Mysteries of the Smith Chart

Transmission Lines, Impedance Matching,
and Little Known Facts

Stephen D. Stearns, K6OIK

Chief Technologist

TRW Firestorm Wireless Communication Products

stearns@ieee.org

Outline

- ***Transmission Line Theory***
  - Historical development
  - Heaviside's rewrite of Maxwell's theory, Telegrapher's equations,
  - Impedance, reflection coefficient, SWR, phase constant, and velocity factor
  - Special facts for $\lambda/2$, $\lambda/4$, and $\lambda/8$ lossless lines
- ***The Smith Chart***
  - Bilinear complex functions
  - Impedance and admittance coordinates (circles, circles, and more circles)
- ***Impedance Matching***
  - Why match? Impedance matching vs. conjugate impedance matching
  - Single frequency matching
  - Multiple-frequency and broadband matching

Part 1: Transmission Line Theory

Key Dates in Electrical Transmission

- **1830s** Magnetic telegraphs - Gauss, Henry
- **1839** Electromagnetic telegraph - Wheatstone & Cook
- **1844** Telegraph in America - Morse
- **1850s** Thousands of miles of telegraph line U.S. and Europe
- **1851** 40-mile cable under English Channel
- **1855** Distributed analysis of transmission line - Lord Kelvin
- **1858** Transatlantic cable, project delayed by civil war
- **1873** Theory of electrodynamics - Maxwell
- **1876** Invention of telephone - Bell
- **1880s** Vectors, vector calculus, reformulation of Maxwell's theory, transmission line theory - Heaviside
- **1886** Experimental confirmation of Maxwell's Theory - Hertz
- **1937** Early Smith Chart, published 1939 and 1944 - Smith

Numbers to Remember!

1.4142135623...

1.7320508075…

1.6180339887...

3.1415926535...

2.718281828459045…

2.54

299,792,458

376.7303134...

Heaviside's Vector Formulation of Maxwell's Theory

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial \mathbf{t}}$$

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = \mathbf{0}$$

$$\mathbf{D} = \varepsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

"And God said, Let there be light; and there was light." Genesis 1:3

Frequency Domain or Phasor Form

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

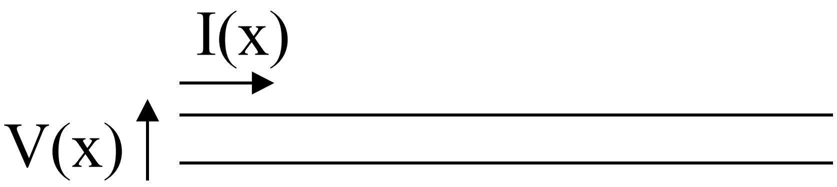
$$\nabla \times \mathbf{H} = (\sigma + j\omega\varepsilon)\mathbf{E}$$

$$\nabla \cdot \mathbf{E} = \mathbf{0}$$

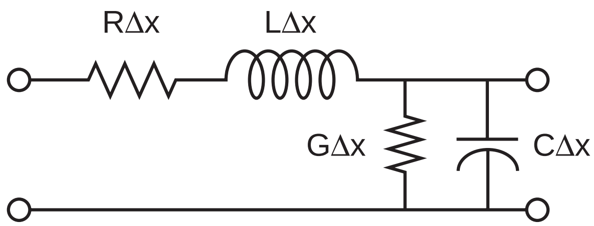
$$\nabla \cdot \mathbf{H} = \mathbf{0}$$

Heaviside's Telegrapher's Equations

Uniform transmission line



Equivalent circuit of infinitesimal segment



$$\frac{dV}{dx} = -(R + j\omega L)I(x)$$

$$\frac{dI}{dx} = -(G + j\omega C)V(x)$$

Transmission Line Solution
TEM Waves

Traveling wave

$$V(x) = \mathrm{V_o} e^{\gamma x}$$

$$I(x) = \frac{V(x)}{Z_o}$$

Propagation constant

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Characteristic impedance

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Notations
Real Parameters

- ***R =*** ***Series resistance per unit length (Ohms/meter)***
- ***L =*** ***Series inductance per unit length (Henries/meter)***
- ***G =*** ***Shunt conductance per unit length (Siemens/meter)***
- ***C =*** ***Shunt capacitance per unit length (Farads/meter)***
- α = ***Attenuation constant (nepers/meter)***
- β = ***Phase constant (radians/meter)***
- λ = ***Wavelength (meters)***
- v_f = ***Velocity factor (dimensionless)***
- ***X =*** ***Reactance (Ohms)***
- ***B =*** ***Susceptance (Siemens)***
- ***s =*** ***Standing wave radio (dimensionless)***

Notations (Cont'd)
Complex Parameters

$Z =$ $R + jX$ = impedance (Ohms)

$Z_L =$ Load impedance (Ohms)

$Z_i =$ Input impedance (Ohms)

$Z_0 =$ Characteristic impedance (Ohms)

$z =$ $Z/Z_0 = r + jx$ = normalized impedance (dimensionless)

$Y =$ $G + jB$ = admittance (Siemens)

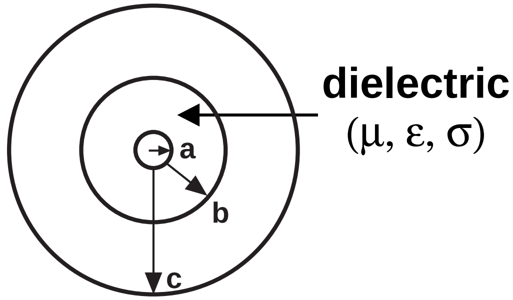
$y =$ $Y/Y_0 = g + jb$ = normalized admittance (dimensionless)

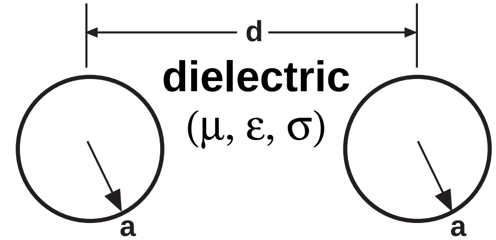
$\Gamma =$ $\Gamma_r + j\,\Gamma_i$ = complex reflection coefficient (dimensionless)

$\gamma =$ $\alpha + j\beta$ = propagation constant (inverse meters)

Transmission Line Parameters

Physical Dimensions and Material Properties





Parameter	Coax	Twinlead
R Ω/m	$\frac{1}{2\pi\delta\sigma_c}\left(\frac{1}{a}+\frac{1}{b}\right)$	$\frac{1}{\pi a\delta\sigma_c}$
L H/m	$\frac{\mu}{2\pi}\left[\ln\frac{b}{a}+\frac{\delta}{2}\left(\frac{1}{a}+\frac{1}{b}\right)\right]$	$\frac{\mu}{\pi}\left[\frac{\delta}{2a}+\cosh^{-1}\frac{d}{2a}\right]$
G S/m	$\frac{2\pi\sigma}{\ln\frac{b}{a}}$	$\frac{\pi\sigma}{\cosh^{-1}\frac{d}{2a}}$
C F/m	$\frac{2\pi\varepsilon}{\ln\frac{b}{a}}$	$\frac{\pi\varepsilon}{\cosh^{-1}\frac{d}{2a}}$

Where skin depth is

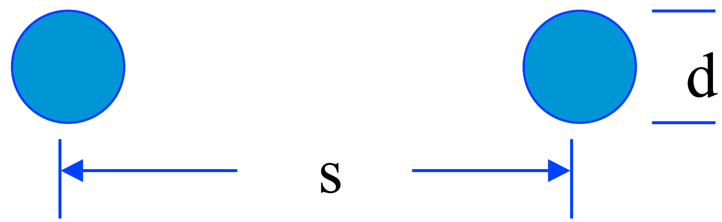
$$\delta = \frac{1}{\sqrt{\pi f\mu\sigma_c}}$$

For copper

$$\sigma_c = 5.8\times10^{7}\ \text{S/m}$$

$$\delta = \begin{cases} 8.5\ \text{mm at 60 Hz} \\ 6.6\ \mu\text{m at 100 MHz} \end{cases}$$

Round Open-Wire Transmission Line Formulas



❑ *Approximate formula*

- ➤ Widely published by ARRL and others
- ➤ Accurate only for large spacings: s/d > 3
  or large impedances: Z_0 > several hundred

