8. Radio frequency transmission lines

A. Objectives

- Measure the output of a voltage-controlled oscillator on a digital oscilloscope, and learn basic operation of the oscilloscope.
- Measure the capacitance of RG58 coaxial cable by its contribution to an *RC* time constant.
- Measure the propagation speed of an electromagnetic wave in an RG58 coaxial cable.
- Measure the amplitude of a wave reflected from the end of a coaxial cable relative to the incident wave, for the cases in which the cable end is (i) open-circuited (ii) short-circuited, (iii) terminated with an impedance-matched terminator, and (iv) terminated with a mis-matched terminator.
- Measure the relative amplitudes of the incident, reflected, and transmitted waves from an impedance discontinuity at the junction between two coaxial cables.

B. Equipment required

1. Voltage controlled oscillator with power supply, frequency control, and SMA to BNC adapter
2. Transistor avalanche pulser and power supply
3. 100 MHz two-channel digital oscilloscope
4. (2) Radio frequency directional couplers
5. RF coaxial cables:

(3) 50 Ohm, 3' length	(2) 50 Ohm, 6' length
(1) 50 Ohm, 10' length	(1) 50 Ohm, 40' length
(1) 93 Ohm, 5' length	(1) 93 Ohm, 30' length

6. (3) BNC Tees
7. (2) BNC unions
8. (4) 50 Ohm BNC terminators
9. (1) 93 Ohm BNC terminator
10. (1) BNC shorting cap

C. Introduction

Radio frequencies

Radio frequencies (RF) are frequencies in the range from about 300 kHz to 3 GHz. Radio waves are radio frequency electromagnetic (EM) waves, widely used for wireless communication. In the US, most frequencies are assigned to specific, licensed users by government regulation. The full assignment can be found here. Specific assignments include AM radio broadcast in the range from 535 to 1606 kHz, FM radio broadcast in the range from 88 to 108 MHz, over-the-air television broadcast in the frequency bands from 54 to 72 MHz, 76 to 88 MHz, 174 to 216 MHz, and large parts of 470 to 794 MHz, and cell phone transmission over five different frequency bands in the range from 698 MHz to 2.5 GHz. Computer wi-fi connections use bands in the spectrum at about 2.4 GHz and 5.8 GHz.

Radio frequency techniques are widely used in experimental physics and astronomy. Examples include RF excitations of confined plasmas, RF modulation and demodulation for signal extraction, nuclear or electronic magnetic resonance experiments, RF resonators for charged particle accelerators, and radio astronomy.

Transmission lines

The wavelength of radio waves can be comparable to or smaller than the size of an experiment or even a piece of electronic equipment. For instance, at 300 MHz the wavelength is 1 meter. This fundamentally alters the nature of electronic circuits relative to lower frequencies. For one thing, isolated wires have a strong tendency to act as antennas at radio frequencies, both radiating power as EM waves and picking up voltages from the EM waves produced by other wires. This coupling is often unwanted and must be suppressed for a circuit to work as intended. Also, the rule that the electric potential must be the same everywhere on a conductor is no longer valid. This rule is enforced physically by the actions of electric fields, and is strictly valid only for static electric fields. At radio frequencies, the time for an EM wave to propagate from one part of a metal surface to another can be comparable to a period of oscillation. Thus, by the time the field produced by one part of a surface reaches another part, the field near the first part will already have changed.

One of the most important radio frequency components is the *transmission line*. A transmission line consists of two parallel conductors. One of the most common types is the *coaxial cable*, shown in Figure 8.1. It has an inner conducting wire and an outer cylindrical conductor separated by an insulator. The outer conductor is covered with another insulating layer. These cables are usually made of stranded, flexible conductors and flexible plastic insulators so that they can easily be bent.

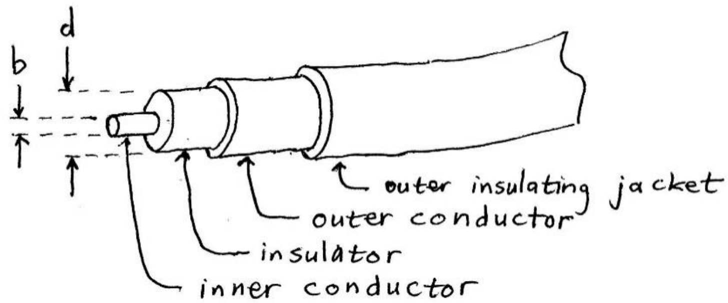

Figure 8.1. Coaxial cable.

At radio frequencies, transmission lines have the virtue that the currents on the two conductors are equal and opposite. The fields radiated by these two currents therefore cancel. A transmission line does not radiate radio waves, and it does not act as an antenna that can pick up voltages from radio waves. The outer conductor is sometimes called the *shield* because of it can be viewed as shielding the inner conductor from EM fields outside the cable.

We review here the basics of transmission line theory. Let z measure the displacement along the length of the line, $V(z,t)$ the potential difference between the two conductors, and $I(z,t)$ the current carried by the inner conductors. The currents in the two conductors are equal and opposite; *i.e.* the current carried by the outer conductor is $-I(z,t)$. It is possible to show that V and I obey the coupled partial differential equations

$$\frac{\partial V}{\partial z} = -\mathcal{L}\frac{\partial I}{\partial t} \tag{8.1}$$

$$\frac{\partial I}{\partial z} = -\mathcal{C}\frac{\partial V}{\partial t} \tag{8.2}$$

where $\mathcal{L}$ is the inductance per unit length and $\mathcal{C}$ the capacitance per unit length of the transmission line.

Equations (8.1) and (8.2) have wave solutions. To see this we substitute the following trial solutions for V and I into (8.1) and (8.2):

$$V(z,t) = V_0 \cos(\omega t - kz) \tag{8.3}$$

$$I(z,t) = I_0 \cos(\omega t - kz + \phi) \tag{8.4}$$

We find they are solutions if and only if

$$\phi = 0 \tag{8.5}$$

and $$\frac{V_0}{I_0} = \mathcal{L}\frac{\omega}{k} = \frac{k}{\mathcal{C}\omega} = \sqrt{\frac{\mathcal{L}}{\mathcal{C}}} = Z \tag{8.6}$$

That is, the voltage and current waves on the line must oscillate in phase. Also, the voltage to current ratio must have a fixed value, Z. This quantity has dimension of resistance (Ohms), and is called the *impedance* of the line.

From equation (8.6), we can also determine that the phase velocity of the waves is

$$\mathrm{v}_\varphi = \frac{\omega}{k} = \sqrt{\frac{1}{\mathcal{L}\mathcal{C}}} \tag{8.7}$$

In this lab, we'll use coaxial cables. The inductance and capacitance per unit length of these is

$$\mathcal{L} = \frac{\mu_0}{2\pi}\ln\left(\frac{d}{b}\right) \tag{8.8}$$

$$\mathcal{C} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(d/b)} \tag{8.9}$$

where d is the inside diameter of the outer conductor, b the diameter of the inner conductor, ε_r the dielectric constant of the insulator, $\varepsilon_0 = 8.854\times10^{-12}$ F/m the electric constant, and $\mu_0 = 4\pi\times10^{-7}$ N/A^2 the magnetic constant. From this, we find that the speed of the wave is

$$\mathrm{v}_\varphi = \sqrt{\frac{1}{\mathcal{L}\mathcal{C}}} = \sqrt{\frac{1}{\varepsilon_0\mu_0\varepsilon_r}} = \frac{c}{\sqrt{\varepsilon_r}} \tag{8.10}$$

where $c = \sqrt{1/\varepsilon_0\mu_0} = 2.998\times10^8$ m/s is the speed of light in vacuum. In real cables, v_φ is usually somewhere in the range from 65% to 85% of the speed of light.

The characteristic impedance of the cable is

$$Z = \sqrt{\frac{\mathcal{L}}{\mathcal{C}}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}}\ln\left(\frac{d}{b}\right) \tag{8.11}$$

The most commonly used cable in physics is type RG58, which has characteristic impedance $Z = 50$ Ohms. Cables used for analog video signals usually have impedance $Z = 75$ Ohms. Cables with other values of impedance are sometimes used, but nearly all have impedances in the range from 30 to 150 Ohms. It is difficult to produce a practical, economical cable with impedance very far outside this range due to the weak, logarithmic dependence of Z on the diameter ratio d/b, and practical limitations on the properties of the insulating material.

Sinusoidal *vs.* pulsed waves

Equations (8.1) and (8.2) can be combined to give the one-dimensional wave equation

$$\frac{\partial^2 V}{\partial z^2} + \frac{1}{\mathrm{v}_\varphi^{\,2}}\frac{\partial^2 V}{\partial t^2} = 0 \tag{8.12}$$

By now, you're familiar with the fact that this equation has sinusoidal wave solutions

$$V(z,t) = V_0 \cos(\omega t - kz) = V_0 \cos\left(\omega\left(t - \frac{z}{\mathrm{v}_\varphi}\right)\right) \tag{8.13}$$

You may also be familiar with the fact that

$$V\left(t - \frac{z}{\mathrm{v}_\varphi}\right) \tag{8.14}$$

is a solution of the wave equation (8.12)*, where V is any function at all.* (This statement is true only if the wave is non-dispersive, *i.e.* if v_φ is constant. This is the case for an RF transmission line.)

