Radiological Sciences @ OUHSC

Radiation Detection and Measurement

Lecture 23

Chapter 16: Pulse Processing and Shaping

Device impedances

- Impedance is a frequency dependent response of a circuit component or system
- In general they can include inductive and capacitive characteristics, but will focus on purely resistive
- The input impedance, Z_i represents the extent to which a device loads a given signal source

Device impedances

- High input impedance draws little current and is a light load, i.e. an oscilloscope always has high impedance to prevent it from affecting the device under test
- Other factors may dictate the requirement to be low enough to load the source significantly
- The output impedance Z_0 can be thought of as an internal resistance in series with voltage generator, representing the output stage of a given component (Fig 16.1)

Device impedances

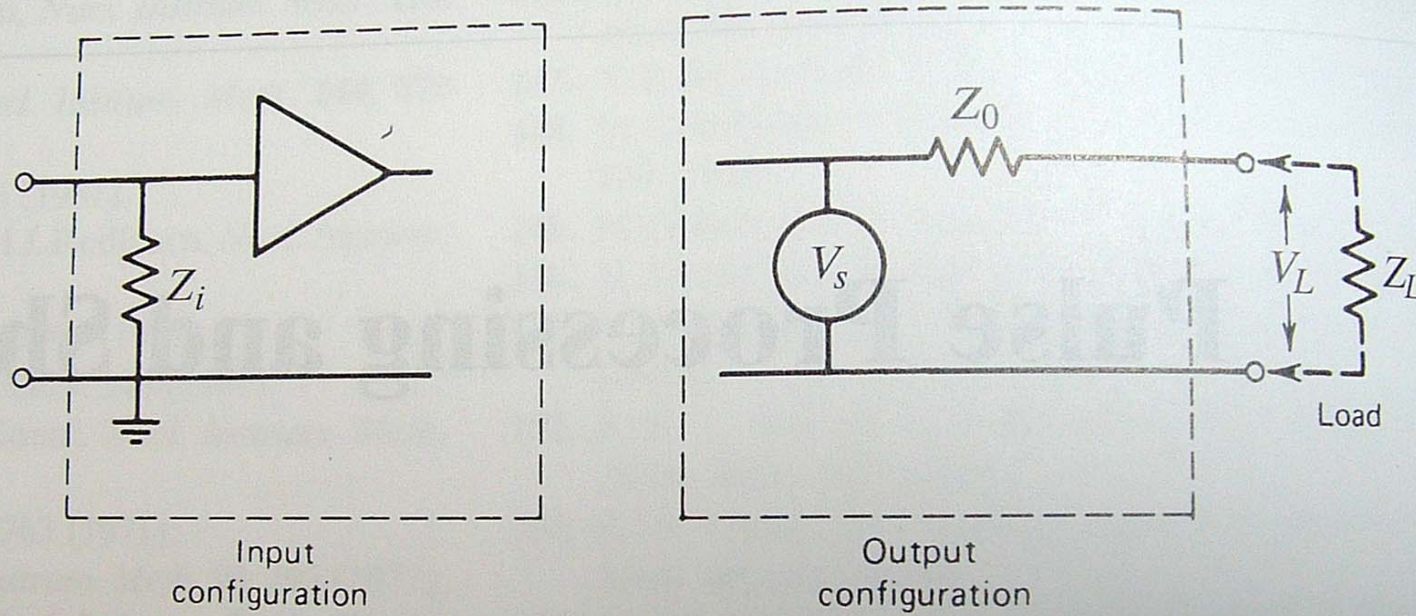

Figure 16.1 Idealized input and output configurations. For the input configuration, the triangle represents an ideal operational amplifier with infinite input impedance. Therefore, the effective device input impedance is Z_i. For the output configuration, Z_0 represents the output impedance in series with an ideal voltage generator V_S.

Device impedances

- For most applications one wants the output impedance to be low so there is little signal loss to the next component being fed
- The voltage (V_L) appearing across the load (Z_L) is given by the voltage divider relation:

$$V_L = V_S \left(Z_L \middle/ Z_0 + Z_L \right)$$

Device impedances

- The open circuit voltage ($Z_L = \infty$) appearing at the output device is just Vs, and if the output impedance is low compared with the load ($Z_0 << Z_L$) then $V_L \cong V_S$ and the signal voltage is transferred to the load
- If the output impedance is equal to the load ($Z_0 = Z_L$) then $V_L = V_S / 2$, only half the output voltage is seen by the load.