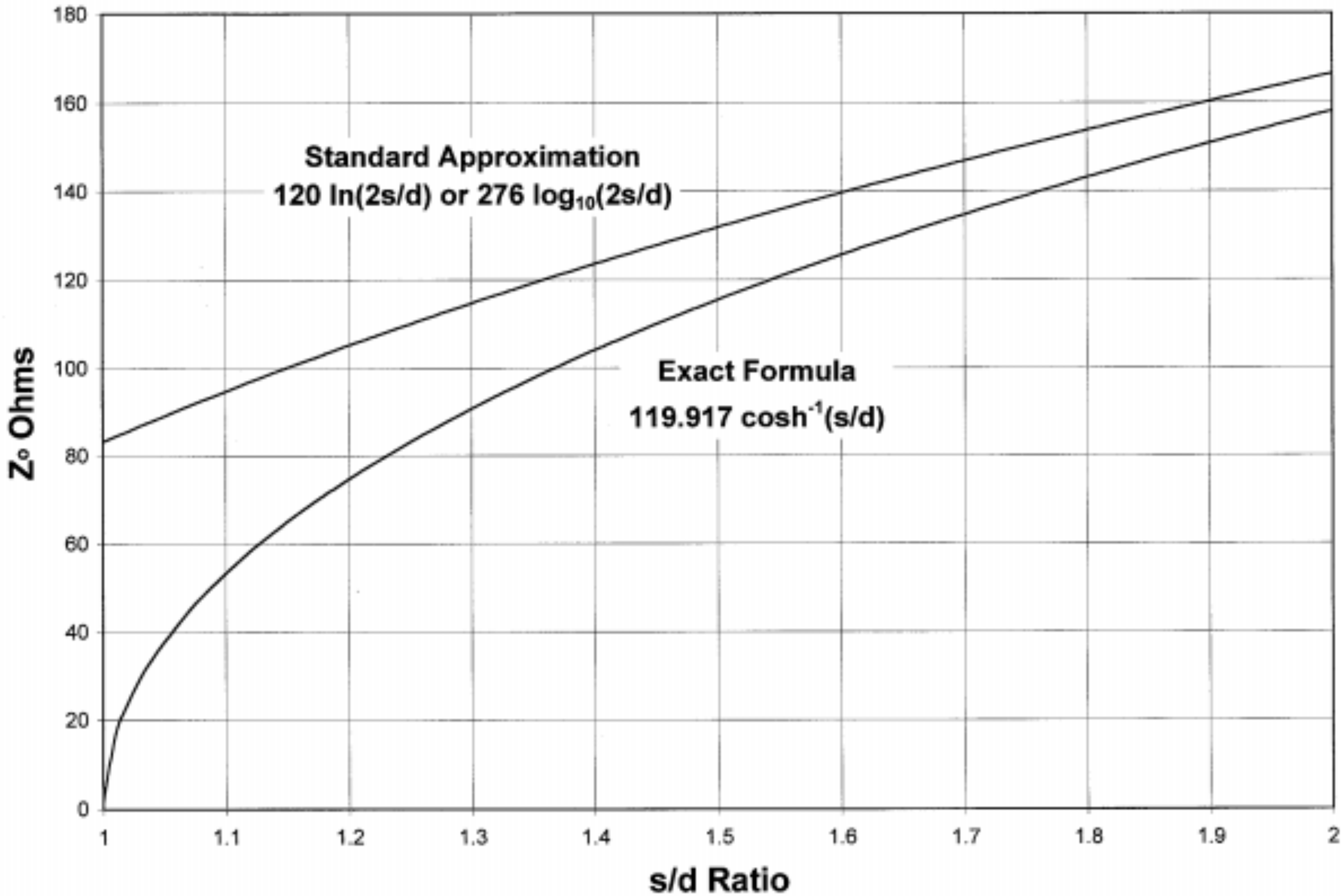
$$Z_0 = 120 \ln\left(\frac{2s}{d}\right) = 276 \log_{10}\left(\frac{2s}{d}\right)$$

❑ *Exact formula*

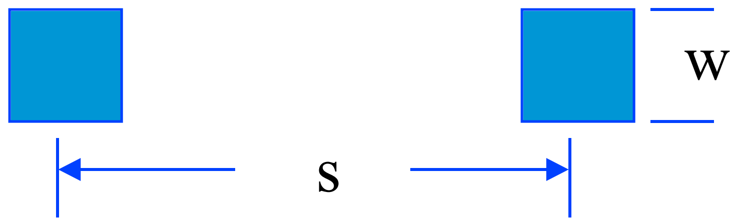
- ➤ Accurate for all spacings and impedances

$$Z_0 = 119.917 \cosh^{-1}\left(\frac{s}{d}\right)$$

Comparison of Impedance Formulas
Round Open-Wire Line



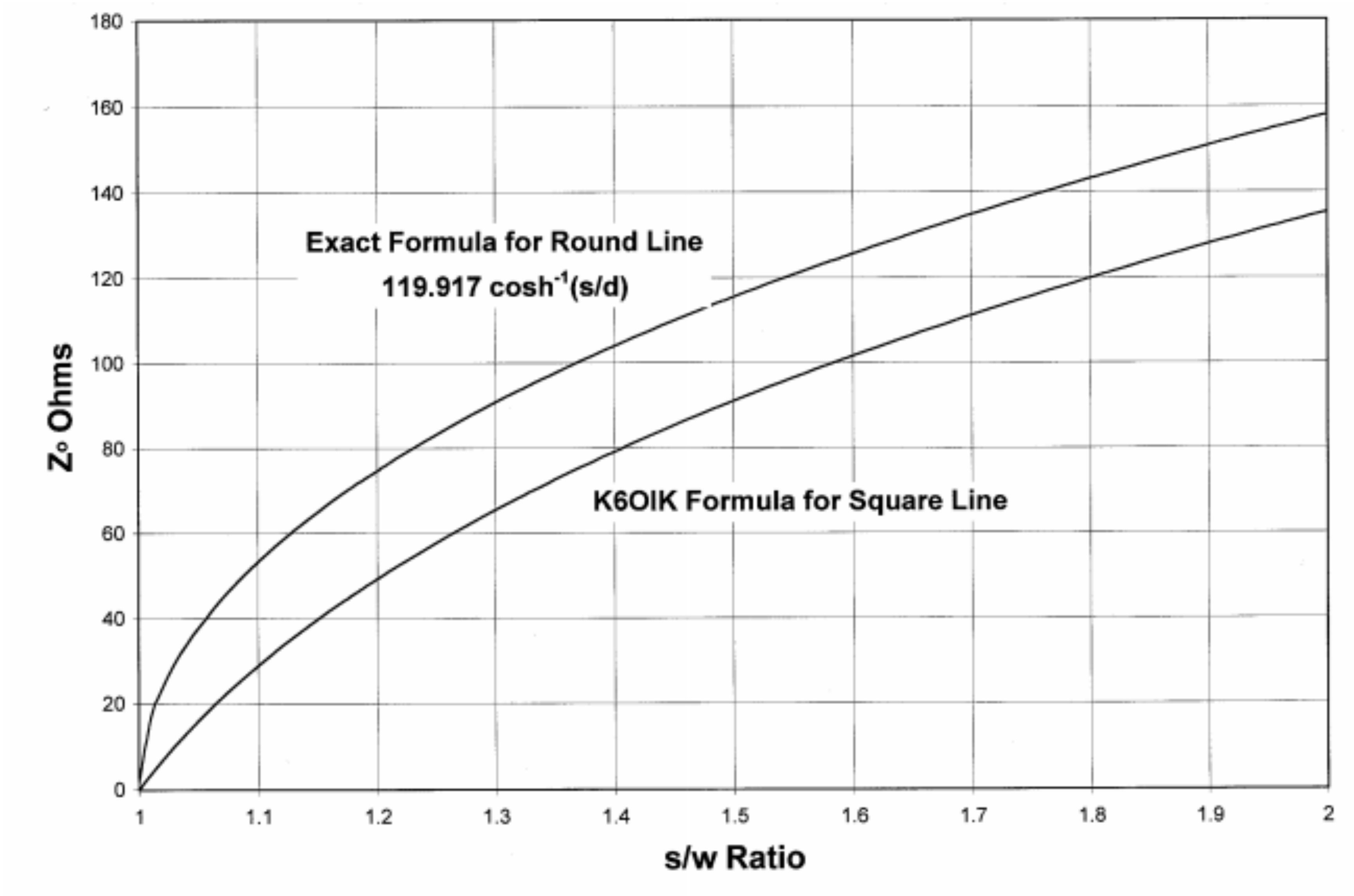
K6OIK Square Open-Wire Transmission Line Formula



- ***Excellent approximation in the range of practical interest***
  - Accurate for small spacings: $1 < s/w < 3$
    or small impedances: $0 < Z_0 <$ several hundred

$$Z_0 = \frac{376.730313461}{\frac{1}{s/w-1} + 0.483 + \frac{2}{\pi}\ln\left(\frac{s/w}{s/w-1}\right) + \frac{1}{(s/w)^{1/3}-0.1}}$$

Round vs Square Open-Wire Lines



Optimal Characteristic Impedances

Coax

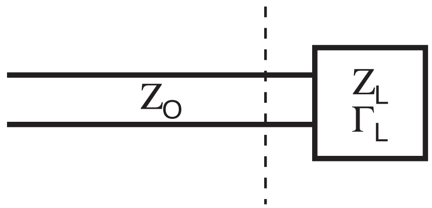
For minimum loss $Z_o = 77\Omega$

For maximum breakdown voltage $Z_o = 30\Omega$

For minimum temperature rise $Z_o = 60\Omega$

$Z_o = 50\Omega$ has no special significance

Reflection Coefficient and Impedance Relation at a Terminal Plane



Definition

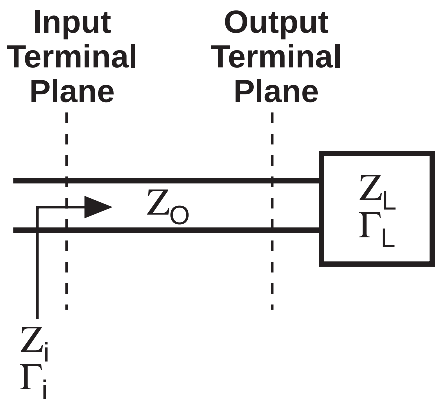
$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{z-1}{z+1}$$

Inverse

$$z = \frac{1+\Gamma}{1-\Gamma}$$

- ***For every terminal plane, the complex load impedance and complex reflection coefficient seen to the right give the same information for that terminal plane***
- ***Question: How do Γ and z change as the terminal plane moves?***