Expression (8.14) is a wave "pulse" of shape *V* that moves to the left (or right, if v_φ is negative) at speed v_φ. For example, *V* could consist of the *square pulse*

$$V(\xi) = \begin{cases} V_0, \text{ if } 0 < \xi < \tau \\ 0, \text{ otherwise} \end{cases} \tag{8.15}$$

The wave $V\left(t - \frac{z}{\mathrm{v}_\varphi}\right)$ for this function is shown in Figure 8.2. At time $t = 0$, the voltage *vs.* position takes the form of a square pulse with non-zero voltage V_0 only over the interval $[-\mathrm{v}_\varphi \tau, 0]$. As time moves forward, the square pulse moves to the right at speed v_φ. For instance, at time $t = 3\tau$ the square pulse has moved by a distance $3\mathrm{v}_\varphi \tau$. You'll be working with such square pulses later in this lab.

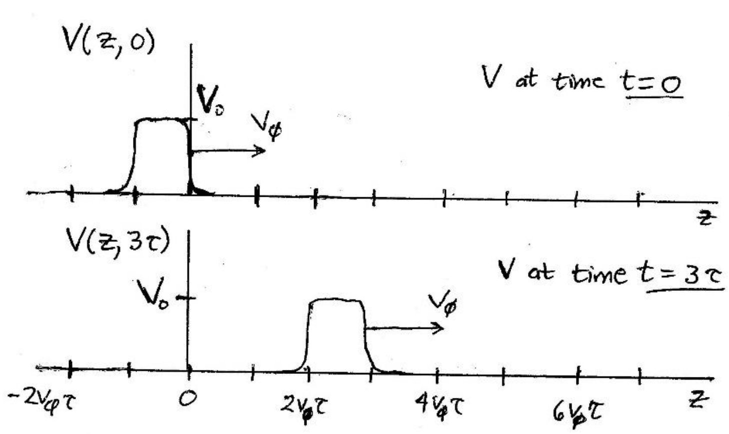

Figure 8.2. Voltage *V* as a function of position *z* at two different times, $t = 0$ and $t = 3\tau$, for the square pulse $V\left(t - \frac{z}{\mathrm{v}_\varphi}\right)$, with *V* given by equation (8.15).

Bandwidth and pulsed electronics

Imagine that you measure the pulse of equation (8.15) with a voltage probe at $z = 0$. In that case, what you'll see is the square pulse as a function of *time* $V(t)$. If you take some other position, you'll see the same square pulse *vs.* time, only with some time delay.

One way to understand why *any* $V\left(t - \frac{z}{v_\varphi}\right)$ solves the wave equation is to think in terms of Fourier transforms. The pulse $V(t)$ can always be written in terms of its Fourier transform $\tilde{V}(f)$, *i.e.* as a linear combination of sinusoidal vibrations of many different frequencies. Since the wave equation is linear, any linear combination of solutions is a solution. Therefore $V\left(t - \frac{z}{v_\varphi}\right)$, being a superposition of many sinusoidal wave solutions of the equation, is also solution.

A short pulse will have a broad Fourier transform. For example, Figure 8.3 shows the Fourier transform of a 10 ns square pulse. The Fourier transform of this pulse has significant amplitude out to hundreds of MHz.

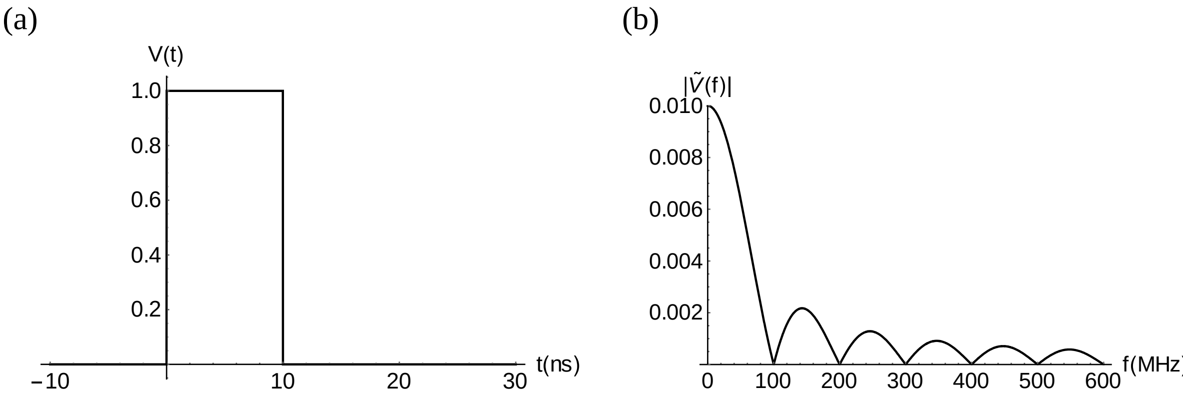

Figure 8.3. (a) Square voltage pulse of 10 ns duration. (b) Magnitude of the Fourier transform of the pulse.

Consider the simple low-pass *RC* filter shown in Figure 8.4(a). Suppose that we apply an oscillating voltage $V_{in}(t) = V_{in}^{(0)} \cos(2\pi ft)$ to its input. The voltage at its output will be $V_{out}(t) = V_{out}^{(0)} \cos(2\pi ft + \phi)$, where both the output amplitude $V_{out}^{(0)}$ and the phase shift ϕ are functions of the frequency *f*. The ratio of the output amplitude to the input amplitude, as a function of frequency, is shown in Figure 8.4(b). The ratio is 1 at low frequencies, but then drops at high frequencies.

The frequency f_c at which the amplitude ratio has fallen to $1/\sqrt{2} \approx 0.71$ is called the *bandwidth* of the filter. Roughly speaking, the filter allows frequencies below f_c to pass, and blocks frequencies above f_c. Other electronic devices may have a frequency response curve that is similar, although not exactly identical, to that of a low-pass *RC* filter. For those components it is also conventional to refer to the frequency at which the transmitted amplitude has fallen by 30% as the "bandwidth" of the component.

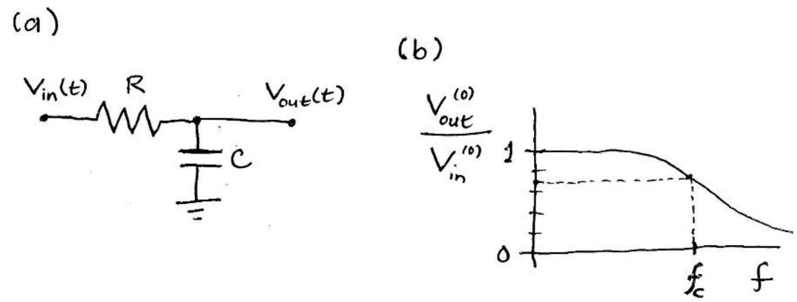

Figure 8.4 (a) Low-pass *RC* filter. (b) Ratio of the output to the input voltage amplitude as a function of frequency, for the case of sinusoidal time dependence of the voltages.

If a pulse is to be processed by an electronic system without significant distortion, the bandwidth of that system must be comparable to the width of the Fourier spectrum of the pulse. For this reason, *electronics to process sub-microsecond pulses must have a bandwidth in the radio-frequency range.*

In practice, it is usually sufficient for the bandwidth, in Hz, to be roughly equal to the inverse pulse duration. For instance a 100 MHz bandwidth is usually good enough for 10 ns pulses. This might seem doubtful because the spectrum shown in Figure 8.3(b) extends well past 100 MHz. However, most of the very high frequency Fourier components come from the sharp corners on the pulse. The main effect of limiting the bandwidth to 100 MHz is to round these corners off a bit, so that the signal takes 3 or 4 nanoseconds rather than a small fraction of a nanosecond to switch between the maximum and minimum voltages. That softening of the edges of the pulse is often not important for applications.

Fast pulsed electronics is also widely used in physics experiments. The most common applications involve pulsed signals from photon or particle detectors. Often, the ability to time detection events on the nanosecond or sub-nanosecond time scale is important to the experiment.

Reflections due to impedance discontinuity

Suppose that a cable of impedance Z_1 is joined onto another cable of impedance Z_2 at position $z=0$, as shown in Figure 8.5, and suppose that a traveling voltage wave $V_I = V_0 \cos(\omega t - k_1 z)$ is incident on the joint from the left. The voltage wave will partially reflect from the joint.

This happens because the following two conditions must be satisfied at the same time:

(i) The current I and voltage V must be continuous across the joint.

