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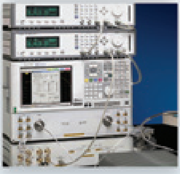

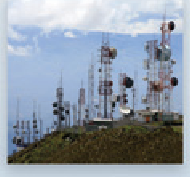

smiths microwave

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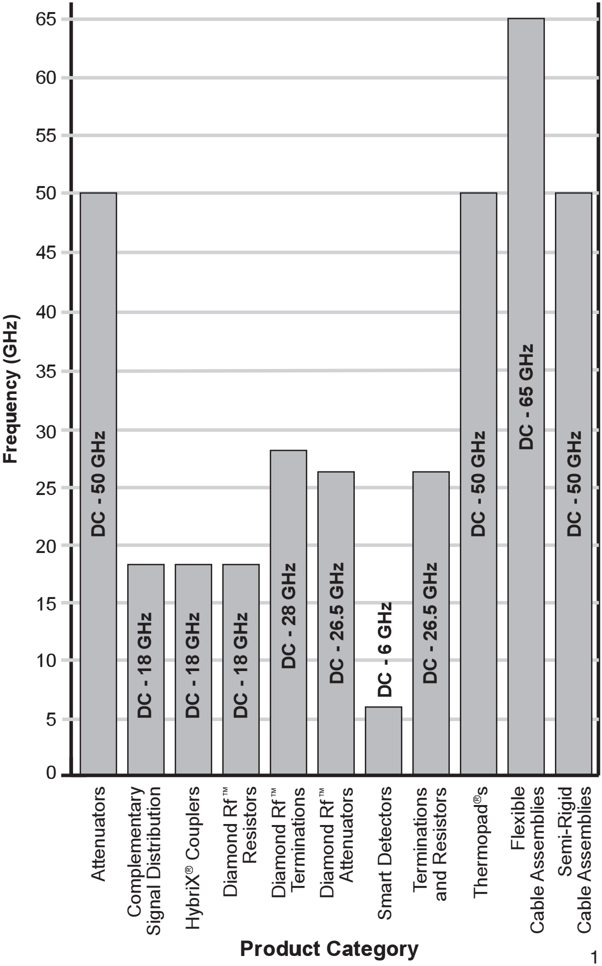
Product Frequency Bands



Useful Equations

Reduction of SWR by a Matched Attenuator

$$\frac{1}{SWR_{input}} = \tanh\left[\frac{dB}{8.686} + \tanh^{-1}\frac{1}{SWR_{load}}\right]$$

Input Reflection Coefficient

$$\Gamma_{in} = S_{11} + \frac{S_{21}\,S_{12}}{1 - S_{22}\,\Gamma_{l}}$$

Reflection Coefficient (ρ) to SWR

$$SWR = \frac{1 + \rho}{1 - \rho}$$

Equivalent Parallel Capacitance

$$C_P = \frac{jB}{\omega}$$

SWR to Reflection Coefficient (ρ)

$$\rho = \frac{SWR - 1}{SWR + 1}$$

Reflection Coefficient (ρ) to Return Loss

$$R.L.(dB) = -20 \log \rho$$

Return Loss to Reflection Coefficient (ρ)

$$\rho = \log^{-1}\left(\frac{R.L.}{-20}\right)$$

Useful Equations

Reflected and Transmitted Power Due to SWR

$$P_{refl} = P_{in}\left(\frac{SWR - 1}{SWR + 1}\right)^2 = P_{in}\,\rho^2$$

$$P_{trans} = P_{in}\,\frac{4SWR}{(SWR + 1)^2} = P_{in}\,(1 - \rho^2)$$

Normalized Impedance to Reflection Coefficient

$$\Gamma = \frac{\bar{Z} - 1}{\bar{Z} + 1}$$

Electrical Length ϕ (degrees)

$$\phi = -360\sqrt{\varepsilon_r}$$

$$Lf$$

$$\frac{\sqrt{\varepsilon_r}\,L}{c} = T_D = \text{Time Delay (seconds)}$$

$$\phi = -360\,T_d f$$

$$\phi = \frac{\Delta\phi}{\Delta f}\,f$$

Total Power Dissipated in Attenuator

$$P_d = P_{in}\left(1 - \log^{-1}\frac{dB}{-10}\right)$$

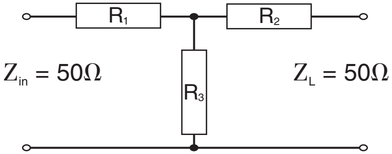
Parallel Plate Capacitance

$$Cpp = \frac{A\varepsilon_r\varepsilon_o}{h}$$

Useful Equations

(continued)

"T" Attenuator Network Design



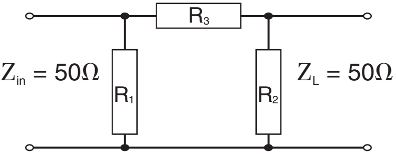
$N = \log^{-1}\left(\frac{db}{10}\right)$

$R_1 = R_2$

$$R_1 = \frac{Z(\sqrt{N} - 1)}{(\sqrt{N} + 1)}$$

$$R_3 = \frac{2Z\sqrt{N}}{N - 1}$$

π Attenuator Network Design



$N = \log^{-1}\left(\frac{db}{10}\right)$

$R_1 = R_2$

$$R_1 = \frac{Z(\sqrt{N} + 1)}{(\sqrt{N} - 1)}$$

$$R_3 = \frac{Z(N - 1)}{2\sqrt{N}}$$

N: *the ratio of power corresponding to a given value of attenuation in decibels.*

Useful Equations

Reactance

$$X_L = 6.28 f_{GHz} L_{nH} \quad \text{and} \quad X_C = \frac{159}{f_{GHz} C_{pF}}$$

Conductance

$$G = \frac{1}{R} \quad \text{and} \quad g = \frac{1}{r}$$

Susceptance

$$B = \frac{1}{X} \quad \text{and} \quad b = \frac{1}{x}$$

Impedance (Z_0 is the Characteristic Impedance)

$$Z = R \pm jX = \frac{1}{Y} = Z_0 \left(\frac{1 - \Gamma}{1 + \Gamma} \right) \text{ and } z = \frac{Z}{C}$$

Admittance (Y_0 is the Characteristic Admittance)

$$Y = G \pm jB = \frac{1}{Z} = Y_0 \left(\frac{1 - \Gamma}{1 + \Gamma} \right) \text{ and } Y = \frac{Y}{Y_0}$$

Reflection Coefficient

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} = \frac{Y_0 - Y}{Y_0 + Y} = \frac{VSWR - 1}{VSWR + 1} = \frac{z - 1}{z + 1}$$

Voltage Standing Wave Ratio

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{R_{LARGER}}{R_{SMALLER}}$$

Return Loss

$$RL = 20\log|\Gamma| = -20\log\left|\frac{Z - Z_0}{Z + Z_0}\right|$$

Useful Equations

(continued)

Mismatch Loss ($\Gamma_S = 0$, $\Gamma_L \neq 0$)

$$ML = -10\log\left(1-|\Gamma_L|^2\right) = -10\log\left(1-\left|\frac{Z_L - Z_0}{Z_L + Z_0}\right|^2\right) = -10\log\left[1-\left(\frac{VSWR-1}{VSWR+1}\right)^2\right]$$

Mismatch Loss ($\Gamma_S \neq 0$, $\Gamma_L \neq 0$)

$$ML = -10\log\left[\frac{(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-\Gamma_L\Gamma_S|}\right]$$

Wavelength

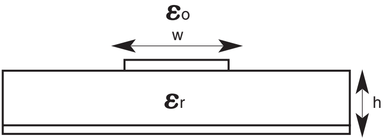
$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}\mu_r} = \frac{3 \cdot 10^8 m}{f_{Hz}\sqrt{\varepsilon_r}\mu_r} = \frac{30cm}{f_{GHz}\sqrt{\varepsilon_r}\mu_r}$$