Relations Between Two Terminal Planes



Impedance relation

$$z_i = \frac{z_L + j\tan\beta l}{1 + jz_L \tan\beta l}$$

Cross relations

$$z_i = \frac{1 + \Gamma_L e^{-j2\beta l}}{1 - \Gamma_L e^{-j2\beta l}}$$

$$z_L = \frac{1 + \Gamma_i e^{j2\beta l}}{1 - \Gamma_i e^{j2\beta l}}$$

Reflection coefficient relation

$$\Gamma_i = \Gamma_L \, e^{-j2\beta l}$$

Velocity Factor

TRW

Wavelength

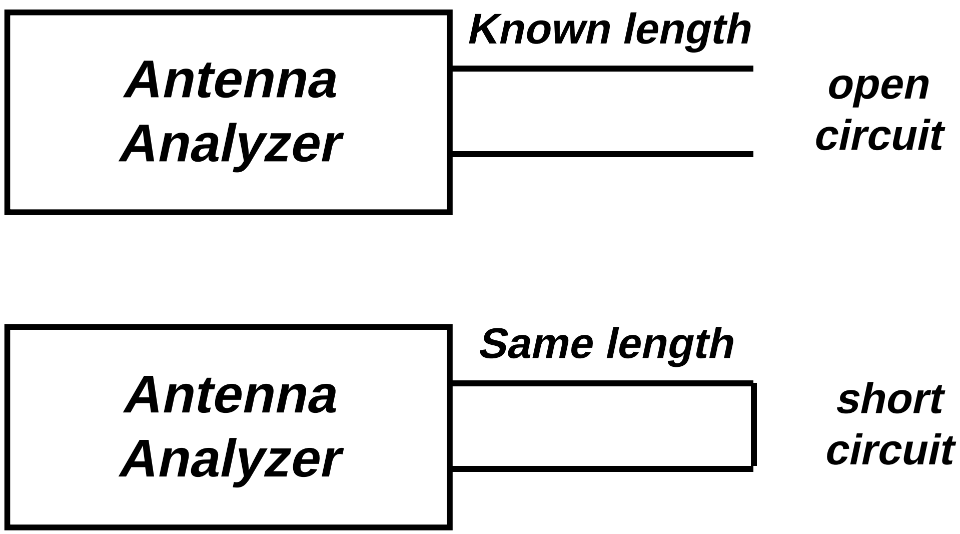
$$\lambda_{free\ space} = \frac{c}{f}$$

$$\lambda_{actual} = \frac{v}{f}$$

Velocity factor

$$v_f = \frac{v}{c} = \frac{\lambda_{actual}}{\lambda_{free\ space}}$$

How To Measure Velocity Factor of a Line
(One Way To Do It)



$$v_f = \frac{2\pi f l}{c} \frac{1}{\cot^{-1}\sqrt{\dfrac{-Z_{open}}{Z_{short}}}}$$

Phase Constant

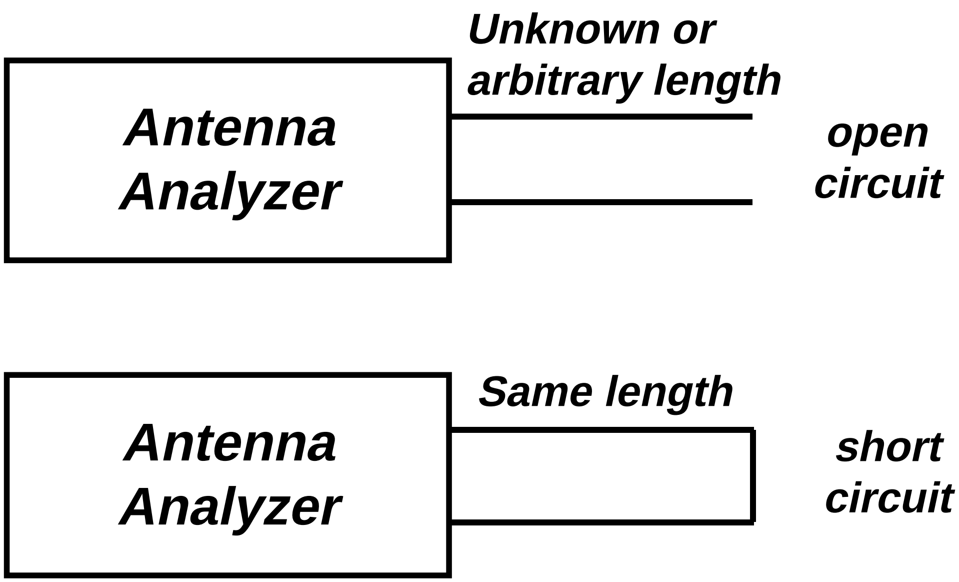
$$\beta = \frac{2\pi}{\lambda_{actual}} = \frac{2\pi f}{v_f \; c} \qquad \text{radians/meter}$$

- ***Phase constant* β *and velocity factor* v_f *give equivalent information***
- ***Both can be calculated from line dimensions and material properties***

$$\beta = \mathrm{Im}\sqrt{(R + j\omega L)(G + j\omega C)}$$

- ***Best to measure!***

How to Measure Complex Z_o of A Line
(One Way to Do It)



$$Z_o = \sqrt{Z_{open} \times Z_{short}}$$

- ❑ ***Geometric mean of two complex numbers***
- ❑ ***Calculation is trivial in polar form on Smith Chart***

What Special Lengths of Lossless Line Do

***Half wavelength**, l = _/2*

$$Z_i = Z_L$$

***Quarter wavelength,** l = _/4*

$$Z_i = \frac{Z_o^2}{Z_L}$$

***Eighth wavelength,** l = _/8*

$$|Z_i| = Z_o \quad \text{if } Z_L \text{ and } Z_o \text{ are real (resistive)}$$

