R. Ludwig and G. Bogdanov
"RF Circuit Design: Theory and Applications"
2nd edition

Figures for Appendices

Table A-1 Physical constants

Quantity	Symbol	Units	Value
Permittivity in vacuum	ε_0	F/m	8.85418×10^{-12}
Permeability in vacuum	μ_0	H/m	$4\pi \times 10^{-7}$
Speed of light in vacuum	c	m/s	2.99792×10^{8}
Boltzmann's constant	k	J/K	1.38066×10^{-23}
Electron charge	e	C	1.60218×10^{-19}
Electron rest mass	m_0	kg	0.91095×10^{-30}
Electon volt	eV	J	1.60218×10^{-19}

Table A-2 Relevant quantities, units, and symbols

Quantity	Symbol	Units	Value
femto	f	—	10^{-15}
pico	p	—	10^{-12}
nano	n	—	10^{-9}
micro	μ	—	10^{-6}
milli	m	—	10^{-3}
kilo	k	—	10^{3}
mega	M	—	10^{6}
giga	G	—	10^{9}
tera	T	—	10^{12}
mil	mil	0.001 inch = 25.4 μm	
International System of Units			
Quantity	**Symbol**	**Units**	**Dimensions**
Electric Charge	C	coulomb	A · s
Current	A	ampere	C ⁄ s
Voltage	V	volts	J ⁄ C
Frequency	Hz	hertz = cycles per second	1 ⁄ s
Electric field	E	V/m	
Magnetic field	H	A/m	
Magnetic flux	Wb	weber	V · s
Energy	J	joule	N · m
Power	W	watt	J ⁄ s
Capacitance	F	farad	C ⁄ V
Inductance	H	henry	Wb ⁄ A
Resistance	Ω	ohm	V ⁄ A
Conductance	S	siemens	A ⁄ V
Conductivity	σ	S/m	
Resistivity	ρ	Ω · m	

Table A-3 Relative permittivity and loss tangent for different dielectric materials

Material	ε_r	Loss Tangent			
		f = 1 kHz	f = 1 MHz	f = 100 MHz	f = 3 GHz
Aluminum oxide	9.8	0.00057	0.00033	0.0003	0.001
Barium titanate	37	0.00044	0.0002		0.0023
Porcelain	5	0.0140	0.0075	0.0078	
Silicon dioxide	4.5	0.00075	0.0001	0.0002	0.00006
Araldite CN-501	3.35	0.0024	0.0190	0.0340	0.0270
Epoxy resin RN-48	3.52	0.0038	0.0142	0.0264	0.0210
Foamed polystyrene	1.03	<0.0002	<0.0001	<0.0002	0.0001
Bakelite BM120	3.95	0.0220	0.0280	0.0380	0.0438
Polyethylene	2.3	<0.0002	<0.0002	0.0002	0.00031
Polystyrene	2.5	<0.00005	0.00007	<0.0001	0.00033
Teflon	2.1	<0.0003	<0.0002	<0.0002	0.00015
Sodium chloride	5.9	<0.0001	<0.0002		<0.0005
Water (distilled)	80		0.0400	0.0050	0.1570

Table A-4 American wire gauge chart

Wire Size (AWG)	Diameter in mils	Diameter in millimeters	Area in square mils	Area in square millimeters
1	289.3	7.34822	262934	169.6345
2	257.6	6.54304	208469	134.4959
3	229.4	5.82676	165324	106.6606
4	204.3	5.18922	131125	84.59682
5	181.9	4.62026	103948	67.06296
6	162.0	4.1148	82448.0	53.19212
7	144.3	3.66522	65415.8	42.20364
8	128.5	3.2639	51874.8	33.46752
9	114.4	2.90576	41115.2	26.52585
10	101.9	2.58826	32621.1	21.04581
11	90.7	2.30378	25844.2	16.67370
12	80.8	2.05232	20510.3	13.23244
13	72.0	1.8288	16286.0	10.50709
14	64.1	1.62814	12908.2	8.327859
15	57.1	1.45034	10242.9	6.608296
16	50.8	1.29032	8107.32	5.230518
17	45.3	1.15062	6446.83	4.159237
18	40.3	1.02362	5102.22	3.291754
19	35.9	0.91186	4048.92	2.612199
20	32.0	0.8128	3216.99	2.075474
21	28.5	0.7239	2551.76	1.646293
22	25.3	0.64262	2010.90	1.297354
23	22.6	0.57404	1604.60	1.035224
24	20.1	0.51054	1269.23	0.818860

Table A-4 American wire gauge chart (Continued)

Wire Size (AWG)	Diameter in mils	Diameter in millimeters	Area in square mils	Area in square millimeters
25	17.9	0.45466	1006.60	0.649417
26	15.9	0.40386	794.226	0.512403
27	14.2	0.36068	633.470	0.408690
28	12.6	0.32004	498.759	0.321780
29	11.3	0.28702	401.150	0.258806
30	10.0	0.254	314.159	0.202683
31	8.9	0.22606	248.846	0.160545
32	8.0	0.2032	201.062	0.129717
33	7.1	0.18034	158.368	0.102172
34	6.3	0.16002	124.690	0.080445
35	5.6	0.14224	98.5203	0.063561
36	5.0	0.127	78.5398	0.050671
37	4.5	0.1143	63.6173	0.041043
38	4.0	0.1016	50.2654	0.032429
39	3.5	0.0889	38.4845	0.024829
40	3.1	0.07874	30.1907	0.019478

