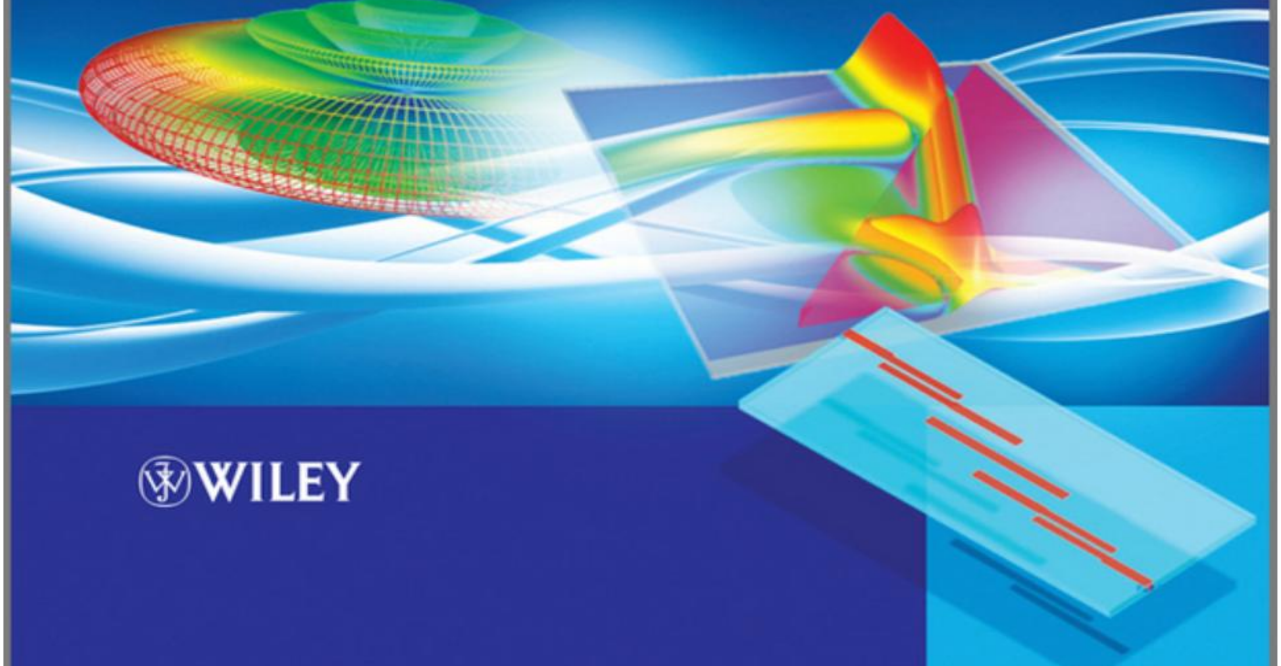
FRANK GUSTRAU

RF AND MICROWAVE ENGINEERING

FUNDAMENTALS OF WIRELESS COMMUNICATIONS



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FUNDAMENTALS OF WIRELESS COMMUNICATIONS

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For Sabine, Lisa & Benni

Preface

This textbook aims to provide students with a fundamental and practical understanding of the basic principles of radio frequency and microwave engineering as well as with physical aspects of wireless communications.

In recent years, wireless technology has become increasingly common, especially in the fields of communication (e.g. data networks, mobile telephony), identification (RFID), navigation (GPS) and detection (radar). Ever since, radio applications have been using comparatively high carrier frequencies, which enable better use of the electromagnetic spectrum and allow the design of much more efficient antennas. Based on low-cost manufacturing processes and modern computer aided design tools, new areas of application will enable the use of higher bandwidths in the future.

If we look at circuit technology today, we can see that high-speed digital circuits with their high data rates reach the radio frequency range. Consequently, digital circuit designers face new design challenges: transmission lines need a more refined treatment, parasitic coupling between adjacent components becomes more apparent, resonant structures show unintentional electromagnetic radiation and distributed structures may offer advantages over classical lumped elements. Digital technology will therefore move closer to RF concepts like transmission line theory and electromagnetic field-based design approaches.

Today we can see the use of various radio applications and high-data-rate communication systems in many technical products, for example, those from the automotive sector, which once was solely associated with mechanical engineering. Therefore, the basic principles of radio frequency technology today are no longer just another side discipline, but provide the foundations to various fields of engineering such as electrical engineering, information and communications technology as well as adjoining mechatronics and automotive engineering.

The field of radio frequency and microwave covers a wide range of topics. This full range is, of course, beyond the scope of this textbook that focuses on the fundamentals of the subject. A distinctive feature of high frequency technology compared to classical electrical engineering is the fact that dimensions of structures are no longer small compared to the wavelength. The resulting wave propagation processes then lead to typical high frequency phenomena: reflection, resonance and radiation. Hence, the centre point of attention of this book is wave propagation, its representation, its effects and its utilization in passive circuits and antenna structures.

