

PH424/524: 1-DIMENSIONAL WAVES

OSU Department of Physics
Winter, 2009

Laboratory exercise

Waves in transmission lines

We have discussed wave propagation in mechanical systems in class; here we look at an electrical analog. In this laboratory exercise, you will explore some of the concepts we have discussed in class, as well as a few that we have yet to discuss. This set up will remain available to you so that you can repeat measurements, or make new ones. By the end of this section of the class, you should be able to discuss, qualitatively, and quantitatively, the concepts of

- wave propagation
- impedance
- reflection
- transmission
- attenuation
- impedance matching
- (standing waves & resonance)

Reading: Read carefully section 10.3 (Cable waves) in Main's "*Vibrations and Waves in Physics*"

Read this lab guide (twice) thoroughly before class.

Consider:

How do cable companies find flaws and breaks in their transmission lines? This experiment might suggest a way to do it.

Experimental Assignment:

There are 3 experiments - they are stated in the boxes. Everything else is discussion to help you and guide your questions. You should complete the first two experiments, and make as much progress on the third as you can. If this means you don't "finish" the lab, so be it. Everyone is different – you will all accomplish different things. I want to provide enough material to challenge everyone in the class. The first experiment is easy, at least conceptually. The second one requires explores reflections of waves at boundaries (which we have discussed in class), but also requires you to extend the model to give a better explanation of the data. Some will find this challenging, others only moderately so. For the latter group, the third experiment provides further investigation.

There are “predictions” that you are asked to make. These are intended to prompt questions from you as you read, so that your discussions in class time will be more fruitful. Such predictions are generally a useful part of your report, because they can make your discussion more interesting.

You are required to turn in a report describing the experiments you have done, displaying your understanding of the phenomena listed above. You should collaborate on data acquisition and the interpretation of your results, but your written report must be independently generated. Your written report represents your synthesis and understanding of the material you have investigated. Please do not view this report as a major term paper, but rather as a detailed homework

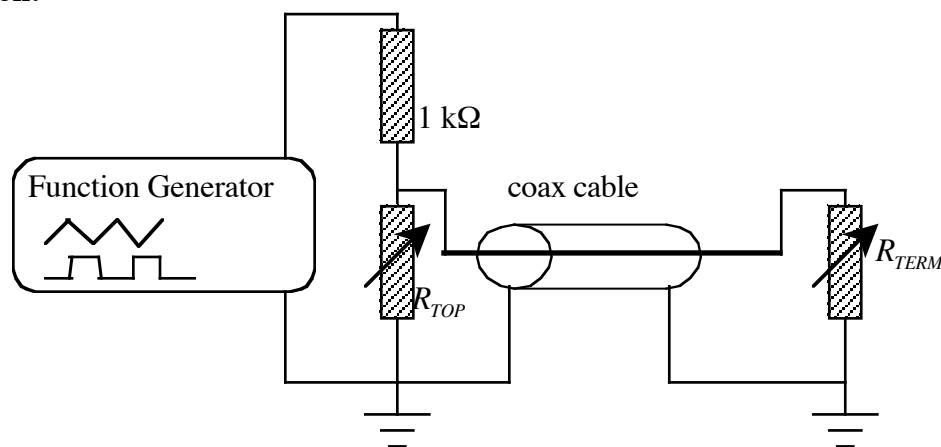
assignment. For further guidance, look in the writing guide, accessible from the General Information section of the class web page.

The basic idea: You have a cable that has a characteristic impedance, Z_1 , and you can propagate voltage waves and pulses in this cable. The cable should, in principle, be connected to a second cable, with another impedance, Z_2 . However, this second cable should really be infinite in length, and we'd like to vary Z_2 , and this is too difficult to do in practice. So, we in place of the second cable, we use a variable resistor (R_{TERM} in the diagram below), which has precisely the same effect. In class, we discuss what happens when a wave (or pulse) propagating in one medium encounters a different medium. Your job is to see how good this model is.

Equipment at hand:

- **Oscilloscope:** the trusty companion that should never be far from your side. Understand it; it is your friend.
- **Function generator:** used for generating pulses and waveforms of different frequencies.
- Various **transmission lines:** a.k.a. coaxial cables ("co-ax" cables). They have different impedances, and all have BNC* connectors on both ends. The center pin of the BNC connector connects to the central wire of the coax, while the outer connection is the ground and is connected to the outer braid. You MUST examine a piece of coax to the physical arrangement of the various components – ask the instructor. (*BNC is an acronym – ask your friend Wikipedia for more some history)
- Various connectors and wires:
- **Resistors** and **variable resistors:** to terminate the coaxial cable
- **Multimeter:**

Familiarization:



This is the basic circuit you'll consider. You'll apply some voltage (sine, pulse, square, depending on the application) with the function generator, and use an oscilloscope to measure the voltage at various places. For example, you might measure across resistor R_{TOP} and/or R_{TERM} as you change R_{TERM} . (R_{TOP} itself is variable also -- set it to the impedance of the cable and leave it at that value). **Pay attention** to the ground connections – they must all be connected to the same point, and when you connect the oscilloscope, connect the scope ground to the ground points shown above.

Familiarize yourself with the function generator (FG) and oscilloscope (scope). Experiment with the knobs on both the FG and scope. You will find it easiest if you start with the scope trigger set to the same channel as the FG. The FG is the signal source. Change its frequency and shape. Use the amplitude, duty cycle, and DC offset knobs. The scope is a measuring tool. Be sure you know how to take accurate time and voltage readings from it. Try to determine the effect of the AC/DC coupling switch, the triggering switches, and the view switch (ch1, alt, chop, add, ch2).

