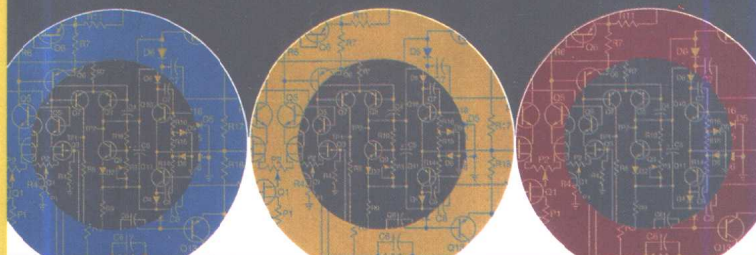


英文版

《通信与信息科学教育丛书》

T H I R D E D I T I O N

RF CIRCUIT DESIGN



射频电路设计 (第3版)

[美] JOSEPH J. CARR 著

SECRETS OF RF CIRCUIT DESIGN THIRD EDITION



麦格劳-希尔教育出版集团



电子工业出版社

PUBLISHING HOUSE OF ELECTRONICS INDUSTRY
<http://www.phei.com.cn>

Secrets of RF Circuit Design
Third Edition

射频电路设计(第3版)

[美] Joseph J. Carr 著

麦格劳-希尔教育出版集团

电子工业出版社

Publishing House of Electronics Industry

北京·BEIJING

Joseph J. Carr

Secrets of RF Circuit Design, Third Edition

ISBN:0-07-137067-6

Copyright (c) 2001 by The McGraw-Hill Companies, Inc.

All rights reserved.

Original language published by The McGraw-Hill Companies, Inc. All rights reserved. No part of this publication may be reproduced or distributed in any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

Authorized English language reprint edition jointly published by McGraw-Hill Education (Asia) Co. And Publishing House of Electronics Industry.

This edition is authorized for sale in the People's Republic of China only, excluding Hong Kong, Macao SAR and Taiwan. Unauthorized export of this edition is a violation of the Copyright Act. Violation of this Law is subject to Civil and Criminal Penalties.

本书英文影印版由电子工业出版社和美国麦格劳-希尔教育出版(亚洲)公司合作出版。此版本仅限在中华人民共和国境内(不包括香港、澳门特别行政区和台湾地区)销售。未经许可之出口,视为违反著作权法,将受法律制裁。未经出版者预先书面许可,不得以任何方式复制或抄袭本书的任何部分。

图书在版编目(CIP)数据

射频电路设计:第3版/(美)卡尔(Carr,J.J.)著.-北京:电子工业出版社,2001.10
(通信与信息科学教育丛书)

书名原文:Secrets of RF Circuit Design

ISBN 7-5053-7045-6

I. 射… II. 卡… III. 射频电路-电路设计-英文 IV. TN710.02

中国版本图书馆 CIP 数据核字(2001)第 068714 号

原书名:Secrets of RF Circuit Design, Third Edition

书名:射频电路设计(第3版)

著者:[美]Joseph J. Carr

责任编辑:段颖

排版制作:电子工业出版社计算机排版室

印刷者:

装订者:北京李史山胶印厂

出版发行:电子工业出版社 <http://www.phei.com.cn>

北京市海淀区万寿路173信箱 邮编 100036

经销:各地新华书店

开本:850×1168 1/32 印张:17.25

版次:2001年10月第3版 2001年10月第1次印刷

书号:ISBN 7-5053-7045-6

TN·1473

印数:4000册 定价:38.00元

版权贸易合同登记号 图字:01-2001-3311

凡购买电子工业出版社的图书,如有缺页、倒页、脱页、所附磁盘或光盘有问题者,请向购买书店调换;若书店售缺,请与本社发行部联系调换。电话 68279077

出版说明

近年来,通信与信息科技发展之快和应用之广,大大超出了人们的预料和专家的预测。从国民经济到社会生活的日益信息化,标志着通信与信息科技的空前发展。

为了满足高等院校师生教改和教学的需求以及广大技术人员学习通信与信息新技术的需要,电子工业出版社约请北京地区的清华大学、北京大学、北京航空航天大学、北京邮电大学、北方交通大学,南京地区的东南大学、解放军通信工程学院、南京邮电学院,上海地区的上海交通大学、成都地区的西南交通大学、电子科技大学,西安地区的西安电子科技大学、西安交通大学,天津地区的南开大学,深圳地区的深圳大学,东北地区的哈尔滨工业大学等全国知名高等院校教学第一线上的教授和信息产业部有关科研院所的专家,请他们推荐和反复论证,从国外优秀的英文版教材中精选出版了这套《通信与信息科学教育丛书》(英文版)。