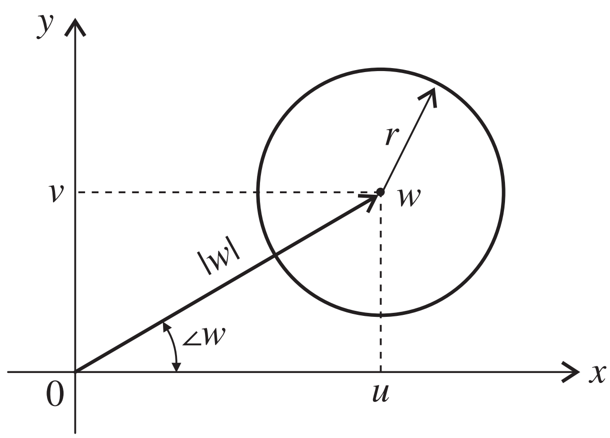


Figure C-1 Circle representation in the complex *z*-plane.

Conversion between **Z**, **Y**, **h**, and **ABCD** representations

	[**Z**]	[**Y**]	[**h**]	[**ABCD**]
[**Z**]	$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$	$\begin{bmatrix} \frac{Z_{22}}{\Delta Z} & -\frac{Z_{12}}{\Delta Z} \\ -\frac{Z_{21}}{\Delta Z} & \frac{Z_{11}}{\Delta Z} \end{bmatrix}$	$\begin{bmatrix} \frac{\Delta Z}{Z_{22}} & \frac{Z_{12}}{Z_{22}} \\ -\frac{Z_{21}}{Z_{22}} & \frac{1}{Z_{22}} \end{bmatrix}$	$\begin{bmatrix} \frac{Z_{11}}{Z_{21}} & \frac{\Delta Z}{Z_{21}} \\ \frac{1}{Z_{21}} & \frac{Z_{22}}{Z_{21}} \end{bmatrix}$
[**Y**]	$\begin{bmatrix} \frac{Y_{22}}{\Delta Y} & -\frac{Y_{12}}{\Delta Y} \\ -\frac{Y_{21}}{\Delta Y} & \frac{Y_{11}}{\Delta Y} \end{bmatrix}$	$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$	$\begin{bmatrix} \frac{1}{Y_{11}} & -\frac{Y_{12}}{Y_{11}} \\ \frac{Y_{21}}{Y_{11}} & \frac{\Delta Y}{Y_{11}} \end{bmatrix}$	$\begin{bmatrix} -\frac{Y_{22}}{Y_{21}} & -\frac{1}{Y_{21}} \\ -\frac{\Delta Y}{Y_{21}} & -\frac{Y_{11}}{Y_{21}} \end{bmatrix}$
[**h**]	$\begin{bmatrix} \frac{\Delta h}{h_{22}} & \frac{h_{12}}{h_{22}} \\ -\frac{h_{21}}{h_{22}} & \frac{1}{h_{22}} \end{bmatrix}$	$\begin{bmatrix} \frac{1}{h_{11}} & -\frac{h_{12}}{h_{11}} \\ \frac{h_{21}}{h_{11}} & \frac{\Delta h}{h_{11}} \end{bmatrix}$	$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$	$\begin{bmatrix} -\frac{\Delta h}{h_{21}} & -\frac{h_{11}}{h_{21}} \\ -\frac{h_{22}}{h_{21}} & -\frac{1}{h_{21}} \end{bmatrix}$
[**ABCD**]	$\begin{bmatrix} \frac{A}{C} & \frac{\Delta ABCD}{C} \\ \frac{1}{C} & \frac{D}{C} \end{bmatrix}$	$\begin{bmatrix} \frac{D}{B} & -\frac{\Delta ABCD}{B} \\ -\frac{1}{B} & \frac{A}{B} \end{bmatrix}$	$\begin{bmatrix} \frac{B}{D} & \frac{\Delta ABCD}{D} \\ -\frac{1}{D} & \frac{C}{D} \end{bmatrix}$	$\begin{bmatrix} A & B \\ C & D \end{bmatrix}$

$$\Delta Z = Z_{11}Z_{22} - Z_{12}Z_{21}, \quad \Delta Y = Y_{11}Y_{22} - Y_{12}Y_{21},$$

$$\Delta h = h_{11}h_{22} - h_{12}h_{21}, \ \Delta ABCD = AD - BC$$

Conversion from *S*-parameters to **Z**, **Y**, **h**, or **ABCD** representations

$[\mathbf{Z}]$	$Z_{11} = Z_0 \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{\Psi_1}$ $\quad Z_{12} = Z_0 \frac{2S_{12}}{\Psi_1}$ $\quad Z_{21} = Z_0 \frac{2S_{21}}{\Psi_1}$ $Z_{22} = Z_0 \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{\Psi_1}$ where $\Psi_1 = (1-S_{11})(1-S_{22})-S_{12}S_{21}$
$[\mathbf{Y}]$	$Y_{11} = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{Z_0\Psi_2}$ $\quad Y_{12} = \frac{-2S_{12}}{Z_0\Psi_2}$ $\quad Y_{21} = \frac{-2S_{21}}{Z_0\Psi_2}$ $Y_{22} = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{Z_0\Psi_2}$ where $\Psi_2 = (1+S_{11})(1+S_{22})-S_{12}S_{21}$
$[\mathbf{h}]$	$h_{11} = Z_0 \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{\Psi_3}$ $\quad h_{12} = \frac{2S_{12}}{\Psi_3}$ $\quad h_{21} = \frac{-2S_{21}}{\Psi_3}$ $h_{22} = \frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{Z_0\Psi_3}$ where $\Psi_3 = (1-S_{11})(1+S_{22})+S_{12}S_{21}$
$[\mathbf{ABCD}]$	$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}$ $\quad B = Z_0 \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$ $C = \frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}Z_0}$ $\quad D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}$