Device impedances

- When devices are connected in a signal chain, the load Z_L for the given component is the impedance of the following component
- Therefore if all Z_L are low, the signal level is preserved along the chain – a condition often realized in normal detector pulse processing systems

Device impedances

- For fast pulses, reflections in coaxial cables can dictate impedance matching conditions where the output/input impedance ratio is not always small and signal attenuation will occur. Note the maximal power transfer occurs when impedance are matched between components.

Coaxial cables: cable construction

- Virtually all interconnection of components in a detector system is carried out with shielded coaxial cable (Fig 16.2)
- The shielding is designed to minimize the pickup noise from stray EM fields
- For flexibility, the outer sheath is generally braided stranded of copper wire (thin)

Coaxial cables: cable construction

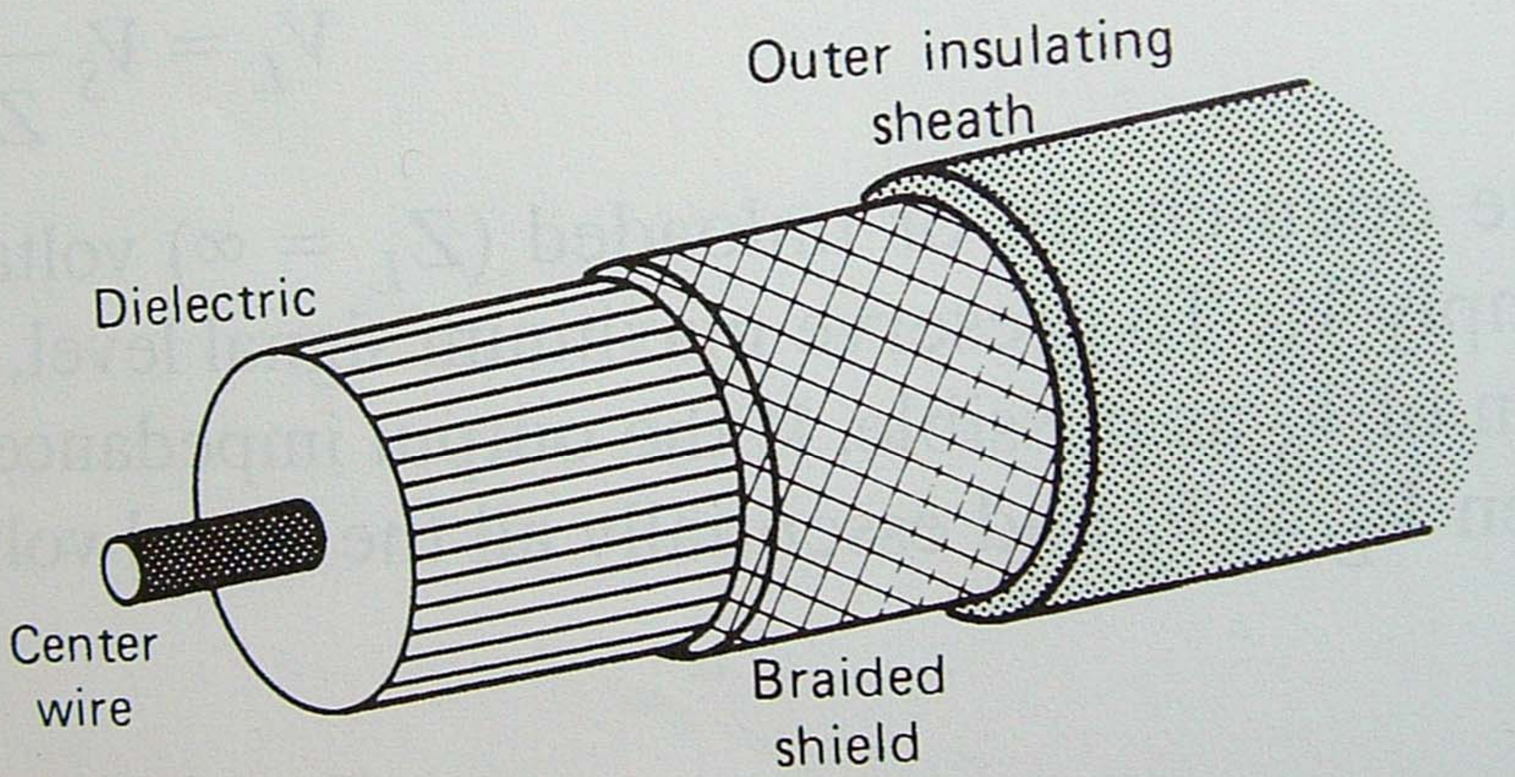

Figure 16.2 Construction of a standard coaxial cable.

I.B. Rutel

Coaxial cables: cable construction

- The ability to shield low frequency signals resides in the tightness of the braiding, while high frequencies are shielded by the skin effect, where for higher frequencies the skin depth is less than the thickness of the conductor
- One can use double shielding to minimize noise, but for cases where the noise must be unusually minimal, it is better to run a single cable inside a solid conductor tube.

Coaxial cables: skin depth

- Skin depth: (Jackson, Classical Electrodynamics, p 220) In a conductor, electromagnetic waves show an exponential damping with distance. For example an electromagnetic wave entering into a conductor is damped to 1/e = 0.369 of its initial amplitude in a skin depth (penetration depth)

Coaxial cables: skin depth

- Example of skin depth calculation (δ)

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}}$$

  - where μ is the permeability, σ is the conductivity and ω is the angular frequency of the wave.

- For copper at room temperature:

$$\sigma^{-1} = 1.68\times10^{-8}\,\Omega\cdot m,\ or\,\delta = 6.52\times10^{-2}/\sqrt{\upsilon[Hz]}\cdot m$$

$$where\ \upsilon = \omega/2\pi$$

Coaxial cables: skin depth

- Cu calculation continued:

  $\delta \approx 0.84$ cm for 60 cps

  $\delta \approx 0.65 \times 10^{-3}$ cm for 100 Mcps
- This means the higher frequencies travel in a very small layer on the surface of a conductor, which determines the overall resistance of the transmission line (this would be calculated over the volume the signal occupies)

Coaxial cables: skin depth

- To generally reduce the resistance of the line one must either reduce the resistivity ($1/\sigma$) of the material or make the diameter larger (resistance decreases with increasing volume)

Coaxial cables: cable properties

- The velocity of propagation for pulses through a coax is a function only of the dielectric materials separating the central conductor and the outer shield,

$$\propto 1 / \sqrt{dielectric\ constant}$$

- Cables using air or other gas can have velocities ~ c (speed of light) 3.0×10^8 m/s

Coaxial cables: cable properties

- Generally cables utilize a solid such as polyethylene for the dielectric, where the velocity of propagation is about 0.66 c.
- At the other extreme, special delay cables with helically wound central conductors can reduce the velocity of propagation by factors of 100 or more
- Table 16.1 lists many important properties of coax cables used for nuclear instrumentation

Coaxial cables: cable properties

Table 16.1 Properties of Coaxial Cables[a]

	Insulating Material	Cable Diameter (cm)	Characteristic Impedance (ohms)	Signal[b] Propagation	HV Rating	Cable Capacitance (pF/m)	Signal Attenuation per Meter MHz	dB
RG-8/U	Polyethylene	1.03	52	0.659	5000	96.8	100 400	0.066 0.154
RG-11/U	Polyethylene	1.03	75	0.659	5000	67.3	100 400	0.066 0.138
RG-58/U	Polyethylene	0.50	53.5	0.659	1900	93.5	100 400	0.135 0.312
RG-58C/U	Polyethylene	0.50	50	0.659	1900	100.1	100 400	0.174 0.413
RG-59/U	Polyethylene	0.61	73	0.659	2300	68.9	100 400	0.112 0.233
RG-62/U	Semisolid polyethylene	0.61	93	0.840	750	44.3	100 400	0.102 0.207
RG-174/U	Polyethylene	0.25	50	0.659	1500	101.0	100 400	0.289 0.656
RG-178/U	TFE teflon	0.18	50	0.694	1500	95.1	400	0.951
	Double Shielded Coaxial Cables							
RG-9/U	Polyethylene	1.07	51	0.659	5000	98.4	100 400	0.062 0.135
RG-223/U	Polyethylene	0.52	50	0.659	1900	101.0	100 400	0.157 0.328

[a] Data derived in part from Coaxial Cable Catalog, Belden Corporation, Richmond, IN.

