band, packaged in two of the terminals, with the noise levels, and the dc different amplifiers for low noise or large dynamic range frequencies. In many cases, the 15dB of gain of 30MHz to 2dB (max.), ±0.75dB. It is used singly or in pairs for the best performance.

For RF circuitry, using the metal box with the RF fitting, we have the Avantek or Aertech TR dewar. For single modules, the Aertech TR dewar is superior. These are important additions to the RF circuitry.

RADIOFREQUENCY CIRCUIT ELEMENTS

13.09 Transmission lines

Before proceeding to the subject of communications circuits, it is necessary to deal briefly with the interesting subject of transmission lines. You have met these earlier in connection with digital signal communications in Chapter 9, where we introduced the ideas of characteristic impedance and line terminations. Transmission lines play a central role in radiofrequency circuits, where they are used to pipe signals around from one place to another within a circuit, and often to an antenna system. Transmission lines provide one of the most important exceptions to the general principles (see Chapter 1) that a signal source ideally should have a zero impedance small compared with the impedance of the load being driven and that the load should present an input impedance large compared with the source impedance driving it. The equivalent rule for transmission lines is that the load (and possibly the source) should present an impedance equal to the characteristic impedance of the line. The line is then widely used in short lengths with BNC fittings to carry signals between instruments (Fig. 13.14).

In the domain of ultra-high-frequency circuitry there are "stripeline" techniques that involve parallel-conductor transmission lines as part of the actual circuit, and at the higher "microwave" frequencies (upwards of 2GHz, say) conventional lumped circuit elements and transmission lines are replaced by cavity and waveguide techniques, respectively. Except at these extremes of frequency, the familiar coaxial cable is probably the best choice for most radiofrequency applications. Compared with parallel-conductor line, a properly matched coax line has the advantage of being totally shielded, i.e., there is no radiation or pickup of external signals.

Characteristic impedance and matching

A transmission line, whatever its form, has a "characteristic impedance" $Z_0$, meaning that a wave moving along the line has a ratio of voltage to current equal to $Z_0$. For a lossless line, $Z_0$ is resistive and equal to the square root of $L/C$, where $L$ is the inductance per unit length and $C$ is the capacitance per unit length. Typical coaxial lines have impedances in the range of 50 to 100 ohms, whereas parallel-conductor lines have
impedances in the range of 300 to 1000 ohms.

When used with high-frequency (or short-rise-time) signals, it is important to "match" the load to the characteristic impedance of the line. The important facts are the following: (a) A transmission line terminated with a load equal to its characteristic impedance (resistance) will transfer an applied pulse to the termination without reflection. In that case all the power in the signal is transferred to the load. (b) The impedance looking into such a terminated line, at any frequency, is equal to its characteristic impedance (Fig. 13.15).

This property of a shorted cable is sometimes exploited to generate a short pulse from a step waveform. The step input is applied to the cable input through a resistance equal to \(Z_0\), with the other end of the cable shorted. The waveform at the input is a pulse of width equal to the round-trip travel time, since the reflected step cancels the input (Fig. 13.16).

Cables terminated with a resistance \(R\) unequal to \(Z_0\) also produce reflections, although of lesser amplitude. The reflected wave is inverted if \(R < Z_0\) and uninvetered if \(R > Z_0\). The ratio of reflected wave amplitude to incident wave amplitude is given by:

\[
A_r/A_i = (R - Z_0)/(R + Z_0)
\]

**Transmission lines in the frequency domain**

Looked at in the frequency domain, a transmission line matched at the far end looks like a load of impedance \(Z_0\) i.e., a pure resistance if line losses are neglected. That makes sense, since it just swallows any wave you apply, all the power going into the matching resistor. This is true independent of cable length or wavelength. It is when you deal with mismatched lines that things begin to get interesting in the frequency domain.

Since, for a given line length, the reflected wave arrives back at the input with a phase (relative to the applied signal) that depends on applied frequency, the impedance seen looking into the input depends on the mismatch and on the electrical length of the transmission line, in wavelengths. As an example, a line that is an odd number of quarter wavelengths long terminated in an impedance \(Z_{load}\) at the far end presents an input impedance \(Z_i = Z_0^2/Z_{load}\). If the load is resistive, the input will look resistive. On the integral present an input terminating impedance.

