Transmission Lines and Antennas, 2012-3
Exercises on physical transmission lines and waveguides

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1 Wave propagation below cutoff

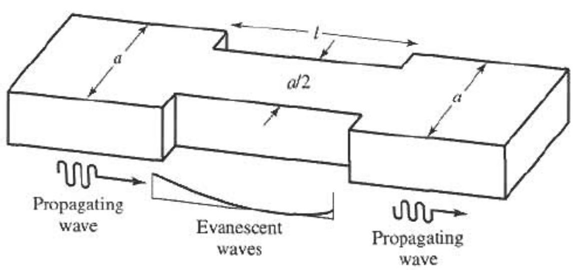
Consider propagation inside a waveguide in a non-TEM mode below cutoff. Compute the normalized cutoff k_c/k such that a wave suffers an attenuation of 30dB per meter in such a waveguide as it propagates.

2 Pozar, 3.4

Compute the TE_{10} mode attenuation, in dB/m, for a K-band rectangular waveguide operating at f=20 GHz (see physical characteristics in the appencices below). The waveguide is made from brass, and is filled with a dielectric material having $\epsilon_r = 2.2$ and $\tan\delta = 0.002$.

3 Pozar, 3.5

An attenuator can be made using a section of waveguide operating below cutoff, as shown below. If $a = 2.286cm$ and the operating frequency is 12 GHz, determine the required length of the below-cutoff section of waveguide to achieve an attenuation of 100 dB between the input and output guides. Ignore the effect of reflections at the step discontinuities.



4 Pozar, 3.6

Using the fact hat $\mathbf{J} = \hat{n} \times \mathbf{H}$, find expressions for the electric surface current density on the walls of a rectangular waveguide for a TE_{10} mode. Why can a narrow slot be cut along the centerline of the broad wall of a rectangular waveguide without perturbing the operation of the guide? (Such a slot is often used in a slotted line for a probe to sample the standing wave field inside the guide.)

5 Pozar example 2.7, exercises 2.28 & 3.28

This exercise deals with a circular coaxial line with radii a and b (internal and external respectively) operating in the TEM mode.

1. Show that attenuation constant due to finite conductivity is given by:
   $\alpha_c = \frac{R_s}{2\eta \ln(b/a)} \left(\frac{1}{a} + \frac{1}{b}\right)$
2. Compute the ratio of the radii that minimizes the above constant and compute the corresponding transmission line impedance for air filling.

3. Considering the fundamental (TEM) mode, show that the maximum power that can be handled by the guide, if the electric field intensity can be at most E_d to avoid dielectric breakdown of the filling material, is:

   $P_{max} = \frac{\pi a^2 E_d^2}{\eta} \ln \frac{b}{a}$

4. Compute the ratio of the radii that maximizes the power handling capability and the corresponding transmission line impedance for air filling.

6 Pozar 3.20

Design a microstrip transmission line for a 100Ω characteristic impedance.The substrate thickness is 0.158 cm, with $\epsilon_r = 2.20$. What is the guided wavelength on this transmission line if the frequency is 4.0 GHz?

7 Pozar 3.21

A 100Ω microstrip line is printed on a substrate of thickness 0.0762cm, with a dielectric constant of 2.2. Ignoring losses and fringing fields, find the shortest length of this line that appears at its input as a capacitor of 5 pF at 2.5 GHz. Repeat for an inductance of 5 nH. Using a microwave CAD package with a physical model for the microstrip line, compute the actual input impedance seen when losses are included (assume copper conductors and $\tan\delta = 0.001$).

8 Pozar 3.22

A microwave antenna feed network operating at 5 GHz requires a 50Ω printed transmission line that is 16λ long. Possible choices are (1) copper microstrip, with d=0.16cm, $\epsilon_r = 2.20$ and $\tan\delta = 0.001$, or (2) copper stripline, with b=0.32 cm, ϵ_r =2.2O, t=0.01 mm, and $\tan\delta$=0.001. Which line should be used, if attenuation is to be minimized?

9

For a WR-284 standard rectangular waveguide, compute the extreme values of the conduction attenuation constant in the “recommended” band of operation when it is made of Aluminum (see Appendices).

