Transmission Line Nanosecond Pulses Experiment

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We performed a transmission line nanosecond pulse experiment to determine the intrinsic properties of the RG-58/U coaxial cable. Such properties include signal velocity, signal loss, and impedance. The signal velocity was found to be 1.93×10^8 m/s or 64.3% the speed of light. The impedance was found to be about 51Ω.

I. INTRODUCTION

The objective of the Transmission Line Nanosecond Pulse experiment was to determine the various characteristics of an RG-58/U coaxial cable. This included measuring the signal velocity and impedance of a coaxial cable transmission line in order to study its properties. We also looked into how the coaxial cable's performance is impacted by the addition of various terminations, such as resistors, capacitors, inductors, and an LC circuit. We were able to identify the relationship between resistance and reflection amplitude, the resonance frequency and quality factor of the LC circuit, the length dependence on the signal amplitude, and more as discussed later in the paper. These are all significant factors in comprehending the behavior of the transmission line. We can better understand how coaxial cables behave and how to tailor them for certain uses by researching their features.

A. Transmission Line Background

The purpose in studying transmission line properties is because transmission lines are crucial parts of contemporary electronics and communication systems. Coaxial transmission lines "pass high radio frequency (RF) signals from one point to another with low signal loss." [1] Which allows electrical signals to be transferred over great distances with the least amount of distortion. The signal frequency, transmission distance, and cable type are only a few of the variables that affect how transmission lines are designed and perform. One of the most often utilized transmission line types in a variety of applications, including data transmission, telephone lines, and scientific investigations, is coaxial cable.

An insulating material surrounds the core conductor of coaxial cables, which is then further encircled by an outer conductor or shield. This design offers a considerable benefit over other cable types because it reduces signal loss and distortion by minimizing interference from outside electromagnetic fields. Additionally, the coaxial cable's architecture enables it to send signals with a high bandwidth, making it appropriate for applications requiring high-speed data transfer.

II. EXPERIMENT APPARATUS

A. Experimental Setup

The Transmission Line experimental setup consisted of a frequency generator, an oscilloscope, and a breadboard. The frequency generator was used to generate a signal, which was then transmitted through a coaxial cable connected to the oscilloscope. The same cable was then extended and terminated on a breadboard, allowing the attachment of various circuit components. The experiment's setup allowed for precise measurements for meaningful results.

B. Components

There are five key components that make up the experiment apparatus and one external measuring device. These six pieces of equipment all served an important role in the conducting of the experiment. The six components used in the experiment:

- Frequency Generator: Generates the nanosecond and microsecond pulses used in the entirety of the experiment. This machine allows for full control of the width, amplitude, and frequency of the pulses sent out.

- Oscilloscope: Measures the incident and reflected pulses sent from the frequency generator. Attaches to the coaxial cable via a T-junction which enables the measuring and transmitting of the pulses sent through the cable. The machine outputs a visual display of the pulses as well as allowing for measurement of the pulses using cursors on the screen.

- Cable Extender: Extends the cable used in the experiment. The cable can be extended by 100, 200, 300, or 500 feet allowing for the study of the signal velocity as well as the amplitude dependence on cable length.

- Breadboard: Attaches to cable termination and allows for the attachment of circuit components such as resistors, capacitors, inductors, and an LC circuit.

- Coaxial Cable: Connects all the previous components and carries the voltage from the frequency generator through the oscilloscope to the breadboard where the signal reflects back to the oscilloscope. The coax used is an RG-58/U coaxial cable. This cable is the main subject of the experiment as its properties are of interest to us

- Multimeter: Measures the resistance, capacitance, and inductance of all the circuit components used in the experiment. This tool is external to the experimental apparatus.

C. Procedure

The Transmission Line Nanosecond Pulses experiment was conducted in five main sections. In the first section, the main experimental setup was established without the breadboard attached. The signal velocity through the coaxial cable was determined by using the four stages of the cable extender.

In the second section, the breadboard was attached to the end of the coaxial cable, and an open-circuit and a closed-circuit were observed to determine the reflected amplitude dependence on the circuit components. Various circuit components were then added to the breadboard, and their effects on the reflected amplitude were observed.

