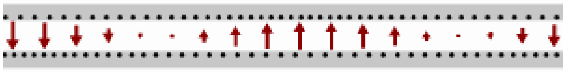
Transmission line

This article is about the radio-frequency transmission line. For the power transmission line, see electric power transmission. For acoustic transmission lines, used in some loudspeaker designs, see acoustic transmission line.



Schematic of a wave moving rightward down a lossless two-wire transmission line. Black dots represent electrons, and the arrows show the electric field.

One of the most common types of transmission line, coaxial cable.

In communications and electronic engineering, a **transmission line** is a specialized cable or other structure designed to conduct alternating current of radio frequency, that is, currents with a frequency high enough that their wave nature must be taken into account. Transmission lines are used for purposes such as connecting radio transmitters and receivers with their antennas, distributing cable television signals, trunklines routing calls between telephone switching centres, computer network connections and high speed computer data buses.

This article covers two-conductor transmission line such as parallel line (ladder line), coaxial cable, stripline, and microstrip. Some sources also refer to waveguide, dielectric waveguide, and even optical fibre as transmission line, however these lines require different analytical techniques and so are not covered by this article; see Waveguide (electromagnetism).

1 Overview

Ordinary electrical cables suffice to carry low frequency alternating current (AC), such as mains power, which reverses direction 100 to 120 times per second, and audio signals. However, they cannot be used to carry currents in the radio frequency range,[1] above about 30 kHz, because the energy tends to radiate off the cable as radio waves, causing power losses. Radio frequency currents also tend to reflect from discontinuities in the cable such as connectors and joints, and travel back down the cable toward the source.[1][2] These reflections act as bottlenecks, preventing the signal power from reaching the destination. Transmission lines use specialized construction, and impedance matching, to carry electromagnetic signals with minimal reflections and power losses. The distinguishing feature of most transmission lines is that they have uniform cross sectional dimensions along their length, giving them a uniform *impedance*, called the characteristic impedance,[2][3][4] to prevent reflections. Types of transmission line include parallel line (ladder line, twisted pair), coaxial cable, and planar transmission lines such as stripline and microstrip.[5][6] The higher the frequency of electromagnetic waves moving through a given cable or medium, the shorter the wavelength of the waves. Transmission lines become necessary when the length of the cable is longer than a significant fraction of the transmitted frequency's wavelength.

At microwave frequencies and above, power losses in transmission lines become excessive, and waveguides are used instead,[1] which function as "pipes" to confine and guide the electromagnetic waves.[6] Some sources define waveguides as a type of transmission line;[6] however, this article will not include them. At even higher frequencies, in the terahertz, infrared and light range, waveguides in turn become lossy, and optical methods, (such as lenses and mirrors), are used to guide electromagnetic waves.[6]

The theory of sound wave propagation is very similar mathematically to that of electromagnetic waves, so techniques from transmission line theory are also used to build structures to conduct acoustic waves; and these are called acoustic transmission lines.

2 History

Mathematical analysis of the behaviour of electrical transmission lines grew out of the work of James Clerk

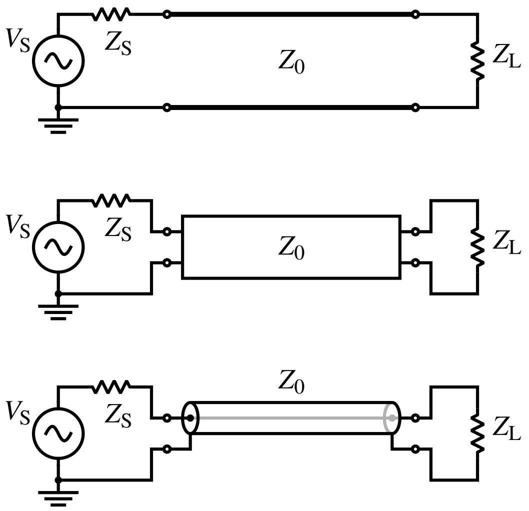
Maxwell, Lord Kelvin and Oliver Heaviside. In 1855 Lord Kelvin formulated a diffusion model of the current in a submarine cable. The model correctly predicted the poor performance of the 1858 trans-Atlantic submarine telegraph cable. In 1885 Heaviside published the first papers that described his analysis of propagation in cables and the modern form of the telegrapher's equations.[7]

3 Applicability

In many electric circuits, the length of the wires connecting the components can for the most part be ignored. That is, the voltage on the wire at a given time can be assumed to be the same at all points. However, when the voltage changes in a time interval comparable to the time it takes for the signal to travel down the wire, the length becomes important and the wire must be treated as a transmission line. Stated another way, the length of the wire is important when the signal includes frequency components with corresponding wavelengths comparable to or less than the length of the wire.