Conversion to dB

$$dB = 20\log\frac{V_2}{V_1} = 20\log\frac{i_2}{i_1} = 10\log\frac{P_2}{P_1}$$

Notes

Microstrip Transmission Line Reference Table



	Trace width for a 50Ω ± 1Ω microstrip, transmission line (in mils)													
	1 oz copper				@ 1 GHz					Data from MWO				
		2.1	**2.2**	**2.33**	**2.5**	**3**	**4.5**	**5.7**	**6**	**6.5**	**8**	**8.6**	**9.4**	**10**
Dielectric Thickness (h mils)	**3**	8.6	8.3	8	7.6	6.7	4.9	4	3.8	3.5	2.8			
	4	11.7	11.3	10.9	10.4	9.1	6.7	5.5	5.2	4.8	3.9	3.7	3.3	3.1
	5	14.8	14.3	13.8	13.1	11.6	8.5	7	6.7	6.2	5.1	4.7	4.3	4
	10	30.4	29.5	28.4	27.1	23.9	17.7	14.6	14	13.1	10.8	10	9.2	8.6
	15	46.2	44.8	43.1	41.2	36.4	27	22.4	21.4	20	16.5	15.4	14.1	13.3
	20	61.9	60.1	57.9	55.3	48.9	36.4	30.1	28.8	26.9	22.3	20.9	19.1	18
	25	77.7	75.4	72.7	69.4	61.4	45.7	37.9	36.3	33.9	28.2	26.3	24.1	22.7
	31	96.7	93.9	90.4	86.4	76.4	56.9	47.2	45.2	42.3	35.1	32.8	30.1	28.3
	40	125	122	117	112	98.9	73.8	61.2	58.7	54.8	45.6	42.6	39.1	36.8
	50	157	152	147	140	124	92.5	76.8	73.6	68.8	57.3	53.6	49.2	46.3
	62	195	189	182	174	154	115	95.5	91.6	85.6	71.3	66.7	61.2	57.6

The above values are from the Txline 2003 calculator

The Effect of VSWR on Transmitted Power

VSWR	Return Loss (dB)	Trans. Loss (dB)	Volt. Refl. Coeff.	Power Trans. (%)	Power Refl. (%)
1.00	∞	.000	.00	100.0	.0
1.01	46.1	.000	.00	100.0	.0
1.02	40.1	.000	.01	100.0	.0
1.03	36.6	.001	.01	100.0	.0
1.04	34.2	.002	.02	100.0	.0
1.05	32.3	.003	.02	99.9	.1
1.06	30.4	.004	.03	99.9	.1
1.07	29.4	.005	.03	99.9	.1
1.08	28.3	.006	.04	99.9	.1
1.09	27.3	.008	.04	99.8	.2
1.10	26.4	.010	.05	99.8	.2
1.11	25.7	.012	.05	99.7	.3
1.12	24.9	.014	.06	99.7	.3
1.13	24.3	.016	.06	99.6	.4
1.14	23.7	.019	.07	99.6	.4
1.15	23.1	.021	.07	99.5	.5
1.16	22.6	.024	.07	99.5	.5
1.17	22.1	.027	.08	99.4	.6
1.18	21.7	.030	.08	99.3	.7
1.19	21.2	.033	.09	99.2	.8
1.20	20.8	.036	.09	99.2	.8
1.21	20.4	.039	.10	99.1	.9
1.22	20.1	.043	.10	99.0	1.0
1.23	19.7	.046	.10	98.9	1.1
1.24	19.4	.050	.11	98.9	1.1
1.25	19.1	.054	.11	98.8	1.2
1.26	18.8	.058	.12	98.7	1.3
1.27	18.5	.062	.12	98.6	1.4
1.28	18.2	.065	.12	98.5	1.5
1.29	17.9	.070	.13	98.4	1.6
1.30	17.7	.075	.13	98.3	1.7

The Effect of VSWR on Transmitted Power *(continued)*

VSWR	Return Loss (dB)	Trans. Loss (dB)	Volt. Refl. Coeff.	Power Trans. (%)	Power Refl. (%)
1.32	17.2	.083	.14	98.1	1.9
1.34	16.8	.093	.15	97.9	2.1
1.36	16.3	.102	.15	97.7	2.3
1.38	15.9	.112	.16	97.5	2.5
1.40	15.6	.122	.17	97.2	2.8
1.42	15.2	.133	.17	97.0	3.0
1.44	14.9	.144	.18	96.7	3.3
1.46	14.6	.155	.19	96.5	3.5
1.48	14.3	.166	.19	96.3	3.7
1.50	14.0	.177	.20	96.0	4.0
1.52	13.7	.189	.21	95.7	4.3
1.54	13.4	.201	.21	95.5	4.5
1.56	13.2	.213	.22	95.2	4.8
1.58	13.0	.225	.22	94.9	5.1
1.60	12.7	.238	.23	94.7	5.3
1.62	12.5	.250	.24	94.4	5.6
1.64	12.3	.263	.24	94.1	5.9
1.66	12.1	.276	.25	93.8	6.2
1.68	11.9	.289	.25	93.6	6.4
1.70	11.7	.302	.26	93.3	6.7
1.72	11.5	.315	.26	93.0	7.0
1.74	11.4	.329	.27	92.7	7.3
1.76	11.2	.342	.28	92.4	7.6
1.78	11.0	.356	.28	92.1	7.9
1.80	10.9	.370	.29	91.8	8.2
1.82	10.7	.384	.29	91.5	8.5
1.84	10.6	.398	.30	91.3	8.7
1.86	10.4	.412	.30	91.0	9.0
1.88	10.3	.426	.31	90.7	9.3
1.90	10.2	.440	.31	90.4	9.6
1.92	10.0	.454	.32	90.1	9.9

The Effect of VSWR on Transmitted Power

VSWR	Return Loss (dB)	Trans. Loss (dB)	Volt. Refl. Coeff.	Power Trans. (%)	Power Refl. (%)
1.94	9.9	.468	.32	89.8	10.2
1.96	9.8	.483	.32	89.5	10.5
1.98	9.7	.497	.33	89.2	10.8
2.00	9.5	.512	.33	88.9	11.1
2.50	7.4	.881	.43	81.6	18.4
3.00	6.0	1.249	.50	75.0	25.0
3.50	5.1	1.603	.56	69.1	30.9
4.00	4.4	1.938	.60	64.0	36.0
4.50	3.9	2.255	.64	59.5	40.5
5.00	3.5	2.553	.67	55.6	44.4
5.50	3.2	2.834	.69	52.1	47.9
6.00	2.9	3.100	.71	49.0	51.0
6.50	2.7	3.351	.73	46.2	53.8
7.00	2.5	3.590	.75	43.7	56.2
7.50	2.3	3.817	.76	41.5	58.5
8.00	2.2	4.033	.78	39.5	60.5
8.50	2.1	4.240	.79	37.7	62.3
9.00	1.9	4.437	.80	36.0	64.0
9.50	1.8	4.626	.81	34.5	65.5
10.00	1.7	4.807	.82	33.1	66.9
11.00	1.6	5.149	.83	30.6	69.4
12.00	1.5	5.466	.85	28.4	71.6
13.00	1.3	5.762	.86	26.5	73.5
14.00	1.2	6.042	.87	24.9	75.1
15.00	1.2	6.301	.88	23.4	76.6
16.00	1.1	6.547	.88	22.1	77.9
17.00	1.0	6.780	.89	21.0	79.0
18.00	1.0	7.002	.89	19.9	80.1
19.00	.9	7.212	.90	19.0	81.0
20.00	.9	7.413	.90	18.1	81.9
25.00	.7	8.299	.92	14.8	85.2
30.00	.6	9.035	.94	12.5	87.5

Dielectric Constant (ε_r) & Loss Tangent (tan δ) @ 3.0 GHz

Material	ε_r	***tan*** δ
Air	1.000649	
Polystyrene Foam	1.03	.0001
PTFE	2.1	.0002
Vaseline	2.16	.00066
RT/Duroid® 5880	2.2	.0004
Polyethylene	2.3	.0003
Polystyrene	2.55	.00033
RO/Duroid® 3003	3.0	.0013
Quartz	3.78	.00006
Glass, Soda	4.82	.0054
Mica, Ruby	5.4	.0003
Diamond (CVD)	5.6	.0005
RT/Duroid® 6006	6.15	.0027
Beryllium Oxide (BeO)	6.5	.004
Aluminum Nitride (AIN)	8.9	.0005
Alumina (Al_2O_3) 99.6%	9.9	.0001
RT/Duroid® 6010	10.2	.0028