In the third section, reflected pulses were passed through ten resistors of different magnitude to determine the impedance and corresponding reflection coefficients of the coaxial cable. The reflected pulse amplitude and width were measured and used to calculate the impedance of the cable.

In the fourth section, an LC circuit was attached to the end of the coaxial cable to determine the circuit's resonant frequency, quality factor, and resistance. The circuit's resonant frequency was found by observing the maximum amplitude of the reflected pulse, while the quality factor and resistance were determined using the successive decay oscillation amplitudes.

In the fifth and final section, the relationship between the cable length and the reflected pulse amplitude and width was determined using the four stages of the cable extender. The reflected pulse amplitude and width were measured and used to determine the signal loss relationship with cable length.

III. RESULTS

A. Measuring Signal Velocity

The first task of the Transmission Line Nanosecond Pulses experiment was to measure the signal velocity of the RG-58/U coaxial cable. This was done by sending a 484 mV, 20 ns pulse through the cable, where the incident pulse was measured by the oscilloscope. By using a T-junction attached to the oscilloscope, the same signal was carried through to the cable extender, which extended the cable by 100, 200, 300, and 500 feet, respectively. The reflected pulse was then measured using the oscilloscope. The total signal travel length is twice the sum of the coax cable length and the extender length as the signal has to travel through the entirety of the cable and back to be recorded. By taking into account the cable length and the time delay between pulses (measured by the oscilloscope), the signal velocity was calculated. This calculation was essential in establishing the baseline performance of the coaxial cable and provided valuable insights into its signal transmission properties.

The results of the signal velocity task can be seen in Table 1. The average signal velocity was found to be $(1.93 \pm 0.04) \times 10^8$ m/s or $(64.3 \pm 1.3)\%$ the speed of light. These results match the expected value for the RG-58/U signal velocity within just over one standard deviation. The specifications [3] predict a signal velocity of 66% the speed of light. This fast signal velocity shows the benefit of using coaxial cable to ensure high-speed data transmission.

Table 1: Signal Velocity

Coax Length	Signal Travel Time	Signal Velocity
63.4 m	328 ns	$(1.93 \pm 0.03) \times 10^8$ m/s
124.4 m	650 ns	$(1.91 \pm 0.02) \times 10^8$ m/s
185.3 m	952 ns	$(1.95 \pm 0.01) \times 10^8$ m/s
307.3 m	1.590 μs	$(1.93 \pm 0.01) \times 10^8$ m/s

B. Reflected Amplitude of Various Terminations

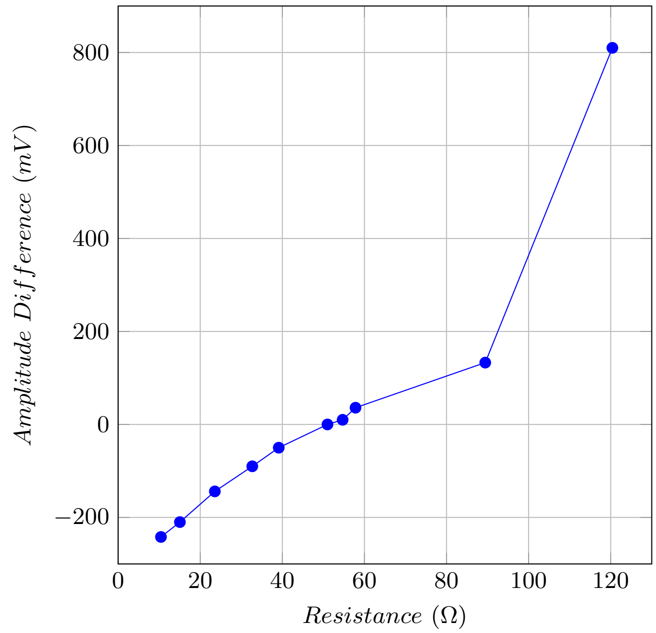
The second task of the Transmission Line Nanosecond Pulses experiment involved observing the effect of different coaxial terminations on the amplitude of a reflected pulse. For this part of the experiment, we used the 100 ft cable extender, resulting in a total coaxial cable length of 65.0 m. We applied both a short (20 ns) and long (> 1 s) pulse while the coaxial cable was attached to various circuit terminations, including an open-circuit, closed-circuit, four different resistors, a capacitor, an RC circuit, an inductor, and an RL circuit. By using these two different pulse lengths, we were able to accurately observe the difference in amplitude between different circuit terminations.

