Electromagnetic Education Module: Introductory Transmission Line Simulation and Experiment

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***Abstract*—An educational module is developed to provide students with a tangible introduction to the fundamental principles of electromagnetic propagation along a transmission line. This module implements an active-learning approach, with both simulated and experimental elements, to demonstrate such concepts as incident and reflected waves, propagation delay, attenuation, and impedance mismatch. This module is designed to be implemented using only standard laboratory equipment and time-domain simulation software.**

***Index Terms*—electromagnetic education, waves, active learning**

I. Introduction

The traditional sequence of courses in an electrical engineering program in North America begins with an introductory circuits class, which provides students with their first introduction to the basic low-frequency lumped-element relationships between voltage, current, and power transfer. These models are then expanded to their distributed high-frequency corollaries in an electromagnetic waves course, typically taken in the junior year. It is here that students first encounter the more advanced topics of forward and backward propagating waves, propagation delay, wave attenuation, and reflection at mismatched impedance boundaries. These foundational transmission-line concepts lay the foundation for more advanced topics, including propagation in free space and reflection at three-dimensional boundaries. It is critical that students establish a firm grasp of these fundamentals early in the curriculum, so that they are ready to build on them in later work. We have therefore developed an educational module that employs an active learning pedagogy with both simulated and experimental components to substantiate the concepts presented in class. This will help to solidify understanding of transmission line fundamentals and develop student intuition in this area [1]–[4].

The development presented herein is built around the simple network model of Fig. 1, which consists of a voltage source V_s with source impedance Z_S, a length of transmission line with characteristic impedance $Z_\circ$, and a load impedance Z_L, as shown. There are two primary parameters under consideration: firstly, the reflection coefficient Γ, given by:

$$\Gamma = \frac{Z_L - Z_\circ}{Z_L + Z_\circ} \tag{1}$$

and secondly, the propagation delay τ, given by:

$$\tau = \frac{\ell}{v_{ph}} = \ell\sqrt{L_\circ C_\circ}. \tag{2}$$

where ℓ is the length of the transmission line in meters, v_{ph} is the phase velocity on the line, and $L_\circ$ and $C_\circ$ are the per-length inductance and capacitance of the line, respectively [5]. For RG-58 cable, the characteristic impedance is $Z_\circ \approx 50\,\Omega$, delay is approximately 4.9 ns/m, $L_\circ \approx 253$ nH/m, $C_\circ \approx 101$ pF/m, and $v_{ph} \approx 0.66\,c$, where c is the velocity of light in vacuum.

The experimental portion of this module has been designed for implementation in an elementary laboratory, and requires only an oscilloscope, pulse generator, and standard RG-58 $50\,\Omega$ coaxial cables, connectors, and terminations. The simulation portion requires basic time-domain simulation software.

II. Educational Module: Experiment

This educational module begins with a simple laboratory experiment. The measurement model shown in Fig. 2, implemented as shown in Fig. 3, consists of a $50\,\Omega$ pulse generator creating a 40 ns wide pulse, connected to a $\ell = 7.6$ m (25 ft) length of RG-58 coaxial transmission line. At the output of the transmission line, an effective load impedance is initially set to $Z_L = 16.7\,\Omega$ by connecting two $50\,\Omega$ terminations in parallel with one another and with a $50\,\Omega$ oscilloscope probe. (For oscilloscopes that do not support a $50\,\Omega$ input impedance setting, an external 10 dB attenuator can be used to to present an impedance of nearly $50\,\Omega$, as illustrated in Fig. 3.) The effective source impedance is set to $Z_S = 25\,\Omega$ by connecting the $50\,\Omega$ pulse generator in parallel with an oscilloscope $50\,\Omega$ probe.

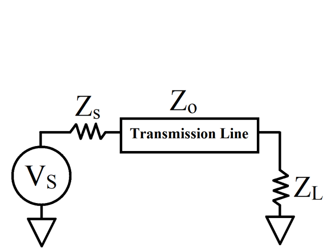


Fig. 1. The basic loaded transmission line model used for simulation and experimental development.