(ii) The ratio of voltage to current must be Z_1 on the left, and Z_2 on the right.

Conditions (i) and (ii) are incompatible if there is only a wave traveling in one direction at all points.

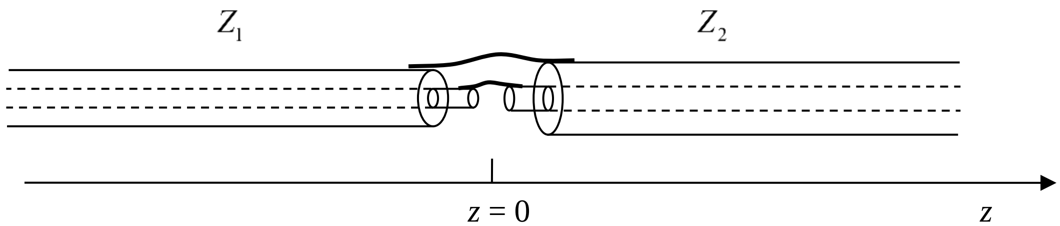

Figure 8.5. Transmission line with an impedance discontinuity.

The general solution of the wave equation has waves traveling both to the left and the right. The solution of the wave equation, subject to conditions (i) and (ii) and the boundary conditions of an incident wave from negative *z* but not from positive *z*, is

$$V(z,t) = \begin{cases} V_0 \cos(\omega t - k_1 z) + rV_0 \cos(\omega t + k_1 z), & \text{if } z < 0 \\ tV_0 \cos(\omega t - k_2 z), & \text{if } z > 0 \end{cases} \tag{8.16}$$

where $r = \dfrac{Z_2 - Z_1}{Z_2 + Z_1}$ (8.17)

is the *amplitude voltage reflection coefficient* and

$$t = 1 + r = \frac{2Z_2}{Z_1 + Z_2} \tag{8.18}$$

is the *amplitude voltage transmission coefficient.*

Equation (8.16) shows that there is a *reflected wave* to the left of the joint, with an amplitude *r* times as large as amplitude of the incident wave, and a *transmitted wave* to the right of the joint, with an amplitude *t* times as large as the amplitude of the incident wave.

Reflection and transmission with relative amplitudes *r* and *t* occur regardless of the exact time-dependence of the voltage. For example, if a square voltage pulse of height V_0 hits the discontinuity, it will produce a reflected square pulse with a height rV_0 and a transmitted square pulse with a height tV_0, as shown in Figure 8.6.

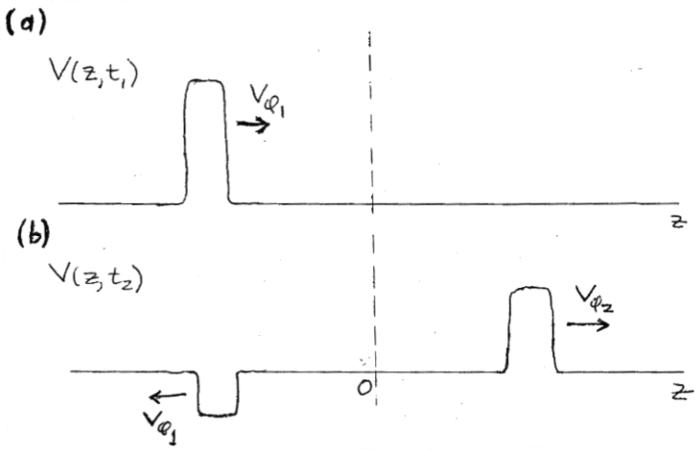

Figure 8.6. Reflection of a voltage pulse from an impedance discontinuity. (a) Voltage *vs*. position *z*, at a time t_1 before the pulse has reached the discontinuity. (b) Voltage *vs*. position *z*, at a time t_2 after the pulse has moved past the discontinuity. The figure illustrates the case $Z_1 = 50\ \Omega,\ Z_2 = 25\ \Omega,$ for which $r = -1/3,$ and $t = 2/3.$

Radio frequency power

Suppose that we drive one end of a cable with a voltage source $V(t)$. It follows that the cable will draw a current $I(t) = V(t)/Z$. This is the same current that would be drawn by a simple resistor of resistance *Z*. Therefore, *from the perspective of the signal source, an infinitely long cable of impedance Z is equivalent to a simple resistor of resistance Z.* Of course, for points past the voltage source everything is completely different. If there is a resistor attached, the power from the voltage source is turned into heat in the resistor. If a cable is attached the power is transmitted as a traveling wave in the cable.

The instantaneous power transmitted past a given point in the line is

$$P(t) = VI = I^2 Z = I_0{}^2 Z \cos^2(\omega t - kz) \tag{8.19}$$

Frequently we only care about the time-averaged power, which is

$$\langle P \rangle = \frac{1}{2} I_0{}^2 Z = \frac{V_0{}^2}{2Z} \tag{8.20}$$

Here, the brackets indicate a time average over one cycle, *i.e.* $\langle f \rangle = \frac{1}{T}\int_0^T f(t)dt,$ where *T* is the period of the oscillation. The *root-mean-square* (rms) voltage is the square root of the time-average of the voltage squared:

$$V_{rms} = \sqrt{\langle V^2(t) \rangle} = \frac{1}{\sqrt{2}} V_0 \tag{8.21}$$

The time-averaged power can also be written as

$$\langle P \rangle = \frac{V_{rms}{}^2}{Z} \tag{8.22}$$

Using these formulas, we can also work out the *power reflection coefficient* and *power transmission coefficient* for an impedance discontinuity:

$$\mathcal{R}_P = \frac{\mathcal{P}_R}{\mathcal{P}_I} = r^2 = \frac{\left(Z_1 - Z_2\right)^2}{\left(Z_1 + Z_2\right)^2} \qquad \mathcal{T}_P = \frac{\mathcal{P}_T}{\mathcal{P}_I} = \frac{Z_2}{Z_1} t^2 = \frac{4 Z_1 Z_2}{\left(Z_1 + Z_2\right)^2} \tag{8.23}$$

where $\mathcal{P}_I$ is the power transported by the incident wave, $\mathcal{P}_R$ the power transported by the reflected wave, and $\mathcal{P}_T$ the power transported by the transmitted wave.

Decibels and dbm.

It is conventional in radio and microwave electronics to measure power ratios in *decibels* (dB). Given two powers P_1 and P_2, their power ratio measured in decibels is

$$\text{Power ratio}\left(\text{dB}\right) = 10 \log_{10}\left(\frac{P_1}{P_2}\right) \tag{8.24}$$

Each 10 dB is a factor of 10 in power. For example, if $P_1 = 10\text{ W}$ and $P_2 = 1\text{ W},$ their power ratio is $+10\text{ dB}.$ If $P_1 = 100\text{ W}$ and $P_2 = 1\text{ W},$ their power ratio is $+20\text{ db}.$ 3 dB is very close to a factor of 2 in power. Power ratios less than 1 will have negative dBs. For instance if $P_1 = 0.2\text{ W}$ and $P_2 = 0.5\text{ W},$ their power ratio is $-3.98\text{ dB}.$ We say that P_1 is "down by 3.98 dB" from P_2.

It is also conventional to define 1 mW as a *reference power* for radio-frequency and microwave electronics. A power measured in dB with respect to this reference power is denoted as a certain number of dBm. That is

$$P(\text{dBm}) = 10 \log_{10}\left(\frac{P}{1\text{ mW}}\right) \tag{8.25}$$

For example, if a source puts out 1 Watt, we would say that it puts out 30 dBm.

Terminations and impedance matching

Suppose that we hook one *Z* = 50 Ohm impedance cable directly up to another one, as illustrated in Figure 8.7. A signal can propagate from one section to the next without significant reflection or loss from the joint, as long as the connecting wires are very short. That’s because the two wires transmit both the voltage difference and the current almost perfectly across the joint.

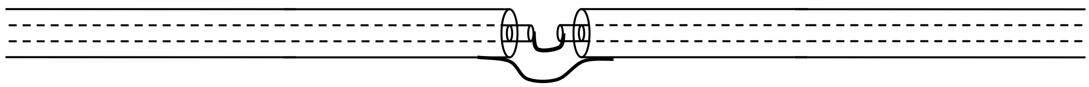

Figure 8.7. Two coaxial cables connected together.

Now, suppose that instead of connecting the right hand section of cable to another section of cable, we connect it to a 50 Ohm resistor, as shown in Figure 8.8.

Question: What happens now if a wave $V(z,t)$ coming from the left hits the resistor?

Answer: The wave is completely absorbed by the resistor. There is no reflection.

Explanation: For our problem, the end of the left-hand cable section acts as a signal source for the component on the right. To the left-hand cable section, it doesn't matter whether that component is another cable section or a resistor of resistance *Z*. Both of them have a resistive impedance of 50 Ohms. ("Resistive" means the current and voltage are in phase. That distinguishes the impedance from "reactive" impedance, for which the current and voltage would not be in phase.) Since there is no reflection for one case (another cable section) there's no reflection for the other case (the 50 Ohm resistor).