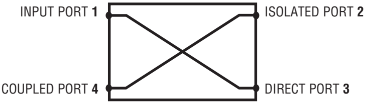
RT/Duroid is a registered trademark of Rogers Corporation

Material Properties

Material	**Conductivity,** σ **(Mho/meter) x 10^8**
Tantalum Nitride	.000074
Carbon	.0006 - .0007
Nichrome *(80%Ni, 20%Cr)*	.0093
Lead	.047
Sn63 Solder	.0667
Tin	.087
Palladium	.0926
Indium	.1111
Nickel	.1449
Tungsten	.184
Rhodium	.1961
Beryllium	.2188
Brass *(66% Cu, 34% Zn)*	.2564
Aluminum	.3817
Gold	.4098
Copper	.5800
Silver	.6173

90˚ Hybrid Couplers Performance Parameters

90˚ Hybrid Couplers



90˚ Crossover Hybrid

PORT	1	2	3	4
1	IN	ISO	-90˚	0˚
2	ISO	IN	0˚	-90˚
3	-90˚	0˚	IN	ISO
4	0˚	-90˚	ISO	IN

Performance Parameters

VSWR

$$\text{VSWR} = \frac{V_{\text{max}}}{V_{\text{min}}}$$

Return Loss

$$\text{Return Loss (dB)} = 20 \bullet \text{Log}\left(\frac{VSWR+1}{VSWR-1}\right)$$

Insertion Loss

$$\text{Insertion Loss (dB)} = 10 \bullet \text{Log}\left(\frac{P_{in}}{P_{coupled} + P_{direct}}\right)$$

Isolation

$$\text{Isolation (dB)} = 10 \bullet \text{Log}\left(\frac{P_{in}}{P_{isolated}}\right)$$

Phase Balance

$$\text{Phase Balance (}^{0}\text{)} = \pm \frac{\left| Phase_{coupled} - Phase_{direct} \right|}{2}$$

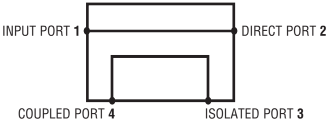
Amplitude Balance

$$\text{Amplitude Balance (dB)} = 10 \bullet \text{Log} \frac{P_{coupled}}{\left(\frac{P_{coupled} + P_{direct}}{2}\right)}$$

$$\text{Amplitude Balance (dB)} = 10 \bullet \text{Log} \frac{P_{direct}}{\left(\frac{P_{direct} + P_{coupled}}{2}\right)}$$

Directional Couplers Performance Parameters

Directional Couplers

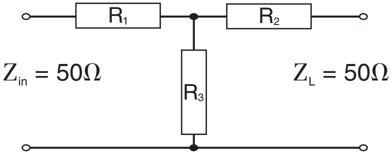


Directional Coupler

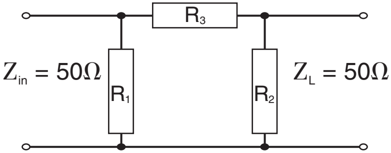
Performance Parameters

Coupling Ratio	$\text{Coupling Ratio (dB)} = 10 \bullet \text{Log}\left(\frac{P_{coupled}}{P_{in}}\right)$
VSWR	$\text{VSWR} = \frac{V_{\text{max}}}{V_{\text{min}}}$
Return Loss	$\text{Return Loss (dB)} = 20 \bullet \text{Log}\left(\frac{VSWR+1}{VSWR-1}\right)$
Insertion Loss	$\text{Insertion Loss (dB)} = 10 \bullet \text{Log}\left(\frac{P_{in}}{P_{coupled} + P_{direct}}\right)$
Transmission Loss	$\text{Transmission Loss (dB)} = 10 \bullet \text{Log}\left(\frac{P_{in}}{P_{direct}}\right)$
Directivity	$\text{Directivity (dB)} = 10 \bullet \text{Log}\left(\frac{P_{coupled}}{P_{isolated}}\right)$
Frequency Sensitivity	$[C_{\text{max}}\text{(dB)} - C_{\text{mean}}\text{ (dB)}]$ $[C_{\text{min}}\text{(dB)} - C_{\text{mean}}\text{ (dB)}]$

"T" Attenuator Network Design



π Attenuator Network Design



EXAMPLE:

- Input Power = 75 Watts
- Attenuation = 3.75 dB
- Power Dissipated in R_1 = .213 (75)
  = 15.975 Watts

Normalized Dissipated Power in "T" & π Attenuator Elements

Attenuation (dB)	Power Dissipation (watts)		
	R_1	R_2	R_3
0.25	.014	.014	.028
0.50	.029	.026	.054
0.75	.043	.037	.079
1.00	.058	.046	.103
1.25	.072	.054	.124
1.50	.086	.061	.145
1.75	.100	.068	.164
2.00	.115	.073	.182
2.25	.129	.076	.199
2.50	.143	.081	.214
2.75	.157	.083	.229
3.00	.171	.086	.242
3.25	.185	.088	.254
3.50	.199	.088	.266
3.75	.213	.089	.276
4.00	.226	.091	.285
4.25	.240	.090	.294

Normalized Dissipated Power in "T" & π Attenuator Elements

(continued)

Attenuation (dB)	Power Dissipation (watts)		
	R_1	R_2	R_3
4.50	.253	.090	.302
4.75	.267	.089	.309
5.00	.280	.089	.315
5.25	.293	.087	.321
5.50	.306	.087	.325
5.75	.319	.085	.330
6.00	.332	.084	.333
7.00	.382	.076	.342
8.00	.431	.068	.342
9.00	.476	.060	.338
10.00	.519	.052	.329
12.00	.598	.038	.301
14.00	.667	.027	.266
16.00	.726	.018	.230
18.00	.776	.013	.195
20.00	.818	.008	.164
30.00	.939	.001	.059

Notes

Power Conversion Table

dBm	Watts	dBm	Watts	dBm	Watts
30.0	1.00	36.8	4.79	43.6	22.91
30.2	1.05	37.0	5.01	43.8	23.99
30.4	1.10	37.2	5.25	44.0	25.12
30.6	1.15	37.4	5.50	44.2	26.30
30.8	1.20	37.6	5.75	44.4	27.54
31.0	1.26	37.8	6.03	44.6	28.84
31.2	1.32	38.0	6.31	44.8	30.20
31.4	1.38	38.2	6.61	45.0	31.62
31.6	1.45	38.4	6.92	45.2	33.11
31.8	1.51	38.6	7.24	45.4	34.67
32.0	1.58	38.8	7.59	45.6	36.31
32.2	1.66	39.0	7.94	45.8	38.02
32.4	1.74	39.2	8.32	46.0	39.81
32.6	1.82	39.4	8.71	46.2	41.69
32.8	1.91	39.6	9.12	46.4	43.65
33.0	2.00	39.8	9.55	46.6	45.71
33.2	2.09	40.0	10.00	46.8	47.86
33.4	2.19	40.2	10.47	47.0	50.12
33.6	2.29	40.4	10.96	47.2	52.48
33.8	2.40	40.6	11.48	47.4	54.95
34.0	2.51	40.8	12.02	47.6	57.54
34.2	2.63	41.0	12.59	47.8	60.26
34.4	2.75	41.2	13.18	48.0	63.10
34.6	2.88	41.4	13.80	48.2	66.07
34.8	3.02	41.6	14.45	48.4	69.18
35.0	3.16	41.8	15.14	48.6	72.44
35.2	3.31	42.0	15.85	48.8	75.86
35.4	3.47	42.2	16.60	49.0	79.43
35.6	3.63	42.4	17.38	49.2	83.18
35.8	3.80	42.6	18.20	49.4	87.10
36.0	3.98	42.8	19.05	49.6	91.20
36.2	4.17	43.0	19.95	49.8	95.50
36.4	4.37	43.2	20.89	50.0	100.00
36.6	4.57	43.4	21.88	50.2	105.00