Standing Wave Ratio

$$s = \frac{1+|\Gamma|}{1-|\Gamma|}$$

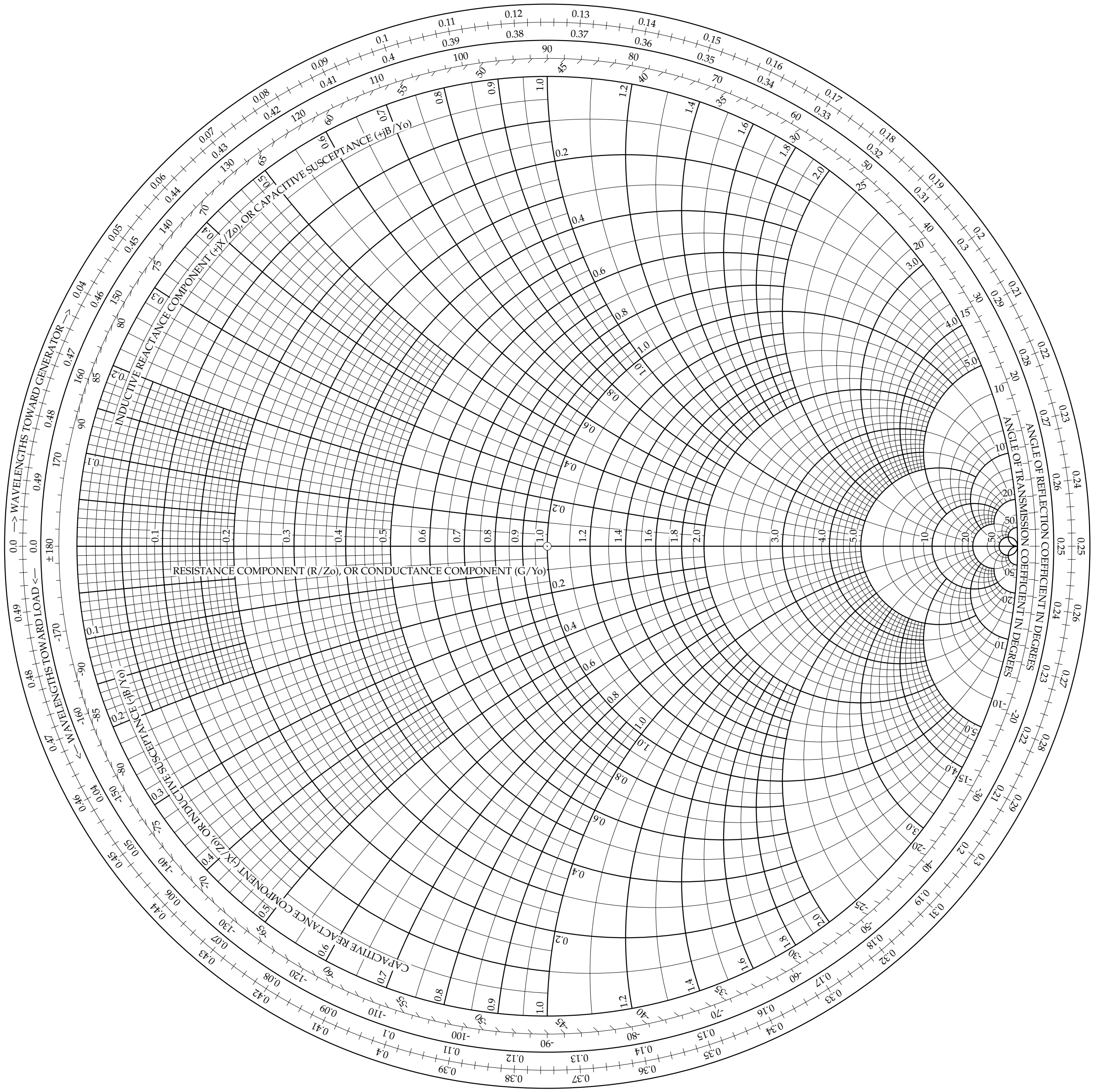
$$|\Gamma| = \frac{s-1}{s+1}$$

Easy to remember from

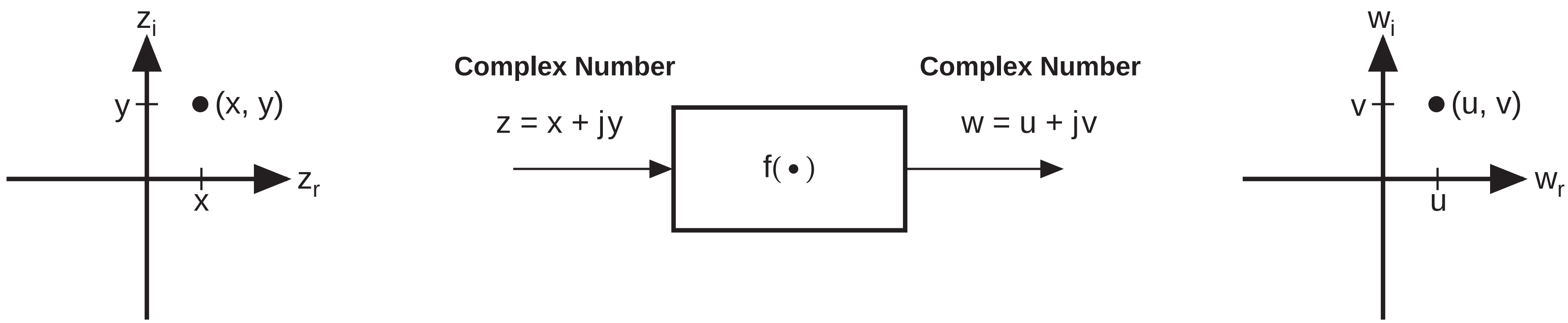
$$z = \frac{1+\Gamma}{1-\Gamma}$$

$$\Gamma = \frac{z-1}{z+1}$$

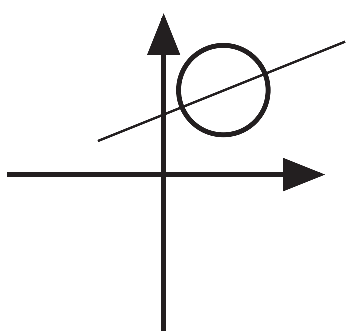
Part 2: The Smith Chart

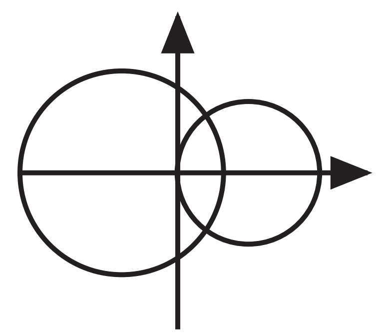

RESISTANCE COMPONENT (R/Zo), OR CONDUCTANCE COMPONENT (G/Yo)
INDUCTIVE REACTANCE COMPONENT (+jX/Zo), OR CAPACITIVE SUSCEPTANCE (+jB/Yo)
CAPACITIVE REACTANCE COMPONENT (-jX/Zo), OR INDUCTIVE SUSCEPTANCE (-jB/Yo)
—> WAVELENGTHS TOWARD GENERATOR —>
<— WAVELENGTHS TOWARD LOAD <—
ANGLE OF REFLECTION COEFFICIENT IN DEGREES
ANGLE OF TRANSMISSION COEFFICIENT IN DEGREES

Complex Functions



- ***Basic types of complex functions***
  - Global Properties
    - – Linear – lines map to lines
    - – Bilinear – circles map to circles
  - Local Properties
    - – Conformal – right angles map to right angles



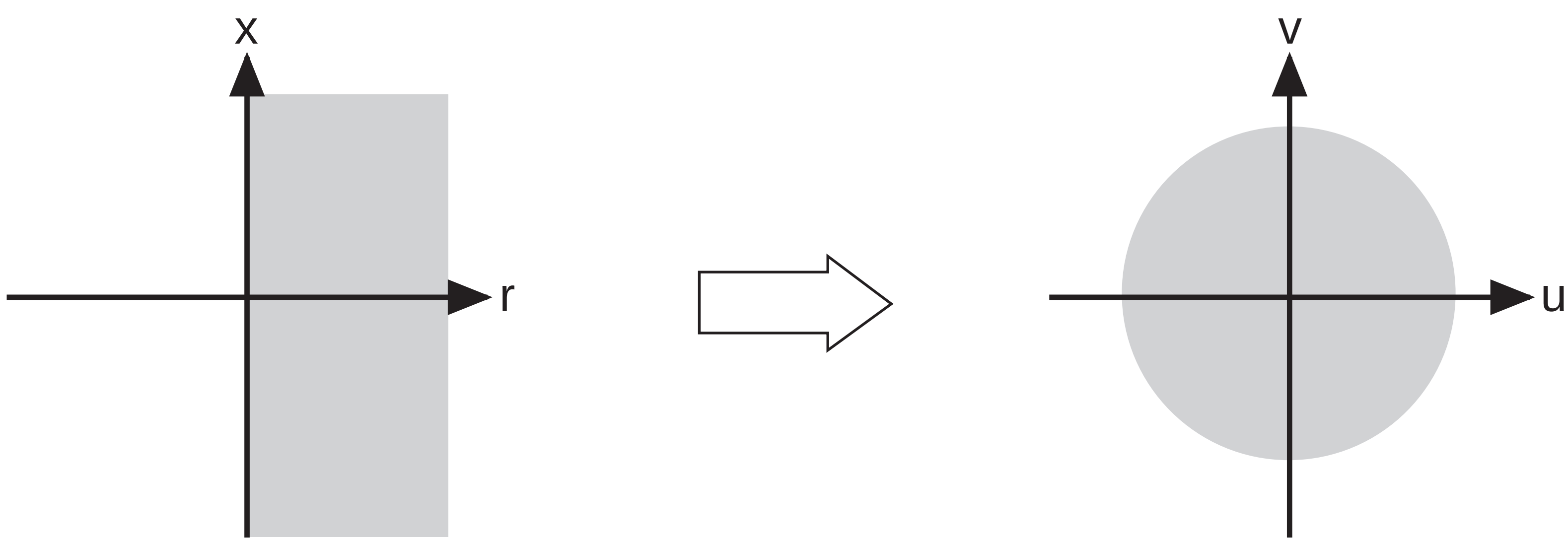


Mathematical Basis of the Smith Chart

$$\Gamma = \frac{z-1}{z+1}$$

A bilinear conformal complex function

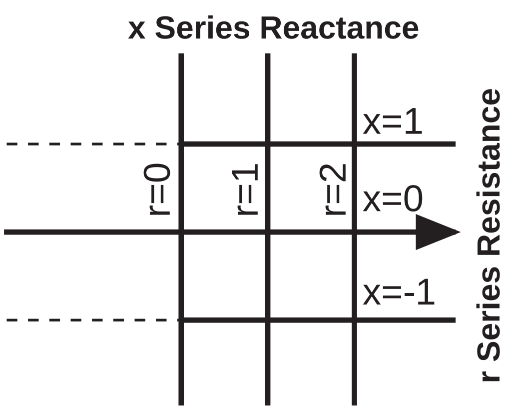
$$u + jv = \frac{(r-1) + jx}{(r+1) + jx}$$

