Experiment 5

Pulses on a Coaxial Cable

I. Purpose

- To measure the pulse amplitude and time intervals using the external triggering feature of an oscilloscope.
- To investigate the behavior of "fast" pulses and to measure the velocity of propagation and the effect of resistive terminations on coaxial cables.

II. Background Information

II.A Electrical Pulses

In this experiment rectangular pulses will be used. The pulse amplitude, duration (often called width), and rise time are illustrated in the figure below:

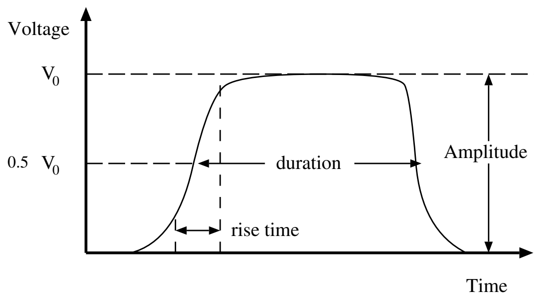

Figure 5.1.

When the pulse rise times and durations are comparable to the time it takes for the pulse to travel from point to point in a system, special problems arise due to the effects of the inductance and capacitance of the conductors. These difficulties arise when the pulse shape has time intervals of 100 ns or less. (1 ns = 10^{-9} sec; speed of light $\approx$ 1 ft/ns)

Electrical pulses in this time domain are referred to as fast pulses and the techniques and equipment needed to handle them are often referred to as fast electronics. The major difficulty in working with fast pulses is that the effect of lead inductance and stray capacitance (capacitance between leads and nearby large metallic surfaces such as chassies, etc.) can distort the pulse shapes while for slow pulses (times below 100 ns) these effects are negligible. To overcome such problems, transmission lines are used to transport fast signals over large distances (greater than a foot or so) without distortion.

II.B Transmission of Fast Pulses

A transmission line is used to transmit fast pulses or high frequency signals over distances of a foot or longer, without distortion. A transmission line is a pair of conductors arranged so that their geometrical cross-section remains constant along the entire length of the conductors. Common types of transmission lines are twin lines, coaxial cables, and strip lines. Their cross sections are shown below.

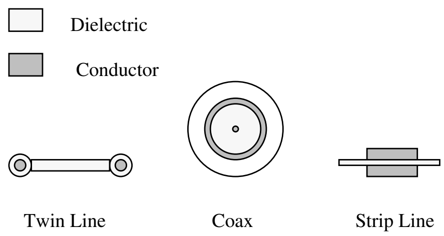

Figure 5.2.

The electrical properties of the transmission lines depend on their resistance, inductance, and capacitance. The ohmic resistance of transmission lines is usually negligible. The inductance arises from the self inductance of the conductors and the capacitance from the capacitance between the two conductors. The inductance and capacitance are distributed uniformly along the length of the line and are described by giving the inductance and capacitance per unit length. The equivalent circuit of a transmission line is thus:

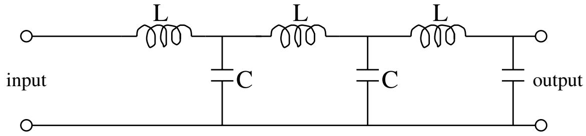

Figure 5.3.

Clearly, for an input voltage that does not vary with time (DC), the input and output voltages will be equal and no current will flow. However, if the input voltage varies with time, the effect of inductance and capacitance must be taken into account. This can be done in a straightforward manner by writing down the differential equations obeyed by the voltage and currents in this system. When this is done a rather simple and elegant result is obtained. It is found that the time varying voltage and currents obey the wave equations. Thus the electrical energy is transmitted down a transmission line in the same way as sound waves travel through air or vibrations transmitted on a string. The velocity of propagation of electrical energy is found to be $1/\sqrt{LC}$ where L and C are the inductance and capacitance per unit length. It is also found that the voltage and current in the cable are in phase and that their ratio is given by $\sqrt{L/C}$. This value is called the characteristic impedance of the line. Recall that the definition of a resistance is a circuit element or device for which the ratio of voltage across it to the current through it is constant and in phase. Thus, for a time varying signal, the equivalent circuit for an *infinitely* long transmission line is just a resistor whose value is that of the characteristic impedance of the line.

A transmission line of constant cross section, *i.e.* constant characteristic impedance, will in principle, transmit a pulse over an infinite length without distortion. In practice distortion is introduced by the dielectric used to separate the conductors. In high quality cable, an air core is utilized as the dielectric, and very little material is used to support the center conductor.

Distortions are also introduced if the characteristic impedance of the line is changed, for example, by connecting together two cables of differing characteristic impedances. The optical/acoustical analogue of this situation is having the wave medium change index of refraction/density respectively. In all of these cases the effect is the same, *i.e.*, partial transmission and some reflection occur at the boundary. The reflected wave can then travel back down the line to the source (beginning of the line) and can be reflected again. Multiple reflections can then be set up on the transmission line. If the times between successive reflections are comparable to the pulse duration, then serious distortion of the pulse can take place. On the other hand, if these reflections take place in times small compared to the rise time of the pulse they will have little effect on the pulse shape.