Appendices

APPENDIX A PREFIXES

Multiplying Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f

APPENDIX B VECTOR ANALYSIS

Coordinate Transformations

Rectangular to cylindrical:

	$\hat{x}$	$\hat{y}$	$\hat{z}$
$\hat{\rho}$	$\cos\phi$	$\sin\phi$	0
$\hat{\phi}$	$-\sin\phi$	$\cos\phi$	0
$\hat{z}$	0	0	1

Rectangular to spherical:

	$\hat{x}$	$\hat{y}$	$\hat{z}$
$\hat{r}$	$\sin\theta\cos\phi$	$\sin\theta\sin\phi$	$\cos\theta$
$\hat{\theta}$	$\cos\theta\cos\phi$	$\cos\theta\sin\phi$	$-\sin\theta$
$\hat{\phi}$	$-\sin\phi$	$\cos\phi$	0

Cylindrical to spherical:

	$\hat{\rho}$	$\hat{\phi}$	$\hat{z}$
$\hat{r}$	$\sin\theta$	0	$\cos\theta$
$\hat{\theta}$	$\cos\theta$	0	$-\sin\theta$
$\hat{\phi}$	0	1	0

These tables can be used to transform unit vectors as well as vector components; e.g.,

$$\hat{\rho} = \hat{x}\cos\phi + \hat{y}\sin\phi$$
$$A_\rho = A_x\cos\phi + A_y\sin\phi$$

Vector Differential Operators

Rectangular coordinates:

$$\nabla f = \hat{x}\frac{\partial f}{\partial x} + \hat{y}\frac{\partial f}{\partial y} + \hat{z}\frac{\partial f}{\partial z}$$
$$\nabla\cdot\bar{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$
$$\nabla\times\bar{A} = \hat{x}\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right) + \hat{y}\left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right) + \hat{z}\left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)$$
$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$$
$$\nabla^2\bar{A} = \hat{x}\nabla^2 A_x + \hat{y}\nabla^2 A_y + \hat{z}\nabla^2 A_z$$

Cylindrical coordinates:

$$\nabla f = \hat{\rho}\frac{\partial f}{\partial \rho} + \hat{\phi}\frac{1}{\rho}\frac{\partial f}{\partial \phi} + \hat{z}\frac{\partial f}{\partial z}$$
$$\nabla\cdot\bar{A} = \frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho A_\rho) + \frac{1}{\rho}\frac{\partial A_\phi}{\partial\phi} + \frac{\partial A_z}{\partial z}$$
$$\nabla\times\bar{A} = \hat{\rho}\left(\frac{1}{\rho}\frac{\partial A_z}{\partial\phi} - \frac{\partial A_\phi}{\partial z}\right) + \hat{\phi}\left(\frac{\partial A_\rho}{\partial z} - \frac{\partial A_z}{\partial\rho}\right) + \hat{z}\frac{1}{\rho}\left[\frac{\partial(\rho A_\phi)}{\partial\rho} - \frac{\partial A_\rho}{\partial\phi}\right]$$
$$\nabla^2 f = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial f}{\partial\rho}\right) + \frac{1}{\rho^2}\frac{\partial^2 f}{\partial\phi^2} + \frac{\partial^2 f}{\partial z^2}$$
$$\nabla^2\bar{A} = \nabla(\nabla\cdot\bar{A}) - \nabla\times\nabla\times\bar{A}$$

Spherical coordinates:

$$\nabla f = \hat{r}\frac{\partial f}{\partial r} + \hat{\theta}\frac{1}{r}\frac{\partial f}{\partial\theta} + \frac{\hat{\phi}}{r\sin\theta}\frac{\partial f}{\partial\phi}$$
$$\nabla\cdot\bar{A} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 A_r) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta A_\theta) + \frac{1}{r\sin\theta}\frac{\partial A_\phi}{\partial\phi}$$
$$\nabla\times\bar{A} = \frac{\hat{r}}{r\sin\theta}\left[\frac{\partial}{\partial\theta}(A_\phi\sin\theta) - \frac{\partial A_\theta}{\partial\phi}\right] + \frac{\hat{\theta}}{r}\left[\frac{1}{\sin\theta}\frac{\partial A_r}{\partial\phi} - \frac{\partial}{\partial r}(rA_\phi)\right] + \frac{\hat{\phi}}{r}\left[\frac{\partial}{\partial r}(rA_\theta) - \frac{\partial A_r}{\partial\theta}\right]$$
$$\nabla^2 f = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial f}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2}$$
$$\nabla^2\bar{A} = \nabla\nabla\cdot\bar{A} - \nabla\times\nabla\times\bar{A}$$

