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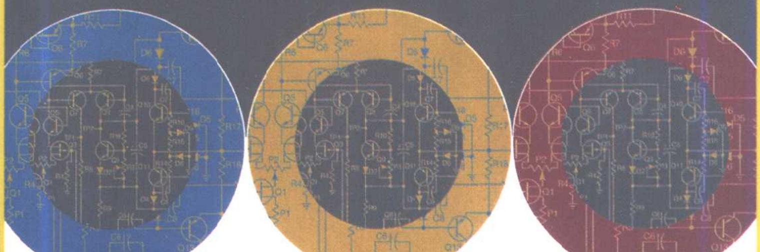

射频电路设计（第3版）

〔美〕JOSEPH J. CARR 著

SECRETS OF RF CIRCUIT DESIGN

THIRD EDITION

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CHAPTER

Introduction to RF electronics

Radio-frequency (RF) electronics differ from other electronics because the higher frequencies make some circuit operation a little hard to understand. Stray capacitance and stray inductance afflict these circuits. Stray capacitance is the capacitance that exists between conductors of the circuit, between conductors or components and ground, or between components. Stray inductance is the normal inductance of the conductors that connect components, as well as internal component inductances. These stray parameters are not usually important at dc and low ac frequencies, but as the frequency increases, they become a much larger proportion of the total. In some older very high frequency (VHF) TV tuners and VHF communications receiver front ends, the stray capacitances were sufficiently large to tune the circuits, so no actual discrete tuning capacitors were needed.

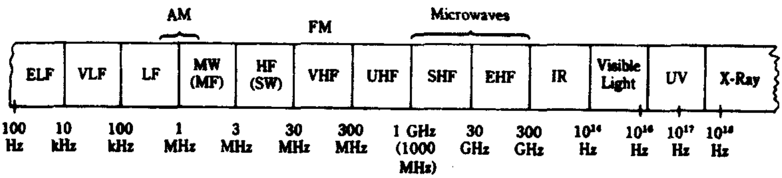
Also, skin effect exists at RF. The term *skin effect* refers to the fact that ac flows only on the outside portion of the conductor, while dc flows through the entire conductor. As frequency increases, skin effect produces a smaller zone of conduction and a correspondingly higher value of ac resistance compared with dc resistance.

Another problem with RF circuits is that the signals find it easier to radiate both from the circuit and within the circuit. Thus, coupling effects between elements of the circuit, between the circuit and its environment, and from the environment to the circuit become a lot more critical at RF. Interference and other strange effects are found at RF that are missing in dc circuits and are negligible in most low-frequency ac circuits.

The electromagnetic spectrum

When an RF electrical signal radiates, it becomes an electromagnetic wave that includes not only radio signals, but also infrared, visible light, ultraviolet light, X-rays, gamma rays, and others. Before proceeding with RF electronic circuits, therefore, take a look at the electromagnetic spectrum.

The electromagnetic spectrum (Fig. 1-1) is broken into bands for the sake of convenience and identification. The spectrum extends from the very lowest ac frequencies and continues well past visible light frequencies into the X-ray and gamma-ray region. The extremely low frequency (ELF) range includes ac power-line frequencies as well as other low frequencies in the 25- to 100-hertz (Hz) region. The U.S. Navy uses these frequencies for submarine communications.



1-1 The electromagnetic spectrum from VLF to X-ray. The RF region covers from less than 100 kHz to 300 GHz.

The very low frequency (VLF) region extends from just above the ELF region, although most authorities peg it to frequencies of 10 to 100 kilohertz (kHz). The low-frequency (LF) region runs from 100 to 1000 kHz—or 1 megahertz (MHz). The medium-wave (MW) or medium-frequency (MF) region runs from 1 to 3 MHz. The amplitude-modulated (AM) broadcast band (540 to 1630 kHz) spans portions of the LF and MF bands.