Conversion from **Z**, **Y**, **h**, and **ABCD** representations to *S*-parameters

[**Z**]	$S_{11} = \frac{(Z_{11} - Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}}{\Psi_4}$ $\quad S_{12} = \frac{2Z_{12}Z_0}{\Psi_4}$ $\quad S_{21} = \frac{2Z_{21}Z_0}{\Psi_4}$ $S_{22} = \frac{(Z_{11} + Z_0)(Z_{22} - Z_0) - Z_{12}Z_{21}}{\Psi_4}$ where $\Psi_4 = (Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}$
[**Y**]	$S_{11} = \frac{(1 - Z_0Y_{11})(1 + Z_0Y_{22}) + Y_{12}Y_{21}Z_0^2}{\Psi_5}$ $\quad S_{12} = \frac{-2Y_{12}Z_0}{\Psi_5}$ $\quad S_{21} = \frac{-2Y_{21}Z_0}{\Psi_5}$ $S_{22} = \frac{(1 + Z_0Y_{11})(1 - Z_0Y_{22}) + Y_{12}Y_{21}Z_0^2}{\Psi_5}$ where $\Psi_5 = (1 + Z_0Y_{11})(1 + Z_0Y_{22}) - Y_{12}Y_{21}Z_0^2$
[**h**]	$S_{11} = \frac{(h_{11}/Z_0 - 1)(h_{22}Z_0 + 1) - h_{12}h_{21}}{\Psi_6}$ $\quad S_{12} = \frac{2h_{12}}{\Psi_6}$ $\quad S_{21} = \frac{-2h_{21}}{\Psi_6}$ $S_{22} = \frac{(h_{11}/Z_0 + 1)(1 - h_{22}Z_0) + h_{12}h_{21}}{\Psi_6}$ where $\Psi_6 = (h_{11}/Z_0 + 1)(h_{22}Z_0 + 1) - h_{12}h_{21}$
[**ABCD**]	$S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{\Psi_7}$ $\quad S_{12} = \frac{2(AD - BC)}{\Psi_7}$ $\quad S_{21} = \frac{2}{\Psi_7}$ $S_{22} = \frac{-A + B/Z_0 - CZ_0 + D}{\Psi_7}$ where $\Psi_7 = A + B/Z_0 + CZ_0 + D$

Table E-5 Properties of Ge, Si, GaAs, InP, 4H-SiC, GaN and SiGe at 300 K

Properties	Ge	Si	GaAs	InP	4H-SiC	GaN	$Si_{.5}Ge_{.5}$
Dielectric constant	16	11.9	13.1	12.5	10	9.5	13.9
Energy gap, eV	0.66	1.12	1.424	1.344	3.23	3.39	0.945
Intrinsic carrier concentration, cm^{-3}	2.40×10^{13}	1.45×10^{10}	1.79×10^{6}	1.30×10^{7}	1.50×10^{-8}	3.00×10^{10}	1.20×10^{13}
Intrinsic resistivity, $\Omega \cdot cm$	47	2.30×10^{5}	1.00×10^{8}	8.60×10^{7}	1.00×10^{12}	1.00×10^{10}	1.15×10^{5}
Minority carrier lifetime, s	1.00×10^{-3}	2.50×10^{-3}	1.00×10^{-8}	2.00×10^{-9}	1.00×10^{-9}	1.00×10^{-9}	1.75×10^{-3}
Electron mobility (drift), $cm^2/(V \cdot s)$	3900	1350	8500	4600	1140	1250	7700
Normalized effective mass of the electron	0.55	1.08	0.067	0.073	0.29	0.2	0.92
Hole mobility (drift), $cm^2/(V \cdot s)$	1900	480	400	150	50	850	1175
Normalized effective mass of the hole	0.37	0.56	0.48	0.64	1	0.8	0.54
Saturated electron velocity, cm/s	6.00×10^{6}	1.00×10^{7}	1.00×10^{7}	1.00×10^{7}	2.00×10^{7}	2.20×10^{7}	1.00×10^{7}
Breakdown electric field, V/cm	1.00×10^{5}	3.00×10^{5}	6.00×10^{5}	5.00×10^{5}	3.50×10^{6}	2.00×10^{6}	2.00×10^{5}
Electron affinity χ, V	4	4.05	4.07	4.38	3.7	4.1	4.025
Specific heat, $J/(g \cdot K)$	0.31	0.7	0.35	0.31	0.69	0.49	0.505
Thermal conductivity, $W/(cm \cdot K)$	0.6	1.5	0.46	0.68	3.7	1.3	0.083
Thermal diffusivity, cm^2/s	0.36	0.9	0.24	0.372	1.7	0.43	0.63

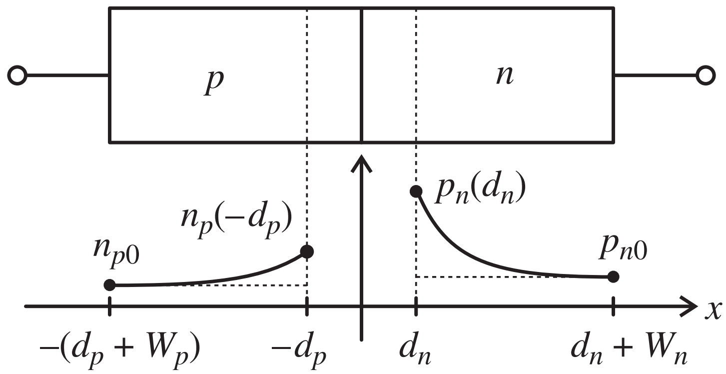


Figure F-1 P_n-junction under forward bias.