We found that an open-circuit caused a positively reflected pulse, whereas the closed-circuit resulted in a negatively reflected pulse. In addition, lower resistance values, such as the 10.4 Ω resistor, resulted in a negatively reflected pulse, whereas higher resistances, such as 54.7, 188.0, and 555.6 Ω, resulted in positively reflected pulses closer to the open-circuit. Next, we found that the capacitor caused a drop in the voltage amplitude followed by a steady increase, whereas the RC circuit saw the same dip in voltage without the subsequent increase. Finally, the inductor showed the opposite effect of the capacitor, as this termination caused an increase in the reflected voltage followed by a steady decrease. In this case, the addition of the resistor into an RL circuit made no qualitative difference. These observations provided crucial insights into the behavior of the coaxial cable under different circuit terminations and helped us understand the potential applications of coaxial cables in different scenarios.

C. Coaxial Impedance

The third task in the experiment involved using ten different resistor terminations to define the relationship between load resistance, coaxial impedance, and the reflection coefficient. The model below from [2] defines the reflection coefficient, Γ, which was assumed true for this task. In this equation the load impedance, Z_R, is equivalent to the resistance of the resistor attached to the end of the coaxial cable. The coaxial impedance, Z_C is the intrinsic impedance or resistance of the coaxial cable that carries the signal. By measuring the difference in amplitude between the incident and reflected pulses for resistors ranging from about 10 to 120 Ω, we were able to plot the results in Fig 1.

FIG. 1. This plot contains the difference in amplitude between the incident pulse and reflected pulse with respect to various resistances. The resistances correspond to the load resistance attached to the end of the coaxial cable receiving the incident pulse. The x-intercept corresponds to the intrinsic impedence of the coaxial cable in use.



$$\Gamma = \frac{Z_R - Z_C}{Z_R + Z_C}$$

From the results of the second task of the experiment, it was known that higher resistances cause a positively reflected pulse and lower resistances cause a negatively reflected pulse. Based on this information and the plot in Fig 1., we observed that the amplitude difference falls to zero at some resistance. Using the reflection coefficient definition above, we determined that this occurs when the coaxial impedance is equal to the attached resistor, i.e. when the reflection coefficient goes to zero. Therefore, the x-intercept of Fig 1. corresponds to the characteristic impedance of the coaxial cable used, which was found to be about 51 Ω.

The model used to determine the impedance of the coaxial cable could also serve as a tool for understanding the capacitor and inductor terminations. In this case the capacitor would act as an infinite resistance whereas the inductor would act as a wire with essentially zero resistance.

D. LC Circuit Characteristics

1. *Resonant Frequency*

In the fourth task of the experiment, we investigated the properties of an LC circuit, such as resonant frequency, quality factor, and impedance. The circuit consisted of an inductor with an inductance of 2.37 mH and a capacitor with a capacitance of 10.6 pF. Using the equation from [4] for the resonant frequency of an LC circuit below, we calculated the expected resonant frequency to be 1.004 ± 0.052 MHz.

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

To measure the resonant frequency, we applied a 460 ns pulse through the LC circuit and measured the period of oscillation for the resultant ringing. The period was found to be 1.073 μs, resulting in a resonant frequency of 932 ± 4 kHz. This value was nearly one standard deviation away from the expected value for the LC resonant frequency.

We used this resonant frequency to set a range of frequencies and corresponding pulse widths to investigate how the amplitude of the oscillation depends on the pulse width. By testing pulse widths of 148 ns, 430 ns, and 1.18 us, we found that the amplitude depends on the proximity to the resonant pulse width, and that the amplitude is maximized when the pulse width is equivalent to the resonant width.

2. *Quality Factor*

Using the decaying amplitude and the resonant frequency, we calculated the quality factor of the damped oscillation within the LC circuit using the equation below that includes the resonant angular frequency, time

FIG. 2. This plot shows the decaying amplitude of successive peaks for the damped oscillation of the LC circuit. The decaying amplitude roughly follows an exponential decay due to the intrinsic resistant properties of the LC circuit. The quality factor is what determines the steepness and quickness of the decay.