[b] Fraction of speed of light in a vacuum (3.00×10^8 m/s).

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Coaxial cables: cable properties

- As a note the RG/U identification were born out of military specification and don't relate to the cable properties
- Important properties of the cables are the characteristic impedence and capacitance per unit length. For bias cables the maximum voltage rating is also important
- No real cable is perfect for transmission, and losses will be realized, especially at higher frequencies

Coaxial cables: cable properties

- For most applications these losses are small and insignificant, however for demanding applications (fast rise time pulses) and attenuation should be paid to the high frequency characteristics
- One should note that losses will grow with the length of the cable, so problems not seen at shorter lengths may appear for longer lengths of cables.

Coaxial cables: noise pickup and component grounding

- Outer shield serves as an interconnect for all the chassis of each component
- This can be redundant (most chassis are connected to the ground potential individually) however if the components are physically separated the potentials of various grounds may differ leading to ground loops.

Coaxial cables: noise pickup and component grounding

- Ground loops: when ground potentials are different for multiple common ground connections causing currents to flow and producing noise in the system. Can be abbreviated by connecting all components to a single outlet.
- Fast switching may also induce voltages in the lines at high frequencies and tend to be exacerbated by long cables

Coaxial cables: noise pickup and component grounding

- Common mode rejection: the receiving device (often a linear amplifier) is designed with a differential input so that a signal is measured in one input relative to a reference voltage in the second. Cables are connected and placed side by side to the signal source, where only one is connected to the source. In theory both lines will now pick up the interference and will be eliminated by the differential input.

Coaxial cables: characteristic impedance and cable reflections

- Discuss in terms of pulse speeds, where we define fast and slow based on the fastest pulse component (generally the rise time) compared to the transit time through the cable (i.e. for cables with solid polyethylene dielectric, the transit time is ~5.1 ns/m)

Coaxial cables: characteristic impedance and cable reflections

- For slow pulses the cable acts like a simple conductor connecting the equipment. The important properties are the resistance and capacitance to ground. The resistance of the central conductor is very small for cables less than a few hundred meters in length. The capacitive loading increases linearly with length, which is a consideration connecting a detector to a pre amplifier.

Coaxial cables: characteristic impedance and cable reflections

- Noise characteristics will deteriorate with capacitive loading but it is not critical for slow pulses
- Fast pulses require consideration of several other properties

Coaxial cables: characteristic impedance and cable reflections

- Characteristic impedance of the cable – illustrated in Fig 16.3, is dependent on the dielectric material , diameters of the inner and outer (shield) conductors but independent of length