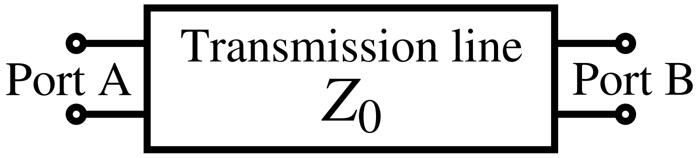
A common rule of thumb is that the cable or wire should be treated as a transmission line if the length is greater than 1/10 of the wavelength. At this length the phase delay and the interference of any reflections on the line become important and can lead to unpredictable behaviour in systems which have not been carefully designed using transmission line theory.

4 The four terminal model



Variations on the schematic electronic symbol for a transmission line.

For the purposes of analysis, an electrical transmission line can be modelled as a two-port network (also called a quadripole), as follows:



In the simplest case, the network is assumed to be linear (i.e. the complex voltage across either port is proportional to the complex current flowing into it when there are no reflections), and the two ports are assumed to be interchangeable. If the transmission line is uniform along its length, then its behaviour is largely described by a single parameter called the *characteristic impedance*, symbol Z_0. This is the ratio of the complex voltage of a given wave to the complex current of the same wave at any point on the line. Typical values of Z_0 are 50 or 75 ohms for a coaxial cable, about 100 ohms for a twisted pair of wires, and about 300 ohms for a common type of untwisted pair used in radio transmission.

When sending power down a transmission line, it is usually desirable that as much power as possible will be absorbed by the load and as little as possible will be reflected back to the source. This can be ensured by making the load impedance equal to Z_0, in which case the transmission line is said to be *matched*.

A transmission line is drawn as two black wires. At a distance x *into the line, there is current* I(x) *travelling through each wire, and there is a voltage difference* V(x) *between the wires. If the current and voltage come from a single wave (with no reflection), then* $V(x) / I(x) = Z_0$*, where* Z_0 *is the characteristic impedance of the line.*

Some of the power that is fed into a transmission line is lost because of its resistance. This effect is called *ohmic* or *resistive* loss (see ohmic heating). At high frequencies, another effect called *dielectric loss* becomes significant, adding to the losses caused by resistance. Dielectric loss is caused when the insulating material inside the transmission line absorbs energy from the alternating electric field and converts it to heat (see dielectric heating). The transmission line is modelled with a resistance (R) and inductance (L) in series with a capacitance (C) and conductance (G) in parallel. The resistance and conductance contribute to the loss in a transmission line.

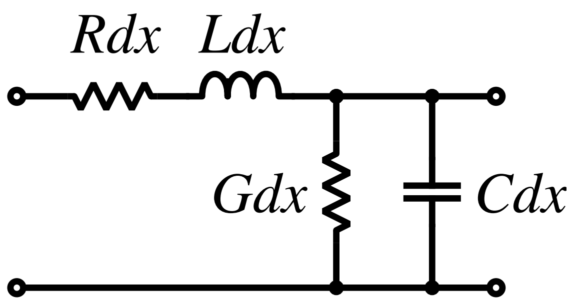
The total loss of power in a transmission line is often specified in decibels per metre (dB/m), and usually depends on the frequency of the signal. The manufacturer often supplies a chart showing the loss in dB/m at a range of frequencies. A loss of 3 dB corresponds approximately to a halving of the power.

High-frequency transmission lines can be defined as those designed to carry electromagnetic waves whose wavelengths are shorter than or comparable to the length of the line. Under these conditions, the approximations useful for calculations at lower frequencies are no longer accurate. This often occurs with radio, microwave and optical signals, metal mesh optical filters, and with the signals found in high-speed digital circuits.

5 Telegrapher's equations

Main article: Telegrapher's equations
See also: Reflections on copper lines

The **telegrapher's equations** (or just **telegraph equations**) are a pair of linear differential equations which describe the voltage and current on an electrical transmission line with distance and time. They were developed by Oliver Heaviside who created the *transmission line model*, and are based on Maxwell's Equations.



Schematic representation of the elementary component of a transmission line.