Power Conversion Table

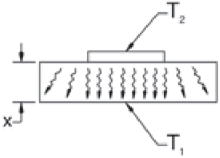
dBm	Watts	dBm	Watts	dBm	Watts
50.4	110	57.0	501	63.6	2291
50.6	115	57.2	525	63.8	2399
50.8	120	57.4	550	64.0	2512
51.0	126	57.6	575	64.2	2630
51.2	132	57.8	603	64.4	2754
51.4	138	58.0	631	64.6	2884
51.6	145	58.2	661	64.8	3020
51.8	151	58.4	692	65.0	3162
52.0	158	58.6	724	65.2	3311
52.2	166	58.8	759	65.4	3467
52.4	174	59.0	794	65.6	3631
52.6	182	59.2	832	65.8	3802
52.8	191	59.4	871	66.0	3981
53.0	200	59.6	912	66.2	4169
53.2	209	59.8	955	66.4	4365
53.4	219	60.0	1000	66.6	4571
53.6	229	60.2	1047	66.8	4786
53.8	240	60.4	1096	67.0	5012
54.0	251	60.6	1148	67.2	5248
54.2	263	60.8	1202	67.4	5495
54.4	275	61.0	1259	67.6	5754
54.6	288	61.2	1318	67.8	6026
54.8	302	61.4	1380	68.0	6310
55.0	316	61.6	1445	68.2	6607
55.2	331	61.8	1514	68.4	6918
55.4	347	62.0	1585	68.6	7244
55.6	363	62.2	1660	68.8	7586
55.8	380	62.4	1738	69.0	7943
56.0	398	62.6	1820	69.2	8318
56.2	417	62.8	1905	69.4	8710
56.4	437	63.0	1995	69.6	9120
56.6	457	63.2	2089	69.8	9550
56.8	479	63.4	2188	70.0	10000

Heat Flow

Flange power devices are all conduction cooled. Conduction cooling is the transfer of heat by molecular motion within one body or between other bodies in contact. This means that the heat dissipated in the resistive element flows through the substrate, to the mounting flange, then to the heat sink and ground plane. Heat flow is a quantity of heat per unit time, such as calories per second or watts. To maintain the heat flow, there must be a temperature difference (ΔT) between the resistive element and the ground plane. The temperature difference is analogous to voltage. The rate at which the heat will flow is directly proportional to the area perpendicular to the heat flow, the temperature, and the thermal conductivity of the material and is inversely proportional to the distance the heat has to travel. In equation form we have:

①

$$P = \frac{KA \cdot \Delta T}{x}$$



where:

P = dissipated power, (W)

K = thermal conductivity of material, $\frac{W}{cm^\circ C}$

$\Delta T = T_2 - T_1$

T_2 = temperature of source, (˚C)

T_1 = reference temperature (heat sink), (˚C)

x = length of heat flow path, (cm)

A = area of heat source, (cm^2)

θ = thermal resistance (˚C/W)

Thermal Resistance

Rearranging equation 1 will yield an equation that will relate power dissipation and temperature differences.

❷
$$\frac{\Delta T}{P} = \frac{x}{KA}$$

The term, $\frac{x}{KA}$, is called the thermal resistance (θ), therefore:

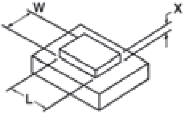
❸
$$P\theta = \Delta T$$

which will give the temperature rise when the element is dissipating power.

Calculating Thermal Resistance

Examining $\theta = \frac{x}{KA}$, it can be seen that thermal resistance decreases when x is made as small as possible. The same is true when thermal conductivity (K) and area (A) are increased. The area is difficult to define because of thermal spreading. The flow of heat will travel laterally, effectively increasing the area and further reducing the thermal resistance. For calculation purposes, assume a 45˚ spreading angle. When the heat source is a rectangle.

❹ $$\theta = \frac{1}{2K(L - W)} \cdot \ln \frac{L}{W}\left(\frac{2x + W}{2x + L}\right)$$



And when the source is square, L = W

❺ $$\theta = \frac{x}{KL(L + 2x)}$$

Thermal Conductivity $\left(\frac{\text{Watts}}{\text{cm} \cdot {}^\circ\text{C}}\right)$

METALS

Silver	(Ag)	4.08
Copper	(Cu)	3.94
Gold	(Au)	2.96
Aluminum	(Al)	2.18
Beryllium	(Be)	2.00
Tungsten	(W)	1.74
Rhodium	(Rh)	1.50
Molybdenum	(Mo)	1.46
Brass	(66% Cu, 34% Zn)	1.110
Chromium	(Cr)	0.937
Nickel	(Ni)	0.920
Platinum	(Pt)	0.716
Tin	(Sn)	0.666
Tantalum	(Ta)	0.575
Lead	(Pb)	0.353
Titanium	(Ti)	0.219
Manganese	(Mn)	0.078

PC BOARD MATERIAL

RT/Duroid® 5880	.0026
G10/FR4	.0027
RT/Duroid® 60 (XX)	.0041 - .0048
TMM® (X)	.0068 - .0075

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Thermal Conductivity

$\left(\frac{\text{Watts}}{\text{cm} \cdot {}^\circ\text{C}}\right)$

(continued)

INSULATORS

Diamond	(CVD)	10.0 - 16.0
Beryllium Oxide 99.5%	(BeO)	2.61
Aluminum Nitride	(AlN)	1.70
Boron Nitride	(HBN 500º)	0.59
Sapphire		0.46
Alumina Oxide 99.6%	(Al_2O_3)	0.36
Alumina Oxide 96%	(Al_2O_3)	0.26
Alumina Oxide 91%	(Al_2O_3)	0.13
Glass		0.015
Mica		0.0043 - 0.0062
Air		0.00026

BONDING

Gold Germanium 88/12		.8834
Gold Tin 80/20		.6824
Tin Lead Solder	(Sn62)	.4921
Indium 100%		.2386
Silver Filled Epoxy		.0156
Epoxy		.0099

MISC.

Thermal Grease	.0042 - .0049

Thermal Conductivity Conversion Factors

Thermal Conductivity

To Convert	To	Multiply By
$\frac{\text{Watt}}{\text{m} \cdot {}^\circ\text{K}}$	$\frac{\text{Watt}}{\text{cm} \cdot {}^\circ\text{C}}$	0.01
$\frac{\text{cal} \cdot \text{cm}}{\text{sec} \cdot \text{cm}^2 \cdot {}^\circ\text{C}}$	$\frac{\text{Watt}}{\text{cm} \cdot {}^\circ\text{C}}$	4.1868
$\frac{\text{BTU} \cdot \text{ft}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}$	$\frac{\text{Watt}}{\text{cm} \cdot {}^\circ\text{C}}$	.01731
$\frac{\text{BTU} \cdot \text{ft}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}$	$\frac{\text{cal} \cdot \text{cm}}{\text{sec} \cdot \text{cm}^2 \cdot {}^\circ\text{C}}$	.004134
$\frac{\text{Watt}}{\text{m} \cdot {}^\circ\text{K}}$	$\frac{\text{cal} \cdot \text{cm}}{\text{sec} \cdot \text{cm}^2 \cdot {}^\circ\text{C}}$	.002397
$\frac{\text{Watt}}{\text{cm} \cdot {}^\circ\text{C}}$	$\frac{\text{Watt}}{\text{inch} \cdot {}^\circ\text{C}}$	2.54
$\frac{\text{BTU} \cdot \text{in}}{\text{ft}^2 \cdot \text{h} \cdot {}^\circ\text{F}}$	$\frac{\text{Watt}}{\text{cm} \cdot {}^\circ\text{C}}$	1.422^{-3}

(AT 20°C)

Thermal Conductivity Conversion Factors *(continued)*

Power

To Convert	To	Multiply By
$\frac{\text{Calories}}{\text{sec}}$	Watts	4.186
$\frac{\text{BTU}}{\text{hr}}$	Watts	.293

(AT 20°C)