The high-frequency (HF) region, also called the *shortwave bands* (SW), runs from 3 to 30 MHz. The VHF band starts at 30 MHz and runs to 300 MHz. This region includes the frequency-modulated (FM) broadcast band, public utilities, some television stations, aviation, and amateur radio bands. The ultrahigh frequencies (UHF) run from 300 to 900 MHz and include many of the same services as VHF. The microwave region begins above the UHF region, at 900 or 1000 MHz, depending on source authority.

You might well ask how microwaves differ from other electromagnetic waves. Microwaves almost become a separate topic in the study of RF circuits because at these frequencies the wavelength approximates the physical size of ordinary electronic components. Thus, components behave differently at microwave frequencies than they do at lower frequencies. At microwave frequencies, a 0.5-W metal film resistor, for example, looks like a complex RLC network with distributed L and C values—and a surprisingly different R value. These tiniest of distributed components have immense significance at microwave frequencies, even though they can be ignored as negligible at lower RFs.

Before examining RF theory, first review some background and fundamentals.

Units and physical constants

In accordance with standard engineering and scientific practice, all units in this book will be in either the CGS (centimeter-gram-second) or MKS (meter-kilogram-second) system unless otherwise specified. Because the metric system depends on using multiplying prefixes on the basic units, a table of common metric prefixes (Table 1-1) is provided. Table 1-2 gives the standard physical units. Table 1-3 gives physical constants of interest in this and other chapters. Table 1-4 gives some common conversion factors.

Table 1-1. Metric prefixes

Metric prefix	Multiplying factor	Symbol
tera	10^{12}	T
giga	10^{9}	G
mega	10^{6}	M
kilo	10^{3}	K
hecto	10^{2}	h
deka	10	da
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	u
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

Table 1-2. Units of measure

Quantity	Unit	Symbol
Capacitance	farad	F
Electric charge	coulomb	Q
Conductance	mhos	
Conductivity	mhos/meter	Ω/m
Current	ampere	A
Energy	joule (watt-second)	j
Field	volts/meter	E
Flux linkage	weber (volt/second)	
Frequency	hertz	Hz
Inductance	henry	H
Length	meter	m
Mass	gram	g
Power	watt	W
Resistance	ohm	Ω
Time	second	s
Velocity	meter/second	m/s
Electric potential	volt	V

Table 1-3. Physical constants

Constant	Value	Symbol
Boltzmann's constant	1.38×10^{-23} J/K	K
Electric chart (e^-)	1.6×10^{-19} C	q
Electron (volt)	1.6×10^{-19} J	eV
Electron (mass)	9.12×10^{-31} kg	m
Permeability of free space	$4\pi \times 10^{-7}$ H/m	U_0
Permitivity of free space	8.85×10^{-12} F/m	ϵ_0
Planck's constant	6.626×10^{-34} J-s	h
Velocity of electromagnetic waves	3×10^8 m/s	c
Pi (π)	3.1416 ……	π

Table 1-4. Conversion factors

1 inch	= 2.54 cm
1 inch	= 25.4 mm
1 foot	= 0.305 m
1 statute mile	= 1.61 km
1 nautical mile	= 6,080 feet (6,000 feet)[a]
1 statute mile	= 5,280 feet
1 mile	= 0.001 in = 2.54×10^{-5} m
1 kg	= 2.2 lb
1 neper	= 8.686 dB
1 gauss	= 10,000 teslas

a Some navigators use 6,000 feet for ease of calculation. The nautical mile is 1/360 of the Earth's circumference at the equator, more or less.

Wavelength and frequency

For all wave forms, the velocity, wavelength, and frequency are related so that the product of frequency and wavelength is equal to the velocity. For radiowaves, this relationship can be expressed in the following form:

$$\lambda F\sqrt{\epsilon} = c, \tag{1-1}$$

where

λ = wavelength in meters (m)
F = frequency in hertz (Hz)
ϵ = dielectric constant of the propagation medium
c = velocity of light (300,000,000 m/s).