$R = 50\ \Omega$

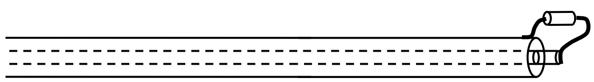

Figure 8.8. A coaxial cable terminated by a $50\ \Omega$ resistor.

The matching of a load impedance to a cable impedance is called *impedance matching.* A load that consists of a simple resistor is called a *terminator*. In the ideal limit of perfect impedance matching (zero reflection), the impedance-matched termination is sometimes referred to as a *perfect termination.*

Consider also a cable of impedance *Z* that is terminated by a resistance $R \neq Z$. The resistor presents a load to the cable that is identical to the load presented by a second cable section of impedance *R*. Therefore, as far as the voltage and the currents in the cable go, this problem is identical to our above analysis of impedance discontinuity, with $Z_1 \to Z$, and $Z_2 \to R$. Therefore a wave hitting the end of the cable is partially reflected, with reflection coefficient

$$r = \frac{R-Z}{R+Z} \tag{8.26}$$

Impedance-matching is standard practice in radio frequency and microwave electronics. For instance, when you buy a radio frequency amplifier, it will nearly always have an input impedance designed to be matched to some specific cable impedance (usually 50 or 75 Ohms). Impedance matching is important because it suppresses reflection of RF power. Reflections have a number of undesirable effects in RF systems, including loss of efficiency, degradation of signal-to-noise-ratio, and inadequate control over power levels. Some RF components are not designed to be used with mismatched loads, and will burn out if they see too much reflected power.

It's also common for microwave components to have *output* impedances that are designed to be matched to a specific cable impedance. This is done because it's impossible to completely suppress reflections from the following components. If there are such reflections, an impedance matched output will suppress the reflections of the reflections.

RF connectors and components

BNC connectors

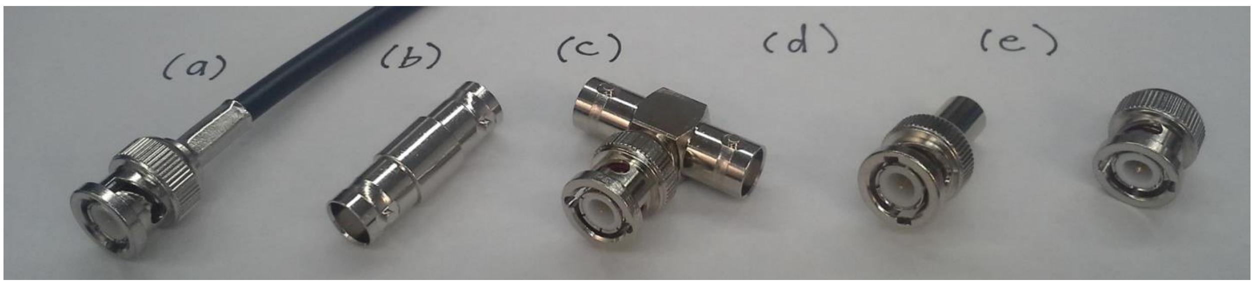

Figure 8.9. Components with BNC connectors. (a) coaxial cable with BNC connector (b) BNC union (c) BNC tee (d) BNC terminator (e) BNC shorting cap.

RF connectors are designed to electrically connect a cable to another cable or to an RF component. This requires that the outer conductor of one cable or component connect to the outer conductor of another, and similarly for the inner conductor. The most common RF connector in physics labs is the *BNC connector*. It has the advantages of being inexpensive and easy to connect and disconnect.

Examples of components with BNC connectors are shown in Figure 8.9. The male connector, visible in Figure 8.9(a), (c), (d), and (e) has a slotted outer conductor and a gold plated pin that connects to the outer and inner conductors of a cable, respectively. The female connector, visible in Figure 8.9(b) and (c) has an outer connector with two bayonets and a gold plated socket that connects to the pin of the male connector. The connecters are attached by fitting the bayonets into the slots and giving the connector a quarter turn.

Unions, tees, and terminators

Figure 8.9(b) is a photo of a *BNC union*. These are used to join two cables together, as shown in Figure 8.10(a). This electrically connects two cables together as shown in Figure 8.7. Figure 8.9(c) is a photo of a *BNC tee.* It's used to connect three components together. Figure 8.9(d) is a photo of a *BNC terminator.* This component has a resistor connected between the outer and inner conductor; *i.e.* it is used to make a termination like that illustrated in Figure 8.8. Figure 8.9(e) is a photo of a *BNC shorting cap*. This component has the inner and outer conductor shorted together; *i.e.* it is a terminator with a resistance of zero Ohms.

(a)

(b) (c)

Figure 8.10 (a) Two cables joined with a BNC union (b) Directional coupler (c) Voltage-controlled oscillator.

Directional couplers

Figure 8.10(b) is a photo of a *directional coupler* used in this experiment (Mini-Circuits model ZDC-20-3). It has three BNC connections - the input, output, and a "coupled" port. In this case, the outer conductors of the connectors are attached to the component case, so the case functions as a continuation of the shield layer. This is usually done for RF components. All three ports have an impedance of $50\ \Omega$, and we will connect to these ports only with $50\ \Omega$ cable. When the device is used in this way, there is very little reflection of any signal from any port.

This function of this component is illustrated in Figure 8.11 for the case of pulsed input. In the figure, we have omitted the outer conductor connections for simplicity, but you should keep in mind that the outer conductors are always present and connected. The left side of the figure shows what happens when a pulse is applied to the input port. In this case, the pulse is transmitted through the device to the output port, so that a (slightly attenuated) pulse is sent into the cable attached to that port. In addition, an attenuated version of the pulse is sent into the coupled port. This particular device has a coupling of -20 dB. This means that the power sent to the coupled port is 20 dB less than the power sent into the input port, *i.e.* its power is 100 times less. Since power is proportional to voltage squared, the signal sent into the coupled port has a voltage 10 times smaller than the signal applied to the input port. Aside from this factor of 10 reduction in voltage, the signal has the same time-dependence as the signal applied to the input.

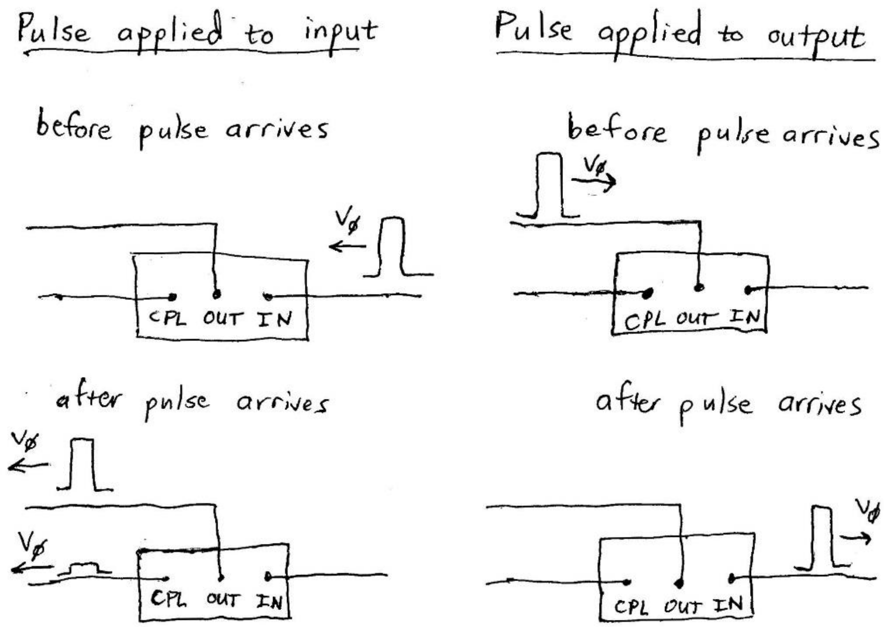

Figure 8.11. Response of a directional coupler to pulsed inputs. The coupled port puts out a signal that is proportional to the signal travelling in the direction from the input to the output port, but not to any signal travelling in the reverse direction.

The right side of the figure shows what happens when the pulse is applied to the output port. In this case, the pulse is transmitted through to the input port. But, *no* signal appears at the coupled port. This is why the device is called a *directional* coupler. The coupled port provides a sample of the voltage wave transmitted through the device *in one direction only* – from "in" to "out." If you think about this, you'll realize that it is non-trivial to design a device with this function – many obvious ideas for coupling do not have the required directional asymmetry. The design of directional couplers is a fascinating topic which we unfortunately don't have time to discuss.