II.C Behavior of Pulses at the end of the transmission line

In this experiment only the simplest case, which is the one most frequently encountered in practice, will be considered. This occurs when the output end of a transmission line is connected across a resistance. This may be a simple resistor, or the equivalent input resistance of the device to which the end of the transmission line is connected. The effect of the terminating resistance is to absorb part of the incident energy and reflect part of it back down the line. The fraction of the incident pulse amplitude reflected depends on the resistance of the termination compared to the characteristic impedance of the line. The reflection coefficient is defined as the ratio of the reflected pulse amplitude to that of the incident amplitude. Note that the the pulse that is present at the termination of a cable is the sum of the incident plus reflected pulses. Also note that the reflected wave is transmitted back down the cable where it eventually reaches the other end; it is reflected once again and multiple reflections can result.

Consider a coaxial cable terminated with a resistance R. There are three limiting cases, illustrated in figure 5.4.

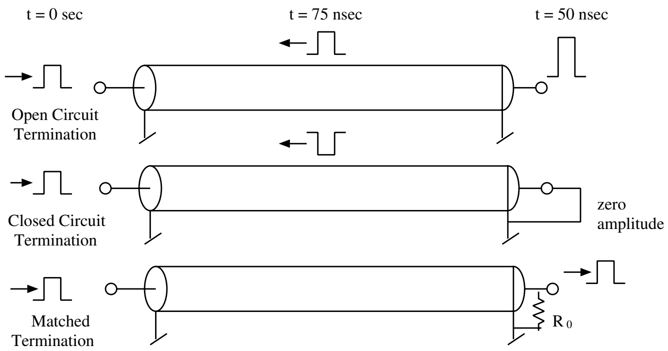

Figure 5.4.

At $t = 0$, a pulse is started down a cable whose delay time is 50 ns. The pulse is shown at $t = 50$ ns when it has reached the end of the cable, and at $t = 75$ ns, when the reflected pulse traveling back along the cable has reached the middle.

$R = \infty$, **open circuit termination.** The reflected pulse is of the same amplitude and sign of the incident pulse. The pulse amplitude at the termination is twice the size of the incident pulse.

$R = 0$, **short circuit termination.** The reflected pulse is of same amplitude but of opposite sign of the incident pulse. The pulse amplitude at the termination is zero.

$R = R_0$, **matched termination.** R_0 is the characteristic impedance given by $R_0 = \sqrt{L/C}$. This resistance is the ratio of the voltage to the current at any point in the cable where a pulse is present. When a cable is terminated in its characteristic impedance, it can be thought of as acting, from the point of view of the sending end, as a cable of infinite length since there is no pulse reflected back. The incident pulse is completely absorbed by the termination. This is an important case: when using coaxial cable to transport signal from one place to another, and no reflections can be tolerated, the far end of the cable must be properly terminated.

The general case can be described by defining a reflection coefficient. R_{ref}, the ratio of the reflected pulse to the incident pulse, is given by

$$R_{ref} = \frac{R - R_0}{R + R_0}.$$

The reflection coefficient for the three special cases above are, from the formula, ± 1, 0.

Type	β	v^{-1} ns/ft	C (pf/ft)	R_0 (Ω)
RG 58 C/U	65.9	1.5	28.5	50
RG 59 B/U	64.9	1.5	20.5	75
RG 62/U	84	1.2	13.5	93
RG 114	85	1.2	6.5	185

Table 5.1. Characteristics of Some Common Coaxial Cable Types

III. Application of Coaxial Cables and Transmission Lines

1. Coaxial cables are used to transport signals from one place to another. Because of their transmission line behavior, they can transmit pulses over long distances without distortion. A properly terminated transmission line behaves as though it were a resistor of value R_0, and the capacitance and inductance of the cable have no effect. This is important when high frequency signals are being transported.

2. Delay lines. Delay lines are used in oscilloscopes, distributed amplifiers, pulse coders and decoders, precise time measurements, radar, television, and in digital computers.

3. Circuit elements. Very often in circuits operating with short rectangular pulses, transmission lines can be used as elements to produce or shape pulses.

IV. Experimental Procedure

1. In the first part of the experiment, the delay time of a known length of cable will be obtained directly by measuring the actual time taken for a pulse to travel from one end of the cable to the other. To do this, advantage is taken of the fact that the time the oscilloscope electron beam takes to travel across the screen depends on the time elapsed between the starting of the sweep and the arrival of the pulse at the vertical input of the oscilloscope. There are two methods for starting the sweep ("triggering the sweep"). The internal triggering mode and the external triggering mode. In the internal triggering mode, the sweep is started by the input signal presented to the vertical amplifiers. In the external triggering mode, the sweep is started by a separate signal which must be supplied to the external trigger input of the oscilloscope. When used in this mode, the starting of the sweep is then locked in time to the external trigger signal. In this mode, the position of a pulse on the sweep will depend on the time relationship between the external trigger signal and the pulse under observation.