The dielectric constant (ϵ) is a property of the medium in which the wave propagates. The value of ϵ is defined as 1.000 for a perfect vacuum and very nearly 1.0 for dry air (typically 1.006). In most practical applications, the value of ϵ in dry air is taken to be 1.000. For media other than air or vacuum, however, the velocity of propagation is slower and the value of ϵ relative to a vacuum is higher. Teflon, for example, can be made with ϵ values from about 2 to 11.

Equation (1-1) is more commonly expressed in the forms of Eqs. (1-2) and (1-3):

$$\lambda = \frac{c}{F\sqrt{\epsilon}} \tag{1-2}$$

and

$$F = \frac{c}{\lambda\sqrt{\epsilon}}. \tag{1-3}$$

[All terms are as defined for Eq. (1-1).]

Microwave letter bands

During World War II, the U.S. military began using microwaves in radar and other applications. For security reasons, alphabetic letter designations were adopted for each band in the microwave region. Because the letter designations became ingrained, they are still used throughout industry and the defense establishment. Unfortunately, some confusion exists because there are at least three systems currently in use: pre-1970 military (Table 1-5), post-1970 military (Table 1-6), and the IEEE and industry standard (Table 1-7). Additional confusion is created because the military and defense industry use both pre- and post-1970 designations simultaneously and industry often uses military rather than IEEE designations. The old military designations (Table 1-5) persist as a matter of habit.

Skin effect

There are three reasons why ordinary lumped constant electronic components do not work well at microwave frequencies. The first, mentioned earlier in this chapter, is that component size and lead lengths approximate microwave wavelengths.

Table 1-5. Old U.S. military microwave frequency bands (WWII–1970)

Band designation	Frequency range
P	225–390 MHz
L	390–1550 MHz
S	1550–3900 MHz
C	3900–6200 MHz
X	6.2–10.9 GHz
K	10.9–36 GHz
Q	36–46 GHz
V	46–56 GHz
Q	56–100 GHz

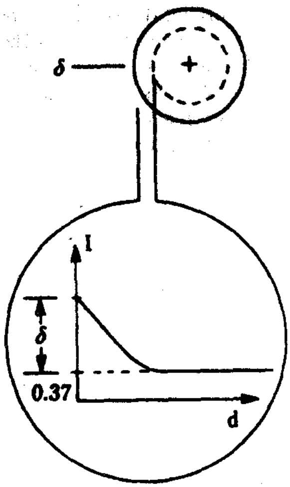
Table 1-6. New U.S. military microwave frequency bands (Post-1970)

Band designation	Frequency range
A	100–250 MHz
B	250–500 MHz
C	500–1000 MHz
D	1000–2000 MHz
E	2000–3000 MHz
F	3000–4000 MHz
G	4000–6000 MHz
H	6000–8000 MHz
I	8000–10000 MHz
J	10–20 GHz
K	20–40 GHz
L	40–60 GHz
M	60–100 GHz

Table 1-7. IEEE/Industry standard frequency bands

Band designation	Frequency range
HF	3–30 MHz
VHF	0–300 MHz
UHF	300–1000 MHz
L	1000–2000 MHz
S	2000–4000 MHz
C	4000–8000 MHz
X	8000–12000 MHz
Ku	12–18 GHz
K	18–27 GHz
Ka	27–40 GHz
Millimeter	40–300 GHz
Submillimeter	>300 GHz

The second is that distributed values of inductance and capacitance become significant at these frequencies. The third is the phenomenon of skin effect. While dc current flows in the entire cross section of the conductor, ac flows in a narrow band near the surface. Current density falls off exponentially from the surface of the conductor toward the center (Fig. 1-2). At the critical depth (δ, also called the depth of penetration), the current density is $1/e = 1/2.718 = 0.368$ of the surface current density.