Voltage-controlled oscillators

Figure 8.10(c) shows a *voltage controlled oscillator* (VCO) that will be used in this experiment. (Mini-Circuits model ZX-95-100+) . It generates a sine wave output with a frequency that can be tuned with a voltage applied to its tuning input. You'll be supplied with this VCO mounted onto a box that contains a power supply and an adjustable voltage, with a knob for the voltage adjustment. The tuning range of this device is 50 to 100 MHz. Its output power is specified as 10 dBm, *i.e.* 10 milliWatts. This particular device is only available with a different type of RF connector called an SMA connector. As shown in Figure 8.10(c), we've placed an SMA to BNC adapter on the output, so that you can connect this device to a BNC cable.

Transistor avalanche pulser

In this experiment, you'll be supplied with a transistor avalanche pulse generator. These were built in the physics department electronics shop by Robert Hasdorff. This pulse generator produces square voltage pulses into a 50 Ohm load with a duration of about 20 ns. It is similar in design to the one described here. A superfast version of this circuit that can produce pulses of a few hundred picosecond duration is described here.

A simplified diagram of the circuit is shown in Figure 8.12(a). To use the circuit, you'll attach an RG-58 coaxial cable of length L_S to the port marked "cable". This becomes the "source cable" shown in Figure 8.12(a). You'll also connect an RG-58 coaxial cable of length L_{out} to the port marked "out". A constant voltage $V_{Supply} \approx 100 \text{ Volts}$ is applied to one end of a resistor R_{ch}. The other end of R_{ch} is connected to the collector of a transistor and to the center conductor of the source cable. A voltage applied to the base of the transistor (not shown) keeps the transistor turned off at all times. While the transistor is off, a charging current flows through R_{ch}, which gradually increases the voltage $V_S(t)$ and the charge $Q_S(t) = C_S V_S(t)$ on the source cable, where C_S is the capacitance of the source cable. The transistor cannot hold off the full voltage $V_{Supply} \approx 100 \text{ Volts}$ between its collector and its emitter. Instead, when $V_S(t)$ reaches about $V_{bd} \approx 50 \text{ to } 70 \text{ Volts}$, the transistor "breaks down", and allows a current to flow between the collector and the emitter. This happens even though the transistor is turned off. It is something like the solid-state version of a spark plug – the resistance is very high until breakdown occurs, but once the device breaks down it presents a very low resistance for the flow of current. The resistance will remain low as long as current flows.

Once transistor breakdown occurs, the source cable finds itself connected to a resistor $R_{out} = 10 \text{ k}\Omega$ in parallel with the output cable. A charge Q flows out of the source cable and into the output circuit. Once the charge has left the source cable, the transistor switches back to a high resistance state, and the charging cycle starts all over again.

There are two limiting cases for the output pulse shape. The first one occurs if the signals on the cable change slowly compared to the time $L_{out} / \text{v}_\varphi$ for signals to travel from one end of the output cable to the other. This happens, for instance, if you just plug the output cable directly into an oscilloscope as shown in Figure 8.12(b). In this limit, the output cable doesn't act very much like a transmission line. Instead, what you have is just two conductors – the inner conductor and the shield – separated by an insulator. Electrically this is just a capacitor with capacitance C_{out}. For RG58 cable, C_{out} is about 30.8 pF per foot of length. The oscilloscope also contributes to the load on the pulser: it has input impedance equivalent to the combination of an $R_{scope} = 1 \text{ M}\Omega$ resistor in parallel with a $C_{scope} = 20 \text{ pF}$ capacitance. Thus the output circuit is equivalent to the RC circuit shown in Figure 8.12(b), where $R = R_{out} \| R_{scope} \approx R_{out} = 10 \text{ k}\Omega$ is the resistance of the parallel combination of R_{out} and R_{scope}, and $C = C_{out} + C_{scope} \approx \left(30.8 \text{ pF} \times L_{out}(\text{feet})\right) + 20 \text{ pF}$ is the capacitance of the parallel combination of C_{out} and C_{scope}. The sudden dump of charge Q onto the output capacitance C causes its voltage to suddenly jump to Q/C, which then exponentially decays with an *RC* time constant. This *RC* time constant is much larger than $L_{out}/\mathrm{v}_{\varphi}$, and that is what causes the signal to change relatively slowly.

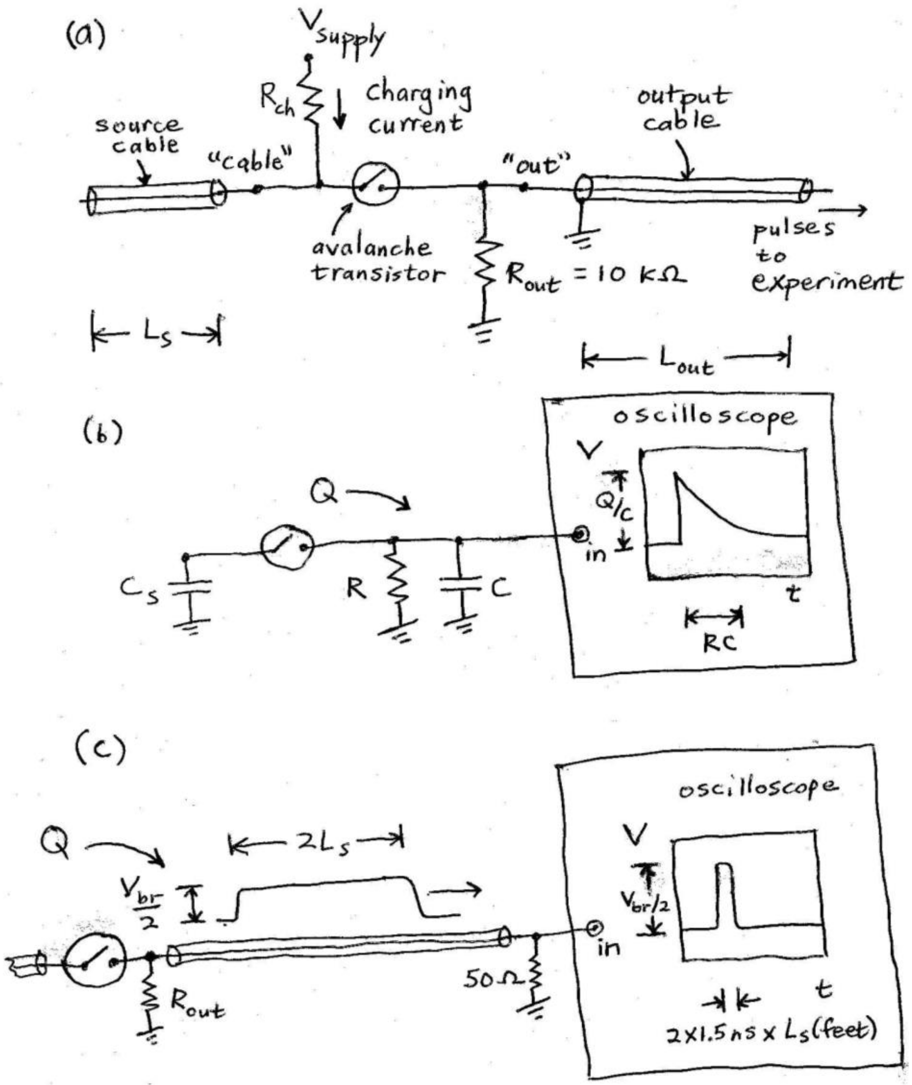

Figure 8.12. (a) Simplified circuit diagram of a transistor avalanche pulser and attached source and output cables. (b) Simplified output circuit when the output cable is connect to an oscilloscope, and the voltage on the output cable changes slowly compared to the transit time of the cable $L_{out}/\mathrm{v}_{\varphi}$.
(c) Simplified output circuit when the output cable is connected to an oscilloscope, the time scale for changes in the voltage is comparable to or faster than $L_{out}/\mathrm{v}_{\varphi}$, and the cable is terminated with a perfect termination.

The second limiting case occurs when the time scale for voltage changes on the cable is comparable to or less than L_{out}/c. This happens, for instance, if you connect a 50 Ohm resistor in parallel with the scope input, as illustrated in Figure 8.12(c). In this case, the output cable does act as a transmission line. When the transistor breaks down, the source cable suddenly finds itself connected to the ouput cable through a very low resistance. It turns out that the source cable outputs a square voltage pulse with a length $2L_S$ and amplitude $V_{br}/2$. (This has to do with the fact that the static voltage V_{br} on the source cable can be decomposed into a left-going square pulse and a right-going square pulse, each of height $V_{br}/2$.) That output pulse travels down the cable to the impedance-matched $50\ \Omega$ load on the scope and is absorbed by that load. The scope just records a square pulse of amplitude $V_{br}/2$. The transit time of signals in RG-58 cable is about 1.5 ns/foot, so for a 6 ft long source cable the time duration of the pulse is about $2\times 6\text{ ft}\times 1.5\text{ ns/ft}=18\text{ ns}$.