What I have excluded from this book are active electronic components—like transistors—and the whole spectrum of high frequency electronics, such as the design of amplifiers, mixers and oscillators. In order to deal with this in detail, the basics of electronic circuit design theory and semiconductor physics would be required. Those topics are beyond the scope of this book.

If we look at conceptualizing RF components and antennas today, we can clearly see that software tools for Electronic Design Automation (EDA) have become an essential part of the whole process. Therefore, various design examples have been incorporated with the use of both circuit simulators and electromagnetic (EM) simulation software. The following programs have been applied:

- ADS (Advanced Design System) from Agilent Technologies;
- Empire from IMST GmbH;
- EMPro from Agilent Technologies.

As the market of such software products is ever changing, the readers are highly recommended to start their own research and find the product that best fits their needs.

At the end of each chapter, problems are given in order to deepen the reader's understanding of the chapter material and practice the new competences. Solutions to the problems are being published and updated by the author on the following Internet address:

http://www.fh-dortmund.de/gustrau_rf_textbook

Finally, and with great pleasure, I would like to say thank you to my colleagues and students who have made helpful suggestions to this book by proofreading passages or initiating invaluable discussions during the course of my lectures. Last but not the least I express gratitude to my family for continuously supporting me all the way from the beginning to the completion of this book.

Frank Gustrau
Dortmund, Germany

List of Abbreviations

3GPP	Third Generation Partnership Project
Al_2O_3	Alumina
Balun	Balanced-Unbalanced
CAD	Computer Aided Design
DC	Direct Current
DFT	Discrete Fourier Transform
DUT	Device Under Test
EM	ElectroMagnetic
EMC	ElectroMagnetic Compatibility
ESR	Equivalent Series Resistance
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
FR4	Glass reinforced epoxy laminate
GaAs	Gallium arsenide
GPS	Global Positioning System
GSM	Global System for Mobile Communication
GTD	Geometrical Theory of Diffraction
GUI	Graphical User Interface
HPBW	Half Power Beam Width
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IFA	Inverted-F Antenna
ISM	Industrial, Scientific, Medical
ITU	International Communications Union
LHCP	Left-Hand Circular Polarization
LHEP	Left-Hand Elliptical Polarization
LNA	Low-Noise Amplifier
LOS	Line of Sight
LTE	Long Term Evolution
LTI	Linear Time-Invariant
MIMO	Multiple-Input Multiple-Output
MMIC	Monolithic Microwave Integrated Circuits
MoM	Method Of Moments
NA	Network Analyser
NLOS	Non Line of Sight
PA	Power Amplifier
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
PML	Perfectly Matched Layer

PTFE	Polytetraflouroethylene
Radar	Radio Detection and Ranging
RCS	Radar Cross-Section
RF	Radio Frequency
RFID	Radio Frequency Identification
RHCP	Right-Hand Circular Polarization
RHEP	Right-Hand Elliptical Polarization
RMS	Root Mean Square
SAR	Specific Absorption Rate
SMA	SubMiniature Type A
SMD	Surface Mounted Device
TEM	Transversal Electromagnetic
UMTS	Universal Mobile Telecommunication System
UTD	Uniform Theory of Diffraction
UWB	Ultra-WideBand
VNA	Vector Network Analyser
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless Local Area Network

List of Symbols

Latin Letters

A	Area (m^2)
A_{dB}	Attenuation (dB)
$\vec{A}$	Magnetic vector potential (Tm)
A_{eff}	Effective antenna area (m^2)
$\mathbf{A}$	ABCD matrix (matrix elements have different units)
$\vec{B}$	Magnetic flux density (magnetic induction) (T; Tesla)
B	Bandwidth (Hz; Hertz)
BW	Bandwidth (angular frequency) (1/s)
c	Velocity of a wave (m/s)
C	Capacitance (F; Farad)
$C(\varphi, \vartheta)$	Radiation pattern function (dimensionless)
C'	Capacitance per unit length (F/m)
D	Directivity (dimensionless)
$\vec{D}$	Electric flux density (C/m^2)
$\vec{E}$	Electric field strength (V/m)
f	Frequency (Hz)
f_c	Cut-off frequency (Hz)
$\vec{F}$	Force (N; Newton)
$\vec{F}_C$	Coulomb Force (N)
$\vec{F}_L$	Lorentz Force (N)
G	Conductance ($1/\Omega = S$)
G	Gain (dimensionless)
G	Green's function (1/m)
G'	Conductance per unit length (S/m)
$\vec{H}$	Magnetic field strength (A/m)
$\mathbf{H}$	Hybrid matrix (matrix elements have different units)
I	Current (A; Ampere)
$\mathbf{I}$	Identity matrix (dimensionless)
j	Imaginary unit (dimensionless)
$\vec{J}$	Electric current density (A/m^2)
$\vec{J}_S$	Surface current density (A/m)
k	Coupling coefficient (dimensionless)

