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Transmission and Attenuation of Electromagnetic Pulses

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The purpose of this experiment is to acquaint you with some of the principles involved in the manipulation of electrical pulses. You will study reflections, measure termination resistances and signal propagation velocities for different cables.

1. PREPARATORY PROBLEMS

1. Derive an expression for the characteristic impedance of a coaxial cable with a central wire of radius a , a cylindrical sheath of radius b , and with the space between the inner and outer conductors filled by a non-conducting medium with a dielectric constant κ . See for example References [1-3].
2. A certain transmission line attenuates pulses at a rate of 2.5% per meter. Derive an exact formula for the pulse amplitude as a function of distance along the cable. Make a plot of the amplitude of a pulse as a function of position along the transmission line from 0 to 200 meters. (The formula is the solution of an elementary differential equation.)
3. Draw the predicted shape and amplitude of an ideal rectangular pulse of amplitude -1 volt and duration 10 nsec **after** it has traversed a coaxial cable 10 m long and returned following reflection from a shorted end.

2. INTRODUCTION

Many experiments involve the production and measurement of electrical pulses. Depending on the length of the signals Δt , the approaches are very different:

- $\Delta t \leq 1\text{ms}$ \rightarrow do with your wires whatever you want. If the signals are small, you may want to use shielded cables.
- $1\text{ms} \geq \Delta t \geq 0.1\mu\text{s}$ \rightarrow typical for computers. Use ribbon cable, “twisted pair” or cables without termination.
- $100\text{ns} \geq \Delta t \geq 0.1\text{ns}$ \rightarrow region of interest for “fast” signals to be studied here. Cables must be terminated or undersirable reflections will occur. In Junior Lab, these types of signals are often present with photomultiplier signals but the subsequent amplifiers slow the signals into the middle category.

One may wish to know their rate, distribution of amplitudes, the relation of their occurrence times relative to other pulses, etc. Such measurements are done with oscilloscopes, multichannel analyzers, amplifiers, discrim-

inators, coincidence circuits, etc.¹, which may or may not be working properly. It is essential, therefore, to gain facility in the use of test equipment such as pulse generators and oscilloscopes so that the performance of a pulse-measuring apparatus can be checked, point by point. Electrical pulses are piped around a laboratory via transmission lines of one sort or another, with consequent delays, attenuations, and reflections. It is important to understand these effects and to know how to measure them. So this experiment is a study of pulses in transmission lines. You learn that you must terminate all transmission lines properly - so as not to be deceived.

3. EXPERIMENTS

3.1. Reflection of electrical pulses from discontinuities in a transmission line

Connect the BNC Model 555 pulse delay generator to the input of a digital oscilloscope by means of a T-connector and attach a long RG-58 cable to the other third side of the T, as shown in Figure 1. Use the fixed output on the pulse generator to produce pulses of amplitude 5.0 V and the shortest possible duration ($\sim 4\text{-}30\text{nsec}$). Be careful to set the repetition rate so that you are not confused by overlapping pulses. Set the oscilloscope vertical amplifier control to 2V/div, the sweep speed (commonly called the time base) to 50nsec/div, and the trigger to internal, normal, and positive slope. Observe the primary pulse from the pulser and describe the pulse reflected from the end of the cable when the end is 1) open, 2) shorted, and 3) terminated with a variable resistor with values in the range from $\sim 10\text{-}200$ ohms, in order to determine the characteristic impedance of RG-58 and RG-59 cable. Connect another piece of cable to the end of the first cable by clip leads (i.e. a very bad connector) and observe the effects of the discontinuity in the

¹ Oscilloscopes display the signals $V(t)$ vs. t as described in the appendix. Multichannel Analyzers (MCA's) sort signal events of different heights into bins - histograms. Amplifiers enlarge the signal but may also alter it's shape. Charge sensitive pre-amplifiers produce an output proportional the amount of charge generated in a detector. Discriminators emit a logical (square $V(t)$) signal if the input exceeds a certain threshold. Coincidence units produce a logical pulse if two (or more) inputs overlap in time

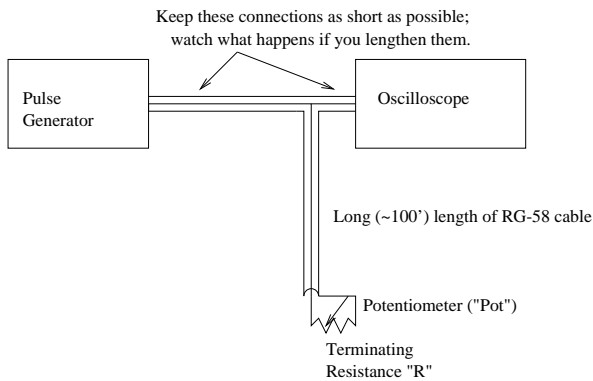


FIG. 1: Experimental setup to test the effect of various terminating resistances on the transmission and reflection of electrical pulses in coaxial cable.

transmission line. **Remember to graph the observed waveforms in your notebook and label both time and amplitude axes!** You will typically see one reflection. Why not $n + 1$? Hint: Pulse generators have an internal resistance too (50Ω).

3.2. Speed and attenuation of pulses in transmission lines.

Determine the velocity of pulses in the cable by measuring the difference in the arrival time of the direct and reflected pulses at the oscilloscope. Record sufficient data and other information to permit an accurate assessment of the random and the systematic errors in your determinations. Compare the velocity in the cable with the velocity of light in vacuum, and explain the cause of the difference. Add three cables of known length to make a plot of time versus length.