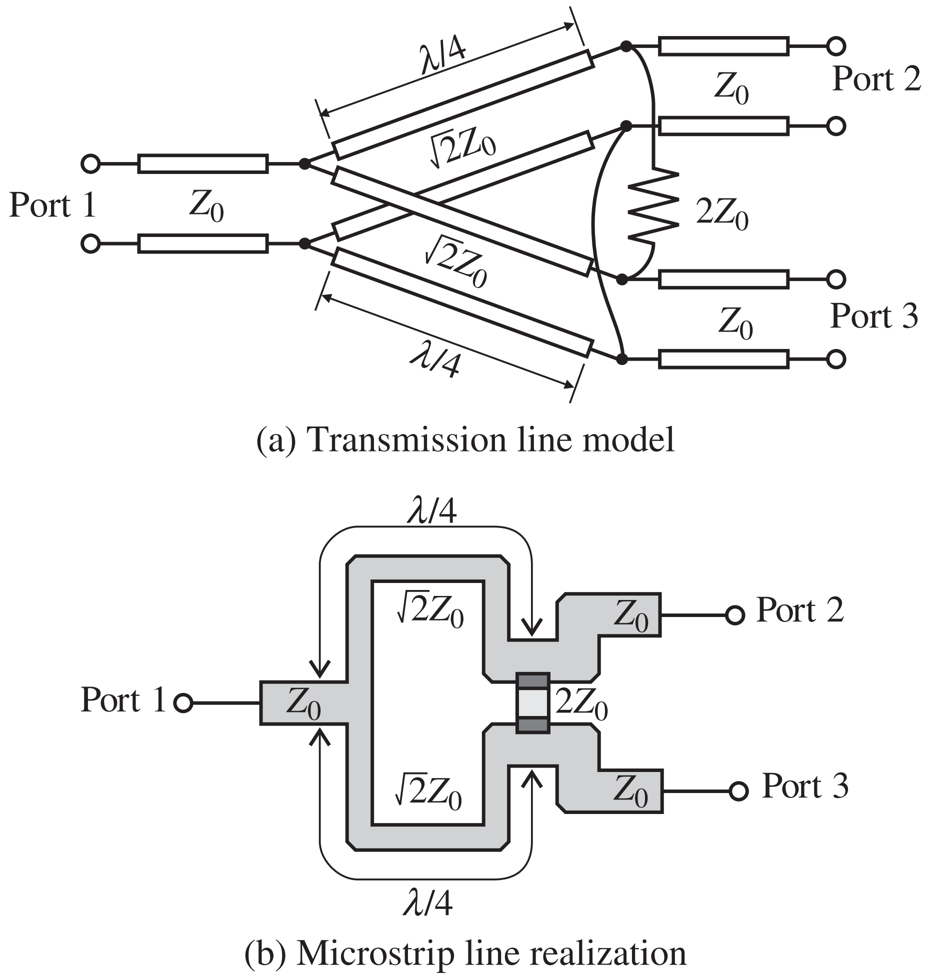


Figure G-1 3 dB Wilkinson power divider.