The role of the $1\text{ k}\Omega$ resistor in the circuit above is to provide a large resistance that draws essentially a constant current from the FG. Even if you change the variable resistors, the total resistance across the FG is not too different from $1\text{ k}\Omega$. The role of the variable resistor R_{TOP} is to eliminate reflections at the “top” end of the cable. Once you have a pulse propagating in the cable, you will see multiple reflections. **Vary R_{TOP} until the second reflection is eliminated. Then leave R_{TOP} at this value.**

Examine a spare bit of coaxial cable that is lying about. What is inside it? Where do you think the signal flows? Why is one connector braided on the outside? What is the stuff between the conductors? Why is it there? If an electrical wave propagates down this line, how fast do you think it will travel?

I. Measurement of the speed of propagation:

Description: Use the function generator to make a voltage pulse (you will have to think about how wide to make it and how often it repeats. Measure the pulse at the "top" end of the cable – you will see the trace as it enters and as it returns.

Prediction: Discuss with your group how long it takes for a voltage pulse to propagate down and back along the coax cable. Record your group’s prediction (qualitative and quantitative) .

Other questions: Record other questions that occur to you about this phenomenon. Perhaps they will be addressed later on in the lab. If not, they will be a guide for further study. For instance, how does this pulse propagate? How do the electrons move? How does ac current differ from dc current? Why use a pulse? What else do you want to ask?

<i>Experiment:</i> Measure the speed of propagation of a voltage pulse in your cable.

Some terminology: If the center cable and the outside braided cable of the transmission line (or coax cable) are connected by a resistor R_T at one end, we say “the cable or line is ‘terminated’ by R_T ohms” If $R_T = 0$, we say the line is ‘short-circuited’ or ‘shorted’ at that end. If R_T is infinite, we say the line is ‘open’. For the special case when R_T is equal to the impedance of the line, we say the line is ‘correctly terminated’ or ‘matched’.

You will probably be able to do the experiment most easily if your FG generates a waveform that approximates a pulse - i.e. the voltage is high for a short time, then low for a long time. You will have to find out what frequency works best.

Discussion: Are your experimental findings in accord with your predictions? If not, can you resolve the discrepancies?

II. Measurement of the reflection and transmission coefficients:

Prediction: Discuss with your group the size and polarity of a square voltage pulse that has propagated (A) down and back along the coax cable, and (B) down the coax cable when the cable is terminated by different resistances. Record your group's prediction (qualitative and quantitative). The presence of the different termination is not enough to account for the change in size. What else is important? You will have to "research" this topic (it's discussed in your textbook).

Experiment: Measure the size of the voltage signal across R_{TOP} and R_{TERM} (the position of the discontinuity) as a function of varying R_{TERM} , relative to the voltage pulse applied by the function generator. Compare quantitatively to your predictions.

Discussion: Are your experimental findings in accord with your initial and possibly revised predictions? Does the sign agree with your prediction? The size? What about limiting or extreme cases? As soon as you have recorded your values, ask an instructor to check that your values are reasonable. We discussed "dispersion" in class. What, if anything, do we assume about the dispersion relation for this system?

Pointers: It is important to understand that when we discussed in class incident, reflected and transmitted waves or pulses at a boundary between two media, we considered what happened at a particular position (which we called $x = 0$ for convenience) at a particular time. In this experiment, you measure the voltages at different positions, and different times, so you must account for the effect of propagation in your analysis, and also account for another important factor that we didn't put into our initial model.

III. Standing waves and resonance (PH 524 advanced; extra depth for PH424)

In the previous experiments, you used a voltage pulse, a superposition of voltage waves of different wavelengths and frequencies. Here we consider single frequency waves that reflect from the boundary. Thus the cable contains a voltage disturbance that is the sum of oppositely propagating waves.

Prediction: Discuss with your group the voltage between the center and ground (shield) in a semi-infinite (extends from $x = \infty$ to $x = 0$), perfect (resistanceless) transmission line in which a *sinusoidal wave* of frequency f propagates in this line at speed c , reflects off the end (call this $x = 0$) and propagates back. Consider cases when the terminating resistance is zero and when it is infinite. Record your predictions, in particular the voltage recorded when the oscilloscope is located at $x = L$ (qualitative, quantitative, sketches, ...). How would this voltage change as f was slowly changed?

Now, the important part - what would happen if the transmission line is resistive? This will take a little effort and some modeling or derivation to get quantitatively, but at least discuss qualitatively before you do the experiment.

Experiment: Use a single-frequency sinusoidal voltage and measure the voltage between the center and ground at the “top” of the cable for a number of frequencies f . Do this for both $R_{TERM} = 0$ and $R_{TERM} = \text{“infinity”}$). Use the values you were given or which you measured for the length of the line and for the speed of propagation of the wave.

Discussion: Demonstrate analytically or by modeling in Maple that your experimental results may be predicted theoretically.

Pointers: You have to decide which frequency range to use (1 Hz, 1 kHz, 1 MHz?), and whether you should vary the frequency by a factor of 2 or 3 or 4 or so in the chosen range or whether to vary it by orders of magnitude. To make these decisions, you must understand what is the interesting phenomenon you might see. (Of course you may find something interesting by random investigation, but experiments are usually more efficiently done when you have some idea of the right range to investigate.) As always, discuss with the instructors ...