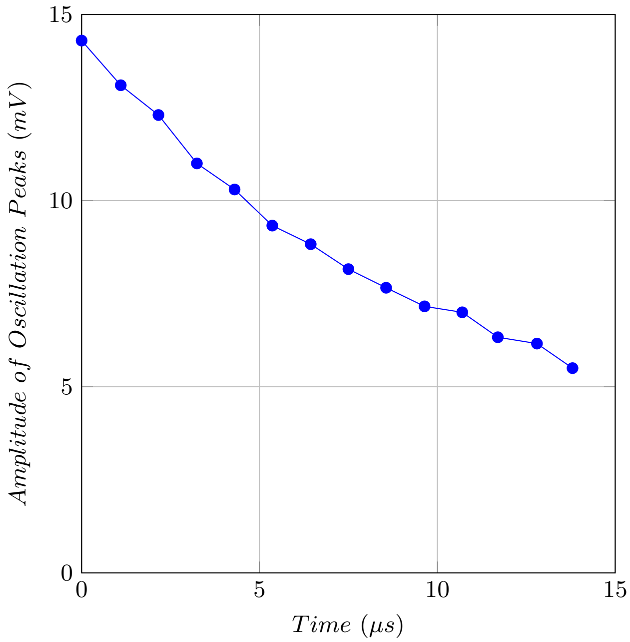
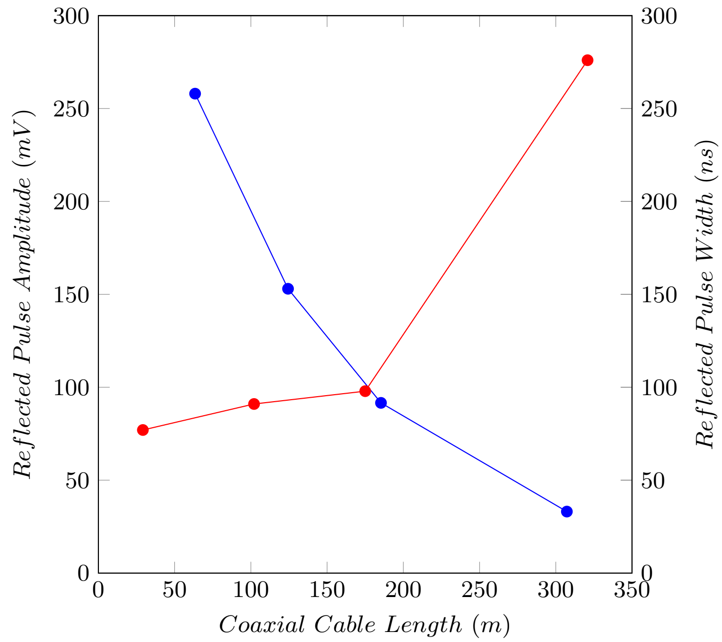


FIG. 3. This plot contains the relationship between the length of the coaxial cable and the corresponding amplitude and width of the reflected pulse. For this plot, the incident pulse sent through the coaxial cable had an amplitude of 545 mV and a pulse width of 71 ns.



delay, and successive amplitudes. With a resonant angular frequency of 6.300 MHz, a time delay $\Delta t = 1.073$ μs, and the successive amplitudes denoted in Fig 2., we found the quality factor to be 107.3, indicating that the damped oscillation for the LC circuit is underdamped.

$$Q = \frac{\omega_0 \Delta t}{\ln \frac{A_i}{A_{i+1}}}$$

3. Circuit Impedance

Finally, we measured the resistance of the LC circuit using a multimeter and found it to be 87.3 Ω. Using the equation below that includes the quality factor, inductance, and resonant frequency, we calculated the expected resistance to be 129.4 Ω. The measured resistance was of the same order of magnitude as the expected calculation, indicating that there is an intrinsic resistance leading to circuit properties more similar to an RLC circuit.

$$R = \frac{2\pi f_0 L}{Q}$$

E. Coaxial Length Dependence

The fifth and final task in the experiment aimed to investigate how the amplitude and width of a reflected pulse are affected by the length of the cable through which the pulse travels. Four different coaxial cable lengths were used, the same as those used in the signal velocity part of the experiment. We sent a 545 mV pulse with a pulse width of 71 ns through each of the different lengths of coaxial cable and measured the resulting amplitude and width of the reflected pulse.