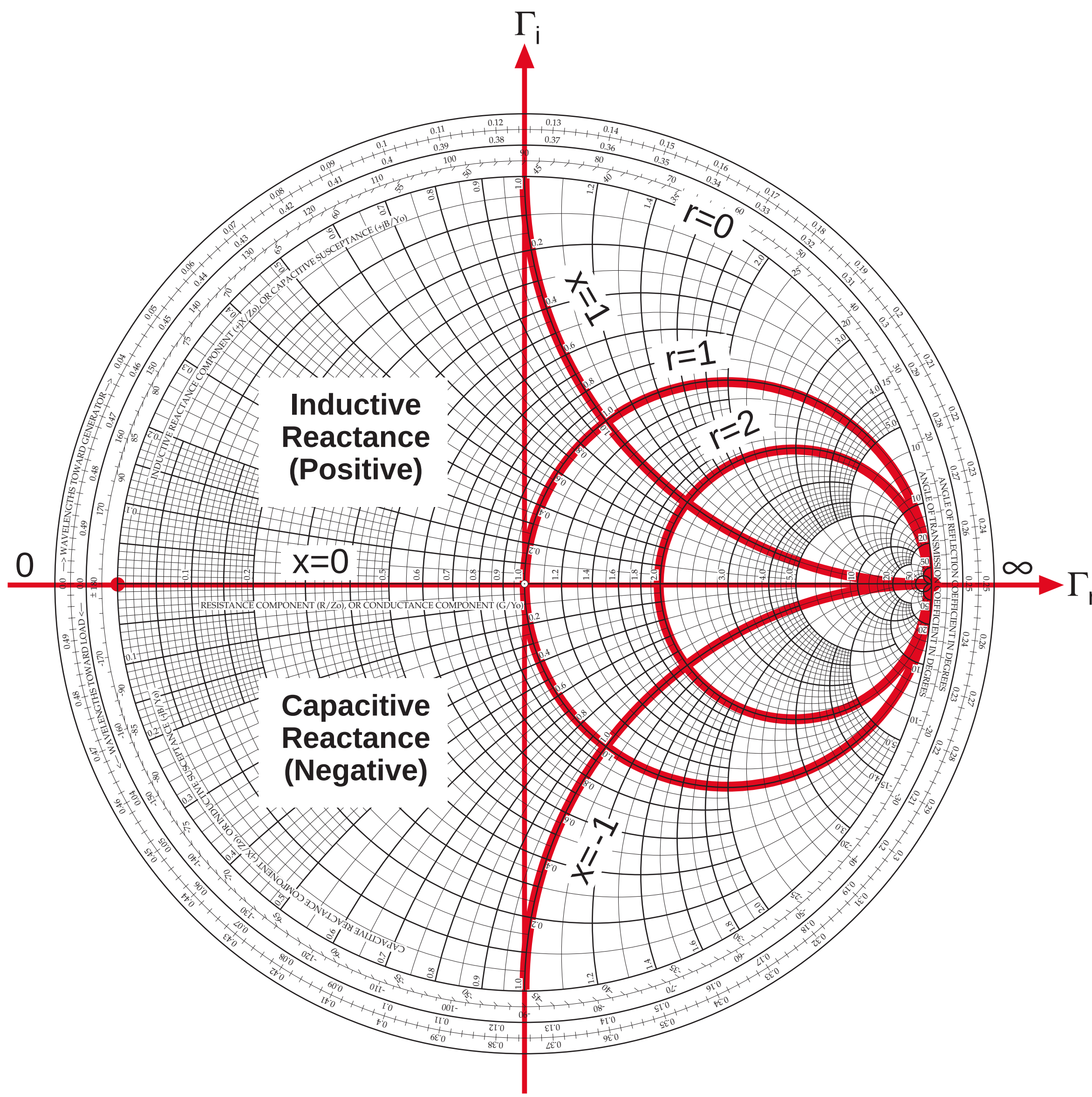


Right Half
z Plane

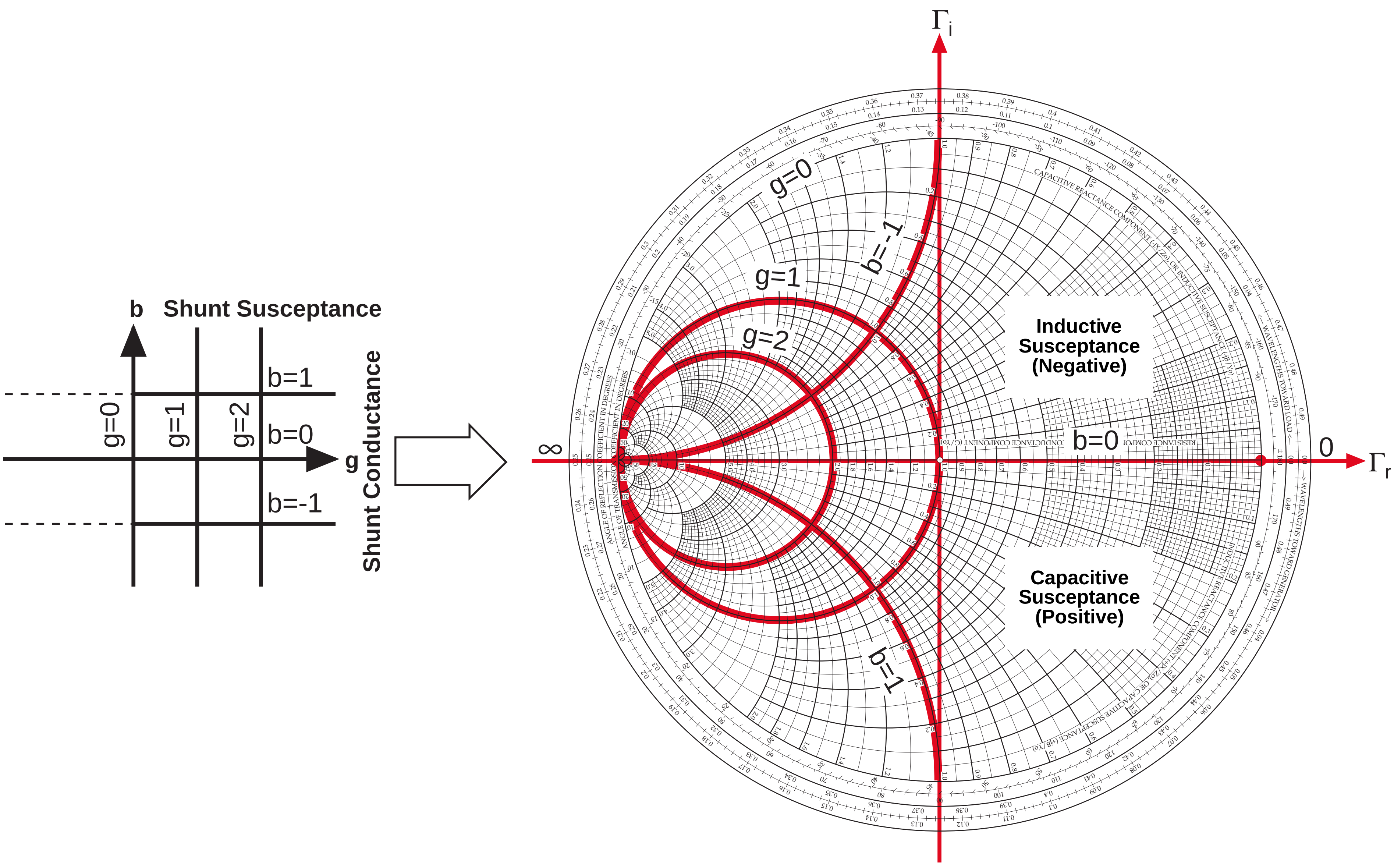
Interior Unit Circle
Γ Plane

Smith Chart: Impedance Coordinates

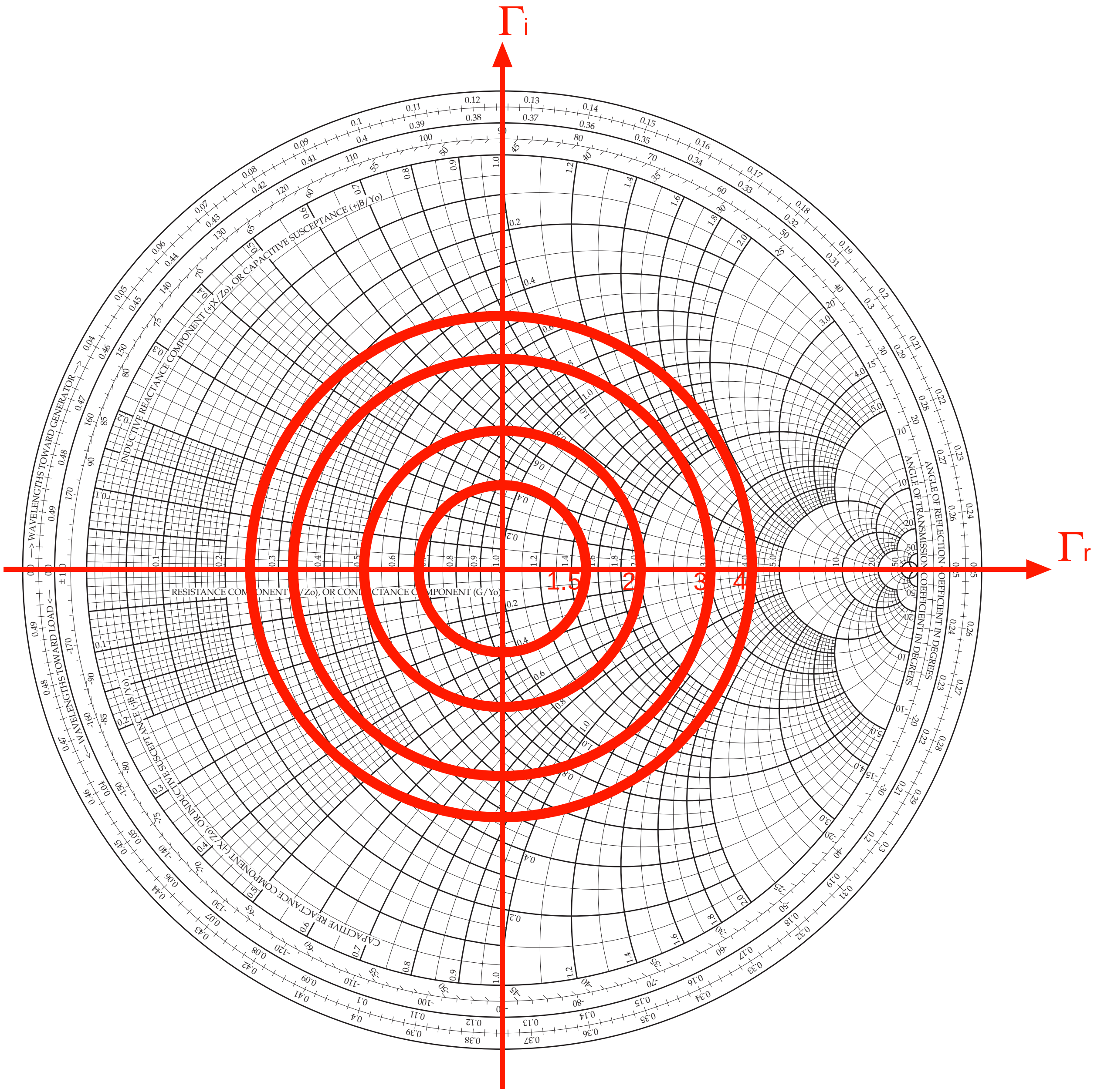




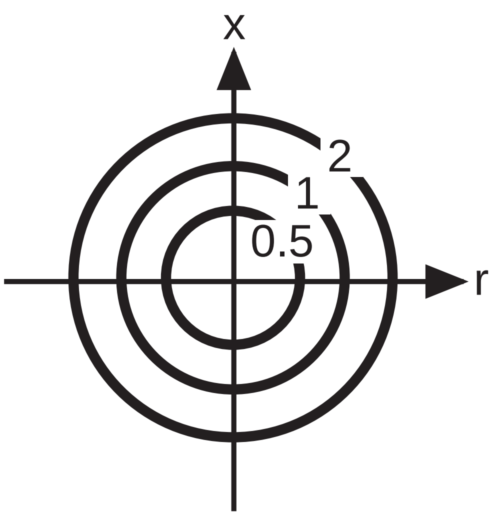
Smith Chart: Admittance Coordinates

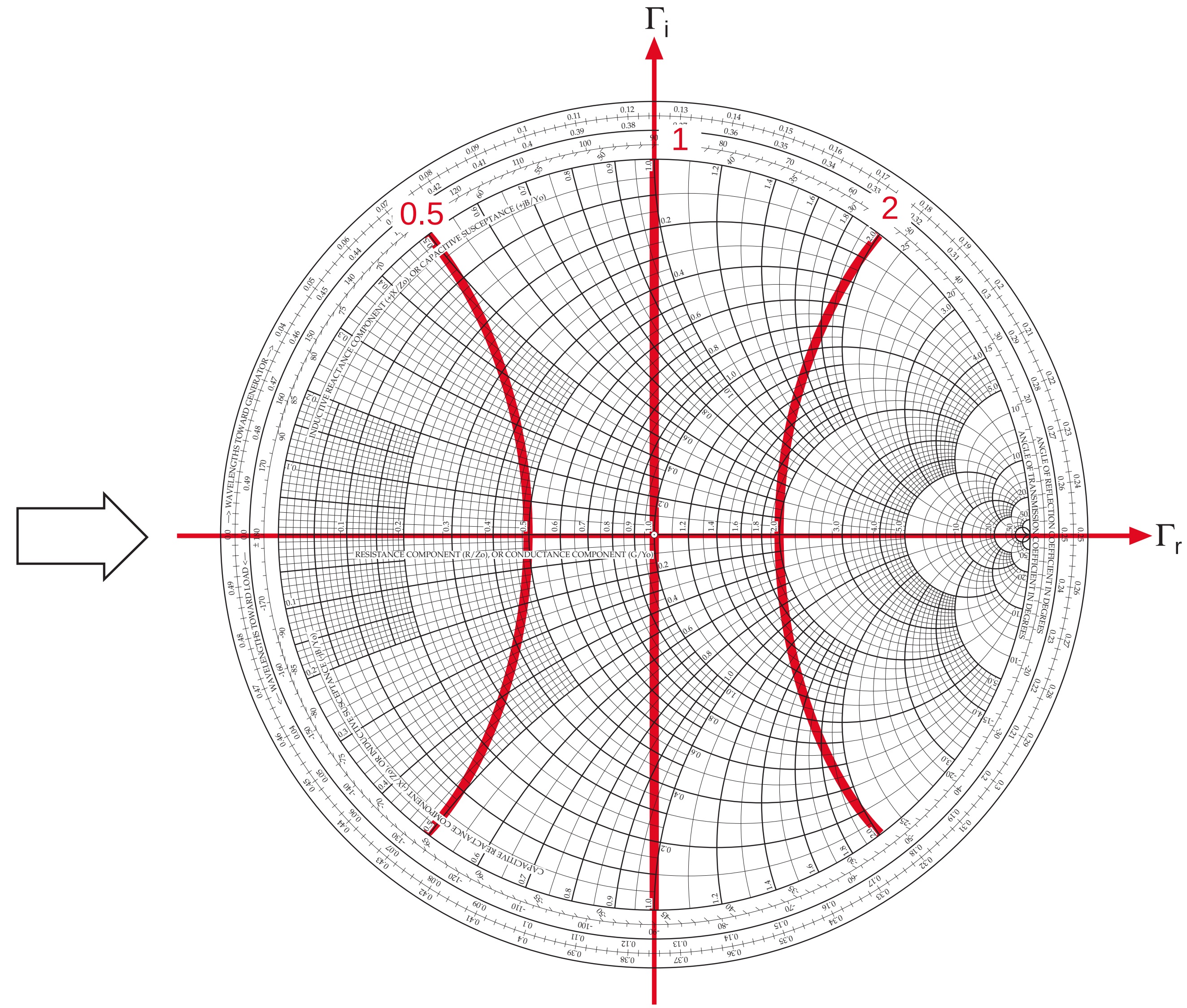


Smith Chart: Constant SWR Circles

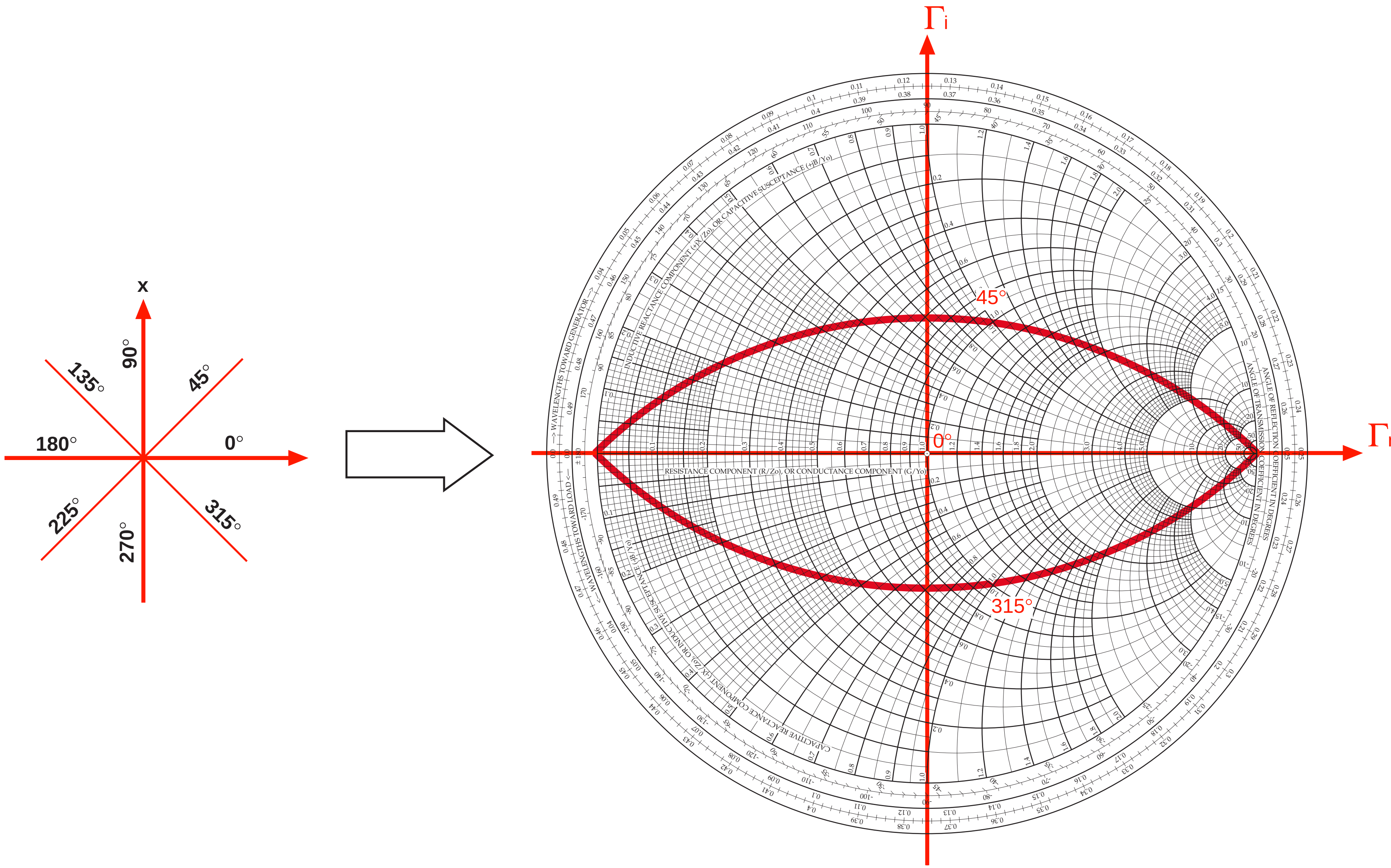