Vector identities:

$$\bar{A}\cdot\bar{B} = |A||B|\cos\theta, \quad \text{where } \theta \text{ is the angle between } \bar{A} \text{ and } \bar{B} \tag{B.1}$$
$$|\bar{A}\times\bar{B}| = |A||B|\sin\theta, \quad \text{where } \theta \text{ is the angle between } \bar{A} \text{ and } \bar{B}. \tag{B.2}$$
$$\bar{A}\cdot\bar{B}\times\bar{C} = \bar{A}\times\bar{B}\cdot\bar{C} = \bar{C}\times\bar{A}\cdot\bar{B} \tag{B.3}$$
$$\bar{A}\times\bar{B} = -\bar{B}\times\bar{A} \tag{B.4}$$
$$\bar{A}\times(\bar{B}\times\bar{C}) = (\bar{A}\cdot\bar{C})\bar{B} - (\bar{A}\cdot\bar{B})\bar{C} \tag{B.5}$$
$$\nabla(fg) = g\nabla f + f\nabla g \tag{B.6}$$
$$\nabla\cdot(f\bar{A}) = \bar{A}\cdot\nabla f + f\nabla\cdot\bar{A} \tag{B.7}$$
$$\nabla\cdot(\bar{A}\times\bar{B}) = (\nabla\times\bar{A})\cdot\bar{B} - (\nabla\times\bar{B})\cdot\bar{A} \tag{B.8}$$
$$\nabla\times(f\bar{A}) = (\nabla f)\times\bar{A} + f\nabla\times\bar{A} \tag{B.9}$$
$$\nabla\times(\bar{A}\times\bar{B}) = \bar{A}\nabla\cdot\bar{B} - \bar{B}\nabla\cdot\bar{A} + (\bar{B}\cdot\nabla)\bar{A} - (\bar{A}\cdot\nabla)\bar{B} \tag{B.10}$$
$$\nabla\cdot(\bar{A}\cdot\bar{B}) = (\bar{A}\cdot\nabla)\bar{B} + (\bar{B}\cdot\nabla)\bar{A} + A\times(\nabla\times\bar{B}) + \bar{B}\times(\nabla\times\bar{A}) \tag{B.11}$$
$$\nabla\cdot\nabla\times\bar{A} = 0 \tag{B.12}$$
$$\nabla\times(\nabla f) = 0 \tag{B.13}$$
$$\nabla\times\nabla\times\bar{A} = \nabla\nabla\cdot\bar{A} - \nabla^2\bar{A} \tag{B.14}$$

Note: the term $\nabla^2\bar{A}$ has meaning only for rectangular components of $\bar{A}$.

$$\int_V \nabla\cdot\bar{A}\,dv = \oint_S \bar{A}\cdot d\bar{s} \quad \text{(divergence theorem)} \tag{B.15}$$

$$\int_S (\nabla\times\bar{A})\cdot d\bar{s} = \oint_C \bar{A}\cdot d\bar{\ell} \quad \text{(Stokes' theorem)} \tag{B.16}$$

APPENDIX C BESSEL FUNCTIONS

Bessel functions are solutions to the differential equation,

$$\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{df}{d\rho}\right) + \left(k^2 - \frac{n^2}{\rho^2}\right)f = 0 \tag{C.1}$$

where k^2 is real and n is an integer. The two independent solutions to this equation are called ordinary Bessel functions of the first and second kind, written as $J_n(k\rho)$ and $Y_n(k\rho)$, and so the general solution to (C.1) is

$$f(\rho) = AJ_n(k\rho) + BY_n(k\rho) \tag{C.2}$$

where A and B are arbitrary constants to be determined from boundary conditions.