<u>Digital oscilloscope and oscilloscope termination</u>

In this experiment you will record signals with a Tektronix model 1152B digital oscilloscope. This oscilloscope has two channels, so it can record two voltage waveforms at the same time. It has a bandwidth of 100 MHz, which is sufficient to record sinusoidal waves from the VCO, and also to record ~ 20 ns width pulses from the transistor avalanche pulser.

Figure 8.13. Photo of the attachment of impedance matched loads to oscilloscope inputs.

The Tektronix 1152B oscilloscope has an input impedance of $1\ \text{M}\Omega$ in parallel with 20 pF. This is very far from an impedance match to a coaxial cable, and would result in very large reflections of signals if we just plug a coaxial cable directly into the oscilloscope. That is not what we want for RF measurements. In order to provide an impedance-matched load at the oscilloscope input, for most of this experiment we'll place a $50\ \Omega$ BNC terminator and a BNC tee at each input as shown in Figure 8.13. This puts the $50\ \Omega$ terminator impedance in parallel with the oscilloscope input impedance. $50\ \Omega$ is so much smaller than the oscilloscope input impedance that the cable end is terminated with $50\ \Omega$ for practical purposes. The oscilloscope then measures the voltage drop across the $50\ \Omega$ termination.

The oscilloscope has high input impedance because it is often desirable to make measurements that do not strongly load a circuit. Designing the oscilloscope with high internal input impedance allows us to make measurements with that high input impedance if we wish, and to lower the impedance with a tee and terminator for measurements if we want to impedance match to a coaxial cable.

We do not use the PASCO 850 interface for this experiment because it only has a bandwidth of 500 kHz. This is 200 times less bandwidth than the oscilloscope, and much too low to record RF signals.

D. Experimental procedure

Observation of the VCO output on the oscilloscope, and basics of oscilloscope operation.

<u>Oscilloscope manual</u>

1. Turn on your lab mac computer, and open up the Tektronix TBS1000B user manual. You can find it by clicking on the “phys” icon in the upper right corner of the desktop, then on “RLM 7322,” then on “115L”. Then open up the section "Operating Basics." Refer to this manual as needed throughout the lab.

<u>Terminators on scope inputs</u>

2. Place a BNC tee and $50\ \Omega$ terminator on the inputs to both channel 1 and channel 2 of your oscilloscope, as shown in Figure 8.13. Leave them there throughout this experiment unless otherwise instructed. The purpose of these terminators is to impedance match the input cables to the oscilloscope inputs, *i.e.* to suppress reflections of signals from the oscilloscope inputs. You will connect signals to the oscilloscope inputs by connecting your cables to the BNC connector opposite the termination, as shown in Figure 8.13.

<u>Basic signal display and scale setting</u>

3. Plug in the oscilloscope and turn it on. After a minute or two, you should see the oscilloscope display, which will have a 10 x 10 grid taking up most of the area, and a number of small windows with numbers and symbols around the edge.

4. Press "Default Setup" and wait for 10 or 20 seconds. This will undo whatever settings the last person used, so that we can proceed with these instructions starting from a known state. Press the "Menu on/off button" (bottom button just to the right of the display). This gets rid of the menu on the right hand side of the screen.

5. Connect your voltage controlled oscillator (VCO) to the channel 1 input of the oscilloscope (*i.e.* to the tee on that input) and turn it on. You should see the screen covered in yellow. This

yellow color shows you that you are looking at the signal coming into channel 1. (A blue trace is a display of the channel 2 signal, which you'll use later. You can always check the color code by the color of the "1" and "2" buttons on the oscilloscope.) You should also see a window on the lower left with the indication "1   1.00 V". This tells you that each vertical division corresponds to a change in the channel 1 signal of 1 Volt (*i.e.* the vertical scale is 1 Volt per division). Beside that, you will see a window with the indication "M 500 μs." That tells you that each horizontal division corresponds to a time increment of 500 microseconds (*i.e.* the horizontal scale is 500 microseconds per division). Change the vertical sensitivity by rotating the knob under the yellow "1" button. Observe the change of sensitivity in the corresponding window. Set the sensitivity to 5 volts per division. You should see that the highest and lowest signal levels are now within the display area. Next, change the horizontal scale with the knob below the "acquire" button. Observe how the horizontal scale factor changes in the corresponding window. Set the horizontal scale to 25 ns/div. You should now see the display of individual cycles of the sine wave from the VCO.

6. Your oscilloscope is still not set correctly. To see this, push the yellow "1" button. This will bring up the channel 1 menu on the right hand side. One of the windows says "Probe 10x Voltage". This indicates that channel 1 is set for use with a scope probe that attenuates the voltage by a factor of 10. Thus, the scope is multiplying the actual input voltage by a factor of 10 for display. You are not using an attenuating scope probe, so that makes your voltage reading too high by a factor of 10. To correct this, push the button next to "Probe 10x Voltage". Push the button next to "Attenuation 10x". This brings up a menu with various attenuation options. Use the Multipurpose knob to change the highlighted selection to "1x". Press *in* on the Multipurpose knob. This will change the attenuation setting to "1x." Press "Menu on/off" to make the menu disappear.

Your scope should now be set correctly for display of the signal. You should see a sine wave with an amplitude of about 1 Volt, and a period somewhere in the range between 8 ns and 24 ns.

7. When you push the yellow "1" knob, you will see several other options in the channel 1 menu. One of them is marked "Coupling DC". Push the button next to this window. You will see three options: DC, AC, and Ground. Ground means that the input is connected to ground. Select ground with the Multipurpose knob and you should see the signal display become a straight line. This is useful because it shows you where zero volts is on the display. Remember that you push the Multipurpose knob to make the selection. Go back to a selection of DC and the signal should return. The only difference between AC and DC coupling is that the AC selection inserts a filter after the input so that the DC (static) part of the signal is blocked. Only the time varying part of the signal gets through. For this lab, set the channel 1 and channel 2 coupling to "DC."

Experiment with the "Position" knob just above the yellow "1" button. This raises and lowers the position of the channel one data on the display. Note that a yellow arrow moves up and down along with that waveform on the left. This shows you the ground level (zero volts) for channel 1.

Finally, press the button next to "Invert On Off". With invert off, the signal is displayed directly on the oscilloscope. With invert on, the signal is multiplied by -1 (*i.e.*, inverted) before display on the scope. You should see the signal invert when you push this button. Leave invert set to "off."

Scope triggering

8. The display you are looking at should be showing time sweeps of the same signal, over and over again. You can usually tell if this is happening by looking for small variations of the signal as you watch the display. Each display of the signal is called a "sweep". You should also see that the sweeps are synchronized. For instance, the signal display should cross zero for the first time at the same place in every sweep and also with the same slope – either a positive or a negative slope.

The synchronization of the waveform from one sweep to the next is called *triggering*. To see how this works, first notice that there is a small orange arrow marked "T" along the top edge of the display. This indicates the time at which the "trigger" is occurring. Next move the knob marked "Position" below “Horizontal”. You should see the position of the trigger indication move, and the waveform move along with it. You can set this position wherever you like. Next, press the "Menu" button under "Trigger." This will bring up the trigger menu. The first window says "Type Edge". This is the trigger type you want throughout this experiment, so just leave the scope at this setting. The next window says "Source Ch 1". This tells you that the scope is using the channel 1 signal to set the trigger. The other trigger source options are to trigger from the channel 2 signal, from a signal that you apply to the Ext Trig input, or from the 60 cycle per second oscillation of the 120V AC power connection of the scope. For this lab, you'll always want to trigger from either channel 1 or channel 2.

9. The next window says "Slope Rising". If you look right below the trigger symbol, you should see that the signal is in fact rising (*i.e.* has positive slope) at that point. Change this to "Slope Falling" and you should see that the signal changes so that it is falling right below the trigger symbol. Change this back to "Slope Rising."

10. Next, turn the "Level" knob under "Trigger." You will see a new yellow line on the screen. This shows you the level at which the trigger occurs. In other words, the alignment of the sweep will be such that the signal will cross that level, right under the trigger symbol, with the correct slope. Note how this condition is satisfied as you vary the trigger level. Try setting the trigger level so high, or so low, that it is outside the range of the signal. You will see "untriggered" display of the signal. In this condition you see repeated sweeps but they are not synchronized. Notice also that the "Triggered" indicator at the top of the screen goes out, and is replaced by "Ready."

There is another setting that has an effect on this display. With the trigger mode set to "Auto", you will see unsynchronized sweeps when there is no trigger. With the trigger mode set to "Normal," the untriggered sweeps will stop, and you'll just see the last triggered sweep on the display. Both settings have their merits. For this lab, the "Auto" setting will probably work best.

There is a small window near the bottom right that shows the trigger settings – source, slope, trigger level, and the number of times per second that the trigger is occurring. For a clean sine wave this will be identical to the sine wave frequency in cycles per second (Hz).

Measurements

11. For this section of the lab, please set your oscillator frequency to about 60 MHz by turning the knob on the VCO supply, and reading the trigger rate indicator on the scope.