   We will use a dual-trace scope and select one channel to perform the triggering. We will then be able to determine the difference in timing by examining the relative delay between the two traces.

The arrangement necessary to measure the delay time of a 100-foot RG-58 cable is shown in figure 5.5.

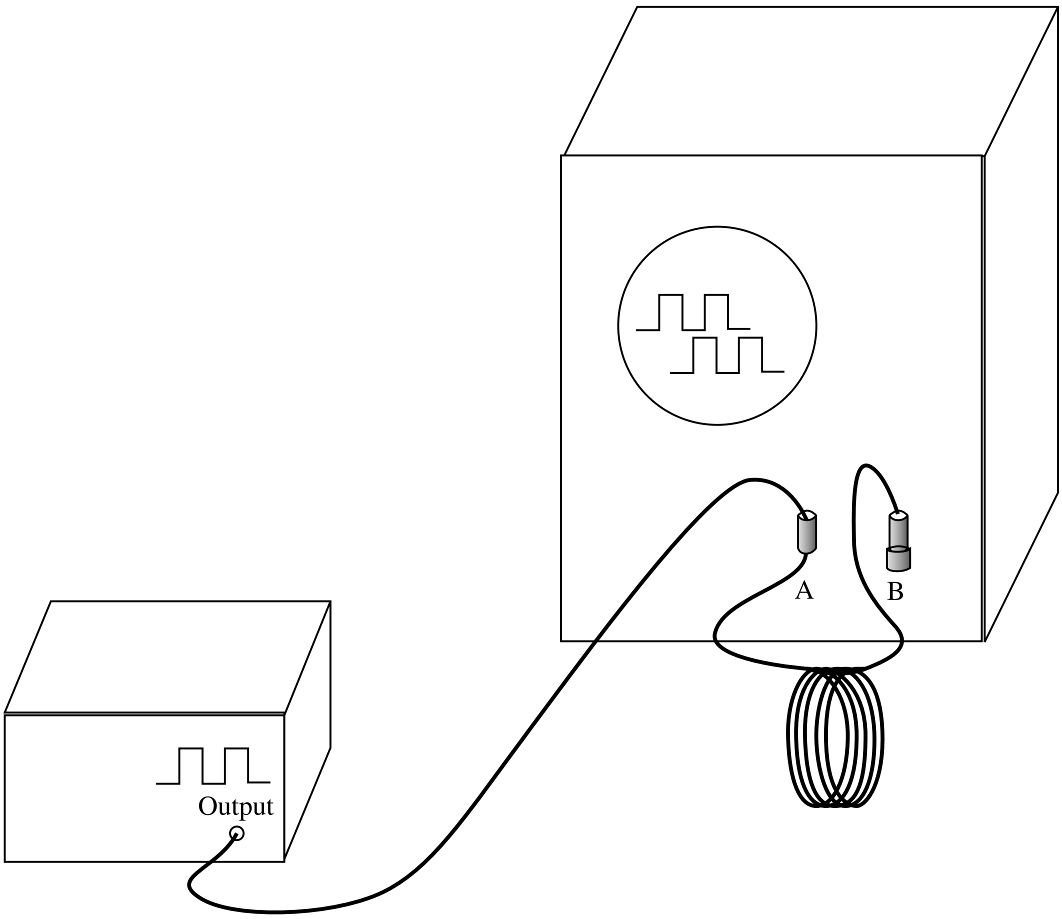

Figure 5.5.

Using a short RG-58 cable, connect the output of your pulse generator to one arm of a T connector on channel A of your scope. Use the 100-foot cable to connect the other arm to a second T on channel B. Put a 50-Ω terminator on the other arm.

Set the scope to trigger on channel A and observer both channels simultaneously by setting either *chop* or *alternate* mode.

Adjust the time base as appropriate until you can see the details of both pulses on the scope.

Using the positioning controls, shift the traces around until the half amplitude point of the leading edge of the channel A pulse is located on the first vertical line of the screen's graticule. Observe and record the time shift of the pulse on channel

B with respect to this. This is the delay time of the cable. Is it close to what you expect? (RG 58 delay time: about 1.5 ns/ft.)

2. In this part, the effects of varying the termination of a cable will be observed. Set up the equipment as in the previous section.

   Observe and record the wave forms produced for values of the terminating resistance on channel B of 1000, 90, and 50 Ω. Record the width, amplitude polarity and the time between the pulses (measured from leading edge to leading edge).

V. Results

Your report should contain a tabulation of measurements and results for the velocity of propagation and comparison with the nominal values given in this write-up.

From the data obtained in step (2), explain the amplitude of the various pulses observed and the time between them. From your data calculate the reflection coefficients for the different terminations and compare them with the calculated values.