These functions can be written in series form as

$$J_n(x) = \sum_{m=0}^{\infty}\frac{(-1)^m(x/2)^{n+2m}}{m!(n+m)!} \tag{C.3}$$

$$Y_n(x) = \frac{2}{\pi}\left(\gamma + \ln\frac{x}{2}\right)J_n(x) - \frac{1}{\pi}\sum_{m=0}^{n-1}\frac{(n-m-1)!}{m!}\left(\frac{2}{x}\right)^{n-2m} - \frac{1}{\pi}\sum_{m=0}^{\infty}\frac{(-1)^m(x/2)^{n+2m}}{m!(n+m)!}$$
$$\times\left(1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{m} + 1 + \frac{1}{2} + \cdots + \frac{1}{n+m}\right) \tag{C.4}$$

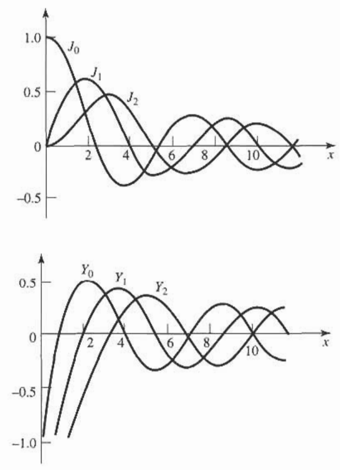


FIGURE C.1 Bessel functions of the first and second kind.

where $\gamma = 0.5772\ldots$ is Euler's constant, and $x = k\rho$. Note that Y_n becomes infinite at $x = 0$, due to the ln term. From these series expressions, small argument formulas can be obtained as

$$J_n(x) \sim \frac{1}{n!}\left(\frac{x}{2}\right)^n \tag{C.5}$$

$$Y_0(x) \sim \frac{2}{\pi}\ln x \tag{C.6}$$

$$Y_n(x) \sim \frac{-1}{\pi}(n-1)!\left(\frac{x}{2}\right)^n, \qquad n > 0 \tag{C.7}$$

Large argument formulas can be derived as

$$J_n(x) \sim \sqrt{\frac{2}{\pi x}}\cos\left(x - \frac{\pi}{4} - \frac{n\pi}{2}\right) \tag{C.8}$$

$$Y_n(x) \sim \sqrt{\frac{2}{\pi x}}\sin\left(x - \frac{\pi}{4} - \frac{n\pi}{2}\right) \tag{C.9}$$

Figure C.1 shows graphs of a few of the lowest order Bessel functions of each type.

Recurrence formulas relate Bessel functions of different orders:

$$Z_{n+1}(x) = \frac{2n}{x}Z_n(x) - Z_{n-1}(x) \tag{C.10}$$

$$Z_n'(x) = \frac{-n}{x}Z_n(x) + Z_{n-1}(x) \tag{C.11}$$

$$Z_n'(x) = \frac{n}{x}Z_n(x) - Z_{n+1}(x) \tag{C.12}$$

$$Z_n'(x) = \frac{1}{2}[Z_{n-1}(x) - Z_{n+1}(x)] \tag{C.13}$$

where $Z_n = J_n$ or Y_n. The following integral relations involving Bessel functions are useful:

$$\int_0^x Z_m^2(kx)x\,dx = \frac{x^2}{2}\left[Z_n'^2(kx) + \left(1 - \frac{n^2}{k^2x^2}\right)Z_n^2(kx)\right] \tag{C.14}$$

$$\int_0^x Z_n(kx)Z_n(\ell x)x\,dx = \frac{x}{k^2 - \ell^2}[kZ_n(\ell x)Z_{n+1}(kx) - \ell Z_n(kx)Z_{n+1}(\ell x)] \tag{C.15}$$

$$\int_0^{p_{nm}}\left[J_n'^2(x) + \frac{n^2}{x^2}J_n^2(x)\right]x\,dx = \frac{p_{nm}^2}{2}J_n'^2(p_{nm}) \tag{C.16}$$

$$\int_0^{p'_{nm}}\left[J_n'^2(x) + \frac{n^2}{x^2}J_n^2(x)\right]x\,dx = \frac{(p'_{nm})^2}{2}\left(1 - \frac{n^2}{(p'_{nm})^2}\right)J_n^2(p'_{nm}) \tag{C.17}$$

where $J_n(p_{nm}) = 0$, and $J_n'(p'_{nm}) = 0$. The zeros of $J_n(x)$ and $J_n'(x)$ are on the following two pages.