The transmission line model represents the transmission line as an infinite series of two-port elementary components, each representing an infinitesimally short segment of the transmission line:

- The distributed resistance R of the conductors is represented by a series resistor (expressed in ohms per unit length).
- The distributed inductance L (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (henries per unit length).
- The capacitance C between the two conductors is represented by a shunt capacitor C (farads per unit length).
- The conductance G of the dielectric material separating the two conductors is represented by a shunt resistor between the signal wire and the return wire (siemens per unit length).

The model consists of an *infinite series* of the elements shown in the figure, and the values of the components are specified *per unit length* so the picture of the component can be misleading. R , L , C , and G may also be functions of frequency. An alternative notation is to use R' , L' , C' and G' to emphasize that the values are derivatives with respect to length. These quantities can also be known as the primary line constants to distinguish from the secondary line constants derived from them, these being the propagation constant, attenuation constant and phase constant.

The line voltage $V(x)$ and the current $I(x)$ can be expressed in the frequency domain as

$$\frac{\partial V(x)}{\partial x} = -(R + j\omega L)I(x)$$

$$\frac{\partial I(x)}{\partial x} = -(G + j\omega C)V(x).$$

When the elements R and G are negligibly small the transmission line is considered as a lossless structure. In this hypothetical case, the model depends only on the L and C elements which greatly simplifies the analysis. For a lossless transmission line, the second order steady-state Telegrapher's equations are:

$$\frac{\partial^2 V(x)}{\partial x^2} + \omega^2 LC \cdot V(x) = 0$$

$$\frac{\partial^2 I(x)}{\partial x^2} + \omega^2 LC \cdot I(x) = 0.$$

These are wave equations which have plane waves with equal propagation speed in the forward and reverse directions as solutions. The physical significance of this is that electromagnetic waves propagate down transmission lines and in general, there is a reflected component that interferes with the original signal. These equations are fundamental to transmission line theory.

If R and G are not neglected, the Telegrapher's equations become:

$$\frac{\partial^2 V(x)}{\partial x^2} = \gamma^2 V(x)$$

$$\frac{\partial^2 I(x)}{\partial x^2} = \gamma^2 I(x)$$

where γ is the propagation constant

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

and the characteristic impedance can be expressed as

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}.$$

The solutions for $V(x)$ and $I(x)$ are:

$$V(x) = V^+ e^{-\gamma x} + V^- e^{\gamma x}$$

$$I(x) = \frac{1}{Z_0}(V^+ e^{-\gamma x} - V^- e^{\gamma x}).$$

The constants $V^\pm$ and $I^\pm$ must be determined from boundary conditions. For a voltage pulse $V_{\text{in}}(t)$, starting at $x = 0$ and moving in the positive x -direction, then the transmitted pulse $V_{\text{out}}(x, t)$ at position x can be obtained by computing the Fourier Transform, $\tilde{V}(\omega)$, of $V_{\text{in}}(t)$, attenuating each frequency component by $e^{-\text{Re}(\gamma)x}$, advancing its phase by $-\text{Im}(\gamma)x$, and taking the inverse Fourier Transform. The real and imaginary parts of γ can be computed as

$$\text{Re}(\gamma) = (a^2 + b^2)^{1/4} \cos(\text{atan2}(b, a)/2)$$

$$\text{Im}(\gamma) = (a^2 + b^2)^{1/4} \sin(\text{atan2}(b, a)/2)$$

where atan2 is the two-parameter arctangent, and

$$a \equiv \omega^2 LC \left[\left(\frac{R}{\omega L}\right)\left(\frac{G}{\omega C}\right) - 1 \right]$$

$$b \equiv \omega^2 LC \left(\frac{R}{\omega L} + \frac{G}{\omega C} \right).$$

For small losses and high frequencies, to first order in $R/\omega L$ and $G/\omega C$ one obtains

$$\text{Re}(\gamma) \approx \frac{\sqrt{LC}}{2}\left(\frac{R}{L} + \frac{G}{C}\right)$$

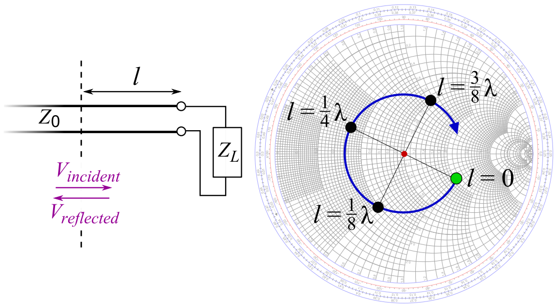
$$\text{Im}(\gamma) \approx \omega\sqrt{LC}.$$

Noting that an advance in phase by $-\omega\delta$ is equivalent to a time delay by δ , $V_{out}(t)$ can be simply computed as

$$V_{\text{out}}(x, t) \approx V_{\text{in}}(t - \sqrt{LC}x) e^{-\frac{\sqrt{LC}}{2}\left(\frac{R}{L} + \frac{G}{C}\right)x}.$$

6 Input impedance of transmission line

The characteristic impedance Z_0 of a transmission line is the ratio of the amplitude of a *single* voltage wave to its current wave. Since most transmission lines also have a reflected wave, the characteristic impedance is generally not the impedance that is measured on the line.