k	Wavenumber (1/m)
k_c	Cut-off wavenumber (1/m)
$\vec{k}$	Wave vector (1/m)
ℓ, L	Length (m)
L	Inductance (H; Henry)
L	Pathloss (dimensionless)
L'	Inductance per unit length (H/m)
p	Power density (W/m^3)
P	Power (W; Watt)
P_antenna	Accepted power (W)
P_inc	Incoming power (W)
P_rad	Radiated power (W)
Q	Charge (C; Coulomb)
Q	Quality factor (dimensionless)
r	Radial coordinate (m)
R	Resistance (Ω)
R_DC	Resistance for steady currents (Ω)
R_ESR	Equivalent series resistance (Ω)
R_RF	Resistance for radio frequencies (Ω)
R_rad	Radiation resistance (Ω)
R'	Resistance per unit length (Ω/m)
s_{kl}	Scattering parameter (dimensionless)
$\mathbf{S}$	Scattering matrix (dimensionless)
$\vec{S}$	Poynting vector (W/m^2)
$\vec{S}_\mathrm{av}$	Average value of Poynting vector (W/m^2)
t	Time (s; second)
T	Period (s)
$\tan\delta$	Loss tangent (dimensionless)
U	Voltage (V; Volt)
$\vec{v}$	Velocity (m/s)
v_gr	Group velocity (m/s)
v_ph	Phase velocity (m/s)
V	Volume (m^3)
w_e	Electric energy density (J/m^3)
W_e	Electric energy (J; Joule)
w_m	Magnetic energy density (J/m^3)
W_m	Magnetic energy (J)
x, y, z	Cartesian coordinates (m)

Y	Admittance (S; Siemens)
$\mathbf{Y}$	Admittance matrix (S)
Z_A	Load impedance (Ω)
Z_F	Characteristic wave impedance (Ω)
Z_F0	Characteristic impedance of free space (Ω)
Z_in	Input impedance (Ω)
Z_0	Characteristic line impedance (Ω)
	Port reference impedance (Ω)
$Z_\mathrm{0,cm}$	Common mode line impedance (Ω)
$Z_\mathrm{0,diff}$	Differential mode line impedance (Ω)
Z_0e	Even mode line impedance (Ω)
Z_0o	Odd mode line impedance (Ω)
$\mathbf{Z}$	Impedance matrix (Ω)

Greek Letters

α	Attenuation coefficient (1/m)
β	Phase constant (1/m)
δ	Skin depth (m)
Δ	Laplace operator (1/m^2)
$\varepsilon = \varepsilon_0\varepsilon_\mathrm{r}$	Permittivity (As/(Vm))
ε_r	Relative permittivity (dimensionless)
$\varepsilon_\mathrm{r,eff}$	Effective relative permittivity (dimensionless)
η	Radiation efficiency (dimensionless)
η_total	Total radiation efficiency (dimensionless)
γ	Propagation constant (1/m)
λ	Wavelength (m)
λ_W	Wavelength inside waveguide (m)
$\mu = \mu_0\mu_\mathrm{r}$	Permeability (Vs/(Am))
μ_r	Relative permeability (dimensionless)
∇	Nabla operator (1/m)
φ	Phase angle (rad)
φ	Azimuth angle (rad)
ϕ	Scalar electric potential (V)
φ_0	Initial phase (rad)
Ψ_e	Electric flux (C)
Ψ_m	Magnetic flux (Wb, Weber) (Vs)
ρ	Volume charge density (C/m^3)
ρ_S	Surface charge density (C/m^2)

σ	Conductivity (S/m; Siemens/m)
σ	Radar cross-section (m^2)
ϑ	Elevation angle (rad)
ϑ_{iB}	Brewster angle (rad)
ϑ_{ic}	Critical angle (rad)
ω	Angular frequency (1/s)

Physical Constants

μ_0	$4\pi \cdot 10^{-7}$ Vs/(Am)	Permeability of free space
ε_0	$8.854 \cdot 10^{-12}$ As/(Vm)	Permittivity of free space
c_0	$2.99792458 \cdot 10^{8}$ m/s	Speed of light in vacuum
e	$1.602 \cdot 10^{-19}$ C	Elementary charge
Z_{F0}	$120\,\pi\,\Omega \approx 377\,\Omega$	Characteristic impedance of free space