Zeros of Bessel Functions of First Kind: $J_n(x) = 0$ for $0 < x < 12$

n	1	2	3	4
0	2.4048	5.5200	8.6537	11.7951
1	3.8317	7.0155	10.1743	
2	5.1356	8.4172	11.6198	
3	6.3801	9.7610		
4	7.5883	11.0647		
5	8.7714			
6	9.9361			
7	11.0863			

Extrema of Bessel Functions of First Kind: $dJ_n(x)/dx = 0$ for $0 < x < 12$

n	1	2	3	4
0	3.8317	7.0156	10.1735	13.3237
1	1.8412	5.3314	8.5363	11.7060
2	3.0542	6.7061	9.9695	
3	4.2012	8.0152	11.3459	
4	5.3175	9.2824		
5	6.4156	10.5199		
6	7.5013	11.7349		
7	8.5778			
8	9.6474			
9	10.7114			
10	11.7709			

APPENDIX D OTHER MATHEMATICAL RESULTS

Useful Integrals

$$\int_0^a \cos^2 \frac{n\pi x}{a} dx = \int_0^a \sin^2 \frac{n\pi x}{a} dx = \frac{a}{2}, \qquad \text{for } n \geq 1 \tag{D.1}$$

$$\int_0^a \cos \frac{m\pi x}{a} \cos \frac{n\pi x}{a} dx = \int_0^a \sin \frac{m\pi x}{a} \sin \frac{n\pi x}{a} dx = 0, \qquad \text{for } m \neq n \tag{D.2}$$

$$\int_0^a \cos \frac{m\pi x}{a} \sin \frac{n\pi x}{a} dx = 0 \tag{D.3}$$

$$\int_0^\pi \sin^3 \theta d\theta = \frac{4}{3} \tag{D.4}$$

Taylor Series

$$f(x) = f(x_0) + (x - x_0)\frac{df}{dx}\bigg|_{x=x_0} + \frac{(x-x_0)^2}{2!}\frac{d^2 f}{dx^2}\bigg|_{x=x_0} + \cdots \tag{D.5}$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \tag{D.6}$$

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \cdots, \qquad \text{for } |x| < 1 \tag{D.7}$$

$$\sqrt{1+x} = 1 + \frac{x}{2} - \frac{x^2}{8} + \cdots, \qquad \text{for } |x| < 1 \tag{D.8}$$

$$\ln x = 2\left(\frac{x-1}{x+1}\right) + \frac{2}{3}\left(\frac{x-1}{x+1}\right)^3 + \cdots, \qquad \text{for } x > 0 \tag{D.9}$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} + \cdots \tag{D.10}$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \cdots \tag{D.11}$$

APPENDIX E PHYSICAL CONSTANTS

- Permittivity of free-space $= \epsilon_0 = 8.854 \times 10^{-12}$ F/m
- Permeability of free-space $= \mu_0 = 4\pi \times 10^{-7}$ H/m
- Impedance of free-space $= \eta_0 = 376.7\ \Omega$
- Velocity of light in free-space $= c = 2.998 \times 10^8$ m/s
- Charge of electron $= q = 1.602 \times 10^{-19}$ C
- Mass of electron $= m = 9.107 \times 10^{-31}$ kg
- Boltzmann's constant $= k = 1.380 \times 10^{-23}$ J/°K
- Planck's constant $= h = 6.626 \times 10^{-34}$ J-sec
- Gyromagnetic ratio $= \gamma = 1.759 \times 10^{11}$ C/Kg (for $g = 2$)

APPENDIX F CONDUCTIVITIES FOR SOME MATERIALS

Material	Conductivity S/m (20°C)	Material	Conductivity S/m (20°C)
Aluminum	3.816×10^7	Nichrome	1.0×10^6
Brass	2.564×10^7	Nickel	1.449×10^7
Bronze	1.00×10^7	Platinum	9.52×10^6
Chromium	3.846×10^7	Sea water	3–5
Copper	5.813×10^7	Silicon	4.4×10^{-4}
Distilled water	2×10^{-4}	Silver	6.173×10^7
Germanium	2.2×10^6	Steel (silicon)	2×10^6
Gold	4.098×10^7	Steel (stainless)	1.1×10^6
Graphite	7.0×10^4	Solder	7.0×10^6
Iron	1.03×10^7	Tungsten	1.825×10^7
Mercury	1.04×10^6	Zinc	1.67×10^7
Lead	4.56×10^6		

