Experiment: Transmission Lines

Module: EEE225 Advanced Electrical Circuit and Electromagnetics
Mark: This lab (including the pre-lab exercise and lab report) takes 20% of the total mark;
The pre-lab report takes 30% of the lab mark, and the lab report takes 70%.
Notice: Answer all the questions in "EEE225_lab2_Pre-lab_Exercise.docx" before you come to the lab and attach it at the end of the formal report.
Report: Individual report: 1 report from each person.
Deadline: Submit the electronic version on ICE before Dec. 21st, 23:55 pm.
Time: 11:00 am – 18:00 pm (lunch break 13:00 – 14:00)
Date: Thursday, Nov. 29th
Room: EE213 and EE215

Objectives

To illustrate the effects of electromagnetic waves travelling along cables, the importance of cable impedance matching, and the effects of resonance.

Equipment

Coaxial cable reel 'A' 100 m long
High frequency oscilloscope (50MHz bandwidth)
Pulse generator
56 ohms resistor
Multimeter
100Ω and 500Ω Cermet potentiometers
Coaxial termination box
Coaxial in-line connection box

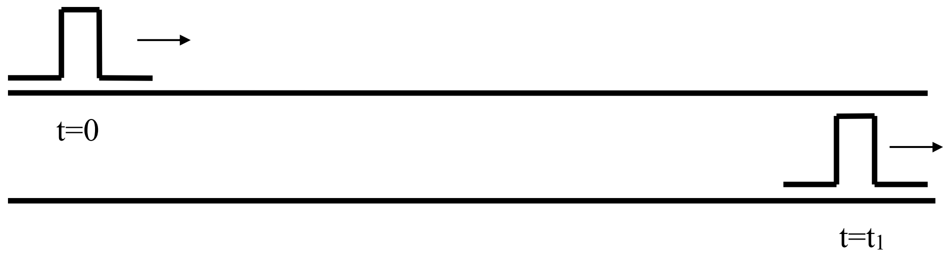
Introduction

Electrical signals propagate with a velocity which is equal to the speed of the light in the surrounding medium. This result is a triumph of Maxwell's theory which thereby identified light as a form of electromagnetic wave propagation. Maxwell's electromagnetic theory shows that this velocity in the case of free space (vacuum) is actually given by:

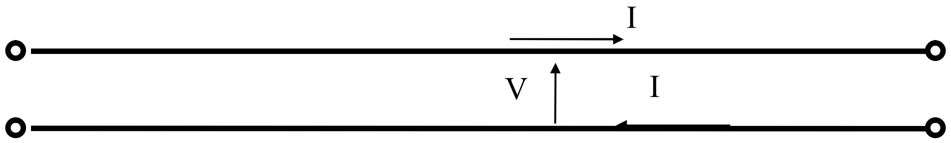
$$\upsilon = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 3 \times 10^8 m/s \quad . \quad (1)$$

Here ε_0 is the (electrostatic) permittivity of vacuum, and μ_0 is the corresponding (magnetic) permeability, with values $\varepsilon_0 = 8.85 \times 10^{-12} F/m$ and $\mu_0 = 4\pi \times 10^{-7} H/m$. For material other than free space, the permittivity and permeability terms are modified to $\varepsilon = \varepsilon_r \varepsilon_0$ and $\mu = \mu_r \mu_0$ where ε_r and μ_r (both dimensionless quantities) are the relative permittivity and relative permeability of the material, respectively. For plastics and most other insulators, ε_r >1, while μ_r is only greater than unity for iron and its alloys and a few other special materials.

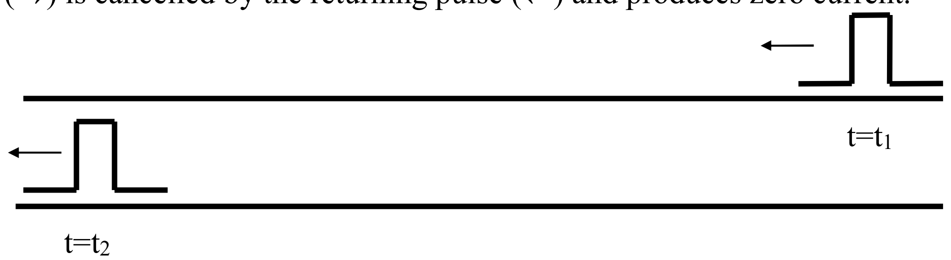
Wave propagation along the length of a uniform pair of conductors, forming what we know as a transmission line, can be studied by observing the voltage and current fronts associated with the electric and magnetic fields at the line (in terms of electromagnetic theory, the conductors of the cable serve to guide the electromagnetic field energy). If a voltage pulse (V_i) is applied to one end of a transmission line formed as a long cable, then the voltage travels down the cable from the *sending end* to the *receiving end* at a velocity which depends on the dielectric material between the conductors. For a cable, say 300m long, a short voltage pulse will take more than 1 μs to travel to the other end



