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HOROWITZ + HILL
"The Art of Electronics"

(±0.25dB) with an astounding 1.8dB noise figure.

There is plenty of commercial competition in these amplifier modules, as well as other RF modular components. For complete amplifier modules, some of the larger suppliers are Aertech/TRW, Avantek, Aydin Vector, Hewlett-Packard, Narda, Scientific Communications, and Watkins-Johnson. In practice, when designing an RF system you might well choose to thumb through catalogs of available (and custom) modules in order to assemble a system. Screw them all down to a plate, connect them together with coaxial cable, and off you go!

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 source 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 "matched."

Transmission lines for signals of moderate frequency (up to 1000MHz, say) come in two major types: parallel conductors and coaxial line. The former is typified by the inexpensive molded 300 ohm "twin lead" used to bring the signal from a television antenna to the receiver, and the latter is widely used in short lengths with BNC fittings to carry signals between instruments (Fig. 13.14).

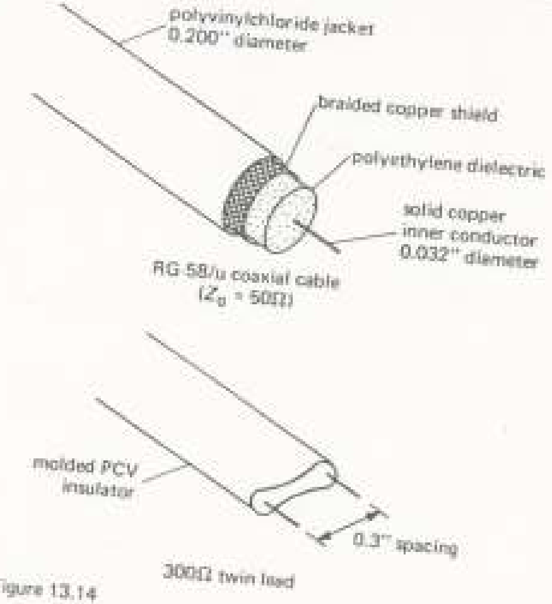


Figure 13.14

In the domain of ultra-high-frequency circuitry there are "stripline" 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).

no reflections, all power goes to load

Figure 13.15

This is surprising at first, since at low frequencies you tend to think of a length of coax as a small capacitive load, generally a pretty high (capacitive) impedance. Also, at low frequencies (wavelength ≫ length of cable) there is no need to match the line's impedance, provided you can handle the capacitance (typically 30pF per foot). If the cable is terminated with a resistor, on the other hand, it magically becomes a pure resistance at all frequencies.

Mismatched transmission lines

A mismatched transmission line has some interesting, and occasionally useful, properties. A line terminated in a short circuit produces a reflected wave of opposite polarity, with the delay time of the reflected wave determined by the electrical length of the line (the speed of wave propagation in coax lines is about two-thirds the speed of light, because of the solid dielectric spacing material). You can see the reason for this, since the short circuit enforces a point of zero voltage at the end; the cable produces this obligatory boundary condition by creating a wave of opposite phase at the short. In similar manner, an open-circuited cable (boundary condition of zero current at the end) produces a noninverted reflection of amplitude equal to the applied signal.

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). TH3 V [illegible]

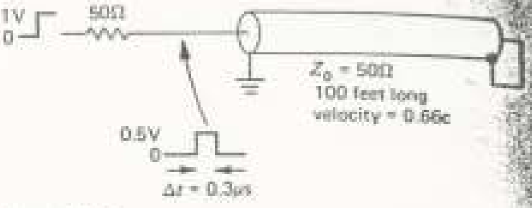


Figure 13.16
Pulse generation with shorted transmission lines (inverted reflection).

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 uninverted 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 $Z_{in} = Z_0^2/Z_{load}$. If the load is resistive, the input will look

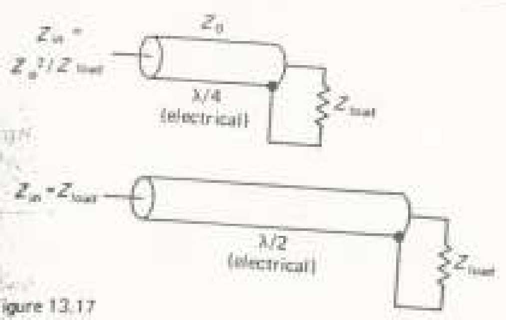


Figure 13.17

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).