Our results, shown in Fig 3., indicate that the amplitude of the reflected pulse decreases as the length of the cable increases. This can be explained by the fact that longer cables have more resistance, resulting in a greater loss of energy as the pulse travels through the cable. On the other hand, we found that the width of the reflected pulse increases as the cable length increases. This can be attributed to the fact that the longer the cable, the more time it takes for the pulse to travel to the end and reflect back, resulting in a wider reflected pulse.

F. Uncertainty Calculations

In any scientific experiment, there are always uncertainties to consider. In this experiment, there were both systematic and statistical uncertainties involved in the measurements. For example, the measurement of signal velocity involved a systematic uncertainty related to the limitations of the meter stick used to measure the coaxial cable length, as well as an assumed uncertainty of 5 ns in the time delay measured by the oscilloscope. We were then able to determine the uncertainty of the calculated signal velocity using the generalized uncertainty equation below. An equation similar to this was used for the other calculations. In addition to the systematic uncertainty, there were also statistical uncertainties involved in the measurements of the quality factor and impedance, as well as the calculation of the resonant frequency. These uncertainties were taken into account when calculating the average values. It is important to consider and quantify uncertainties in scientific experiments to ensure the reliability and accuracy of the results. By doing so, the conclusions drawn from the experiment can be appropriately qualified and the limitations of the study can be understood.

$$\delta v = |v|\sqrt{(\frac{\delta x}{\Delta x})^2 + (\frac{\delta t}{\Delta t})^2}$$

IV. CONCLUSION

Our experiment investigated the properties of electromagnetic waves through coaxial cables and LC circuits. We started by measuring the signal velocity in four different coaxial cables, where we found that the average signal velocity is about 64.3% the speed of light. Next, we found the impedance of the coaxial cable using a model for the reflection coefficient. We then studied the properties of an LC circuit, where we determined the resonant frequency, quality factor, and impedance. We found that the amplitude of the oscillating wave depends on the pulse width proximity to the resonant pulse width. We also found that the LC circuit has an intrinsic resistance leading to circuit properties more similar to an RLC circuit. Finally, we investigated how the amplitude and width of a reflected pulse depends on the length of the cable through which the pulse travels. We found that the amplitude of the reflected pulse decreases as the cable length increases, while the width of the reflected pulse increases.

Throughout the experiment, we took into account systematic and statistical uncertainties in our measurements. We found that the signal velocity and other measurements had systematic uncertainties due to the limitations of our measurement tools, while statistical uncertainties were accounted for in our average values.

In conclusion, this experiment allowed us to gain a better understanding of radio waves through coaxial cables and LC circuits. The results obtained can be used in a variety of applications, such as in the design and analysis of electronic circuits, signal processing, and data transmission. The systematic and statistical uncertainties that were accounted for in this experiment highlight the importance of accurate measurements and the need for careful consideration of potential sources of error in scientific experimentation.

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REFERENCES

[1] Wilson Amplifiers. *Understanding Coaxial Cables - The Complete Guide*. Jan. 2023. URL: `https://www.wilsonamplifiers.com/blog/understanding-coaxial-cables-the-complete-guide`.

[2] Steven W. Ellingson. "3.12: Voltage Reflection Coefficient". In: *Electromagnetism 1*. Spring 2019 Edition. Virginia Tech, 2019. URL: `https://www.ece.vt.edu/swe/lwa/antennas2019/EM1Textbook.pdf`.

[3] Tomi Engdahl. "Coaxial Cables". In: *ePanorama.net* (accessed 2023). URL: `https://www.epanorama.net/circuits/coaxial_cable.html`.

[4] Linquip Team. *What is LC Circuit? Formula, Equation & Diagram*. Website. Jan. 2023. URL: `https://www.linquip.com/blog/what-is-lc-circuit/`.