Chapter 1

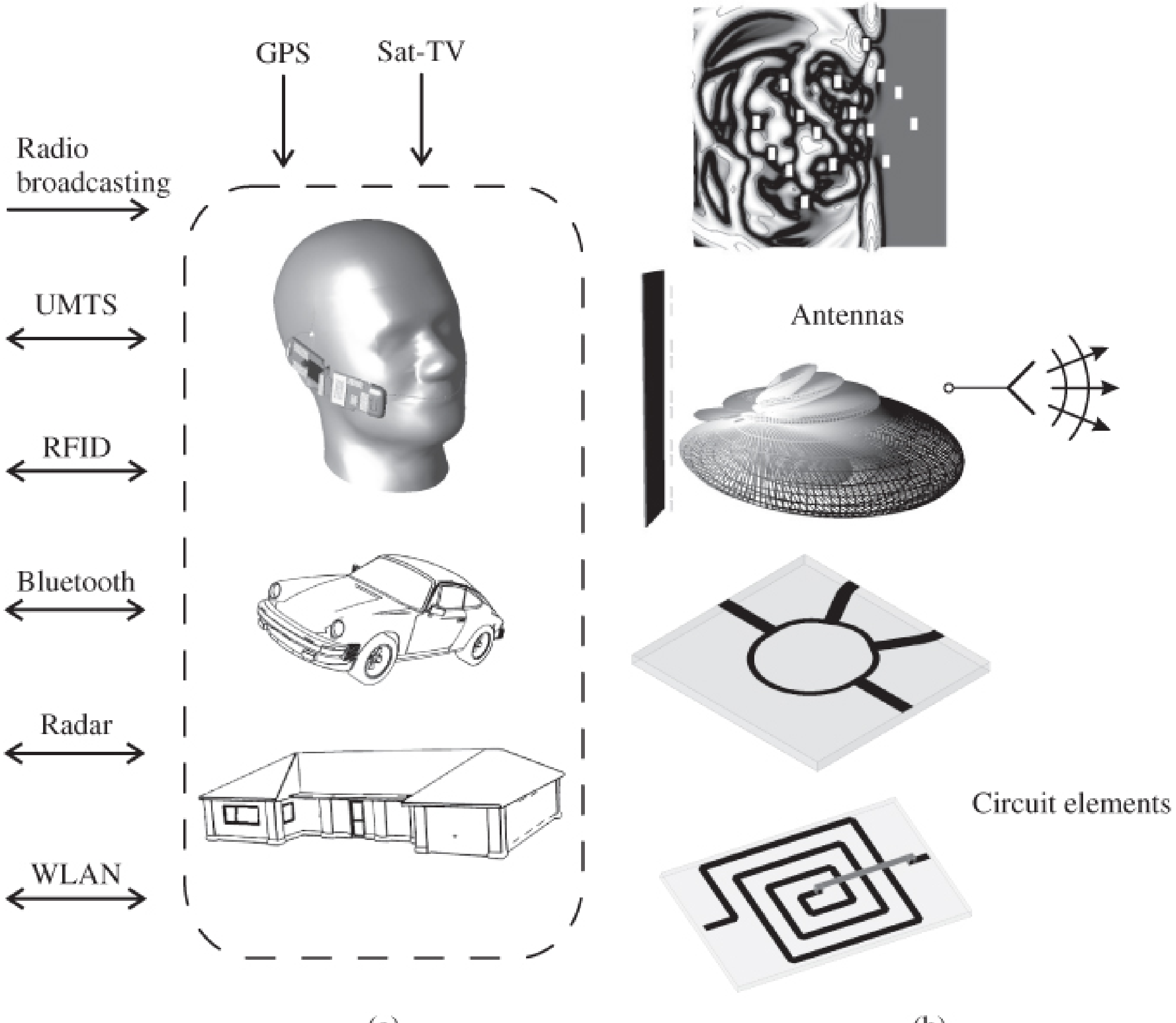
Introduction

This chapter provides a short overview on widely used microwave and RF applications and the denomination of frequency bands. We will start out with an illustrative case on wave propagation which will introduce fundamental aspects of high frequency technology. Then we will give an overview of the content of the following chapters to facilitate easy orientation and quick navigation to selected issues.

1.1 Radiofrequency and Microwave Applications

Today, at home or on the move, every one of us uses devices that employ wireless technology to an increasing extent. Figure 1.1 shows a selection of wireless communication, navigation, identification and detection applications.

Figure 1.1 (a) Examples of wireless applications (b) RF components and propagation of electromagnetic waves.



(a) (b)

In the future we will see a growing progression of the trend of applying components and systems of high frequency technology to new areas of application. The development and maintenance of such systems requires an extensive knowledge of the high frequency behaviour of basic elements (e.g. resistors, capacitors, inductors, transmission lines, transistors), components (e.g. antennas), circuits (e.g. filters, amplifiers, mixers) including physical issues such as electromagnetic wave propagation.

High frequency technology has always been of major importance in the field of radio applications, recently though RF design methods have started to develop as a crucial factor with rapid digital circuits. Due to the increasing processing speed of digital circuits, high frequency signals occur which, in turn, create demand for RF design methods.

In addition, the high frequency technology's proximity to electromagnetic field theory overlaps with aspects of electromagnetic compatibility (EMC). Setups for conducted and radiated measurements, which are used in this context, are based on principles of high frequency technology. If devices do not comply with EMC limits in general a careful analysis of the circumstances will be required to achieve improvements. Often, high frequency issues play a major role here.