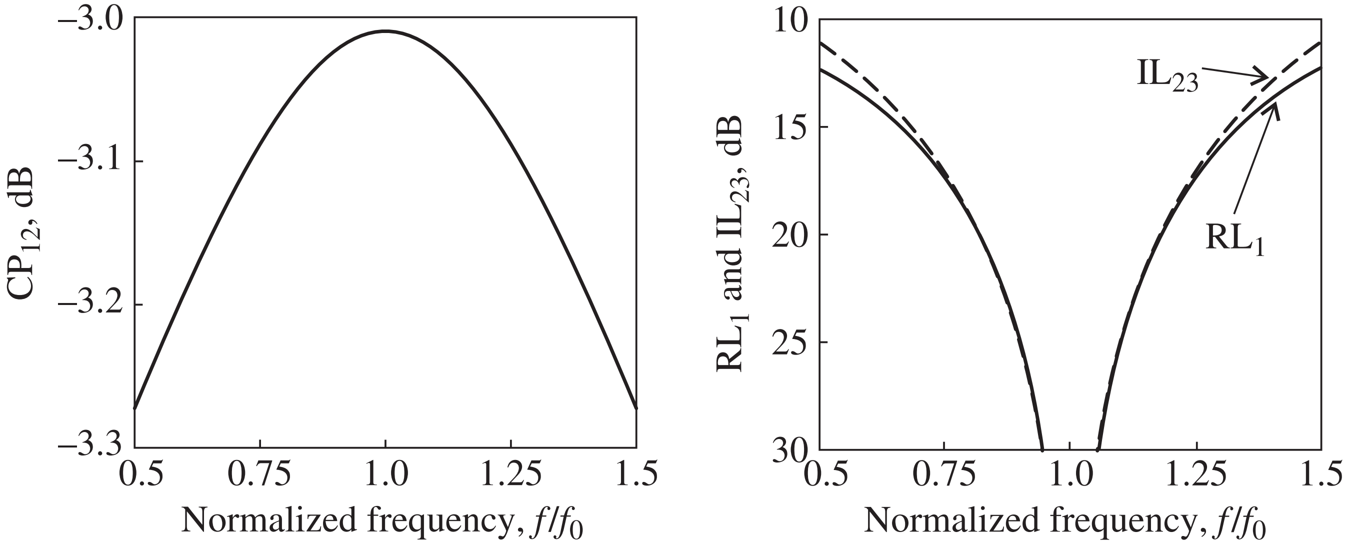
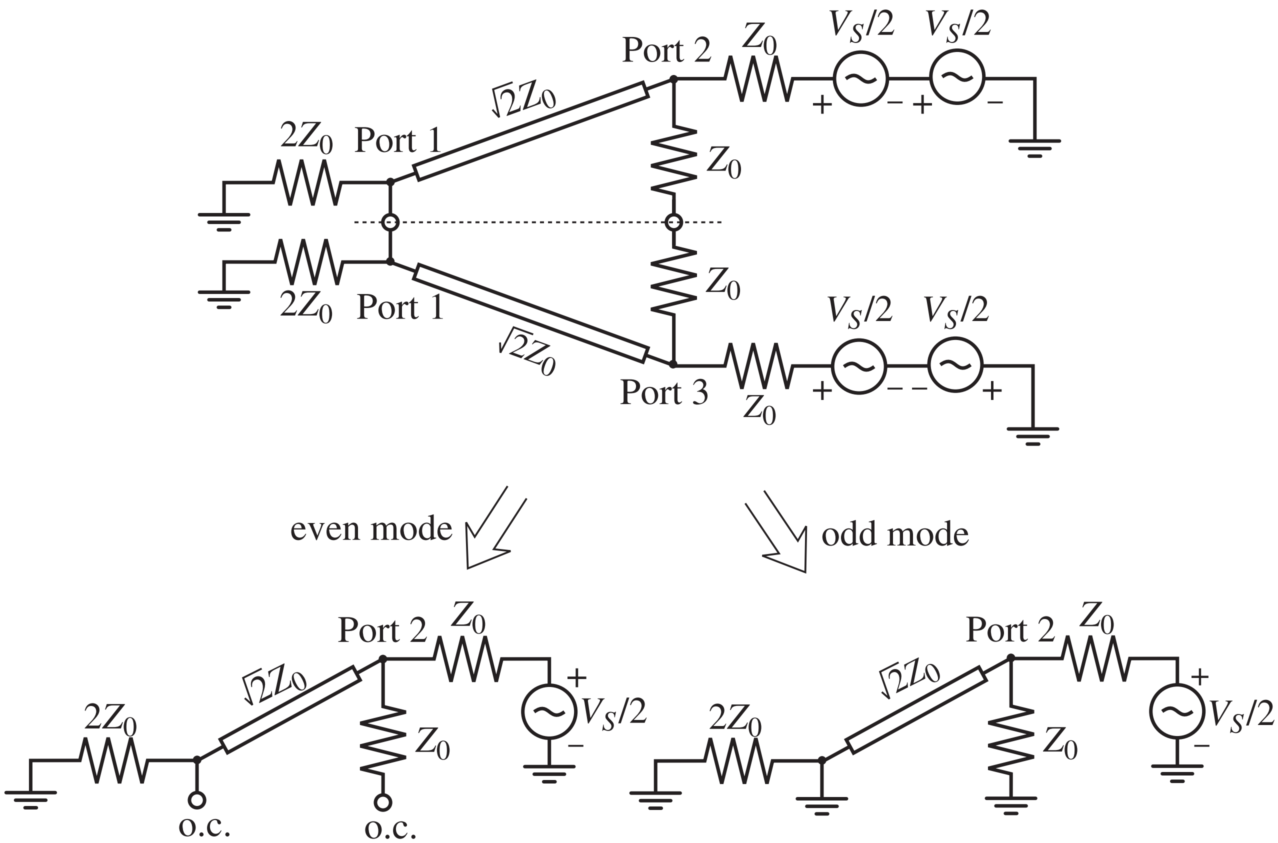


Figure G-2 Frequency response of Wilkinson power divider.



(a) Even mode (b) Odd mode

Figure G-3 Even and odd mode representation of Wilkinson divider (o.c.= open circuit).

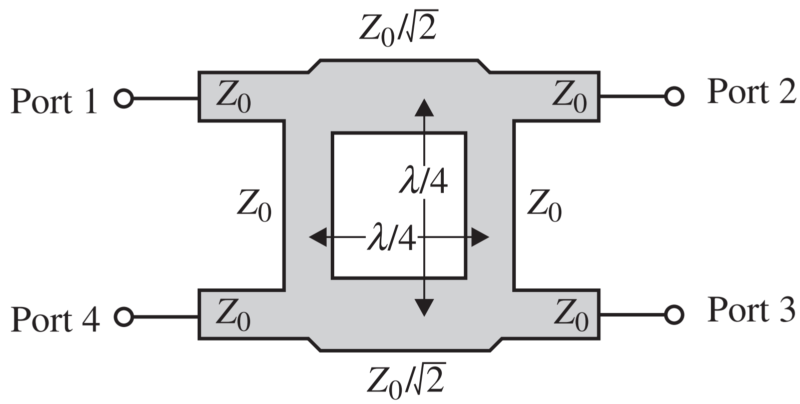


Figure G-4 Microstrip line realization of quadrature hybrid.