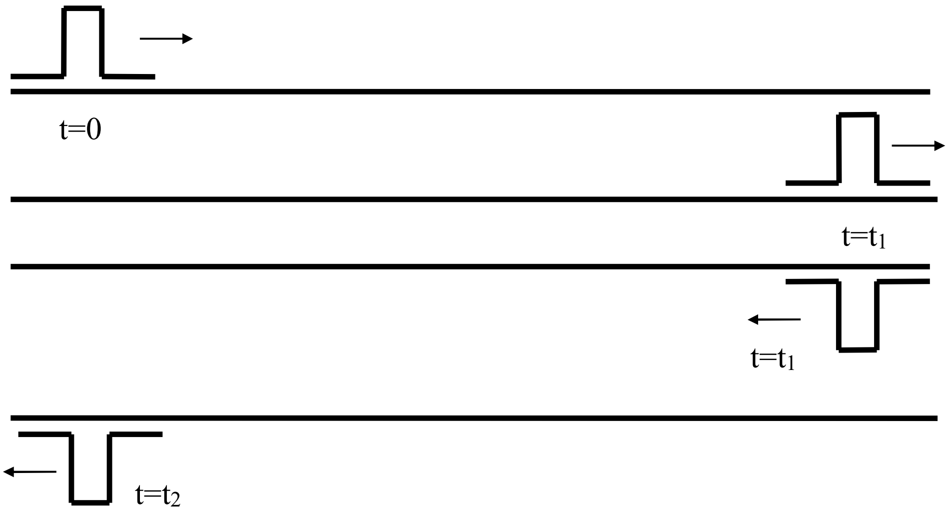
As the pulse travels down the cable, the voltage between the two wires and the current in the wires are related by the *characteristic impedance Z_0* of the cable. (The value of Z_0 depends on the cable geometry and on the dielectric)



When the pulse reaches the other end, its voltage and current are determined by the impedance connected to the receiving end. If the receiving end is open-circuit there can be no flow of current at the receiving end terminals. The pulse is therefore *reflected* as V_r from the open-circuit, and travels back towards the sending end; at the receiving end the current pulse ($\rightarrow$) is cancelled by the returning pulse ($\leftarrow$) and produces zero current.



If the receiving end is short-circuit, there can be no voltage at that point. The pulse entering the receiving end is reflected with a reversal of polarity and travels back to the sending end; at the receiving end the superposition of the forward voltage pulse ($\Uparrow$) and the reflected pulse ($\Downarrow$) upholds the zero voltage at this point.



For a finite impedance Z_L at the receiving (or Load) end, a fraction of the pulse is reflected, given by the *reflection coefficient* Γ *(sometimes also designated by ρ)* ,

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{V_r}{V_i} \quad (2)$$

For an open-circuit, Γ = 1, and for a short-circuit Γ = -1. If $Z_L = Z_0$, then there is no reflection (Γ = 0) and the load impedance is said to be *matched* to the cable; the impedance is then constant everywhere along the line and load and equal to Z_0.

Pulse Experiments

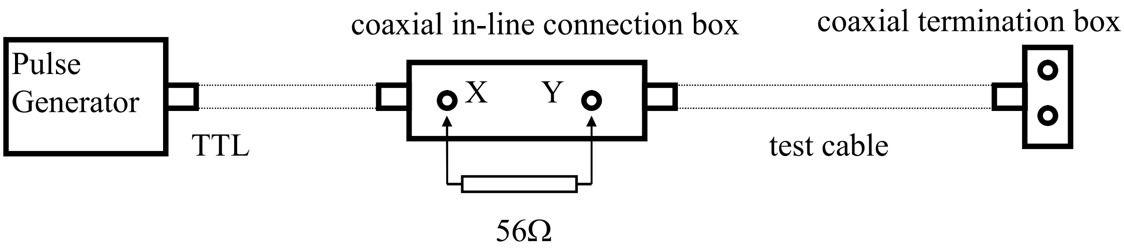
For this experiment the cable is a coaxial transmission line, where the two conductors are the inner wire and outer screen of a cylindrical arrangement. The outer screen is itself insulated with PVC (Polyvinyl Chloride), but the inner conductor is insulated from the outer screen by a plastic dielectric. This plastic has $\varepsilon_r > 1$, and so waves travel down the cable slightly slower than waves in a vacuum. This cable is used for TV antenna connections, and for computer networks (Ethernet).

Experiment 1

Set the pulse generator to produce pulses of about 0.1μs width and about 2μs period and the output voltage to be 3V. (The DELAY control of the pulse generator should be set OFF.) Use a BNC (Bayonet Neill-Concelman: http://en.wikipedia.org/wiki/BNC_connector) terminated cable (forming an electrical contact between the terminal and the conductor) to connect from the pulse generator TTL terminal to the oscilloscope for setting up the generator.