Table 1.1 shows a number of standard RF and microwave applications and their associated frequency bands [1–3]. The applications include terrestrial voice and data communication, that is cellular networks and wireless communication networks, as well as terrestrial and satellite based broadcasting systems. Wireless identification systems (RFID) within ISM bands enjoy increasing popularity among cargo traffic and logistics businesses. As for the field of navigation, GPS should be highlighted, which is already installed in numerous vehicles and mobile devices. Also in the automotive sector, radar systems are used to monitor the surrounding aresa or serve as sensors for driver assistance systems.

Table 1.1 Wireless applications and frequency ranges

Cellular mobile telephony		
GSM 900	Global System for Mobile Communication	880 … 960 MHz
GSM 1800	Global System for Mobile Communication	1.71 … 1.88 GHz
UMTS	Universal Mobile Telecommunications System	1.92 … 2.17 GHz
Tetra	Trunked radio	440 … 470 MHz
Wireless networks		
WLAN	Wireless local area network	2.45 GHz, 5 GHz
Bluetooth	Short range radio	2.45 GHz
Navigation		
GPS	Global Positioning System	1.2 GHz, 1.575 GHz

Identification		
RFID	Radio-Frequency Identification	13.56 MHz, 868 MHz, 2.45 GHz, 5 GHz
Radio broadcasting		
FM	Analog broadcast transmitter network	87.5 … 108 MHz
DAB	Digital Audio Broadcasting	223 … 230 MHz
DVB-T	Digital Video Broadcasting - Terrestrial	470 … 790 MHz
DVB-S	Digital Video Broadcasting - Satellite	10.7 … 12.75 GHz
Radar applications		
SRR	Automotive short range radar	24 GHz
ACC	Adaptive cruise control radar	77 GHz

1.2 Frequency Bands

For better orientation, the electromagnetic spectrum is divided into a number of frequency bands. Various naming conventions have been established in different parts of the world, which often are used in parallel. Table 1.2 shows a customary classification of the frequency range from 3 Hz to 300 GHz into eight frequency decades according to the recommendation of the *International Telecommunications Union* (ITU) [4].

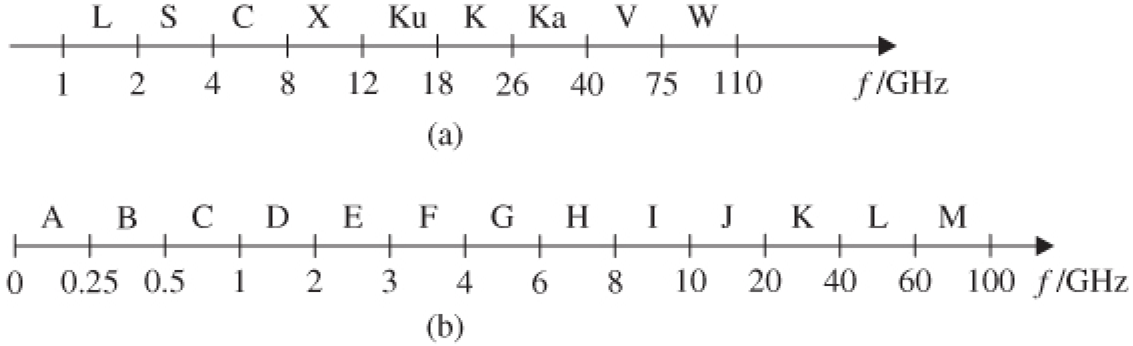
Table 1.2 Frequency denomination according to ITU

Frequency range	Denomination
3 … 30 kHz	VLF - Very Low Frequency
30 … 300 kHz	LF - Low Frequency
300 kHz … 3 MHz	MF - Medium Frequency
3 … 30 MHz	HF - High Frequency
30 … 300 MHz	VHF - Very High Frequency
300 MHz … 3 GHz	UHF - Ultra High Frequency
3 … 30 GHz	SHF - Super High Frequency
30 … 300 GHz	EHF - Extremely High Frequency

Figure 1.2a shows a commonly used designation of different frequency bands according to IEEE-standards [5]. The unsystematic use of characters and band ranges, which has developed over the years, can be regarded as a clear

disadvantage. A more recent naming convention according to NATO is shown by Figure 1.2b [6, 7]. Here, the mapping of characters to frequency bands is much more systematic. However, the band names are not common in practical application yet.

Figure 1.2 Denomination of frequency bands according to different standards. (a) Denomination of frequency bands according to IEEE Std. 521–2002 (b) Denomination of frequency bands according to NATO.



A number of legal foundations and regulative measures ensure fault-free operation of radio applications. Frequency, as a scarce resource, is being divided and carefully administered [8, 9]. Determined frequency bands are allocated to *industrial, scientific and medical* (ISM) applications. These frequency bands are known as ISM bands and are shown in Table 1.3. As an example, the frequency range at 2.45 GHz is for the operation of microwave ovens and WLAN systems. A further frequency band reserved for wireless non-public short-range data transmission (in Europe) uses the 863 to 870 MHz frequency band [10], for example for RFID applications.