There are at least three ways to take measurements of your signal from the scope.

(i) Direct reading from the grid by eye, using the calibrated volts per division and seconds per division of the scope display.

Using this method, determine the amplitude and period of your sine wave.

(ii) Use of measurement cursors.

Press the "Cursor" button. In the "Type" window, select "Amplitude". Leave the cursor "Source" set to Channel 1. With the Multipurpose knob, move the upper cursor line until it coincides with the top of the sine wave. Then, push the button next to "Cursor 2", and use the Multipurpose knob to move the lower cursor line until it coincides with the bottom of the sine wave. You will see the voltage level for both cursors indicated in the windows on the right hand side of the screen, along with the difference between the voltage levels. Use these measurements to determine the amplitude of your sine wave. Next, change "Type" to "Time". Measure the period of the oscillation with the cursors.

Notice that with the cursor set to "Time", you also have a display of the voltage level at the selected time. This provides a useful way to read out the voltage at some specific point on a waveform.

Turn the cursor Type to "Off" when you're done, to unclutter the display.

(iii) Use of the scope's automatic measurement function.

Press the "Measure" button. Leave "Measure Gating" set to "Off". Press the button next to "Channel 1". Using the multipurpose knob, select the following measurements: Period, Frequency, Peak-Peak, and RMS.

You will see a new window on the display that gives automated measurements of these quantities from your waveform. These result from fits to the first complete cycle on each waveform. Often, this method will provide the most accurate measurements.

Check that your various measurements are consistent with each other. If they aren't try to determine why and redo them as needed so they are consistent.

When you are done with this part of the lab, uncheck all of the selected automatic measurements to unclutter the display.

<u>Determination of oscillator output power</u>

12. The output power of your VCO is specified as 10 dBm. The RMS quantity displayed in your above measurement procedure gives V_{rms}, the root-mean-square of your voltage signal. Using this value, determine the output power of your VCO. Express your answer in units of mW and in units of dBm. How close is your measurement to the specified output power?

<u>Saving data</u>

13. With the scope triggered, press the "Single" button. This triggers a single sweep and displays the result. This is a useful function for close-up examination of a single example of a waveform. Return to the previous operating mode by pushing "Run/Stop". Then push "Single" again, and leave the resulting sweep displayed on the scope.

Let's suppose you wish to transfer this data to your USB drive. To do this, you insert your drive into the scope's front USB port. (The scope only works with a USB drive capacity of 64 GB or less.) Then, push the "Save Recall" button. Select "Print Button Saves All To Files", and make sure that "Saves All To Files" is selected. If you wish, you may also select a specific folder on your USB drive to save the files to with the "Select Folder" function.

To save your data, press the front panel "Save" button (button with diskette icon next to Multipurpose knob). This will save a folder with a set of data files in your selected USB drive folder. These include a bitmap screenshot, and one or more Excel files containing the oscilloscope settings and the individual data points.

Save your data, and verify that you have succeeded by viewing your files on the lab Mac Computer. Include a printout of the screenshot in your lab report.

According to the scope manual, you do not need to eject the USB drive from the scope. If you have just saved data, you are instructed to wait until you see the notification that the data has been saved at the bottom of the display, and then remove the drive if you wish.

Measurement of the capacitance of an RG-58 coaxial cable.

Turn the VCO off, disconnect it from the scope, and set it aside. Remove the tee and 50 Ohm terminator from the scope channel 1 input. Plug in the avalanche pulser power supply, and connect the 6 foot long $50\ \Omega$ cable to the port marked "cable." (You will have nothing connected to the other end of this cable; *i.e.* it is left open-circuited. The output pulse duration is equal to twice the round-trip time of this cable, so changing this cable length changes the pulse duration.) Connect the output of the pulser directly to the scope channel 1 input (no terminator) using the 10 foot long cable. Adjust the scope controls until you can see the waveform generated by the pulser. You will need to increase the time per division to something like 2.5 microseconds. You should see a sudden jump in the voltage at the trigger point, followed by an exponential decay as shown in Figure 8.12(b).

Using the scope's time cursors, measure the time constant of the exponential decay. (To get an accurate measurement, place cursor 1 at a time for which the voltage has decayed to a value in the range 5 to 10 volts - well *after* the early transients in the signal have died out. Place the cursor 2 at a time for which the voltage is a fraction $1/e = 0.3679$ of the voltage of cursor 1.)

Assume that R_{out} is $10\ \mathrm{k}\Omega$ (see Figure 8.12) and that the scope has input impedance of $1\ \mathrm{M}\Omega$ in parallel with 20 pF. Using your measured *RC* time constant, determine the capacitance of your cable. What is the capacitance per foot, and how does that compare with the specified capacitance of RG58?

Examine the early-time behavior of the signal (first few hundred ns). Try substituting the 40 foot cable for the 10 foot cable and see how the early time signal changes. See if you can explain what is happening during this time.

Measurement of the propagation speed of a signal in an RG-58 coaxial cable.

Place the tee and 50 Ohm terminator back on the oscilloscope input to channel 1, and plug the pulser back in to the scope input using the 10 foot cable. Adjust the scope controls until you can clearly see the pulse shape. You should now be in the "transmission line" limit discussed in connected with Figure 8.12(c), and see a short pulse like that illustrated in Figure 8.15.

Next, place a tee and 50 Ohm terminator on the pulser *output*, and reconnect the pulser to the scope. You will leave this terminator in place for the rest of the experiment. The purpose of this terminator is to suppress reflections of any pulses that travel back to the pulser. (It will also reduce the amplitude of the voltage pulse by a factor of 2.) Your set up should match Figure 8.14.

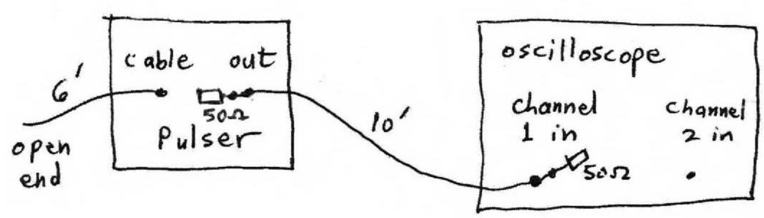

Figure 8.14. Set-up for viewing output of pulser on an oscilloscope. All cables have $50\ \Omega$ impedance. The cable connecting the pulser to the scope is terminated with a $50\ \Omega$ terminator at *both* ends.

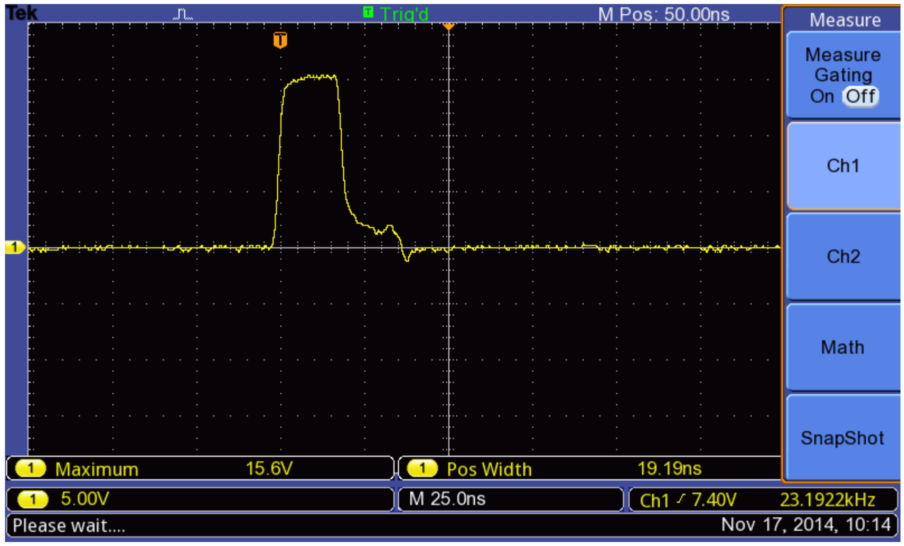

Figure 8.15. Appearance of the pulse on the scope display, with the set-up shown in Figure 8.14.

Next, set the experiment up as shown in Figure 8.16, so that channel 1 records the signal sent through the directional coupler from in to out, and channel 2 records the output of the coupled port. Press the "2" button on the scope to activate display of channel 2. Set the attenuation of channel 2 to 1x, set the channel 2 coupling to DC, and adjust the vertical sensitivity until you see the pulsed signal for channel 2 on the scope display.