Looking towards a load through a length l *of lossless transmission line, the impedance changes as* l *increases, following the blue circle on this impedance Smith chart. (This impedance is characterized by its reflection coefficient* $V_{\text{reflected}}$ / V_{incident}*.) The blue circle, centred within the chart, is sometimes called an* SWR circle *(short for* constant standing wave ratio*).*

The impedance measured at a given distance, *l*, from the load impedance *ZL* may be expressed as,

$$Z_{in}(l) = \frac{V(l)}{I(l)} = Z_0 \frac{1 + \Gamma_L e^{-2\gamma l}}{1 - \Gamma_L e^{-2\gamma l}}$$

where γ is the propagation constant and $\Gamma_L = (Z_L - Z_0)/(Z_L + Z_0)$ is the voltage reflection coefficient at the load end of the transmission line. Alternatively, the above formula can be rearranged to express the input impedance in terms of the load impedance rather than the load voltage reflection coefficient:

$$Z_{in}(l) = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)}$$

6.1 Input impedance of lossless transmission line

For a lossless transmission line, the propagation constant is purely imaginary, $\gamma = j\beta$, so the above formulas can be rewritten as,

$$Z_{\text{in}}(l) = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)}$$

where $\beta = \frac{2\pi}{\lambda}$ is the wavenumber.

In calculating β, the wavelength is generally different inside the transmission line to what it would be in free-space and the velocity constant of the material the transmission line is made of needs to be taken into account when doing such a calculation.

6.2 Special cases of lossless transmission lines

6.2.1 Half wave length

For the special case where $\beta l = n\pi$ where n is an integer (meaning that the length of the line is a multiple of half a wavelength), the expression reduces to the load impedance so that

$$Z_{\text{in}} = Z_L$$

for all *n*. This includes the case when *n*=0, meaning that the length of the transmission line is negligibly small compared to the wavelength. The physical significance of this is that the transmission line can be ignored (i.e. treated as a wire) in either case.

6.2.2 Quarter wave length

Main article: quarter wave impedance transformer

For the case where the length of the line is one quarter wavelength long, or an odd multiple of a quarter wavelength long, the input impedance becomes

$$Z_{\text{in}} = \frac{{Z_0}^2}{Z_L}.$$

6.2.3 Matched load

Another special case is when the load impedance is equal to the characteristic impedance of the line (i.e. the line is *matched*), in which case the impedance reduces to the characteristic impedance of the line so that

$$Z_{\text{in}} = Z_L = Z_0$$

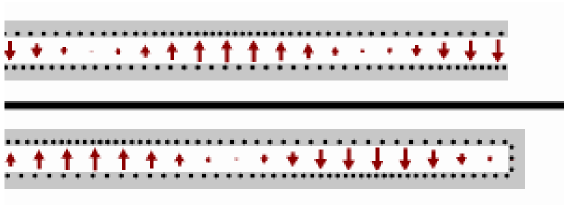
for all l and all λ .

6.2.4 Short

Main article: stub

For the case of a shorted load (i.e. $Z_L = 0$), the input impedance is purely imaginary and a periodic function of position and wavelength (frequency)

$$Z_{\text{in}}(l) = jZ_0 \tan(\beta l).$$



Standing waves on a transmission line with an open-circuit load (top), and a short-circuit load (bottom). Black dots represent electrons, and the arrows show the electric field.

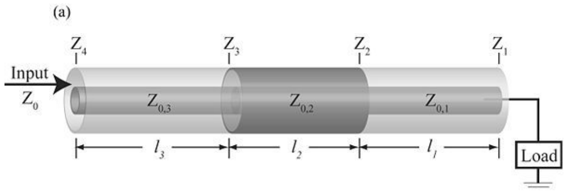
6.2.5 Open

Main article: stub

For the case of an open load (i.e. $Z_L = \infty$), the input impedance is once again imaginary and periodic

$$Z_{\text{in}}(l) = -jZ_0 \cot(\beta l).$$

6.3 Stepped transmission line



A simple example of stepped transmission line consisting of three segments.