Coaxial cables: characteristic impedance and cable reflections

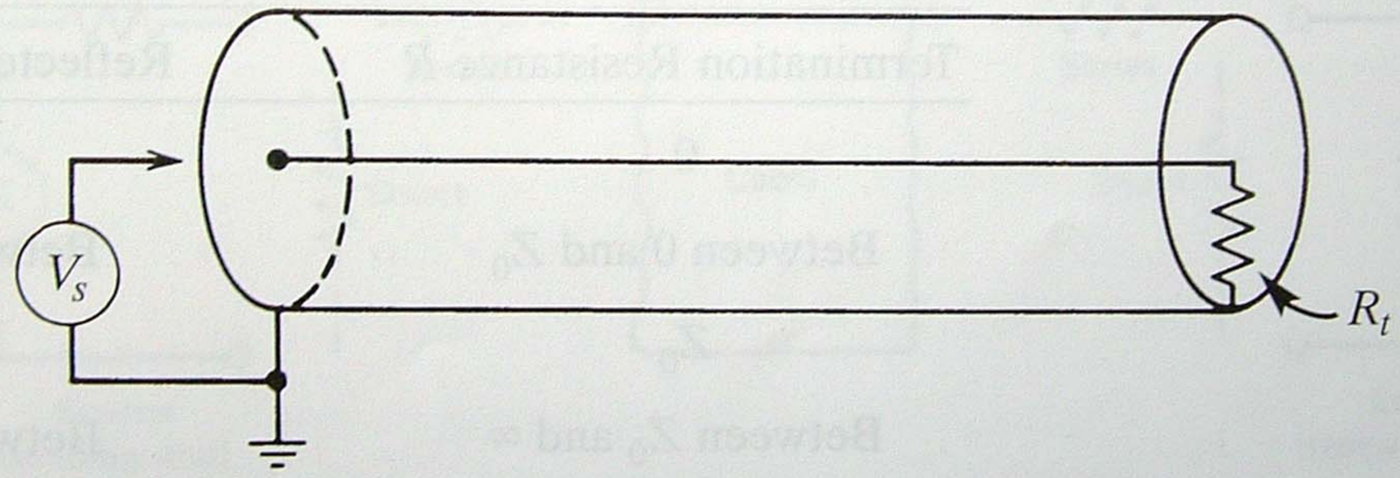

Figure 16.3 Application of a step voltage V_S to a coaxial cable terminated in R_t.

Coaxial cables: characteristic impedance and cable reflections

- Imagine a step voltage traveling down the cable changing the voltage from 0 to V_0 at t = 0, which propagates with a velocity (as previously discussed). Stretch the length to infinity and note that the propagating voltage (V_0) will continue with a current draw that never stops. The characteristic impedance is the voltage draw, V_0, divided by the current for an infinite cable length.

Coaxial cables: characteristic impedance and cable reflections

- Terminating a cable with its own characteristics impedance will provide the effect of having an infinite cable. For example, take V_0 = 5 V with a characteristic impedance of 50 ohms, the current draw is 100 mA if a R_t = 50 ohm resister is placed between the inner cable and shield and will continue to draw 100 mA as long as the 5 V is exciting the cable, so it appears infinite.

Coaxial cables: characteristic impedance and cable reflections

- Shorted cable ($R_t = 0$), the pulse is reflected and inverted with an amplitude equal to V_0.
- A cable with infinite resistance ($R_t = \infty$), un-terminated will reflect the signal with the same polarity and amplitude back to the sending end
- Table 16.2 sums up the effects of reflection and terminations

Coaxial cables: characteristic impedance and cable reflections

Table 16.2 Reflection Conditions Created by Various Terminations at the End of a Coaxial Cable with Characteristic Impedance Z_0. Step Input Waveform with Amplitude A Is Assumed

Termination Resistance R	Reflected Step Amplitude
0	$-A$
Between 0 and Z_0	Between $-A$ and 0
Z_0	0
Between Z_0 and ∞	Between 0 and $+A$
∞	$+A$

Coaxial cables: useful accessories

- Figure 16.4 shows the various geometries for inserting terminators on either end of the cable
- A terminator acts as a shunt to convert a high impedance input at one end of the cable to an impedance that matches the characteristic impedance of the cable to prevent reflections