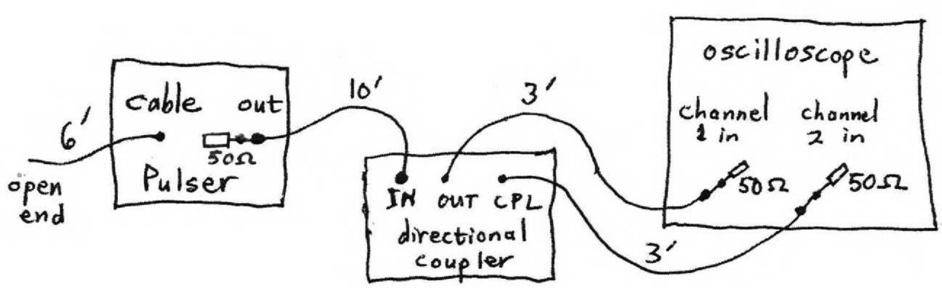

Figure 8.16. Set-up for simultaneously recording pulse transmitted through a directional coupler, and pulse from the coupler's "coupled" port, for a forward propagating pulse. All cables have $50\ \Omega$ impedance.

Some of our couplers produce an inverted coupled output, and others do not. You have one of the inverting ones if the channel 2 pulse in this set-up goes negative instead of positive. If you have one of these couplers, always set "Invert" to "On" for the channel that the coupled port is connected to. For all other connections, including the in and out ports of all couplers, always set "Invert" to "Off." By doing this, you'll see all of your signals with the correct sign.

Note that you still have one trigger, which is still set to channel 1. That trigger determines when the sweeps for *both* channels start and stop. The time scale for the two channels is precisely the same. If a voltage step occurs at precisely the same time in the two channels, it will occur at precisely the same horizontal position on the scope display.

Measure the heights of these two pulses. By comparing the pulse height in channel 1 to the pulse height you measured without the coupler, determine the attenuation of the signal that is transmitted through the output port by the coupler. Include this attenuation factor as appropriate as you calculate measured pulse height ratios in this experiment. Also, determine the ratio of the coupled port signal to the input port signal. How close does your coupler come to its specified -20 dB coupling? Include your measured coupling factor as appropriate as you calculate measured pulse height ratios in this experiment.

Next, modify your set-up as shown in Figure 8.17. **Note that the "out" port of one coupler is connected to the "out" port of the other coupler.** In this set-up, we use two directional couplers in series, one which couples out the signal moving in the forward direction, and the other which couples out the signal in the reverse direction. This is called a *bi-directional coupler*. In this set-up, channel 1 records the outcoupled forward moving signal, and channel 2 records the outcoupled backwards moving signal. Thus, channel 2 will show a reflected pulse coming back down the 40' cable, if any.

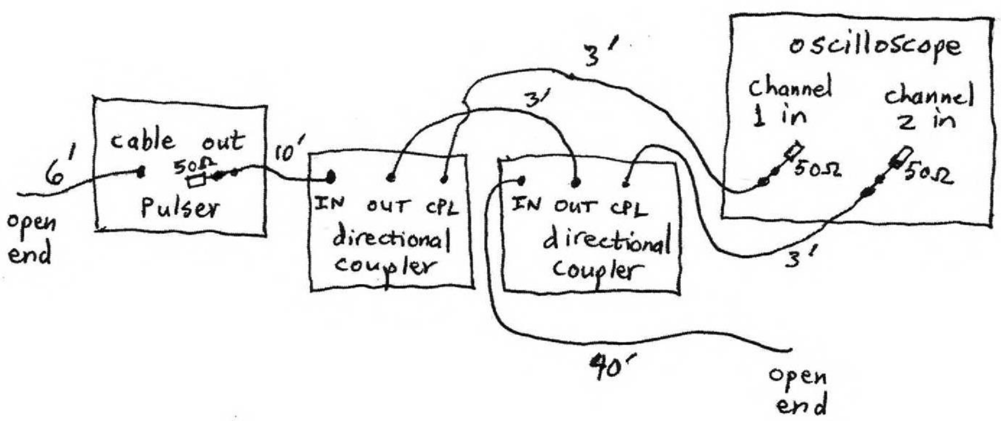

Figure 8.17. Set up to simultaneously record a forward propagating pulse and a backward propagating pulse. Two directional couplers are combined to make a bi-directional coupler. The backward propagating pulse is the pulse reflected from the open end of the 40 foot cable. All cables have $50\ \Omega$ impedance.

Make sure that your two scope channels have the correct "invert" setting for your particular couplers. Readjust the scope sensitivity and the scope trigger until you again see the pulse from channel 1 on the display. You will need to increase the sensitivity since you are now looking at the coupled port rather than the direct signal. If you can't see the signal, it probably means that your trigger level is wrong. If that happens, try setting the trigger level a little above and a little below zero. Remember you can see the numerical value of the trigger level in one of the scope display windows.

Try putting a $50\ \Omega$ terminator at the end of the 40' cable with a BNC union. You should see the reflected pulse disappear, because the end of the 40' cable is impedance matched to the load. Now, remove the $50\ \Omega$ termination. You should see the reflected pulse in channel 2 reappear. This demonstrates that you're looking at the reflection from the end of the 40' cable. If you can't see the reflection, you may need to adjust the horizontal time scale.

Measure the delay between the leading edge of the channel 1 pulse, and the leading edge of the channel 2 pulse. Then, remove the 40' cable from the directional coupler. Measure the delay again. The difference between the two delays you just measured is the round trip time of the pulse in the 40' cable. From this measurement, deduce the speed v_φ of voltage waves in your 40' cable, which is type RG58. We've labelled each cable with its measured length to the nearest inch, so use that measured length rather than the nominal 40' length to calculate the speed. Also, determine the dielectric constant of the insulator in your cable. The dielectric constant of the most common cable insulators is given in Table 8.1. Assuming the insulator is one of these, can you tell which one?

Insulator	Dielectric constant
Solid polyethylene (PE)	2.3
Solid Poly Tetrafluoroethylene (PTFE)	2.1
Polyethylene foam (PE foam)	1.4 to 2.1
Cellular Poly Tetrafluoroethylene (PTFE foam)	1.4

Table 8.1 Common insulators in coaxial cables.

Reflection coefficients from different cable terminations

Replace the 40' cable from your previous set-up with a 6', $50\ \Omega$ cable. (We're doing this so your measurements are less affected by losses in the cable.) Next, using your measurement system, observe the reflected pulses for the cases in which the end of that 6' cable is

(i) terminated with a $50\ \Omega$ terminator

(ii) left open circuited

(iii) shorted out with the shorting cap, and

(iv) terminated with the $93\ \Omega$ terminator.

You will need to use the BNC union to make these connections. From your measurements, determine the reflection coefficient *r* for signals from the end of the cable for each of these cases. Compare your results with what is expected from equation (8.26).

Reflection and transmission coefficients from an impedance discontinuity.

Next, replace the $93\ \Omega$ terminator at the end of the 6' cable with your 30' long, $93\ \Omega$ cable. You should see two reflected pulses, one from the impedance discontinuity between the $50\ \Omega$ and $93\ \Omega$ cable, and another from the open end of the $93\ \Omega$ cable. Connect the $93\ \Omega$ terminator to the other end of the 30' long cable with a BNC union. This should eliminate the reflection from the cable end. You should now see the outcoupled forward propagating pulse in channel 1, and the reflected pulse from the impedance discontinuity between the $50\ \Omega$ and $93\ \Omega$ cable in channel 2. Use this system to measure the reflection coefficient *r* of this impedance discontinuity.

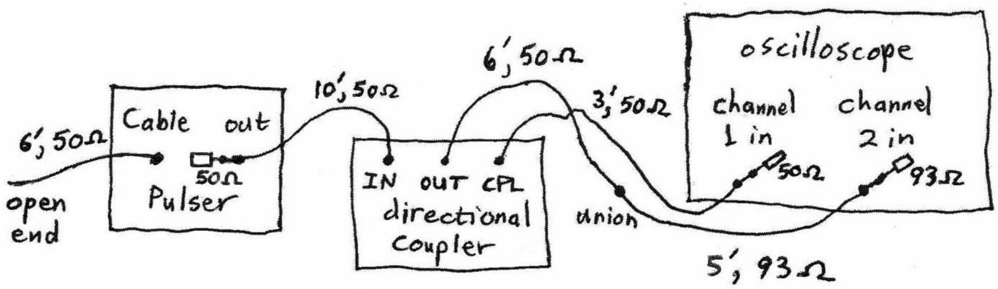

Figure 8.18. Experimental arrangement to measure the transmission coefficient across the impedance discontinuity from a $50\ \Omega$ to a $93\ \Omega$ cable.

Finally, set your experiment up as shown in Figure 8.18. The forward pulse transmitted through the impedance discontinuity should now appear directly on channel 2. Note that, since you are measuring the signal on a $93\ \Omega$ cable, you should have the $93\ \Omega$ ohm termination on that cable at the scope.

From your measurements, determine the transmission coefficient *t* of the pulse across the impedance discontinuity between the $50\ \Omega$ and $93\ \Omega$ cable.

Compare your results for *r* and *t* with those expected from equations (8.17) and (8.18).

- End of experiment 8 –