Temperature Conversion Table

TEMPERATURE CONVERSION TABLE

°C	°F	°C	°F	°C	°F	°C	°F
-100	-148	+60	+140	+220	+428	+380	+716
-95	-139	+65	+149	+225	+437	+385	+725
-90	-130	+70	+158	+230	+446	+390	+734
-85	-121	+75	+167	+235	+455	+395	+743
-80	-112	+80	+176	+240	+464	+400	+752
-75	-103	+85	+185	+245	+473	+405	+761
-70	-94	+90	+194	+250	+482	+410	+770
-65	-85	+95	+203	+255	+491	+415	+779
-60	-76	+100	+212	+260	+500	+420	+788
-55	-67	+105	+221	+265	+509	+425	+797
-50	-58	+110	+230	+270	+518	+430	+806
-45	-49	+115	+239	+275	+527	+435	+815
-40	-40	+120	+248	+280	+536	+440	+824
-35	-31	+125	+257	+285	+545	+445	+833
-30	-22	+130	+266	+290	+554	+450	+842
-25	-13	+135	+275	+295	+563	+455	+851
-20	-4	+140	+284	+300	+572	+460	+860
-15	+5	+145	+293	+305	+581	+465	+869
-10	+14	+150	+302	+310	+590	+470	+878
-5	+23	+155	+311	+315	+599	+475	+887
0	+32	+160	+320	+320	+608	+480	+896
+5	+41	+165	+329	+325	+617	+485	+905
+10	+50	+170	+338	+330	+626	+490	+914
+15	+59	+175	+347	+335	+635	+495	+923
+20	+68	+180	+356	+340	+644	+500	+932
+25	+77	+185	+365	+345	+653	+505	+941
+30	+86	+190	+374	+350	+662	+510	+950
+35	+95	+195	+383	+355	+671	+515	+959
+40	+104	+200	+392	+360	+680	+520	+968
+45	+113	+205	+401	+365	+689	+525	+977
+50	+122	+210	+410	+370	+698	+530	+986
+55	+131	+215	+419	+375	+707	+535	+995

Conversion of Temperatures:

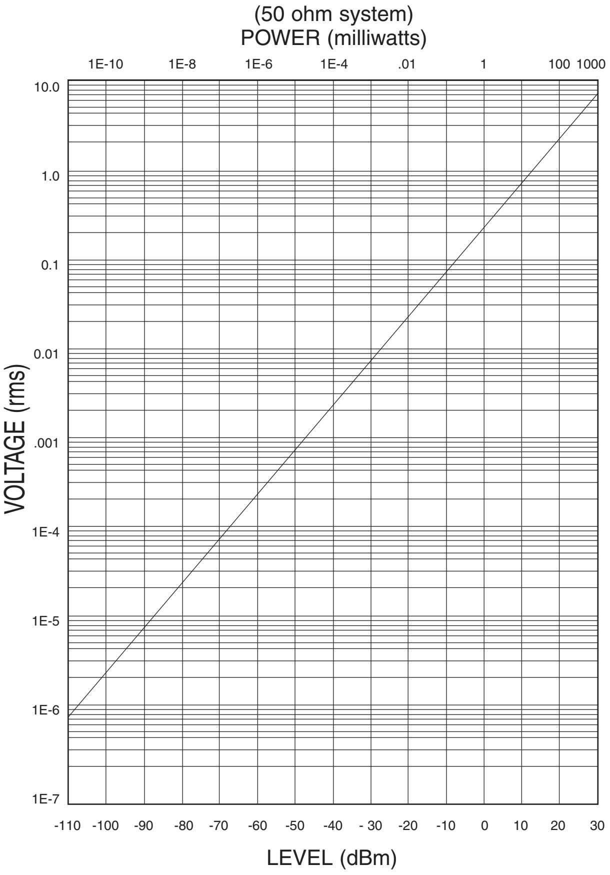
Celsius to Fahrenheit $T_F = 1.8\,T_C + 32$

Celsius to Kelvin $T_K = T_C + 273.15$

Fahrenheit to Celsius $T_C = \frac{T_F - 32}{1.8} = .5556\,(T_F - 32)$

Kelvin to Celsius $T_C = T_K - 273.15$

Voltage vs. Power



Decimal Equivalents Table

STANDARD DECIMAL PREFIXES

MULTIPLIER	PREFIX	ABBREVIATION	MULTIPLIER	PREFIX	ABBREVIATION
10^{18}	exa	E	10^{-2}	centi	c
10^{15}	peta	P	10^{-3}	milli	m
10^{12}	tera	T	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{6}	mega	M	10^{-12}	pico	p
10^{3}	kilo	k	10^{-15}	femto	f
10^{-1}	deci	d	10^{-18}	atto	a

1/64	.015625	33/64	.515625
1/32	.03125	17/32	.53125
3/64	.046875	35/64	.546875
1/16	.0625	9/16	.5625
5/64	.078125	37/64	.578125
3/32	.09375	19/32	.59375
7/64	.109375	39/64	.609375
1/8	.125	5/8	.625
9/64	.140625	41/64	.640625
5/32	.15625	21/32	.65625
11/64	.171875	43/64	.671875
3/16	.1875	11/16	.6875
13/64	.203125	45/64	.703125
7/32	.21875	23/32	.71875
15/64	.234375	47/64	.734375
1/4	.25	3/4	.75
17/64	.265625	49/64	.765625
9/32	.28125	25/32	.78125
19/64	.296875	51/64	.796875
5/16	.3125	13/16	.8125
21/64	.328125	53/64	.828125
11/32	.34375	27/32	.84375
23/64	.359375	55/64	.859375
3/8	.375	7/8	.875
25/64	.390625	57/64	.890625
13/32	.40625	29/32	.90625
27/64	.421875	59/64	.921875
7/16	.4375	15/16	.9375
29/64	.453125	61/64	.953125
15/32	.46875	31/32	.96875
31/64	.484375	63/64	.984375
1/2	.50	1	1.00

Alphabetized Conversion Table

TO CONVERT	MULTIPLY BY	TO OBTAIN
	A	
amperes/sq. cm.	6.452	amps/sq. in.
amperes/sq. in.	1.550×10^{-1}	amps/sq. cm.
angstrom unit	3.937×10^{-9}	inches
angstrom unit	1.0×10^{-4}	microns or (mu)
	B	
btu	2.928×10^{-4}	kilowatt - hours
btu/hr.	2.931×10^{-1}	watts
btu/min.	1.757×10^{1}	watts
	C	
centigrade (degrees)	$(C \times 9/5) + 32$	fahrenheit (degrees)
centigrade (degrees)	$C + 273.18$	kelvin (degrees)
centipoise	1.0×10^{-2}	gr./cm. - sec.
circumference	6.283	radians
cubic centimeters	6.102×10^{-2}	cubic in.
cubic centimeters	2.642×10^{-4}	gallons (u.s. liquid)
cubic inches	1.639×10^{1}	cu cms.
cubic inches	1.639×10^{-2}	liters
	D	
days	8.64×10^{4}	seconds
days	1.44×10^{3}	minutes
days	2.4×10^{1}	hours
degrees (angle)	1.745×10^{-2}	radians
degrees (angle)	3.6×10^{3}	seconds

Alphabetized Conversion Table

TO CONVERT	MULTIPLY BY	TO OBTAIN
	E	
ergs	9.486×10^{-11}	btu
ergs	1.0×10^{-7}	joules
ergs	2.773×10^{-14}	kilowatt - hrs.
ergs/sec.	5.668×10^{-9}	btu/min
ergs/sec.	1.0×10^{-10}	kilowatts
	F	
fathoms	6.0	feet
foot - candle	1.0764×10^{1}	lux
	G	
gallons	3.785×10^{3}	cu. cms.
gausses	1.0×10^{-8}	webers/sq. cm.
gausses	6.452×10^{-8}	webers/sq. in.
gausses	7.958×10^{-1}	amp. - turn/cm.
grams	3.527×10^{-2}	ounces (avdp)
grams	3.215×10^{-2}	ounces (troy)
grams	2.205×10^{-3}	pounds
	H	
horsepower	4.244×10^{1}	btu/min.
horsepower	7.457×10^{-1}	kilowatts