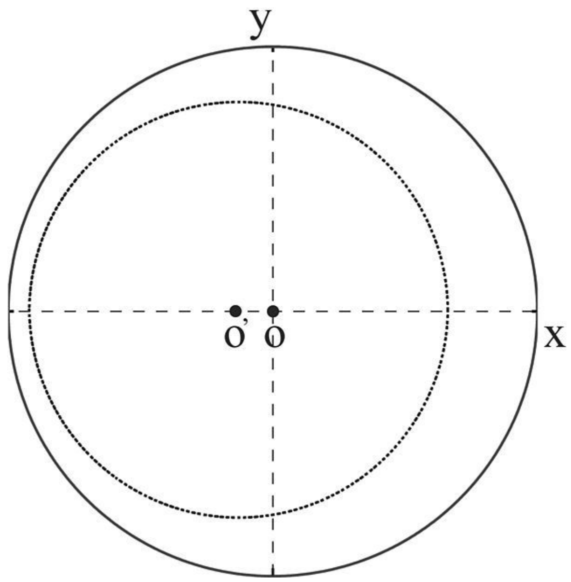
A stepped transmission line[8] is used for broad range impedance matching. It can be considered as multiple transmission line segments connected in series, with the characteristic impedance of each individual element to be $Z_{0,i}$. The input impedance can be obtained from the successive application of the chain relation

$$Z_{i+1} = Z_{0,i} \frac{Z_i + jZ_{0,i} \tan(\beta_i l_i)}{Z_{0,i} + jZ_i \tan(\beta_i l_i)}$$

where β_i is the wave number of the ith transmission line segment and l_i is the length of this segment, and Z_i is the front-end impedance that loads the ith segment.

Because the characteristic impedance of each transmission line segment $Z_{0,i}$ is often different from that of the input cable Z_0, the impedance transformation circle is off-centred along the x axis of the Smith Chart whose impedance representation is usually normalized against Z_0.

7 Practical types



The impedance transformation circle along a transmission line whose characteristic impedance Z0,i is smaller than that of the input cable Z_0. And as a result, the impedance curve is off-centred towards the -x axis. Conversely, if Z0,i > Z_0, the impedance curve should be off-centred towards the +x axis.

7.1 Coaxial cable

Main article: coaxial cable

Coaxial lines confine virtually all of the electromagnetic wave to the area inside the cable. Coaxial lines can therefore be bent and twisted (subject to limits) without negative effects, and they can be strapped to conductive supports without inducing unwanted currents in them. In radio-frequency applications up to a few gigahertz, the wave propagates in the transverse electric and magnetic mode (TEM) only, which means that the electric and magnetic fields are both perpendicular to the direction of propagation (the electric field is radial, and the magnetic field is circumferential). However, at frequencies for which the wavelength (in the dielectric) is significantly shorter than the circumference of the cable, transverse electric (TE) and transverse magnetic (TM) waveguide modes can also propagate. When more than one mode can exist, bends and other irregularities in the cable geometry can cause power to be transferred from one mode to another.

The most common use for coaxial cables is for television and other signals with bandwidth of multiple megahertz. In the middle 20th century they carried long distance telephone connections.

7.2 Microstrip

Main article: microstrip

A type of transmission line called a cage line*, used for high power, low frequency applications. It functions similarly to a large coaxial cable. This example is the antenna feedline for a longwave radio transmitter in Poland, which operates at a frequency of 225 kHz and a power of 1200 kW.*

A microstrip circuit uses a thin flat conductor which is parallel to a ground plane. Microstrip can be made by having a strip of copper on one side of a printed circuit board (PCB) or ceramic substrate while the other side is a continuous ground plane. The width of the strip, the thickness of the insulating layer (PCB or ceramic) and the dielectric constant of the insulating layer determine the characteristic impedance. Microstrip is an open structure whereas coaxial cable is a closed structure.

7.3 Stripline

Main article: Stripline

A stripline circuit uses a flat strip of metal which is sandwiched between two parallel ground planes. The insulating material of the substrate forms a dielectric. The width of the strip, the thickness of the substrate and the relative permittivity of the substrate determine the characteristic impedance of the strip which is a transmission line.

7.4 Balanced lines

Main article: Balanced line

A balanced line is a transmission line consisting of two conductors of the same type, and equal impedance to ground and other circuits. There are many formats of balanced lines, amongst the most common are twisted pair, star quad and twin-lead.