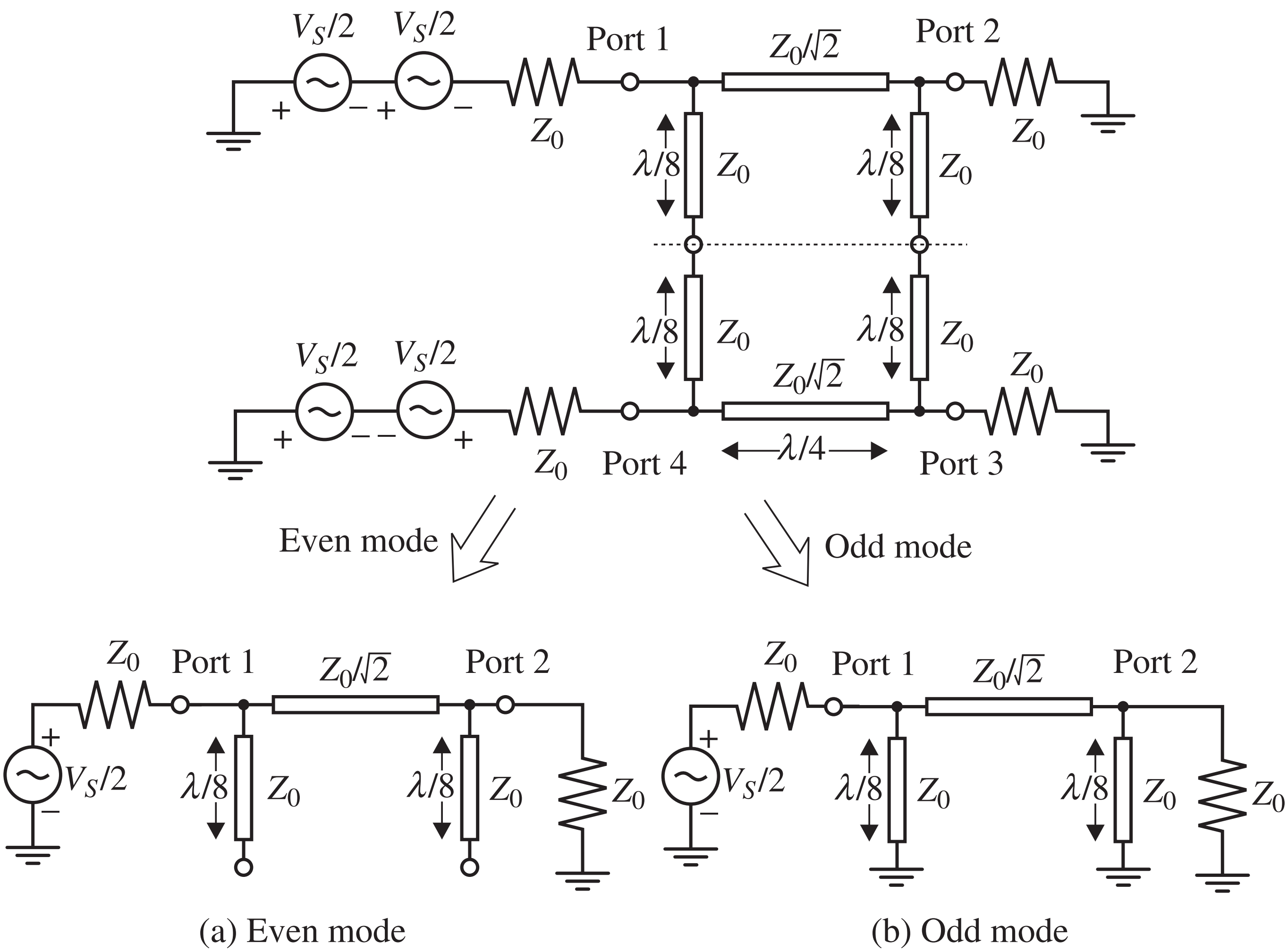


Figure G-5 Building blocks of branch line coupler.

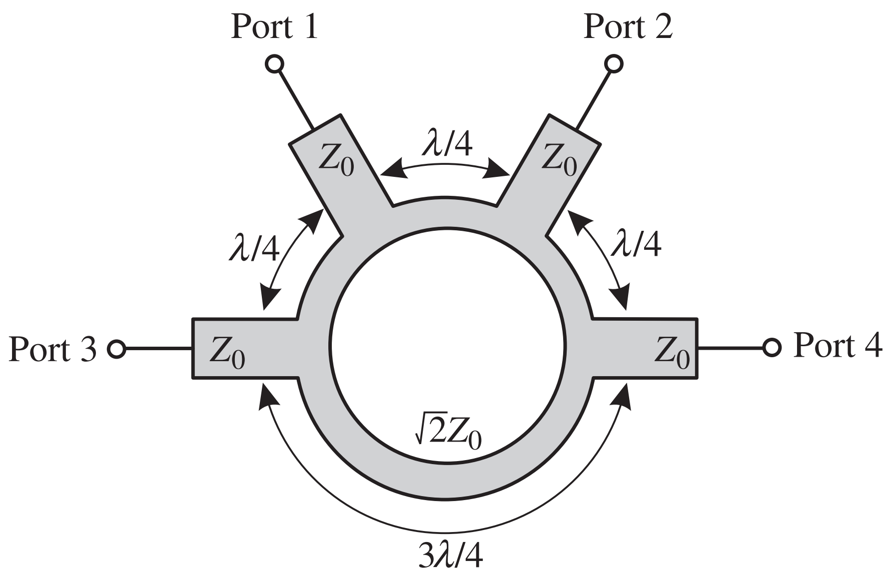


Figure G-6 A 180° ring coupler.