Alphabetized Conversion Table

(continued)

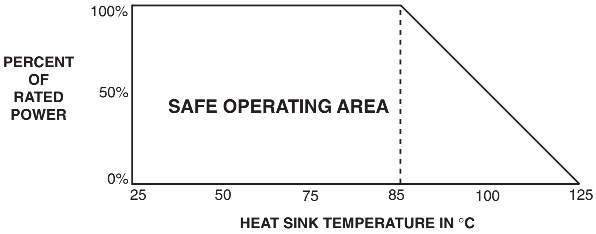
TO CONVERT	MULTIPLY BY	TO OBTAIN
	I	
inches	2.540	centimeters
inches	2.54×10^{1}	millimeters
inches	2.54×10^{8}	angstrom units
	J	
joules	9.486×10^{-4}	btu
joules	1.0×10^{7}	ergs
joules	2.778×10^{-4}	watt-hrs.
	K	
kilograms	2.2046	pounds
kilowatts	1.434×10^{1}	kg. - calories/hr.
knots	1.151	statute miles/hr.
	M	
miles (statute)	1.609	kilometers
miles (statute)	8.684×10^{-1}	miles (nautical)
miles/hr.	1.6093	kms./hr.
millimeters	3.937×10^{-2}	inches
millimeters	3.937×10^{1}	mils
mils	2.54×10^{-3}	centimeters
	O	
ounces	2.8349×10^{1}	grams

Alphabetized Conversion Table

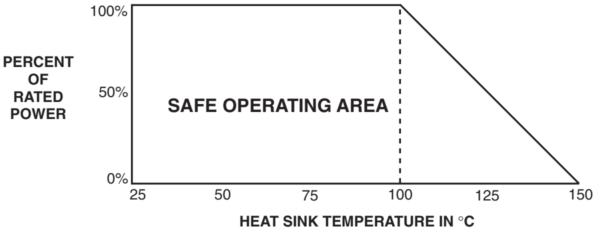
TO CONVERT	MULTIPLY BY	TO OBTAIN
	P	
pounds	4.5359×10^{2}	grams
pounds/sq. in.	7.03×10^{-2}	kgs./sq. cm.
	R	
radians	5.7296×10^{1}	degrees
reams	5.0×10^{2}	sheets
	S	
square centimeters	1.550×10^{-1}	sq. inches
square inches	6.452	sq. cms.
	V	
volt/inch	3.937×10^{-1}	volt/cm.
	W	
watts	3.4129	btu/hr.
watts	1.0×10^{7}	ergs/sec.
watts	9.48027×10^{-4}	btu/sec.
watt-hours	3.6×10^{10}	ergs
weeks	1.68×10^{2}	hours
weeks	1.008×10^{4}	minutes
	Y	
yards	9.144×10^{1}	centimeters
yards	9.144×10^{-1}	meters
yards	9.144×10^{2}	millimeters

Standard Derating Curves

Standard Derating Curve for Attenuators



Standard Derating Curve for Resistors and Terminations

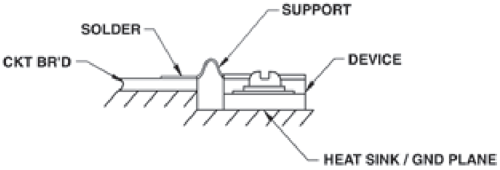


Mounting High Power Devices

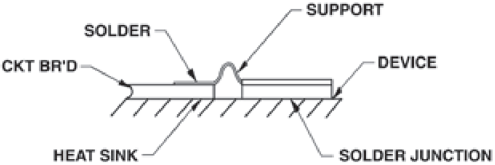
The area under the device should be flat to less than .001” and be free of burrs and scratches. The main criteria when mounting flange power devices is to make intimate contact with the heat sink. Air gaps at this interface will cause a very high thermal resistance barrier and must be avoided. Prior to drilling and tapping threads for the mounting screws, countersink the locations. This operation will prevent raising the threads above the mounting surface while tapping. The heat sink can now be given a coat of thermal grease, keeping the thickness to about .001 to .002 inches. The thermal grease will fill any small air gaps helping maintain good thermal contact. Before mounting the device, a small strain relief should be formed within the tab. While forming a small half loop, the tab should be supported to prevent excessive force toward the cover substrate. Pretinning the tab prior to installation and wicking off the excess will remove most of the gold plating. This is highly recommended as it will prevent gold embrittlement in the final solder connection. Seat the device into the thermal grease, install screws with a lock washer and a flat washer, and torque as specified in the following table:

Thread No.	Mounting Torque
4 - 40	6 inch - lbs
6 - 32	8 inch - lbs
8 - 32	12 inch - lbs
10 - 24	18 inch - lbs

Position the tab over the circuit and solder in place. Sn63 is recommended for all solder operations.



When mounting an unflanged device, pretinning the device ground plane and the heat sink are necessary. In this operation, the device and the heat sink will become an integral part. Sn62 solder is used here because it reduces the amount of leaching between the silver in the ground plane and the solder. The tab contacts are treated the same way as a flanged device. Reflow the solder and position the device on the heat sink. Apply a downward force overcoming the surface tension of the solder, and settle the device down to the heat sink surface. The goal is to eliminate air voids and make the solder junction thin. While maintaining the downward force, allow the solder to cool.



It is recommended that a small amount of RMA flux (per MIL-F-14256) be used in any of the soldering operations. Remove flux when complete with isopropyl alcohol.

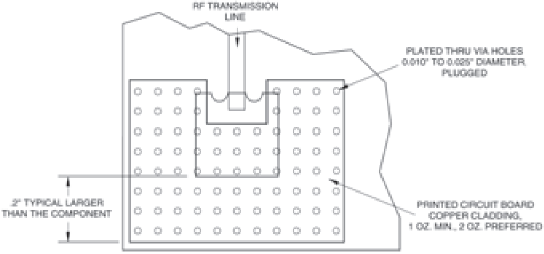
Mounting Surface Mount Terminations & Attenuators

The low cost and convenience of surface mount components and automated installation is inspiring new surface mount high power components that have previously required chassis mounting. The design of systems using high power surface mount components requires careful attention to the electrical grounding and heat sinking of the component to achieve specified performance and power handling. Because the component will be attached to a printed circuit board instead of a metal chassis, finite inductance to ground will be introduced. For terminations, VSWR may rise with increasing frequency and for attenuators, attenuation flatness may degrade. The relatively high thermal resistance of the printed circuit board compared to a metal mounting surface will result in lower power handling limits to maintain reliable operating temperatures. Properly designed surface mount printed circuit will minimize these effects and allow high performance.

The best way to decrease printed circuit board inductance to ground and thermal resistance is to maximize the amount of plated through via holes under and around the surface mount component and specify heavy copper cladding (2 oz.) to spread the dissipated heat.

Mounting Surface Mount Terminations & Attenuators *(continued)*

Typical Printed Circuit Board Layout for a High Power Surface Mount Component



Filled or plugged via holes should be used to avoid component attachment solder from wicking down to the bottom surface of the printed circuit board. High Temperature solder such as Sn96 is preferable to Sn62. Because of relatively high thermal resistance mounting, most devices will be capable of reflowing their attachment solder before device damage occurs if extremely high RF power is applied. Application of thermally conductive elastomers or epoxies around the perimeter of the part will aid in heat spreading also, however the top surface should be avoided to eliminate detuning of the internal matching structures.