Table 1.3 ISM frequency bands

13.553 … 13.567 MHz	26.957 … 27.283 MHz
40.66 … 40.70 MHz	433.05 … 434.79 MHz
2.4 … 2.5 GHz	5.725 … 5.875 GHz
24 … 24.25 GHz	61 … 61.5 GHz
122 … 123 GHz	244 … 246 GHz

1.3 Physical Phenomena in the High Frequency Domain

We will now take a deeper look at RF engineering through two examples that introduce wave propagation on transmission lines and electromagnetic radiation from antennas.

1.3.1 Electrically Short Transmission Line

As a *first example* we consider a simple circuit (Figure 1.3a) with a sinusoidal (monofrequent) voltage source (internal resistance R_I), which is connected to a load resistor $R_\text{A} = R_\text{I}$ by an *electrically short* transmission line. *Electrically short* means that the transmission length ℓ of the line is much shorter than the wavelength λ, that is $\ell \ll \lambda$. In vacuum–or approximately air–electromagnetic waves propagate with the speed of light c_0.

1.1 $$c_0 = 299\,792\,458\frac{\text{m}}{\text{s}} \approx 3\cdot 10^8\ \frac{\text{m}}{\text{s}} \qquad \text{(Speed of light in vacuum)}$$

Therefore, the free space wavelength λ_0 for a frequency f yields:

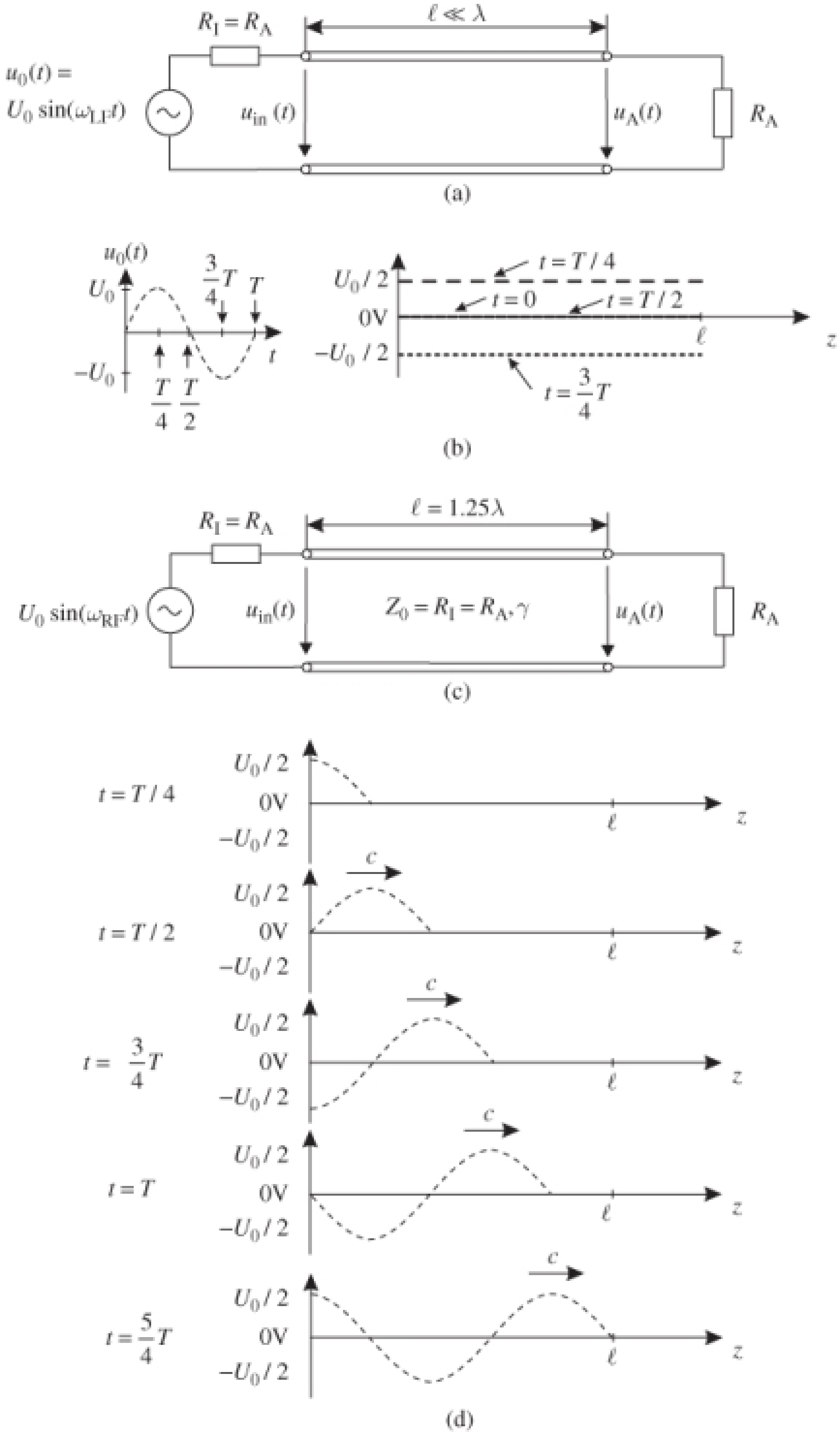
1.2 $$\lambda_0 = \frac{c_0}{f} \gg \ell$$