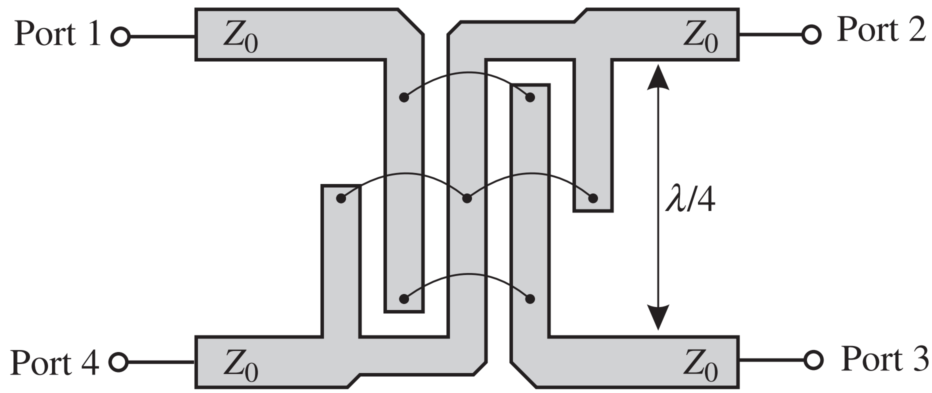


Figure G-7   A 3dB Lange coupler.

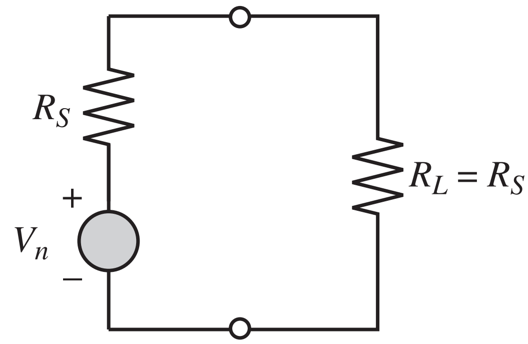


Figure H-1   Noise voltage of a circuit.

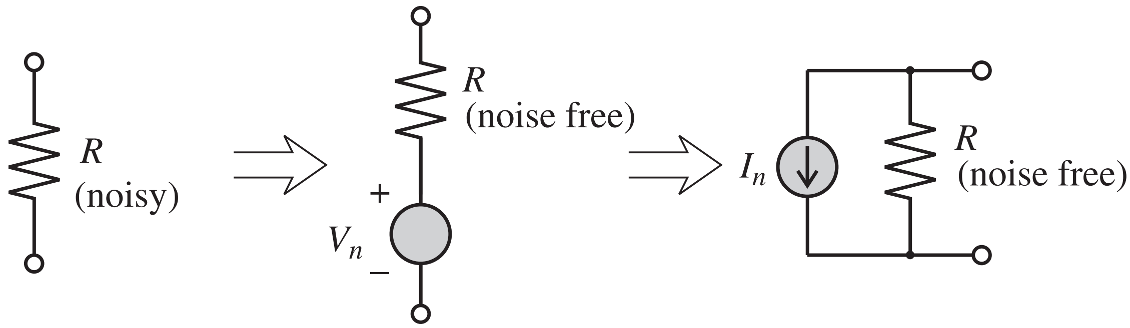


Figure H-2 Equivalent voltage and current models for noisy resistor.

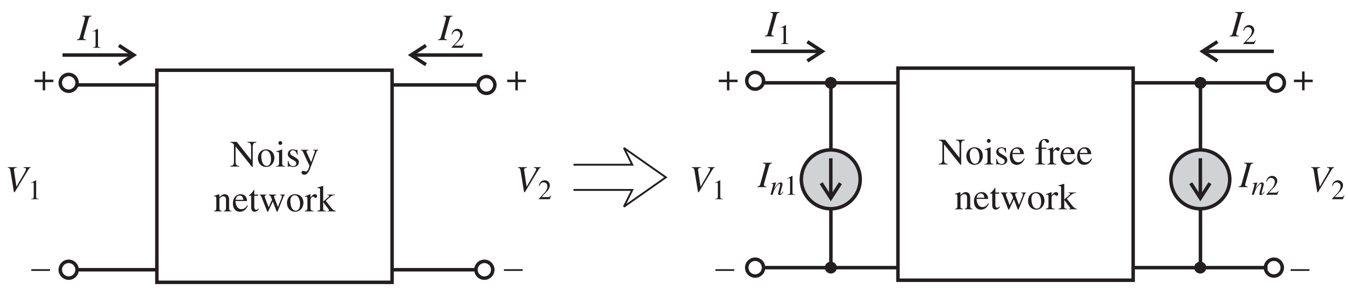


Figure H-3 Noisy two-port network and its equivalent representation.

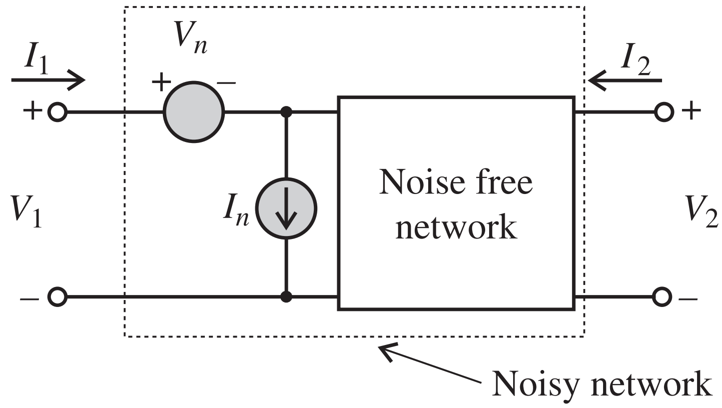


Figure H-4 Transformed network model with noise source at the input.