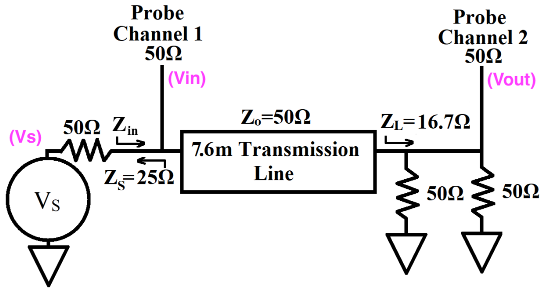
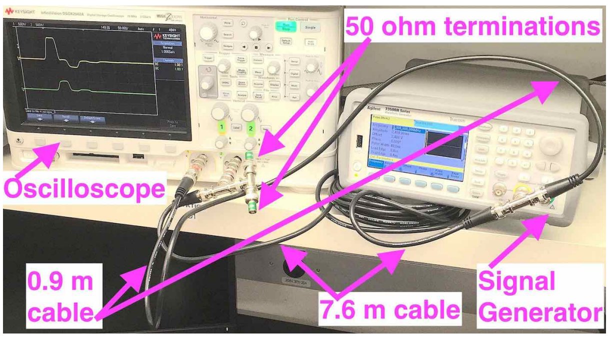
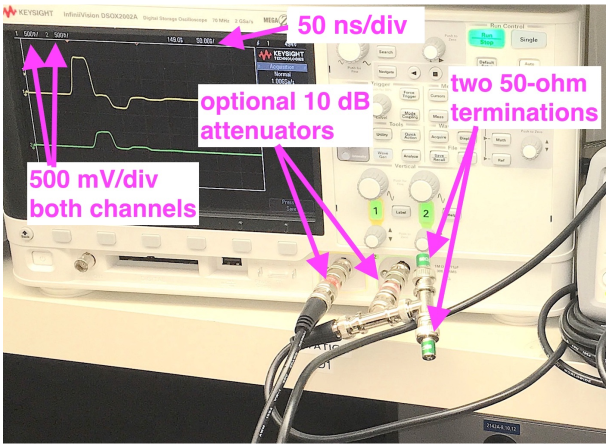


Fig. 2. The experimental network configuration. A $50\,\Omega$ signal generator and $50\,\Omega$ oscilloscope probe create an effective source impedance $Z_S = 25\,\Omega$, and two $50\,\Omega$ terminations in parallel with a $50\,\Omega$ oscilloscope probe create an effective load impedance $Z_L = 16.7\,\Omega$.

The experiment is designed so that students may predict the amplitudes of the multiple reflections on the transmission line using (1) above, and verify their predictions in real time by comparing the relative amplitudes of the pulses observed on the source and load ends of the transmission line. They can also vary the load impedance by removing any or all of the $50\,\Omega$ terminations, and predict and observe the effects of these changes. The propagation delay may also be calculated from the cable specifications, according to (2) above, and may be measured by observing the temporal displacement of the initial pulse as it appears on the two channels of the oscilloscope, as shown in Fig. 3(b). For simplicity in exposition, the small added time delay of the short 0.9 m cable in Fig. 3(a) is not considered, although an instructor may choose to include this.



(a)



(b)

Fig. 3. The experimental measurement setup, showing (a) the overall system, including the 7.6 m length of RG-58 cable with a 40 ns wide pulse, and (b) a closeup of the oscilloscope connections and settings.

