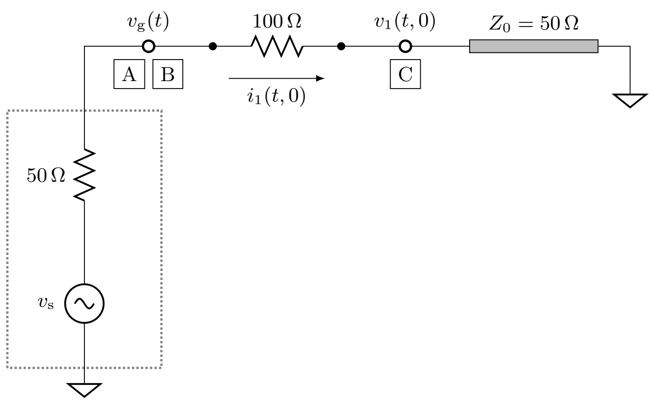


Figure 3 Circuit model for the experimental determination of Z_0 using Ohm's law.

3.4 Observation of Travelling Waves

With the terminating impedance set to equal Z_0 and the switch down, observe the voltage waveforms at various test points on the line (C, D, E, and F). To save the graphs to a USB disk, insert the device and press [Save/Recall] → *Save* → *Format Setup* → *Save to Temporary* → *File Name* → *Press to Save.* Record the time the pulse takes to reach each point on the line.

Plot the voltage waveform as a function of time for the different position using the same time base. Note the total delay experienced by the pulse as it travels to the various test points (Δt at $l = 0$ (port C), 30 m (port D), 60 m (port E), and 90 m (Port F)).

3.5 Determination of Velocity of Propagation

From the data of Section 3.4 and the physical length of the line (90 m), determine the velocity of propagation. Compare this velocity with the velocity of light in free space and determine the dielectric constant of the insulating medium used in the line. Using these results, calculate the theoretical waveform as functions of time at positions C, D, E, and F. Compare with the measured results of Section 3.4.

3.6 Simple Reflection

Set the switch in the Down position so that no multiple reflections occur between the source and the load. Also use a pulse width approximately equal to the total delay of the transmission line found in Section 3.4. Observe the voltage waveforms at the end points C and F with $R_L = 100\,\Omega$. Compare the measured reflection coefficient (V^-/V^+, i.e. the ratio of the magnitudes of the forward and backward travelling waves) with the expected theoretical value ($(Z_\mathrm{L} - Z_0)/(Z_\mathrm{L} + Z_0)$). Calculate the waveform as a function of position for the following time values: $t = T/2$, T, $3T/2$, $2T$ where T is the width of the pulse.

3.7 Multiple Reflections

Move the source switch to the *Up* position to put the $100\,\Omega$ resistor in series with the source and set the load resistor to be $20\,\Omega$. Using the same pulse width as in Section 3.6, observe and plot the voltage at points C and F. Determine the measured source and load reflection coefficients and compare to the expected theoretical values; plot the theoretical V vs. t graphs for these test locations. Repeat with a pulse width approximately 10 times the delay time of the line.

3.8 Input Impedance and Transmission-Line Electrical Length

(a) Terminate the coaxial line in a short circuit by attaching the shorting knob. Drive the line with a sine wave generator at a frequency of approximately 2 MHz through the series $100\,\Omega$ resistor (switch *Up*).

(b) Vary the frequency (1 MHz to 4 MHz in steps of 0.2 MHz, for instance) and observe the voltage waveform at the input of the line v_1, and at the generator terminal v_g on the same time base. Find three frequencies at which v_1 is a minimum.

(c) Determine the length of the line in terms of wavelengths at the noted frequencies and explain why minimum voltage values are obtained. What is the effect on the input current to the line at one of these frequencies?

(d) Terminate the line in a $0.01\,\mu$F capacitor. Observe v_1 versus frequency and note that the frequencies for the minimum voltage values should have shifted slightly. Compare with those of the short circuit case and explain. *Hint: Consider the locations of a short circuit and of a capacitive load on a Smith Chart.*

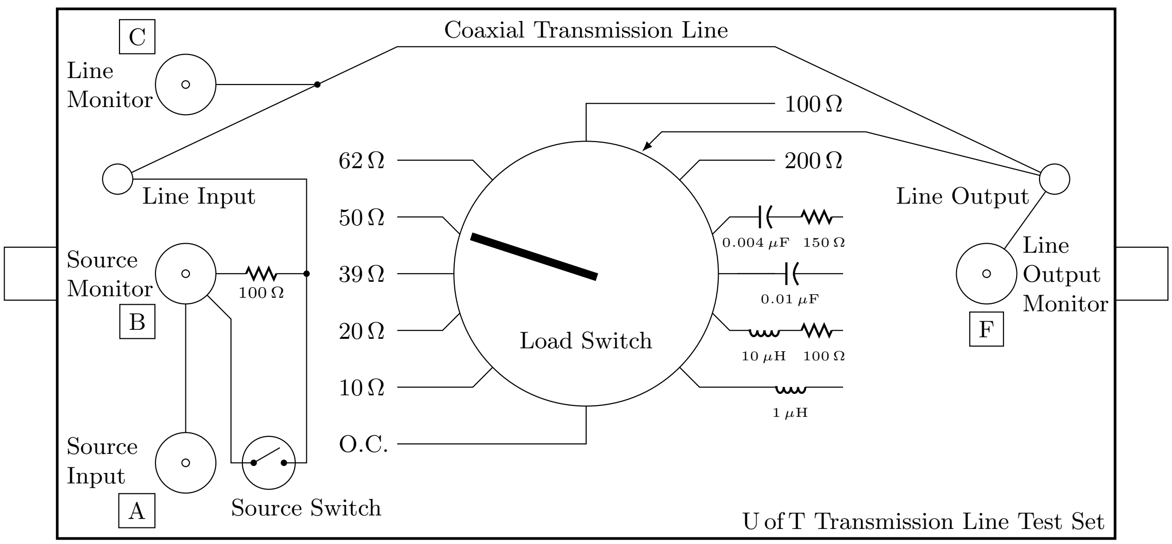


Figure 4 Test box used for this laboratory. Note that the left side of the test box (consisting of ports A, B, and C along with the Source Switch) corresponds to the left portion of the schematic shown in Fig. 1. The right side of the test box (consisting of port F and the variable load) corresponds to the rightmost portion of the schematic.