APPENDIX G DIELECTRIC CONSTANTS AND LOSS TANGENTS FOR SOME MATERIALS

Material	Frequency	ϵ_r	$\tan\delta$ (25°C)
Alumina (99.5%)	10 GHz	9.5–10.	0.0003
Barium tetratitanate	6 GHz	$37 \pm 5\%$	0.0005
Beeswax	10 GHz	2.35	0.005
Beryllia	10 GHz	6.4	0.0003
Ceramic (A-35)	3 GHz	5.60	0.0041
Fused quartz	10 GHz	3.78	0.0001
Gallium arsenide	10 GHz	13.	0.006
Glass (pyrex)	3 GHz	4.82	0.0054
Glazed ceramic	10 GHz	7.2	0.008
Lucite	10 GHz	2.56	0.005
Nylon (610)	3 GHz	2.84	0.012
Parafin	10 GHz	2.24	0.0002
Plexiglass	3 GHz	2.60	0.0057
Polyethylene	10 GHz	2.25	0.0004
Polystyrene	10 GHz	2.54	0.00033
Porcelain (dry process)	100 MHz	5.04	0.0078
Rexolite (1422)	3 GHz	2.54	0.00048
Silicon	10 GHz	11.9	0.004
Styrofoam (103.7)	3 GHz	1.03	0.0001
Teflon	10 GHz	2.08	0.0004
Titania (D-100)	6 GHz	$96 \pm 5\%$	0.001
Vaseline	10 GHz	2.16	0.001
Water (distilled)	3 GHz	76.7	0.157

APPENDIX H PROPERTIES OF SOME MICROWAVE FERRITE MATERIALS

Material	Trans-Tech Number	$4\pi Ms$ G	ΔH Oe	ϵ_r	$\tan\delta$	T_c °C	$4\pi Mr$ G
Magnesium ferrite	TT1-105	1750	225	12.2	0.00025	225	1220
Magnesium ferrite	TT1-390	2150	540	12.7	0.00025	320	1288
Magnesium ferrite	TT1-3000	3000	190	12.9	0.0005	240	2000
Nickel ferrite	TT2-101	3000	350	12.8	0.0025	585	1853
Nickel ferrite	TT2-113	500	150	9.0	0.0008	120	140
Nickel ferrite	TT2-125	2100	460	12.6	0.001	560	1426
Lithium ferrite	TT73-1700	1700	<400	16.1	0.0025	460	1139
Lithium ferrite	TT73-2200	2200	<450	15.8	0.0025	520	1474
Yttrium garnet	G-113	1780	45	15.0	0.0002	280	1277
Aluminum garnet	G-610	680	40	14.5	0.0002	185	515