Coaxial cables: useful accessories

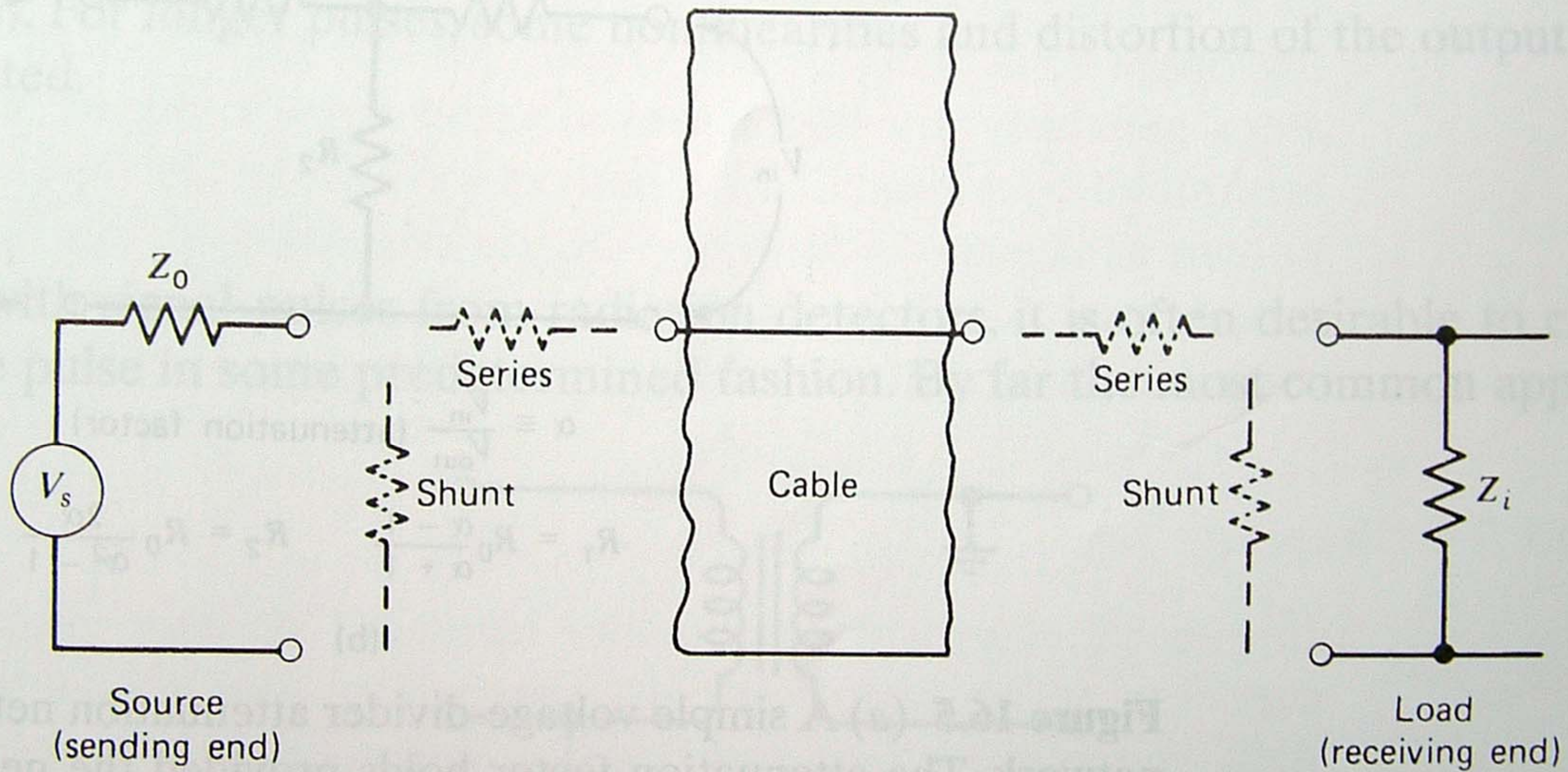

Figure 16.4 Methods of inserting terminators at either end of a coaxial cable.

Coaxial cables: pulse attenuator

- the voltage divider : Shown in 16.5(a), if the source impedance and the input impedance of the next electronic device $Z_i >> R_2$:

  then $$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_1 + R_2}$$

Coaxial cables: pulse attenuator

- this is not very usable for pulses with rise times less than 100 ms due to the non linear attenuation of higher frequency components which results in distortion of the pulse shape.