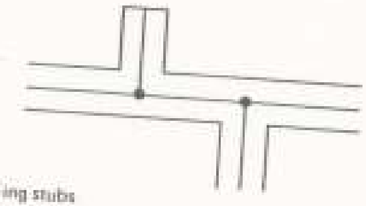
The presence of reflected signals on a transmission line is not necessarily bad. For operation at a single frequency, a mismatched line can be driven (through a line tuner) in such a way as to match its resultant input impedance, often with only negligibly greater line losses (due to higher voltages 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 transmission lines that exploit the properties 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 $Z_{in} = Z_0^2/Z_{load}$. This can be rearranged to read $Z_0 = (Z_{in}Z_{load})^{1/2}$. 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 "tune" a mismatched load by simply putting the 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).

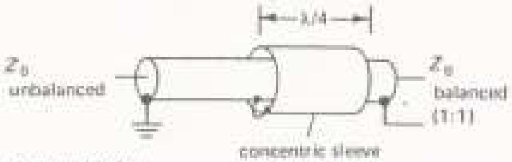
A. quarter-wave matching section



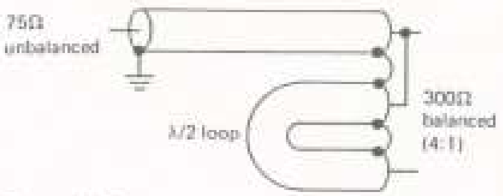
B. matching stubs

Figure 13.18

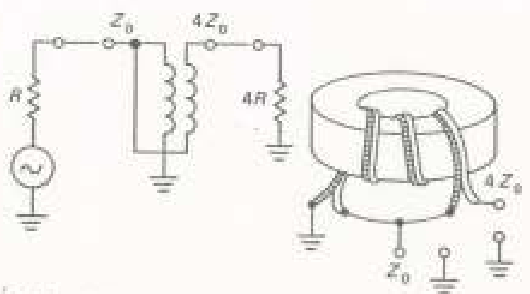
Sections of transmission line (or a transformer made with several interconnected windings) can be used to construct a "balun," a device for matching an unbalanced line (coax) to a balanced load (e.g., an antenna). There are simple configurations for making fixed-impedance transformations at the same 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. Transmis-



A. tuned balun



B. tuned balun



C. 4:1 unbalanced transmission-line transformer

Figure 13.19
Transmission-line transformers.

sion-line transformers are available from the Vari-L Co. and Mini-Circuits Laboratory, among others, as packaged modules. Figure 13.19 shows a few examples of baluns and a transmission-line transformer.

13.11 Tuned amplifiers

In radiofrequency circuits intended for communications, or for other applications where the operating frequency is confined to a narrow range, it is common to use tuned *LC* circuits as collector or drain loads. This has several advantages: (a) higher single-stage gain, since the load presents a high impedance at the signal frequency ($G_V = g_m Z_{load}$) while allowing arbitrary quiescent current; (b) elimination of the undesirable loading effects of capacitance, since the *LC* circuit "tunes out" any capacitance by making it part of the tuned circuit capacitance; (c) simplified interstage coupling, since an *LC* circuit can be tapped or transformer-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_{DSS}. 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.

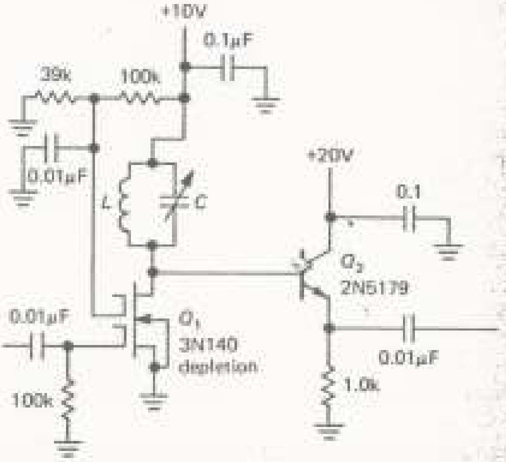


Figure 13.20
Dual-gate MOSFET (cascode) tuned amplifier.

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

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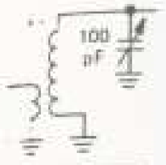

Figure 13.21
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