本套丛书可作为高等院校通信、计算机、电子信息等专业的高年级本科生、研究生的教材或教学参考书,也适合广大信息产业技术人员参考。

本套丛书所选取的均是国际上通信与信息科学领域具有代表性的经典名著,它们在全世界许多大学被用做教材或教学参考书。其主要特点是具有较强的先进性、实用性和权威性。丛书内容丰富,深入浅出,层次清楚,理论与应用并重,能够较好地引导读者将现代通信与信息科学的原理、技术与应用有机结合。我们希望本套丛书能够进一步推动国内高等院校教学与国际接轨,同时满足广大技术人员及时学习通信与信息科学领域中新知识的需求。

恳请广大读者提出宝贵意见和建议,以使我们奉献更多、更好的英文原版精品图书。

电子工业出版社

2001年8月

Contents

Introduction

1 Introduction to RF electronics 1

- The electromagnetic spectrum 1
- Units and physical constants 2
- Microwave letter bands 5
- RF components, layout, and construction 7
- Coaxial cable transmission line ("coax") 14
- Warning 18

2 RF components and tuned circuits 19

- Tuned resonant circuits 19
- Vectors 19
- Inductance and inductors 21
- Capacitors and capacitance 33
- Voltage and current in capacitor circuits 40
- Tuned RF/IF transformers 51

3 Variable capacitors in RF circuits 59

- Straight-line capacitance vs straight-line capacitors 63
- Special variable capacitors 64
- Varactor applications 69
- Note and warning! 70

4 Winding your own coils 73

- Anidon Associates coil system 74
- Making your own toroid-core inductors and RF transformers 77
- Ferrite and powdered-iron rods 92
- Project 4-1 95
- References 104

ii *Contents*

5 Radio receivers: Theory and projects 105

- The tuner 106
- Tuned radio-frequency (TRF) receivers 110
- Superheterodyne receivers 112
- Receiver circuits you can build 126

6 Direct-conversion radio receivers 143

- Basic theory of operation 143
- Problems associated with DCR designs 146
- Some practical design approaches 156
- References and notes 170

7 RF amplifier and preselector circuits 171

- JFET preselector circuits 173
- MOSFET preselector circuits 176
- Noise and preselectors 179
- Broadband RF preamplifier for VLF, LF, and AM BCB 179
- Broadband RF amplifier (50- Ω input and output) 187
- Broadband or tuned RF/IF amplifier using the MC-1350P 188
- VLF preamplifier 189
- Conclusion 192

8 Building IF amplifiers 193

- Amplifier circuits 193
- Cascode pair amplifier 195
- "Universal" IF amplifier 196
- Coupling to other filters 200
- IC IF amplifiers 200
- IF processing ICs 203
- Successive detection logarithmic amplifiers 203
- Filter switching in IF amplifiers 205
- References 206

9 Interpreting radio receiver specifications 207

- A hypothetical radio receiver 207
- Units of measure 211
- Dynamic performance 230
- Dynamic range 235
- Receiver improvement strategies 240
- References 241

10 Building signal-generator and oscillator circuits 243

- Types of oscillator circuits 243
- 1- to 20-MHz crystal oscillator 245
- HF/VHF buffer amplifier 247

- 455-kHz AM IF-amplifier test-and-alignment oscillator 248
- Signal generator for the AM and shortwave bands 249

11 RF directional couplers 253

- Conclusion 257
- References 257

12 The RF hybrid coupler 259

- Applications of hybrids 259
- Phase-shifted hybrids 262
- Conclusion 264

13 Building simple VLF radio receivers 267

- Receiver types 268
- Tuning circuit problems 270
- A VLF receiver project 276
- References and notes 284

14 What's that mess coming from my receiver? 285

- Radio station interference 285
- Other interference 289

15 Filtering circuits against EMI 293

- Means of EMI transmission 293
- Electronic noise 295
- Counters to EMI 296
- Common mode and differential currents 298
- AC power line filtering 302
- Special medical EMI problems 302
- Computer EMI 303
- Conclusion 304

16 Measuring inductors and capacitors at RF frequencies 305

- VSWR method 305
- Voltage divider method 307
- Signal generator method 309
- Frequency-shifted oscillator method 309
- Using RF bridges 310
- Finding parasitic capacitances and inductances 315
- Conclusion 317

17 Building and using the RF noise bridge 319

- Adjusting antennas 321
- Resonant frequency 322
- Capacitance and inductance measurements 324

18 Vectors for RF circuits 327

19 Impedance matching: Methods and circuits 331

- Impedance matching approaches 332
- L-section network 332
- Pi- (π) networks 334
- Split-capacitor network 335
- Transmatch circuit 335
- Coaxial cable balun transformers 338
- Matching stubs 338
- Quarter-wavelength matching sections 339
- Series-matching section 340