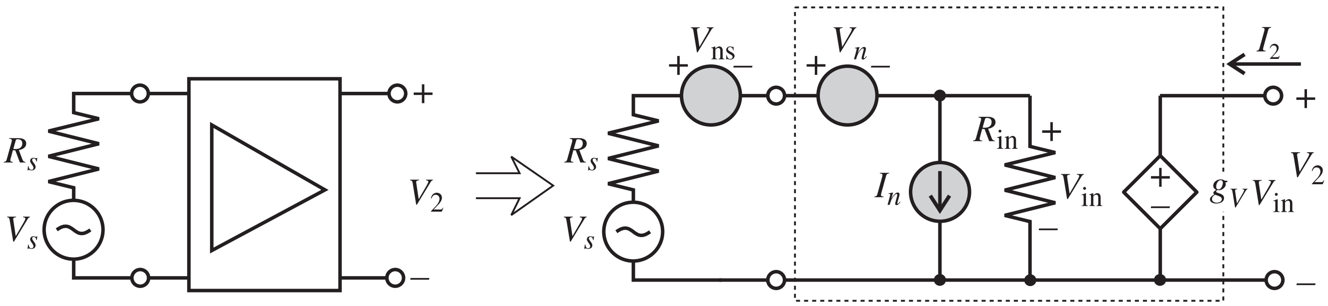


Figure H-5 Amplifier model and network representation with noise source.

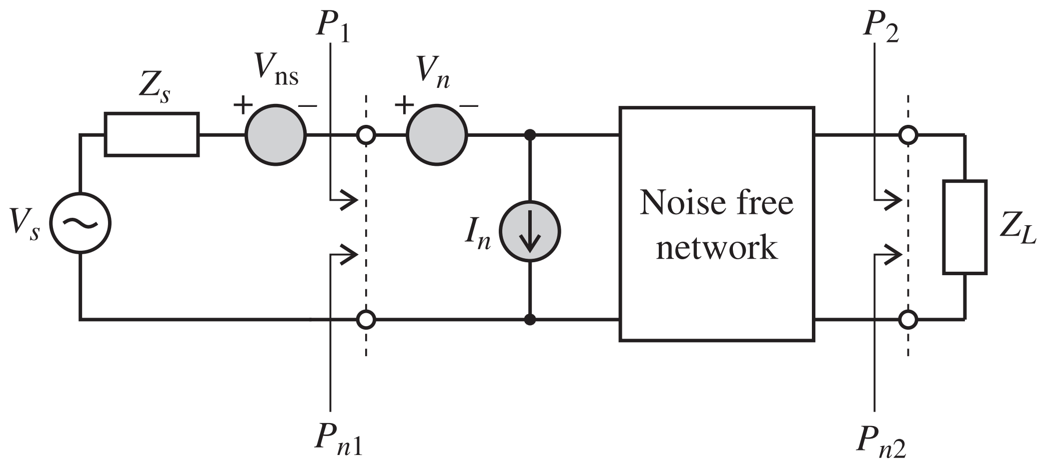


Figure H-6 Generic noise model for noise figure computation.

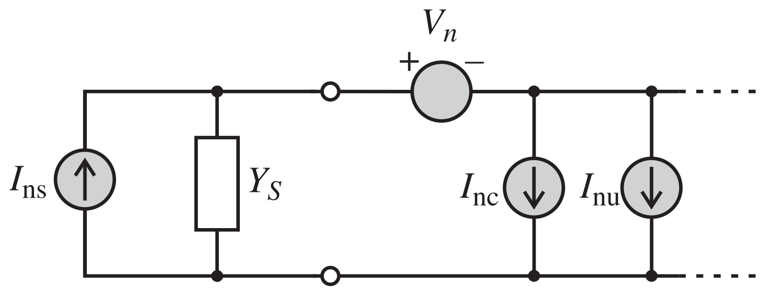


Figure H-7 Noise source modeled at network input.

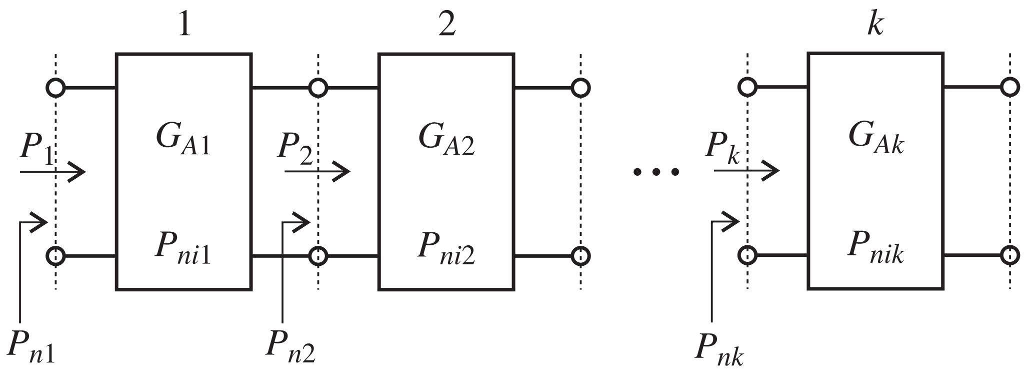


Figure H-8   Cascaded network representation.