APPENDIX I STANDARD RECTANGULAR WAVEGUIDE DATA

Band*	Recommended Frequency Range (GHz)	TE_{10} Cutoff Frequency (GHz)	EIA Designation WR-XX	Inside Dimensions Inches (cm)	Outside Dimensions Inches (cm)
L	1.12–1.70	0.908	WR-650	6.500 × 3.250 (16.51 × 8.255)	6.660 × 3.410 (16.916 × 8.661)
R	1.70–2.60	1.372	WR-430	4.300 × 2.150 (10.922 × 5.461)	4.460 × 2.310 (11.328 × 5.867)
S	2.60–3.95	2.078	WR-284	2.840 × 1.340 (7.214 × 3.404)	3.000 × 1.500 (7.620 × 3.810)
H (G)	3.95–5.85	3.152	WR-187	1.872 × 0.872 (4.755 × 2.215)	2.000 × 1.000 (5.080 × 2.540)
C (J)	5.85–8.20	4.301	WR-137	1.372 × 0.622 (3.485 × 1.580)	1.500 × 0.750 (3.810 × 1.905)
W (H)	7.05–10.0	5.259	WR-112	1.122 × 0.497 (2.850 × 1.262)	1.250 × 0.625 (3.175 × 1.587)
X	8.20–12.4	6.557	WR-90	0.900 × 0.400 (2.286 × 1.016)	1.000 × 0.500 (2.540 × 1.270)
Ku (P)	12.4–18.0	9.486	WR-62	0.622 × 0.311 (1.580 × 0.790)	0.702 × 0.391 (1.783 × 0.993)
K	18.0–26.5	14.047	WR-42	0.420 × 0.170 (1.07 × 0.43)	0.500 × 0.250 (1.27 × 0.635)
Ka (R)	26.5–40.0	21.081	WR-28	0.280 × 0.140 (0.711 × 0.356)	0.360 × 0.220 (0.914 × 0.559)
Q	33.0–50.5	26.342	WR-22	0.224 × 0.112 (0.57 × 0.28)	0.304 × 0.192 (0.772 × 0.488)
U	40.0–60.0	31.357	WR-19	0.188 × 0.094 (0.48 × 0.24)	0.268 × 0.174 (0.681 × 0.442)
V	50.0–75.0	39.863	WR-15	0.148 × 0.074 (0.38 × 0.19)	0.228 × 0.154 (0.579 × 0.391)
E	60.0–90.0	48.350	WR-12	0.122 × 0.061 (0.31 × 0.015)	0.202 × 0.141 (0.513 × 0.356)
W	75.0–110.0	59.010	WR-10	0.100 × 0.050 (0.254 × 0.127)	0.180 × 0.130 (0.458 × 0.330)
F	90.0–140.0	73.840	WR-8	0.080 × 0.040 (0.203 × 0.102)	0.160 × 0.120 (0.406 × 0.305)
D	110.0–170.0	90.854	WR-6	0.065 × 0.0325 (0.170 × 0.083)	0.145 × 0.1125 (0.368 × 0.2858)
G	140.0–220.0	115.750	WR-5	0.051 × 0.0255 (0.130 × 0.0648)	0.131 × 0.1055 (0.333 × .2680)

* Letters in parentheses denote alternative designations.

APPENDIX J STANDARD COAXIAL CABLE DATA

RG/U type	Impedance (Ω)	Inner cond. diam. (In.)	Dielectric material	Dielectric diam. (In.)	Cable type	Overall diam. (In.)	Capacitance (pF/ft)	Max. Oper. voltage	Loss at 1 GHz (dB/100 ft)
RG-8A/U	52	0.0855	P	0.285	braided	0.405	29.5	5000	9.0
RG-9B/U	50	0.0855	P	0.280	braided	0.420	30.8	5000	9.0
RG-55B/U	54	0.0320	P	0.116	braided	0.200	28.5	1900	16.5
RG-58B/U	54	0.0320	P	0.116	braided	0.195	28.5	1900	17.5
RG-59B/U	75	0.0230	P	0.146	braided	0.242	20.6	2300	11.5
RG-141A/U	50	0.0390	T	0.116	braided	0.190	29.4	1900	13.0
RG-142A/U	50	0.0390	T	0.116	braided	0.195	29.4	1900	13.0
RG-174/U	50	0.0189	P	0.060	braided	0.100	30.8	1500	31.0
RG-178B/U	50	0.0120	T	0.034	braided	0.072	29.4	1000	45.0
RG-179B/U	75	0.0120	T	0.063	braided	0.100	19.5	1200	25.0
RG-180B/U	95	0.0120	T	0.102	braided	0.140	15.4	1500	16.5
RG-187/U	75	0.0120	T	0.060	braided	0.105	19.5	1200	25.0
RG-188/U	50	0.0201	T	0.060	braided	0.105	29.4	1200	30.0
RG-195/U	95	0.0120	T	0.102	braided	0.145	15.4	1500	16.5
RG-213/U	50	0.0888	P	0.285	braided	0.405	30.8	5000	9.0
RG-214/U	50	0.0888	P	0.285	braided	0.425	30.8	5000	9.0
RG-223/U	50	0.0350	P	0.116	braided	0.211	30.8	1900	16.5
RG-316/U	50	0.0201	T	0.060	braided	0.102	29.4	1200	30.0
RG-401/U	50	0.0645	T	0.215	semi-rigid	0.250	29.3	3000	—
RG-402/U	50	0.0360	T	0.119	semi-rigid	0.141	29.3	2500	13.0
RG-405/U	50	0.0201	T	0.066	semi-rigid	0.0865	29.4	1500	—