Smith Chart: Constant Impedance Magnitude Circles





Smith Chart: Constant Impedance Phase Angle Circles



Smith Chart: Multiplication, Division, Squares, and Square Roots

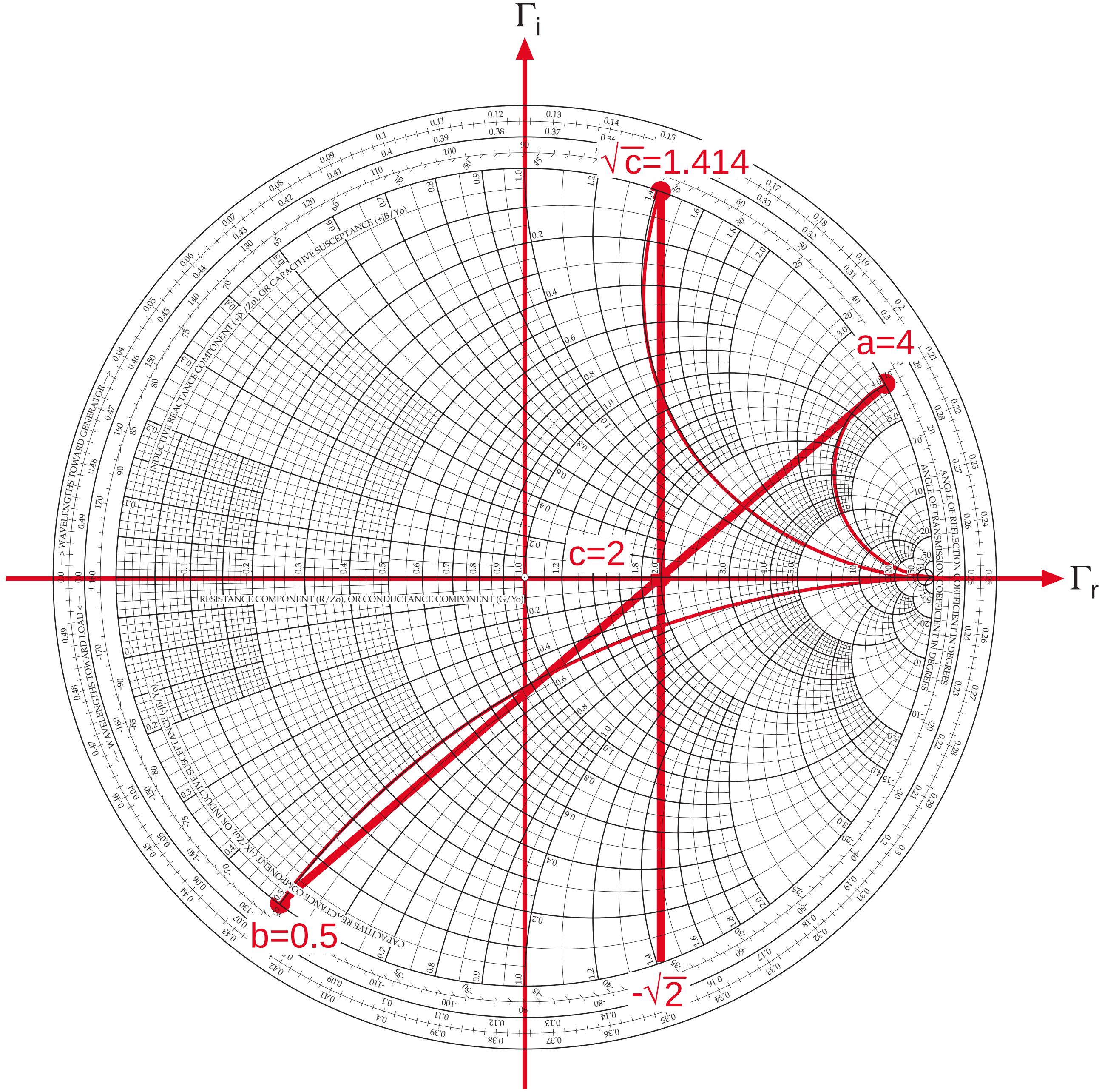
Unary Operators

squares	a^2
square roots	$\sqrt{a}$
tangents	$\tan \theta$
cotangents	$\cot \theta$
inverse tangents	$\tan^{-1} a$
Inverse cotangents	$\cot^{-1} a$