The presence of a transmission line in operation at a matched line creates a greater line loss and currents flow than with a matched line has different frequencies (the be used to measure reflected wave. A broadband or mamp is strive to terminate characteristic input:

**Stubs**

There are some transmission lines of mismatched sections of line. The simplest is the stub, section, which \(Z_0^2/Z_{load}\). This can be section can b impedances on impedance of priately.

In a similar transmission line, the stub acts
A short pulse step input is through a resistive other end of the at the input is the round-trip step cancels resistive. On the other hand, a line that is an integral number of half wavelengths long presents an input impedance equal to its terminating impedance (Fig. 13.17).

The presence of reflected signals on a transmission line is not necessarily bad. For operation at a single frequency, a mismatched line can be driven (through a line tuner) in such a way as to match its resultant input impedance, often with only negligibly greater line losses (due to higher voltages and currents for the same forward power) than with a matched load. But a mismatched line has different properties at different frequencies (the famous "Smith chart" can be used to determine transmission-line impedances and "standing-wave ratio," or SWR, a measure of the amplitude of reflected waves), making it undesirable for broadband or multifrequency use. In general, strive to terminate a transmission line in its characteristic impedance, at least at the receiving end.

13.10 Stubs, baluns, and transformers

There are some interesting applications of mismatched sections or generally use sections of line in an unconventional way. The simplest is the quarter-wave matching section, which exploits the relationship \( Z_m = \frac{Z_0}{\sqrt{2}} \). This can be rearranged to read \( Z_0 = Z_m \sqrt{2} \). In other words, a quarter-wave section can be used to match any two impedances by choosing the characteristic impedance of the matching section appropriately.

In a similar manner, a short length of transmission line (a "stub") can be used to mismatch a load by simply putting a stub across or in series with the mismatched line, choosing the stub length and termination (open or shorted) and its position along the mismatched line correctly. In this sort of application the stub is really functioning as a circuit element, not a transmission line. At very short wavelengths the use of sections of transmission line as circuit elements is common (Fig. 13.18).

Sections of transmission line (or a transformer made with several interconnected windings) can be used to construct a "balun," a device for matching an unbalanced line (coax) to a balanced load (e.g., an antenna). There are simple configurations for making fixed-impedance transformations at the same time (1:1 and 4:1 are common). Perhaps the nicest circuit element made from transmission line is the broadband transmission-line transformer. These gadgets consist simply of a few turns of miniature coax or twisted pair wound on a ferrite core, suitably interconnected. They avoid the high-frequency limitations of conventional transformers (caused by the resonant combination of "parasitic" winding capacitance and inductance) because the coils are arranged so that the winding capacitance and inductance form a transmission line, free of resonances. They can provide various impedance transformations with astounding broadband performance (e.g., less than 1dB loss from 0.1MHz to 500MHz), a property not shared by transformers constructed from simple coupled inductors. Transmission-
former-coupled (or even configured as a resonant matching network, as in the popular pi network) to achieve any desired impedance transformation; (d) elimination of out-of-band signals and noise owing to the frequency selectivity of the tuned circuits.

**Examples of tuned radiofrequency circuits**

You will see tuned RF amplifiers in their natural element when we discuss communications circuits shortly. At this point we would simply like to illustrate the use of tuned circuits in oscillators and amplifiers with a few examples. Figure 13.20 illustrates the classic tuned amplifier. A dual-gate depletion-mode FET is used to eliminate the problems of Miller effect, since the input is untuned. By operating the lower gate at dc ground, the stage runs at $I_{DS}$ (the parallel tuned LC sets the center frequency of amplification, with output buffering via $Q_2$. Since the drain sits at +10 volts, the output follower requires a higher collector voltage. This sort of circuit has quite high voltage gain at resonance, limited by the LC circuit $Q$ and loading by the follower.

In the circuit shown in Figure 13.21 a carefully constructed and tunable LC circuit is used to set the frequency of an oscillator. This is known as a VFO (variable-frequency oscillator); it is used as the tunable element in some transmitters and receivers, as well as variable-frequency circuits. This circuit technique of coupled signal adding a current through the neutralizing network is often used in practice.