Coaxial cables: pulse attenuator

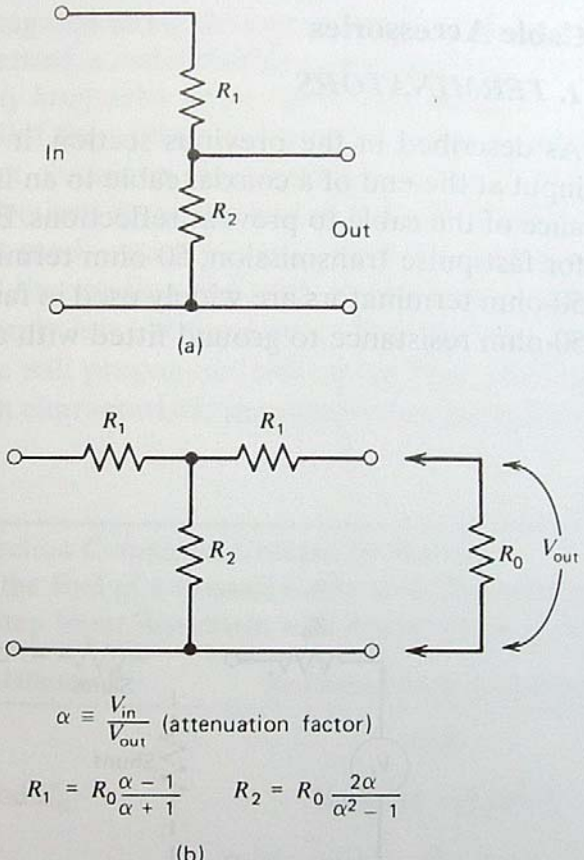

Figure 16.5 (*a*) A simple voltage-divider attenuation network. (*b*) A T-attenuator network. The attenuation factor holds provided the network is loaded with the value of R_0 shown. The input and output impedances are then also equal to R_0.

Coaxial cables: pulse attenuator

- T section: Shown in 16.5(b), the attenuation factor:

$$\alpha = \frac{V_{out}}{V_{in}}$$

  holds if the network load holds to R_0. Then,

$$R_1 = R_0 \frac{\alpha - 1}{\alpha + 1} \text{ and } R_2 = R_0 \frac{2\alpha}{\alpha^2 - 1}$$

- The T section attenuator has excellent high frequency response and can be used with fast (nanosecond) pulses

Coaxial cables: pulse attenuator

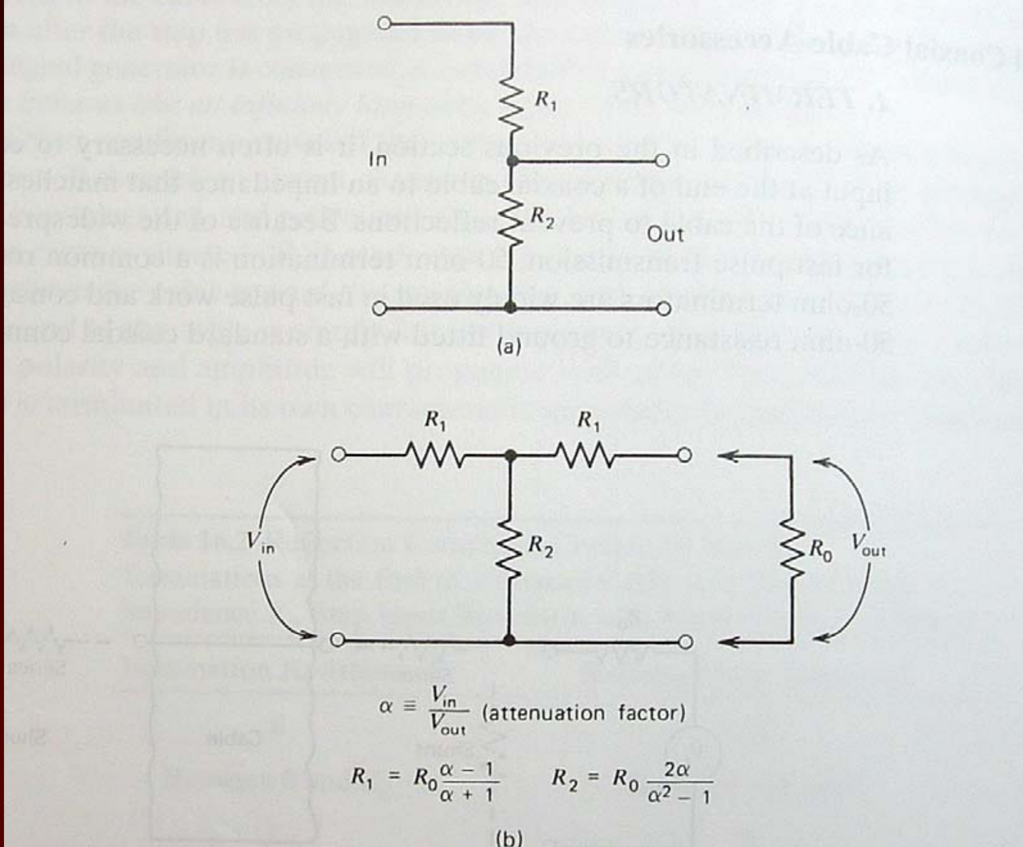

Figure 16.5 (*a*) A simple voltage-divider attenuation network. (*b*) A T-attenuator network. The attenuation factor holds provided the network is loaded with the value of R_0 shown. The input and output impedances are then also equal to R_0.