Binary Operators

multiplication X	$a \bullet b$
division ÷	c/a
geometric mean	$\sqrt{ab}$

Smith Chart: A Nomogram for Math Calculations



Part 3: Impedance Matching

Impedance Matching Categories

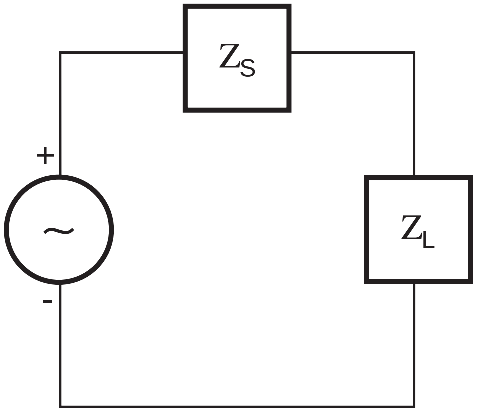
- ***Single frequency matching***
  - Manual synthesis using Smith Chart
  - Eight canonical networks
  - Lumped elements
  - Series and parallel stubs
  - Transmission line sections
- ***Multiple frequency matching***
  - Ladder networks
  - Multiple stubs
  - Multiple line sections
- ***Broadband matching***
  - Maximize SWR bandwidth
  - Software for computer-aided manual design
  - Software for network optimization
  - Smith Chart used for visualization only

Bandwidth Classifications

	Fractional Bandwidth
Narrowband	***< 10%***
Moderate band	***10% to 50%***
Broadband	***> 50%***

Two Kinds of Matching

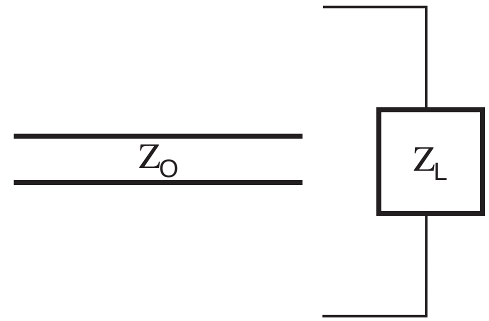
- ***Conjugate Matching***



$$Z_s = Z_L^*$$

- ***Best use at source (transmitter)***
- ***Maximizes power delivery to the load***
- ***Does not minimize reflections unless Z_s is real***
- ***Normally done by the transmitter manufacturer at the circuit design level***
- ***Ideally Z_s (ext) = 50 Ω***

- ***Load Matching***

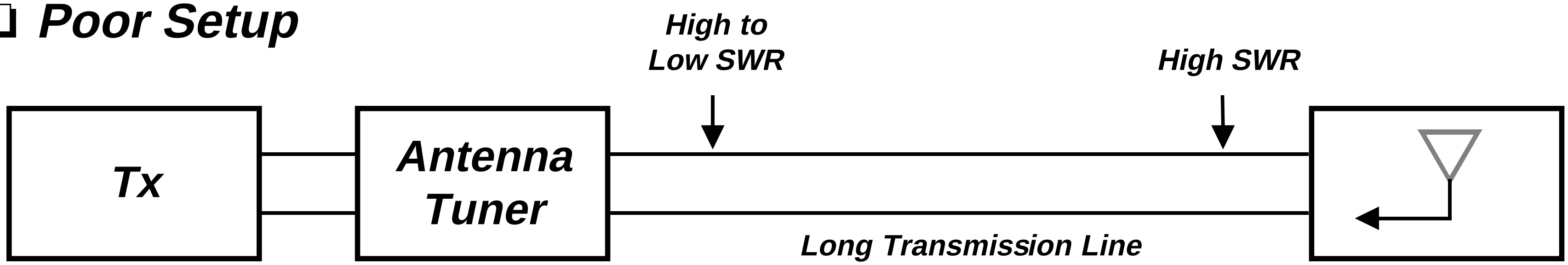


$$Z_L = Z_O$$

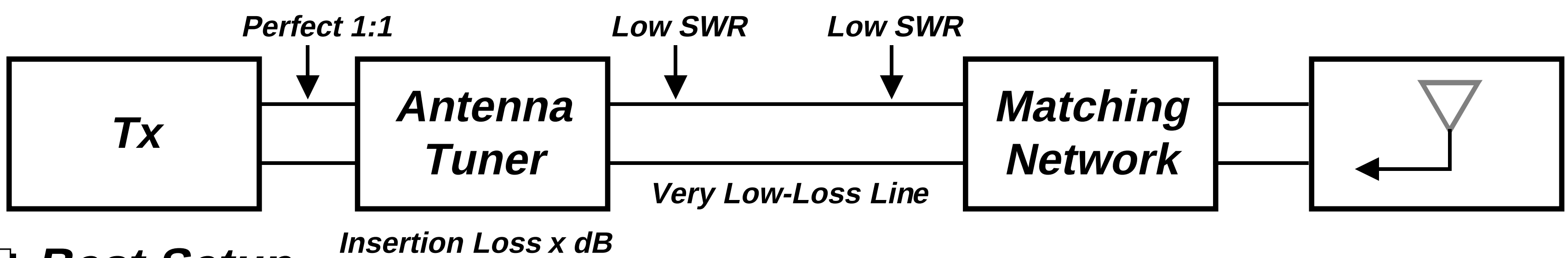
- ***Best used at ends of transmission lines***
- ***Minimizes reflections***
- ***Does not maximize delivered power unless Z_0 is real***

Where Should Matching Network Go?

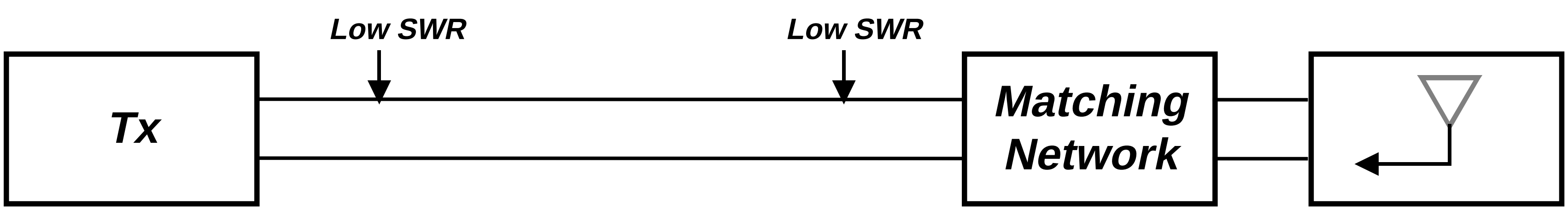
- **Poor Setup**



- **Good Setup**



- **Best Setup**



Necessary Test Equipment

- ***Antenna analyzer***
  - *Autek*
  - *CIA*
  - *MFJ*
- ***Noise bridge (less accurate)***
- ***Network analyzer (more accurate)***
  - *Hewlett-Packard*