1-2
In ac circuits, the current flows only in the outer region of the conductor. This effect is frequency-sensitive and it becomes a serious consideration at higher RF frequencies.

The value of δ is a function of operating frequency, the permeability (μ) of the conductor, and the conductivity (σ). Equation (1-4) gives the relationship.

$$\delta = \sqrt{\frac{1}{2\pi F \sigma \mu}} \tag{1-4}$$

where
- δ = critical depth
- F = frequency in hertz
- μ = permeability in henrys per meter
- σ = conductivity in mhos per meter.

RF components, layout, and construction

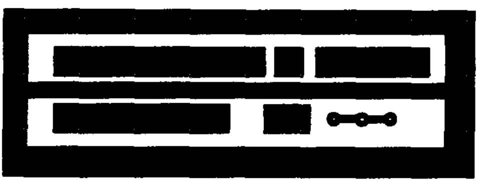
Radio-frequency components and circuits differ from those of other frequencies principally because the unaccounted for "stray" inductance and capacitance forms a significant portion of the entire inductance and capacitance in the circuit. Consider a tuning circuit consisting of a 100-pF capacitor and a 1-μH inductor. According to an equation that you will learn in a subsequent chapter, this combination should resonate at an RF frequency of about 15.92 MHz. But suppose the circuit is poorly laid out and there is 25 pF of stray capacitance in the circuit. This capacitance could come from the interaction of the capacitor and inductor leads with the chassis or with other components in the circuit. Alternatively, the input capacitance of a transistor or integrated circuit (IC) amplifier can contribute to the total value of the "strays" in the circuit (one popular RF IC lists 7 pF of input capacitance). So, what does this extra 25 pF do to our circuit? It is in parallel with the 100-pF discrete capacitor so it produces a total of 125 pF. Reworking the resonance equation with 125 pF instead of 100 pF reduces the resonant frequency to 14.24 MHz.

A similar situation is seen with stray inductance. All current-carrying conductors exhibit a small inductance. In low-frequency circuits, this inductance is not sufficiently large to cause anyone concern (even in some lower HF band circuits), but as frequencies pass from upper HF to the VHF region, strays become terribly important. At those frequencies, the stray inductance becomes a significant portion of total circuit inductance.

Layout is important in RF circuits because it can reduce the effects of stray capacitance and inductance. A good strategy is to use broad printed circuit tracks at RF, rather than wires, for interconnection. I've seen circuits that worked poorly when wired with #28 Kovar-covered "wire-wrap" wire become quite acceptable when redone on a printed circuit board using broad (which means low-inductance) tracks.

Figure 1-3 shows a sample printed circuit board layout for a simple RF amplifier circuit. The key feature in this circuit is the wide printed circuit tracks and short distances. These tactics reduce stray inductance and will make the circuit more predictable.

Although not shown in Fig. 1-3, the top (components) side of the printed circuit board will be all copper, except for space to allow the components to interface with the bottom-side printed tracks. This layer is called the "ground plane" side of the board.



1-3
Typical RF printed circuit layout.

Impedance matching in RF circuits

In low-frequency circuits, most of the amplifiers are voltage amplifiers. The requirement for these circuits is that the source impedance must be very low compared with the load impedance. A sensor or signal source might have an output impedance of, for example, 25 Ω. As long as the input impedance of the amplifier receiving that signal is very large relative to 25 Ω, the circuit will function. "Very large" typically means greater than 10 times, although in some cases greater than 100 times is preferred. For the 25-Ω signal source, therefore, even the most stringent case is met by an input impedance of 2500 Ω, which is very far below the typical input impedance of real amplifiers.

RF circuits are a little different. The amplifiers are usually specified in terms of power parameters, even when the power level is very tiny. In most cases, the RF circuit will have some fixed system impedance (50, 75, 300, and 600 Ω being common, with 50 Ω being nearly universal), and all elements of the circuit are expected to