Solders Per QQ-S-571

Composition	**Melting Range**	
	Solidus	**Liquidus**
Sn96	221˚C	221˚C
Sn70	183˚C	193˚C
Sn63	183˚C	183˚C
Sn62	179˚C	179˚C
Sn60	183˚C	191˚C
Sn50	183˚C	216˚C
Sn40	183˚C	238˚C
Sn35	185˚C	243˚C
Sn30	185˚C	250˚C
Sn20	184˚C	270˚C
Sn10	268˚C	290˚C
Sn5	308˚C	312˚C
Sb5	235˚C	240˚C
Pb80	183˚C	277˚C
Pb70	183˚C	254˚C
Pb65	183˚C	246˚C
Ag1.5	309˚C	309˚C
Ag2.5	304˚C	304˚C
Ag5.5	304˚C	380˚C
Other Commonly Used Solders		
Gold Germanium 88/12	356˚C	356˚C
Gold Tin 80/20	280˚C	280˚C
Indium 100%	157˚C	157˚C

Most microwave testing can be accomplished with scalar analyzers. The classic parameters SWR, return loss, insertion loss and attenuation are magnitude only and are scalar measurements. There are uncertainties in making these measurements but broadband high directivity and well matched detectors minimize them. As such the measurements are adequate for characterizing coaxial cable assemblies, attenuators and terminations.

The electrical lengths of coaxial cable assemblies are often required to be the same. For this kind of measurement, a vector network analyzer is required. A vector network analyzer gives the phase information required to measure electrical length. Measurements can be relative or an absolute electrical length and are units of degrees. It is advisable to create a phase standard when an electrical length requirement is imposed. The derivative of the above measurement, which is the phase slope vs. frequency, is an important parameter and is called group delay. It is a measure of transit time through an assembly and for distortion free output the delay should be linear. Here again a standard should be created and maintained.

Characterizing flanged resistors, terminations, and attenuators begins with fixturing. Florida RF Labs uses soft micostrip transmission lines in its fixtures. Various 50Ω lines with dielectric constants of 2.20 and 6.15 and board thicknesses of .025, .050, and .062 inches allow broad frequency coverage and accommodates different tab contact widths without causing mismatches. Coaxial transitions are also selected to minimize mismatches on both one port and two port test fixtures. Measurements are made with a Wiltron 360 Vector Network Analyzer with 40 GHz capability. The procedure is to set a gate around the DUT (Device Under Test) in time domain and applying the gate in the frequency domain, removing unwanted reflections of the test fixtures. This will allow a clean SWR or Return Loss measurement of the DUT. When impedance information is required the measurement plane is electronically moved to the input of the DUT yielding useful impedance data. When attenuation measurements are required the fixture losses are normalized by the network analyzer.

RF Matching

In most applications of flanged power devices, minimum reflection is the main criteria. Reflections cause standing waves which result in inefficient transmission of energy. The worst case is when the forward wave and the reflected wave are in phase, creating a voltage peak which can lead to total breakdown of the transmission line.

When mounting a device, the line impedance should be considered. If the transmission line is narrow, select a tab width that is slightly narrower, thus eliminating an unwanted shunt capacitive susceptance which would be created by a wider tab. That same tab width can also be used as an inductive reactance by sliding the device away from the end of the transmission line. This kind of a manipulation of a tab usually results in a narrower band match. Broadband matching will require additional elements in the form of a quarter wave open and shorted stubs. There are two types of matching that can be accomplished. One is a conjugate match that results in the maximum transfer of power from the source to the load. In the second, the load is matched to the transmission line and yields a minimum of reflections on the line.

Terminations such as 32-1034 (30 watts), 32-1036 (60 watts), 32-1026 (150 watts), and 32-1037 (250 watts) have been internally matched to reduce the reactive components to a minimum. The only requirement is careful mounting to obtain repeatable performance. Impedance plots are available from Florida RF Labs for these and other high power terminations.

Temperature Co-efficient of Attenuation (TCA) Calculation

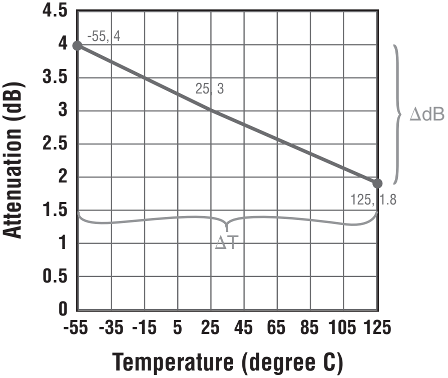
DEFINITIONS:

ΔdB - Total amount of compensation required
ΔT - Total amount of temperature change in the system.
dBnom - Nominal Attenuation

Temp. (C˚)	Atten. (dB)
-55	4
25	3
125	1.8
ΔT = 180	ΔdB = 2.2

TCA = ΔdB / dBnom. / ΔT
= 2.16 dB / 3 dB / 180˚C
= -0.0041

Attenuation vs. Temperature



3N04

TCA (dB/dB/˚C)
TCA Slope (N = Negative)
Nominal Attenuation

Coaxial Transmission Lines

All communication and radar systems incorporate some form of transmission lines. Coaxial transmission lines integrate systems by way of black box interconnections. Configurations include connector cable assemblies ranging from less than one inch to more than a hundred feet. Construction consists of two concentric inner and outer conductors separated by an insulation material. The conductor’s diameter ratio and insulator’s dielectric constant will determine an important parameter, the Characteristic Impedance (Z_o). This typically is 50 ohms for most microwave applications.

There are two basic types of coaxial cable. One is flexible, which has an outer conductor made up of fine silver plated copper wires braided over the insulation material. Other outer conductors using silver plated, wide copper strips braided into a basket weave configuration to hundreds of silver plated, copper wires running parallel to one another in a long spiral have been designed to improve the shielding effectiveness and stability of flexible cables.

Semi-rigid coaxial cable has a solid outer conductor and is manufactured by drawing seamless copper or aluminum tubing over the insulating material. It is electrically superior with 100% shielding effectiveness, lower loss, extended frequency range and uniform impedance. Other outer conductors may include stainless steel, used in cryogenic systems. Insulating materials are commonly known as dielectrics. The more prominent dielectrics are Polyethylene and Polytetrafluoroethylene (PTFE). PTFE is available in solid, splined and expanded or perforated tape wrap. Polyethylene is available in solid or foamed.

Various inner conductors are available to meet a variety of requirements. Semi-rigid inner conductors are typically solid silver plated copper and have the advantage of being non-magnetic with the lowest loss. Silver plated copper clad steel in .141 diameter size allows the center conductor to be used as the mating contact of the SMA interface.

Stranded, flexible inner conductors are common in flexible cable. Larger flexible cables may use copper clad aluminum for weight requirements.

Selection of coaxial cable should begin with the characteristic impedance and operating frequency required for the system. Equation 1 *(in the table of Equations for Coaxial Transmission Lines)* denotes impedance as a function of the inner and outer conductor's dimensional ratio with the dielectric constant of the insulating material. Maintaining the proper ratio will give a wide variety of cable sizes. The operation frequency will dictate the size of cable to select. A large diameter cable will not operate as high in frequency as a smaller diameter cable. If the conductor materials and the cable dielectric are the same, the larger cable will have lower attenuation. Equation 6 and the cable's specifications for attenuation vs. frequency will aid in making a decision as to which cable to choose.

Expanded PTFE and foamed polyethylene are used for low loss applications. If the application is for a specific time delay, the low loss cables may not be an advantage because the propagation velocity is higher. This requires additional line length to obtain a given delay.

In systems such as multichannel radar systems, the signals must arrive at the antenna elements with equal magnitude and at precisely the same time. For this application, the dielectric constant must be uniform and constant with frequency.

When selecting connectors, there are sometimes many variables to consider. Frequency range, VSWR, insertion loss, phase, repeatability, cost and size are among a few. When choosing cable to match a connector, you will always obtain better results by attempting to match cable and connector sizes. For example: A Type N connector is chosen for a particular system. Type N parameters are - Body I.D. = .390 and Contact O.D. = .120. A small cable will require a large (or many) transitions, yielding high magnitude reflections. A good example of compatible sizing would be the case of an SMA connector matched with .141 semi-rigid or RG/U 142 flexible cables. This match will yield low magnitude reflections, resulting in low magnitude and phase deviations over frequency.