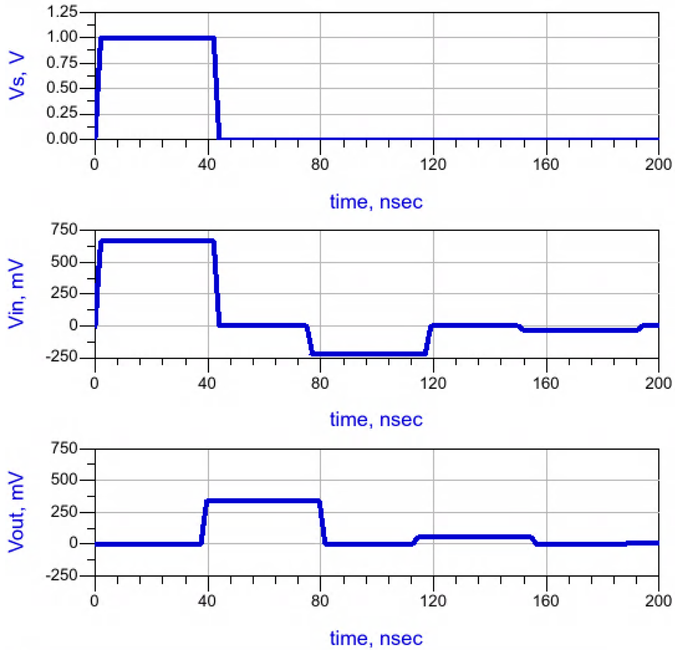


Fig. 4. Simulation results showing time-domain voltages corresponding to V_s, V_{in}, and V_{out} of Fig. 2 .

III. Educational Module: Simulation

The second part of this module consists of simulation of the Fig. 1 model. In this, simulation voltage probes may be set at either end of the transmission line element, to correspond to the oscilloscope measurements of the previous section. The propagation delay assigned to the simulated transmission line may be initialized using calculation with (2), and adjusted as necessary to match the measured results. Fig. 4 shows simulation results corresponding to the experimental setup of Figs. 2 and 3. As in the experimental portion of the module, students can compare calculated and measured reflections using the relative amplitudes of the incident and reflected pulses, and directly observe the propagation delay between the two ends of the transmission line.

For the experimental setup of Fig. 2 with $Z_S = 25\,\Omega$, $Z_L = 16.7\,\Omega$, $Z_\circ = 50\,\Omega$, and open-circuit peak voltage $V_s = V_p$,

TABLE I
Reflection Coefficients and Pulse Voltages

Reflection Coefficient	Pulse Voltage
$\Gamma_{in1} = \frac{Z_\circ - Z_S}{Z_\circ + Z_S} = \frac{1}{3}$	$V_{in1} = \frac{V_p}{2}(1+\Gamma_{in1}) = \frac{2}{3}V_p$
$\Gamma_{out1} = \frac{Z_L - Z_\circ}{Z_L + Z_\circ} = -\frac{1}{2}$	$V_{out1} = V_{in1}(1+\Gamma_{out1}) = \frac{1}{3}V_p$
$\Gamma_{in2} = \frac{Z_S - Z_\circ}{Z_S + Z_\circ} = -\frac{1}{3}$	$V_{in2} = V_{in1}\Gamma_{out1}(1+\Gamma_{in2}) = -\frac{2}{9}V_p$

the reflection coefficients and pulse amplitudes for the multiple reflections along the cable are summarized in Table I. In the first row of the table, Γ_{in1} is the initial reflection coefficient seen by the source for the incident pulse, and V_{in1} is the first pulse voltage observed at V_{in} of Fig. 2. In the second row of the table, Γ_{out1} is the reflection coefficient at the load Z_L, and V_{out1} is the first pulse voltage observed at V_{out} of Fig. 2. In the third row of the table, Γ_{in2} is the reflection coefficient seen by the pulse round-trip reflection at the source, and V_{in2} is the second pulse voltage observed at V_{in} of Fig. 2. As can be seen, all these calculations correspond favorably with the simulated output of Fig. 4.

IV. Conclusion

In this paper, we have presented an educational module for augmentation of an undergraduate electromagnetics class that serves to provide concrete, hands-on, active-learning reinforcement of the transmission line theory presented in class. Both experimental laboratory measurement and simulation were used to confirm theoretical predictions of network behavior. The experiment is designed to use standard laboratory equipment and time-domain simulation software. This module allows direct observation of incident and reflected waves, propagation delay, and the effects of impedance mismatch, and will help students to establish a solid foundational understanding of these fundamental transmission line concepts.

References

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