In media other than vacuum the speed of light c is lower and given by

1.3 $$c = \frac{c_0}{\sqrt{\varepsilon_\text{r}\mu_\text{r}}} \qquad \text{(Speed of light in media)}$$

where ε_r is the relative permittivity and μ_r is the relative permeability of the medium. Typical values for a practical coaxial line would be $\varepsilon_r = 2$ and $\mu_r = 1$, resulting in a speed of light of $c \approx 2.12 \cdot 10^8$ m/s on that line. Given–as an example–a frequency of $f = 1$ MHz we get a wavelength of $\lambda_0 = 300$ m in free space and $\lambda = 212$ m on the previously discussed line. A transmission line of $\ell = 1$ m would then be classified as electrically short ($\ell \ll \lambda$). For simplicity[1], we assume further on that the load resistance R_A equals the internal resistance R_I of the source.

Figure 1.3 Network with voltage source, transmission line and load resistor. Transmission line is *electrically short* in (a), (b) and *electrically long* in (c), (d).



Alternatively, *electrically short* can be expressed by the propagation time τ a signal needs to pass through the entire transmission line. Assuming that electromagnetic processes spread with the speed of light *c*, the transmission of a signal from the start through to the end of a line requires a time span τ

1.4 $$\tau = \frac{\text{distance}}{\text{velocity}} = \frac{\ell}{c} \ll T = \frac{1}{f} \qquad \leftrightarrow \qquad \lambda = \frac{c}{f} \gg \ell$$

If the time span τ needed for a signal to travel through the whole line is substantially smaller than the cycle time *T* of its sinusoidal signal, it seems as if the signal change appears *simultaneously* along the whole line. Signal delay is thus surely negligible.

> A transmission line is defined as being *electrically short*, if its length ℓ is substantially shorter than the wavelength λ of the signal's operating frequency ($\ell \ll \lambda$) or–in other words–if the duration of a signal travelling from the start to the end of a line τ (delay time) is substantially shorter than its cycle time *T* ($\tau \ll T$).

Let us have a look at Figure 1.3b where the current changes *slowly* in a sinus-like pattern. The term *slowly* refers to the period *T* that we assume to be much greater than the propagation time τ along the line. The sine wave starts at $t = 0$ with a value of zero and reaches its peak after a quarter of the time period ($t = T/4$). Again after half the time period ($t = T/2$) it passes through zero and reaches a negative peak at $t = 3T/4$. This sequence repeats periodically. Since signal delay τ can be omitted compared to the time period *T*, the signal along the line appears to be *spatially constant*. According to the voltage divider rule the voltage along the line equals just half of the value of the voltage source $u_0(t)$. The input voltage $u_{\text{in}}(t)$ and the output (load) voltage $u_A(t)$ are–at least approximately–equal.

1.5 $$u_{\text{in}}(t) \approx u_{\text{A}}(t)$$

1.3.2 Transmission Line with Length Greater than One-Tenth of Wavelength

In the next step, we significantly increase the frequency *f*, so that the line is no longer electrically short. We choose the value of the frequency, such that the line length will equal $\ell = 5/4 \cdot \lambda = 1.25\lambda$ (Figure 1.3c). Now signal delay τ compared to period duration *T* must be taken into consideration. In Figure 1.3d we can see how far the wave has travelled at times of $t = T/4$, $t = T/2$ and so forth. The voltage distribution is no longer spatially constant. After $t = 5/4\,T$ the signal reaches the end of the line.

> If the transmission line is not electrically short, the voltage along the line will not show a constant course any longer. On the contrary, a sinusoidal course illustrates the wave-nature of this electromagnetic phenomenon.

Also we can see that the electric voltage $u_A(t)$ at the line termination is no longer equal to that at the line input voltage $u_{in}(t)$. A *phase difference* exists between those two points.

> In order to fully characterize the transmission line effects, a transmission line must be described by two *additional parameters* along with its length: (a) the *characteristic impedance* Z_0 and (b) the *propagation constant* γ. Both must be taken into account when designing RF circuits.