Measure the attenuation of RG-58 cable by comparing the amplitude of the pulse reflected from the open end of the cable with and without an additional length joined by a BNC connector. (Note that this strategy isolates for measurement the effect of the delay in the cable from possible complicating effects of the discontinuities in the circuit at the connections to the oscilloscope and pulser.)

3.3. Propagation of CW in a transmission line

Explore the phenomena of a sinusoidal continuous wave (CW) propagating in a transmission line with various terminations and frequencies. Use two calibrated channels on the oscilloscope to measure V_{input} and V_{output} . Be sure the output is terminated. Why is this necessary?

Produce a graph of attenuation versus frequency for RG-58 transmission line utilizing the Agilent 33120A function generator. Obtain attenuation values for frequencies ranging from one Hz to ten MHz.

The function generator should default to a one KHz sine wave with an amplitude of 100 mV when you turn it on. Make sure you are using the **OUTPUT** terminal and not the **SYNC** terminal. To adjust the frequency, first press the **Freq** button. The current frequency will then be displayed. The flashing digit can be adjusted with the knob in the upper right hand corner. You can also enter the desired frequency by pressing **Enter Number**, entering the numeric value of the frequency and then pressing the the button for the appropriate units. For instance, you can hit the **^** button for MHz.

A common means of expressing attenuation is in dB/100 ft where $\text{dB} = 20\log[V_{out}/V_{in}]$ when the cable termination is matched to its characteristic impedance. (e.g. -3dB corresponds to an voltage ratio of 0.707.) Connect the cable as before but look at the far end with channel-2 of your oscilloscope, terminate.

4. ANALYSIS

1. Determine the characteristic impedance Z for RG58 and for RG59 coaxial cables. Compare your values versus published values. Assess the random and systematic errors.
2. Determine V_{prop} for RG58 and RG59 coaxial cables. Compare your values versus published values. Assess the random and systematic errors.
3. Determine the attenuation in dB/m for RG58 and RG59 coaxial cables. Compare your coefficients versus published values. Assess the random and systematic errors.

4.1. Possible Topics for Oral Exam

1. The step function voltage on an open cable.
2. The partial differential equations for the voltage between the inner and outer elements of a coaxial transmission line carrying a signal.
3. Estimate the attenuation at low frequencies. (Ohm's Law). Why does the attenuation grow rapidly at very high frequencies?
4. The fraction of the energy of a pulse reflected at the junction of two coaxial cables with different radii of the inner and outer conductors.

5. STATISTICAL EXERCISE

1. With the setup described in 1, obtain 25 independent (explain how you ensure their independence) measurements of the characteristic impedance for RG58 and RG59. Plot the two distributions and calculate their mean and variance.

2. Measure the speed of signals in RG58 by using at least 4 different cable lengths. Again, make sufficient measurements to obtain an estimate of the (random) error for the next step.
3. Plot delay vs. cable length and prove a linear relationship by fitting your data to a model.

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- [1] A. French, *Vibrations and Waves* (Norton, 1971).
 - [2] G. Bekefi and A. Barrett, *Electromagnetic Vibrations, Waves and Radiation* (MIT Press, 1977).
 - [3] W. Leo, *Techniques of Nuclear and Particle Experiments* (Springer, 1992).

APPENDIX A: VISUALIZATION OF ELECTRICAL SIGNALS BY OSCILLOSCOPES

A schematic of an analog oscilloscope is shown in Figure 2. A hot wire in the cathode ray tube emits electrons, which are accelerated by an annular anode by about 20 kV. Two pairs of crossed capacitors then deflect the electron beam (AA' horizontally, BB' vertically). The fluorescent screen emits green light when hit by the electron beam. By applying a linearly rising voltage to AA' a horizon line is produced on the screen (aa'). The (amplified or attenuated) signal applied to BB' produces a vertical deflection bb' for the time duration of $\Delta\tau$. This process is started by the trigger, which is initiated by a signal becoming larger than the threshold (adjusted by the knob control), which can be positive or negative.

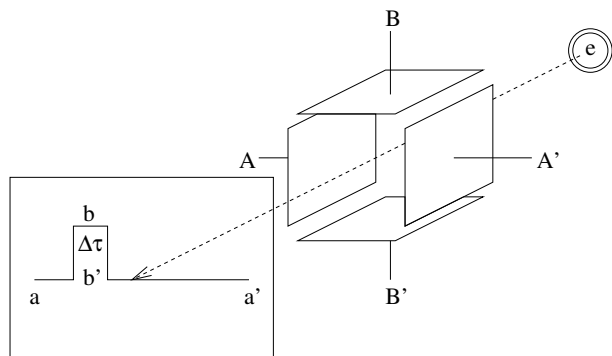


FIG. 2: Schematic of how an oscilloscope works.

Modern digital oscilloscopes utilize a similar principle, but operate differently; they sample the incoming voltage periodically (after receiving a trigger event), then a computer is used to display the resulting data as a function of time, at various user-selectable voltage and time-scales. You may be using such a modern 'scope in this experiment. More information about the digital oscilloscopes used in Junior Lab is available in the online e-library.

APPENDIX B: EQUIPMENT LIST

Manufacturer	Description	URL
HP-Agilent	100 MHz Scope	agilent.com
BNC	8010 Pulse Generator	berkeleyelectronics.com
Various	100' RG/58U Cable	
Various	100' RG/59U Cable	