Equations for Coaxial Transmission Lines

Characteristic Impedance	(eq 1)	$Z_O = \frac{59.959}{\sqrt{\varepsilon_r}} \cdot \ln\frac{b}{a}$
Velocity of Propagation	(eq 2)	$V_P = \frac{c}{\sqrt{\varepsilon_r}}$
Free Space Wavelength	(eq 3)	$\lambda = \frac{c}{f}$
Electrical Length	(eq 4)	$\phi = \frac{-360\sqrt{\varepsilon_r} \cdot Lf}{c}$
Time Delay	(eq 5)	$T_D = \frac{\sqrt{\varepsilon_r} \cdot L}{c}$
Cutoff Frequency	(eq 6)	$f_C = \frac{c}{\pi(a+b)\sqrt{\mu_r \varepsilon_r}}$
Capacitance	(eq 7)	$C' = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln\frac{b}{a}}$
Inductance	(eq 8)	$L' = \frac{\mu_o\mu_r}{2\pi} \cdot \ln\frac{b}{a}$
Skin Depth	(eq 9)	$\delta_S = \frac{1}{\sqrt{\pi f \mu_o \mu_r \sigma}}$
Conductor Loss	(eq 10)	$\alpha_C = 13.6 \; \frac{\delta_S\sqrt{\varepsilon_r} . 1 + \frac{b}{a}}{\lambda b \cdot \ln\frac{b}{a}}$
Dielectric Loss	(eq 11)	$\alpha_\alpha = 27.3 \; \frac{\sqrt{\varepsilon_r}}{\lambda} \cdot \tan(\delta)$
Coaxial Line Loss	(eq 12)	$\alpha_T = \alpha_C + \alpha_\alpha$

Symbols for Coaxial Transmission Lines

Symbol	Description	Units
b	Inside radius of outer conductor	meter
a	Outside radius of center conductor	meter
ε_r	Relative permittivity (dielectric constant)	1
ε_o	Permittivity of free space (8.854×10^{-12})	Farad/meter
c	Velocity of light in free space (299.7925×10^{6})	meter/second
μ_r	Relative permeability	1
μ_o	Permeability of free space ($4\pi \times 10^{-7}$)	Henry/meter
f	Frequency	Hertz
f_C	Cutoff frequency	Hertz
ϕ	Phase length	degree
T_D	Time delay	second
V_P	Velocity of propagation	meter/second

Symbols for Coaxial Transmission Lines

Symbol	Description	Units
Z_o	Characteristic impedance	ohm
C	Capacitance per unit length	Farad/meter
L	Inductance per unit length	Henry/meter
δ_s	Skin depth	meter
σ	Conductivity	Mho/meter
α_c	Attenuation constant, conductors	dB/meter
α_d	Attenuation constant, dielectric	dB/meter
α_T	Attenuation constant, total	dB/meter
λ	Wavelength in free space	meter
tan δ	Loss tangent	meter

International System of Units

INTERNATIONAL SYSTEM OF UNITS

Quantity	Unit	Symbol	Dimensions
Capacitance	farad	F	C/V
Conductance	siemens	S	A/V
Current	ampere	A	A
Electric charge	coulomb	C	A-s
Energy	joule	J	N-m
Force	newton	N	kg-m/s^2
Frequency	hertz	Hz	1/s
Inductance	henry	H	Wb/A
Length	meter	m	m
Magnetic flux	weber	Wb	V-s
Magnetic induction	tesla	T	Wb/m^2
Mass	kilogram	kg	kg
Potential	volt	V	J/C
Power	watt	W	J/s
Pressure	pascal	Pa	N/m^2
Resistance	ohm	Ω	V/A
Temperature	kelvin	K	K
Time	second	s	s

Standard & Current Frequency Designations

STANDARD FREQUENCY DESIGNATIONS

HF	3 MHz - 30 MHz
VHF	30 MHz - 300 MHz
UHF	300 MHz - 1.0 GHz
L	1.0 GHz - 2.0 GHz
S	2.0 GHz - 4.0 GHZ
C	4.0 GHz - 8.0 GHZ
X	8.0 GHz - 12.0 GHz
Ku	12.0 GHz - 18.0 GHz
K	18.0 GHz - 27.0 GHz
Ka	27.0 GHz - 40.0 GHz

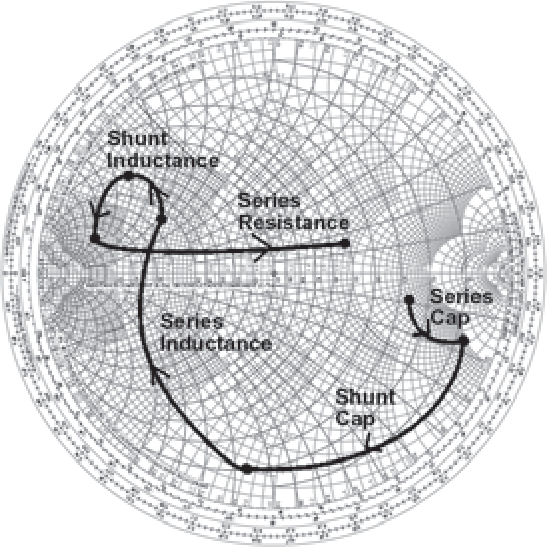
CURRENT FREQUENCY DESIGNATIONS

A	250 MHz - 500 MHz
B	500 MHz - 1.0 GHz
C	1.0 GHz - 2.0 GHz
E	2.0 GHz - 3.0 GHz
F	3.0 GHz - 4.0 GHz
G	4.0 GHz - 6.0 GHz
H	6.0 GHz - 8.0 GHZ
I	8.0 GHz - 10.0 GHz
J	10.0 GHz - 20.0 GHz
K	20.0 GHz - 40.0 GHz
L	40.0 GHz - 60.0 GHz
M	60.0 GHz - 100.0 GHz

Electromagnetic Spectrum

FREQUENCY	WAVELENGTH (free space)	DESIGNATION	APPLICATIONS
< 3 Hz	> 100 Mm		Geophysical prospecting
3-30 Hz	10-100 Mm	ELF	Detection of buried metals
30-300 Hz	1-10 Mm	SLF	Power transmission, submarine communications
0.3-3 kHz	0.1-1 Mm	ULF	Telephone, audio
3-30 kHz	10-100 km	VLF	Navigation, positioning, naval communications
30-300 kHz	1-10 km	LF	Navigation, radio beacons
0.3-3 MHz	0.1-1 km	MF	AM broadcasting
3-30 MHz	10-100 m	HF	Short wave, citizens' band
30-300 MHz	1-10 m	VHF	TV, FM, police
54-72			TV channels 2-4
76-88			TV channels 5-6
88-108			FM radio
174-216			TV channels 7-13
0.3-3 GHz	10-100 cm	UHF	Radar, TV, GPS, cellular phone
470-890 MHz			TV channels 14-83
915 MHz			Microwave ovens (Europe)
800-2500 MHz		"money band"	PCS cellular phones, analog at 900 MHz, GSM/CDMA at 1900
1-2			L-band, GPS system
2.45			Microwave ovens (U.S.)
2-4			S-band
3-30 GHz	1-10 cm	SHF	Radar, satellite communications
4-8			C-band
8-12			X-band (Police radar at 11 GHz)
12-18			K_u-band (dBS Primestar at 14 GHz)
18-27			K-band (Police radar at 22 GHz)
30-300 GHz	0.1-1 cm	EHF	Radar, remote sensing
27-40			K_a-band (Police radar at 35 GHz)
40-60			U-band
60-80			V-band
80-100			W-band
0.3-1 THz	0.3-1 mm	Millimeter	Astronomy, meteorology
10^{12}-10^{14} Hz	3-300 μm	Infrared	Heating, night vision, optical communications
3.95 x 10^{14}-7.7 x 10^{14} Hz	390-760 nm	Visible light	Vision, astronomy, optical communications
	625-760		Red
	600-625		Orange
	577-600		Yellow
	492-577		Green
	455-492		Blue
	390-455		Violet
10^{15}-10^{18} Hz	0.3-300 nm	Ultraviolet	Sterilization
10^{16}-10^{21} Hz		X-rays	Medical diagnosis
10^{18}-10^{22} Hz		γ-rays	Cancer therapy, astrophysics
> 10^{22} Hz		Cosmic rays	Astrophysics

Impedance Smith Chart



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