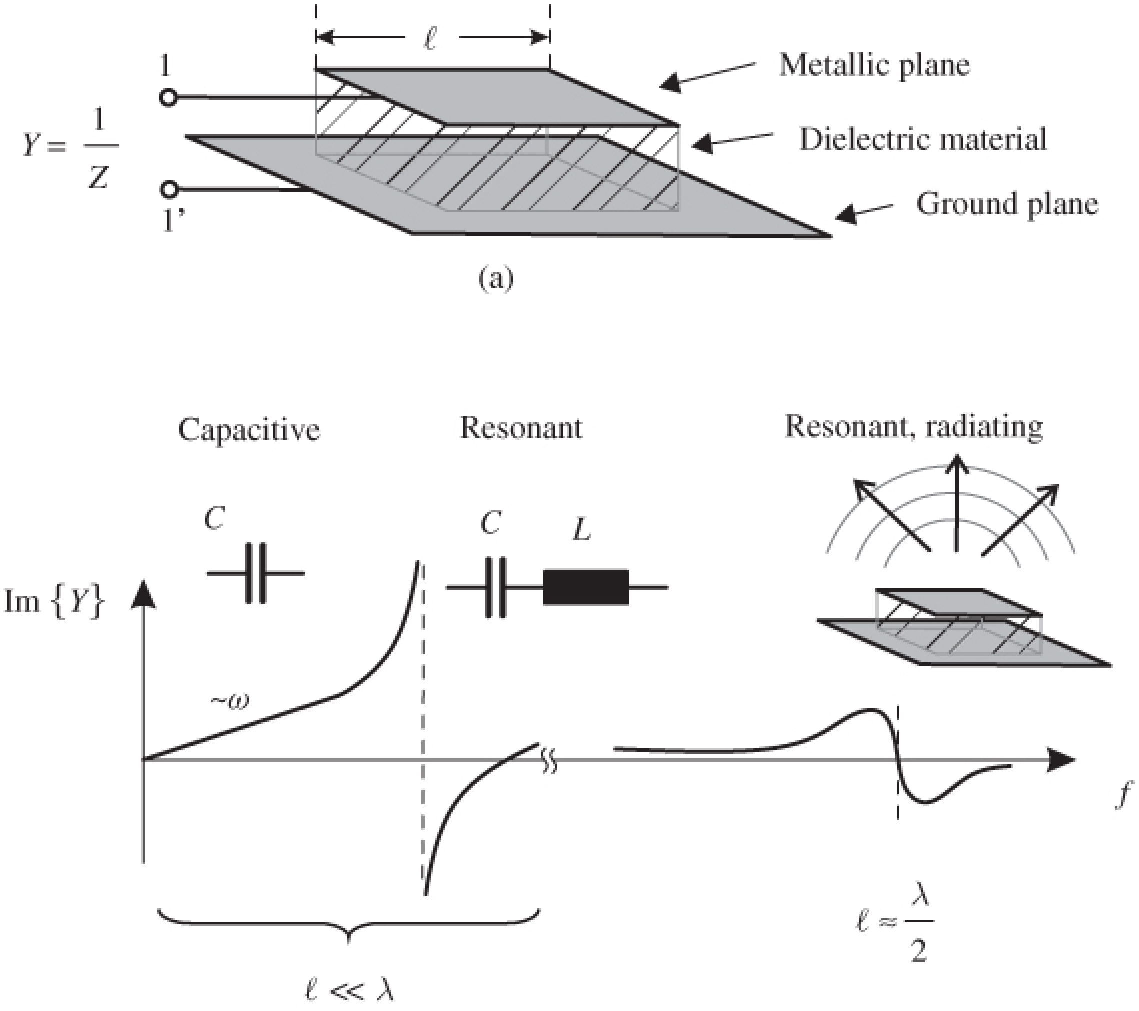
In our example we used a characteristic line impedance Z_0 equal to the load and source resistance ($Z_0 = R_A = R_I$). This is the most simple case and is often applied when using transmission lines. However, if the characteristic line impedance Z_0 and terminating resistor R_A are not equal to each other, the wave will be reflected at the end of the line. Relationships resulting from these effects will be looked at in

Chapter 3 which deals in detail with *transmission line theory*.

1.3.3 Radiation and Antennas

Now let us take a look at a *second example*. Here we have a geometrically simple structure (Figure 1.4a), which consists of a rectangular metallic patch with side length ℓ arranged above a continuous metallic ground plane. Insulation material (dielectric material) is located between both metallic surfaces. Two terminals are connected to feed the structure.

Figure 1.4 Electrical characteristic of a geometrical simple structure: (a) geometry and (b) imaginary part of admittance.



(a)

(b)

The geometric structure resembles that of a parallel plate capacitor, which has a homogeneous electrical field set up between the metal surfaces. Therefore, we see *capacitive behaviour* ((Figure 1.4b) Admittance $Y = j\omega C$) at *low frequency* values (geometrical dimensions are significantly below wavelength ($\ell \ll \lambda$)). By further increasing the frequency, we can observe *resonant behaviour* due to the unavoidable inductance of feed lines.

At high frequency levels a completely new phenomenon can be observed: with the structure's side length approaching half of a wavelength ($\ell \approx \lambda/2$), electromagnetic energy will be radiated into space. Now the structure can be used as an antenna (*patch antenna*).