7.4.1 Twisted pair

Main article: Twisted pair

Twisted pairs are commonly used for terrestrial telephone communications. In such cables, many pairs are grouped together in a single cable, from two to several thousand.[9] The format is also used for data network distribution inside buildings, but the cable is more expensive because the transmission line parameters are tightly controlled.

7.4.2 Star quad

Main article: Star quad cable

Star quad is a four-conductor cable in which all four conductors are twisted together around the cable axis. It is sometimes used for two circuits, such as 4-wire telephony and other telecommunications applications. In this configuration each pair uses two non-adjacent conductors. Other times it is used for a single, balanced line, such as audio applications and 2-wire telephony. In this configuration two non-adjacent conductors are terminated together at both ends of the cable, and the other two conductors are also terminated together.

When used for two circuits, crosstalk is reduced relative to cables with two separate twisted pairs.

When used for a single, balanced line, magnetic interference picked up by the cable arrives as a virtually perfect common mode signal, which is easily removed by coupling transformers.

The combined benefits of twisting, balanced signalling, and quadrupole pattern give outstanding noise immunity, especially advantageous for low signal level applications such as microphone cables, even when installed very close to a power cable.[10][11][12][13][14] The disadvantage is that star quad, in combining two conductors, typically has double the capacitance of similar two-conductor twisted and shielded audio cable. High capacitance causes increasing distortion and greater loss of high frequencies as distance increases.[15][16]

7.4.3 Twin-lead

Main article: Twin-lead

Twin-lead consists of a pair of conductors held apart by a continuous insulator. By holding the conductors a known distance apart, the geometry is fixed and the line characteristics are reliably consistent. It is lower loss than coaxial cable because the wave propagates mostly in air rather than the thin dielectric. However, it is more susceptible to interference.

7.4.4 Lecher lines

Main article: Lecher lines

Lecher lines are a form of parallel conductor that can be used at UHF for creating resonant circuits. They are a convenient practical format that fills the gap between lumped components (used at HF/VHF) and resonant cavities (used at UHF/SHF).

7.5 Single-wire line

Unbalanced lines were formerly much used for telegraph transmission, but this form of communication has now fallen into disuse. Cables are similar to twisted pair in that many cores are bundled into the same cable but only one conductor is provided per circuit and there is no twisting. All the circuits on the same route use a common path for the return current (earth return). There is a power transmission version of single-wire earth return in use in many locations.

8 General applications

8.1 Signal transfer

Electrical transmission lines are very widely used to transmit high frequency signals over long or short distances with minimum power loss. One familiar example is the down lead from a TV or radio aerial to the receiver.

8.2 Pulse generation

Transmission lines are also used as pulse generators. By charging the transmission line and then discharging it into a resistive load, a rectangular pulse equal in length to twice the electrical length of the line can be obtained, although with half the voltage. A Blumlein transmission line is a related pulse forming device that overcomes this limitation. These are sometimes used as the pulsed power sources for radar transmitters and other devices.

8.3 Stub filters

See also: Distributed element filter § Stub band-pass filters

If a short-circuited or open-circuited transmission line is wired in parallel with a line used to transfer signals from point A to point B, then it will function as a filter. The method for making stubs is similar to the method for using Lecher lines for crude frequency measurement, but it is 'working backwards’. One method recommended in the RSGB's radiocommunication handbook is to take an open-circuited length of transmission line wired in parallel with the feeder delivering signals from an aerial. By cutting the free end of the transmission line, a minimum in the strength of the signal observed at a receiver can be found. At this stage the stub filter will reject this frequency and the odd harmonics, but if the free end of the stub is shorted then the stub will become a filter rejecting the even harmonics.

9 Acoustic transmission lines

Main article: Acoustic transmission line

An acoustic transmission line is the acoustic analogue of the electrical transmission line, typically thought of as a rigid-walled tube that is long and thin relative to the wavelength of sound present in it.

10 See also

- Distributed element model
- Heaviside condition
- Longitudinal electromagnetic wave
- Propagation velocity
- Radio frequency power transmission
- Time domain reflectometer
- Transverse electromagnetic wave

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Part of this article was derived from Federal Standard 1037C.

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13 External links

- Transmission Line Calculator (Including radiation and surface-wave excitation losses)
- Transmission Line Parameter Calculator
- Interactive applets on transmission lines
- SPICE Simulation of Transmission Lines

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14.1 Text

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