Note: Throughout this experiment it is important to use properly terminated cables and oscilloscope probes - open wire connections must not be used. If you are not careful, then your measurements will be affected by the extra 'transmission line' which you introduce. At high frequencies the capacitance and inductance of loose pieces of wire is significant.

Connect from the TTL output of the pulse generator to the coaxial in-line connection box, then to the 100m drum of coaxial cable, and then to the coaxial termination box. Fit a resistor of about 56Ω to the in-line connection box.



Use the two channels of the oscilloscope to observe the voltage at point Y at the sending end, and also at the receiving end. (Remember to use properly adjusted oscilloscope probes and be careful if they are set on x10.) Sketch the waveforms in your logbook and explain their shape.

This arrangement can be used to determine Z_0 for the cable. Connect the 100Ω Cermet potentiometer to the receiving end terminals, and adjust the potentiometer until there is no reflection (observe the voltage at point Y on the oscilloscope). Disconnect the cermet potentiometer and measure its value with the multimeter. Deduce the characteristic impedance of the cable using equation (2).

Q. What happens if the receiving end is short circuit?

Experiment 2

A similar test can be used to check the output impedance of the pulse generator. Open-circuit the receiving end and connect the 100Ω Cermet potentiometer to the coaxial in-line connection box in place of the 56Ω resistor. Observe the voltage waveform at the receiving end as the potentiometer is adjusted.

Q. What value of the potentiometer at the sending end removes the second reflection?

Explain why this happens, and deduce the output impedance of the pulse generator. (Hint: regard the resistance placed across XY as being in series with the output impedance of the generator)

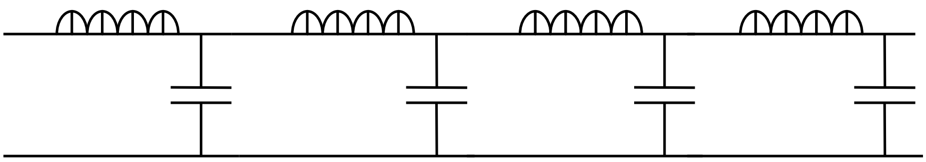
With the sending end matched (its impedance equal to the pulse generator impedance), measure the voltage V_Y at point Y and at the receiving end.

Q. What is the attenuation in the cable in decibels? What is the transit time along the cable?

Calculate the velocity of the wave along the cable, and deduce the relative permittivity of the plastic dielectric using equation (1).

Capacitance and inductance

A transmission line can be represented as a combination of distributed capacitance and inductance.



The characteristic impedance and wave velocity are related to the capacitance per unit length *C* and the inductance per unit length *L*.

$$Z_0 = \sqrt{\frac{L}{C}}$$

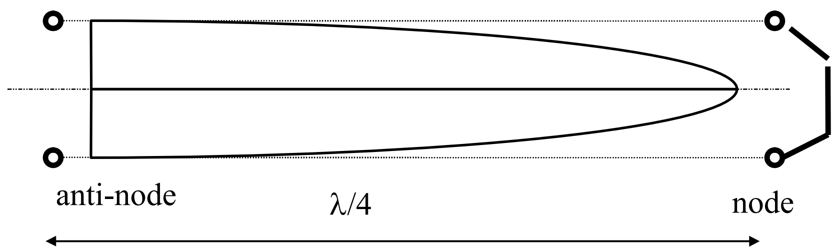
$$\upsilon = \frac{1}{\sqrt{LC}}$$

Calculate C and L for the cable.

Q. Some small campus networks operate at 10MHz close to each PC and at 100MHz between departments. What pulse widths correspond to these frequencies? If the whole campus network is 1km long, what is the delay of pulses travelling along the network?

Resonance

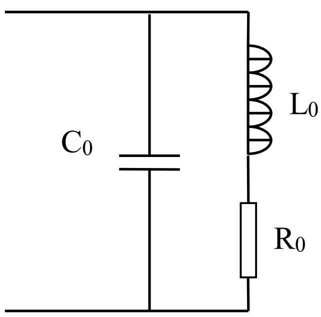
A long transmission line will resonate if the wavelength of the waves is related to the physical length of the cable, just as long pipes resonate with sound. In particular, a short-circuit line resonates if the line is 1/4 wavelength long.



The effective resonant circuit capacitance and inductance of the cable length *l* can be shown to be

$$C_0 = \frac{Cl}{2}$$

$$L_0 = \frac{8Ll}{\pi^2}$$



From the measurements of *C* and *L* above, estimate the resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_0}}$$

The effective resonant circuit series resistance R_0 is related to the physical resistance per unit length R by

$$R_0 = \frac{8Rl}{\pi^2}$$

Calculate R_0 where R=0.023 ohms.

References: Kraus, J.D. and Fleisch, D. "Electromagnetics", McGraw Hill.

Collin, R.E. "Foundations for Microwave Engineering" Chapter 7