Coaxial cables: pulse splitter

- Allows for the branching of a pulse
- Shown in Fig 16.6, one chooses an R to match the impedances, (i.e. 50Ω splitter has 250 Ω loads with R = 16.6 Ω
- Signal level will also drop to half of the level if coupled without the splitter

Coaxial cables: pulse splitter

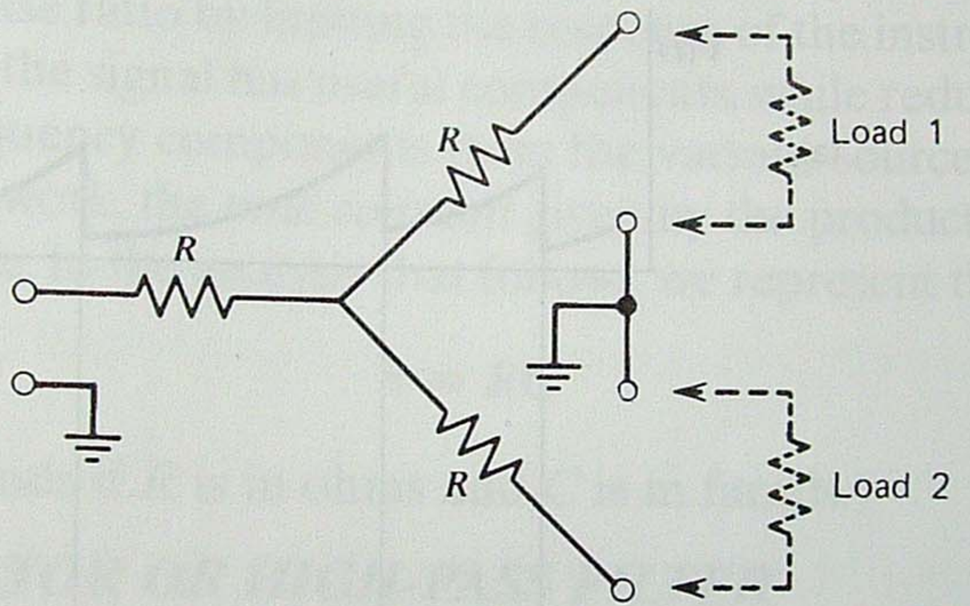

Figure 16.6 A symmetric pulse splitter that can be used to drive two loads while maintaining matched impedance levels.

Coaxial cables: inverting transformer

- For same signals it is desirable to invert the signal
- Shown in Fig 16.7, an inverting transformer will perform a signal inversion
- The basic transformer type will invert pulses that are short (< 100 ns)

Coaxial cables: inverting transformer

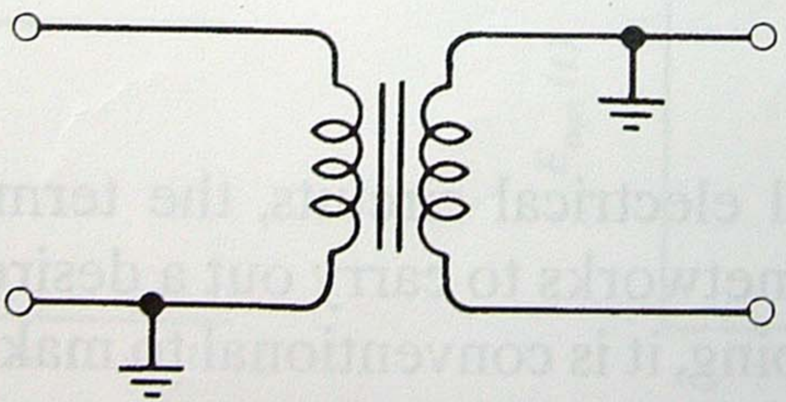

Figure 16.7 The basic configuration of an inverting pulse transformer.