20 Using the double-balanced mixer (DBM) 343

- Diplexer circuits 344
- JFET and MOSFET doubly balanced mixer circuits 347
- Doubly balanced diode mixer circuits 350
- Bipolar transconductance cell DBMs 355
- Preamplifiers and postamplifiers 359
- Conclusion 363
- References 363

21 PIN diodes and their uses 365

- PIN diode switch circuits 366
- PIN diode applications 369
- Conclusion 373

**22 UHF and microwave diodes, transistors,
and integrated circuits 375**

- Diode devices 375
- Introduction to negative resistance ($-R$) devices 382
- UHF and microwave RF transistors 399
- Semiconductor overview 400
- Selecting transistors 413

23 LC RF filter circuits 431

- Low pass, high pass, bandpass, and notch 431
- Filter applications 432
- Filter construction 434
- Filter design approach 435
- Low-pass filters 435
- High-pass filters 437

- Bandpass filters 440
- Notch filters 443
- More on bandpass filters 447
- Conclusion 447

24 Time-domain reflectometry on a budget 449

- The basis of TDR 449
- The pulse source 450
- Test set-up 451
- Some actual measurements 451

25 Solving frequency drift problems 455

- Frequency shift problems 455
- Drift problems 457
- VHF problems 458
- Problems with older equipment 462
- Heat problems 462
- Equipment modifications 462

26 The Smith chart 463

- Smith chart components 463
- Smith chart applications 475

27 Detector and demodulator circuits 487

- AM envelope detectors 487
- Noise 494
- Balanced demodulators 494
- Synchronous AM demodulation 495
- Double-sideband (DSBSC) and single-sideband (SSBSC) suppressed carrier demodulators 495
- FM and PM demodulator circuits 502
- Discriminator circuits 503
- Ratio detector circuits 504
- Pulse-counting detectors 506
- Phase locked loop FM/PM detectors 507
- Quadrature detector 508

Index 511

About the author 534

1

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.

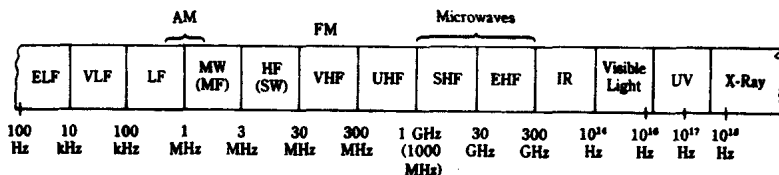
Another problem with RF circuits is that the signals find it easier to radiate both from the circuit and within the circuit. Thus, coupling effects between elements of the circuit, between the circuit and its environment, and from the environment to the circuit become a lot more critical at RF. Interference 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.

2 Introduction to RF electronics

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 de-

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

4 Introduction to RF electronics

Table 1-3. Physical constants

Constant	Value	Symbol
Boltzmann's constant	$1.38 \times 10^{-23} \text{ J/K}$	K
Electric chart (e^-)	$1.6 \times 10^{-19} \text{ C}$	q
Electron (volt)	$1.6 \times 10^{-19} \text{ J}$	eV
Electron (mass)	$9.12 \times 10^{-31} \text{ kg}$	m
Permeability of free space	$4\pi \times 10^{-7} \text{ H/m}$	μ_0
Permittivity of free space	$8.85 \times 10^{-12} \text{ F/m}$	ϵ_0
Planck's constant	$6.626 \times 10^{-34} \text{ J-s}$	h
Velocity of electromagnetic waves	$3 \times 10^8 \text{ m/s}$	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 = $2.54 \times 10^{-5} \text{ m}$
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:

$$\lambda F \sqrt{\epsilon} = c, \quad (1-1)$$

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 prop-

agation 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):

$$\lambda = \frac{c}{F \sqrt{\epsilon}} \quad (1-2)$$

and

$$F = \frac{c}{\lambda \sqrt{\epsilon}} \quad (1-3)$$

[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

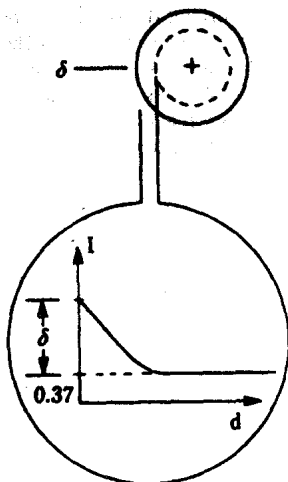
Table 1-6. New U.S. military microwave frequency bands (Post-1970)

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.

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

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- μ H 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