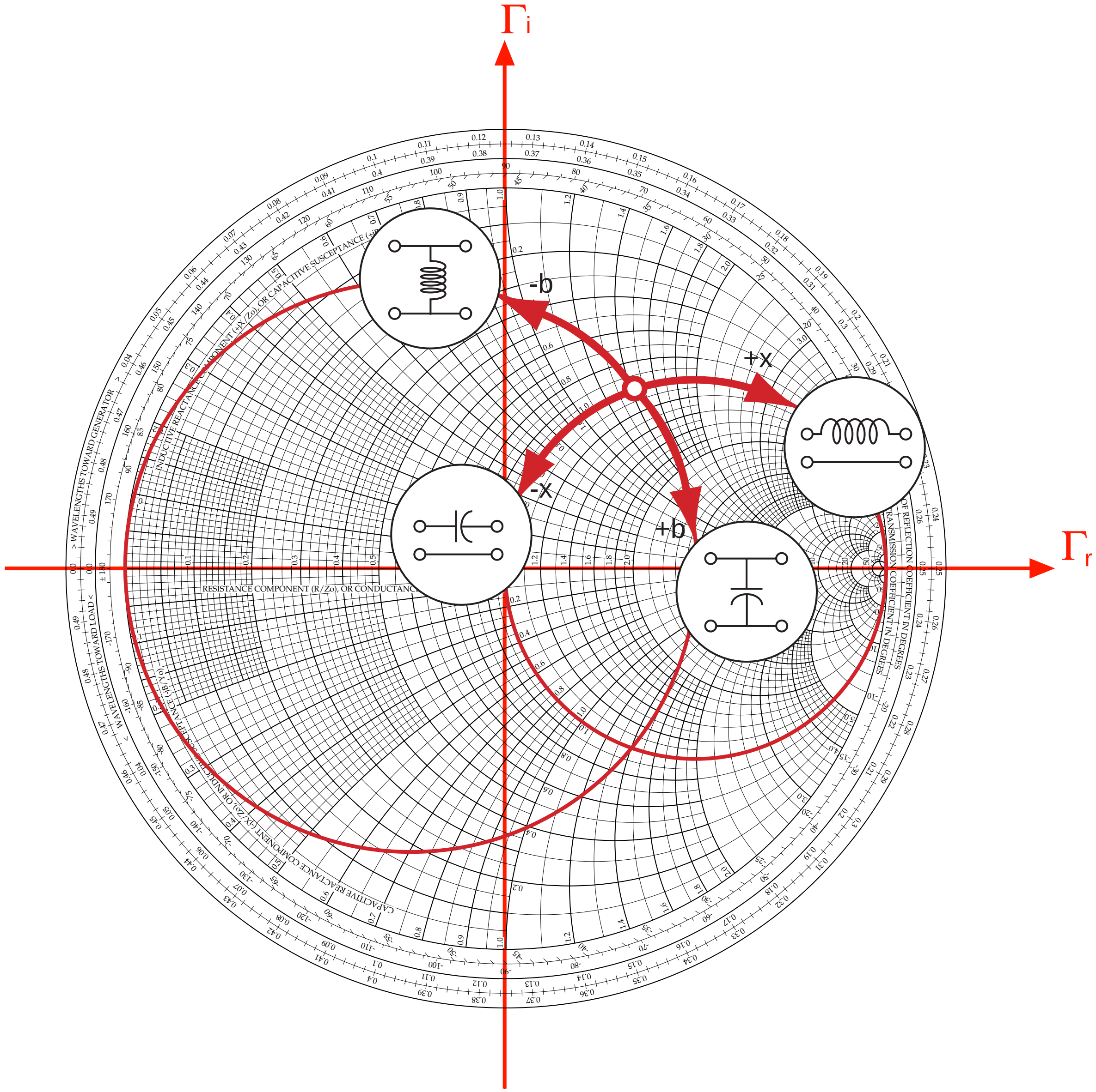
Matching Network Design Recipe

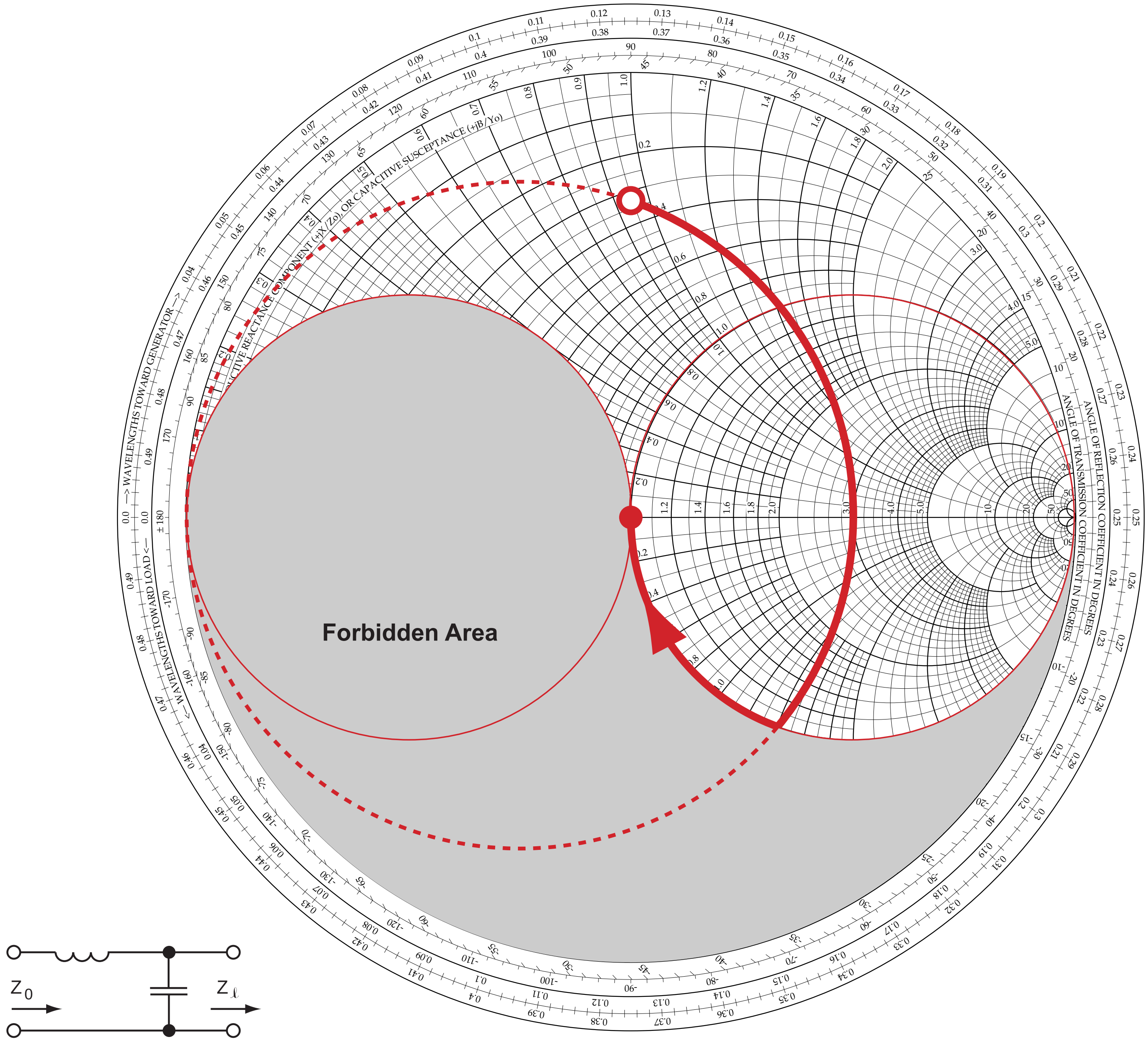
1. ***Measure transmission line parameters Z_o, v_f***
2. ***Measure antenna feedpoint impedance across band(s) of interest***
3. ***Measure or calculate impedance across band(s) of interest at network insertion point***
4. ***Narrowband match:***
   - *Select appropriate lossless L network, 2 or 4 choices*
   - *Select lumped elements vs stubs*
   - *Calculate component values*
   - *Calculate SWR and SWR bandwidth*
   - *Build and test*
5. ***Broadband match:***
   - *Use design software - winSMITH or equivalent*
   - *Design n-stage lossless ladder network*
   - *Select lumped elements vs stubs*
   - *Calculate component values*
   - *Calculate SWR and SWR bandwidth*

How to Measure Antenna Feedpoint Impedance

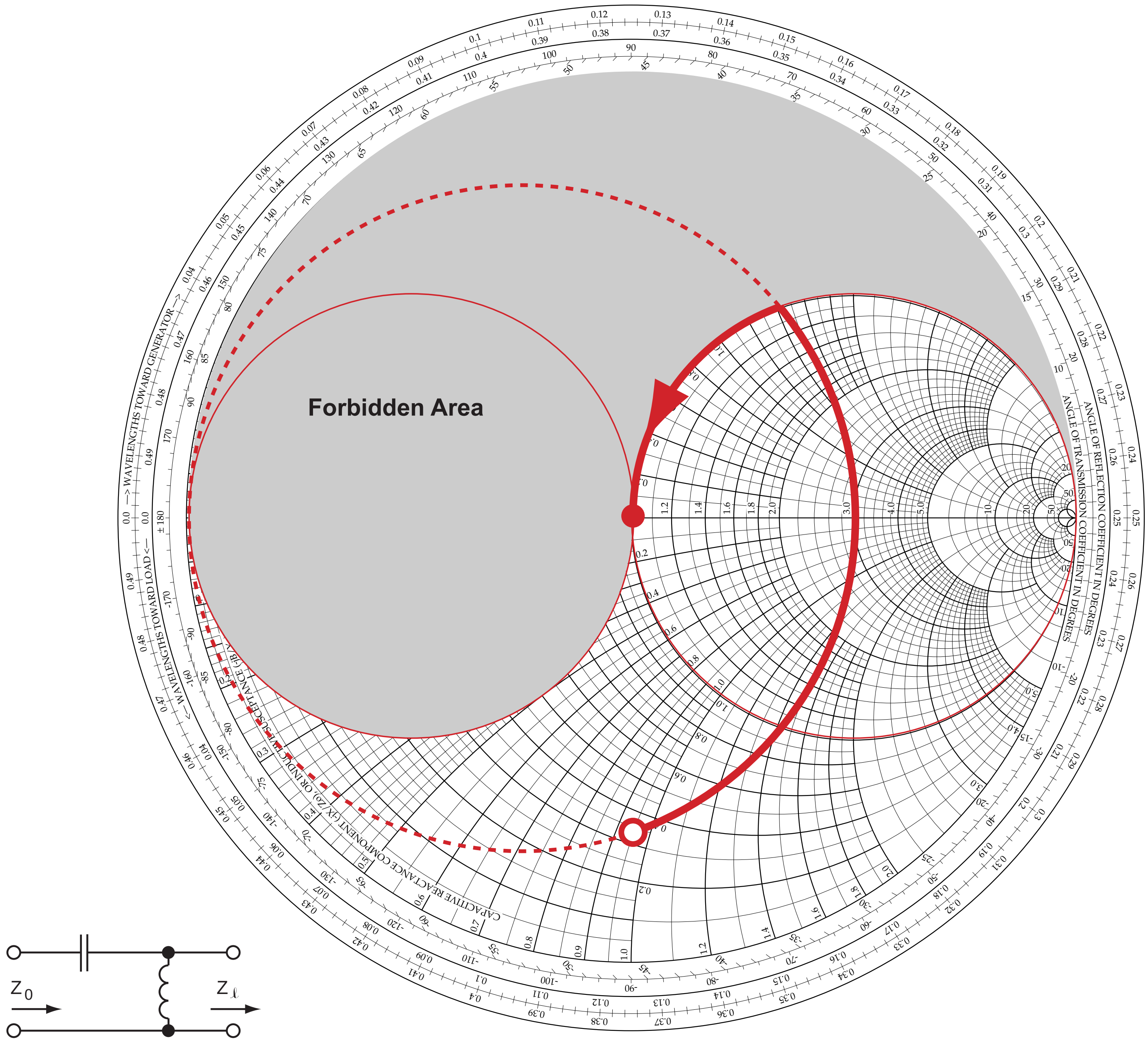
- ❑ ***Measure impedance through known line***
- ❑ ***Divide measure impedance by Z_o***
- ❑ ***Plot impedance point on Smith Chart***
- ❑ ***Move counter clockwise on chart by electrical length of line***
- ❑ ***Read coordinate values from chart***
- ❑ ***Multiply result by Z_o***

Smith Chart: Effect of Adding Series Reactances or Shunt Susceptances

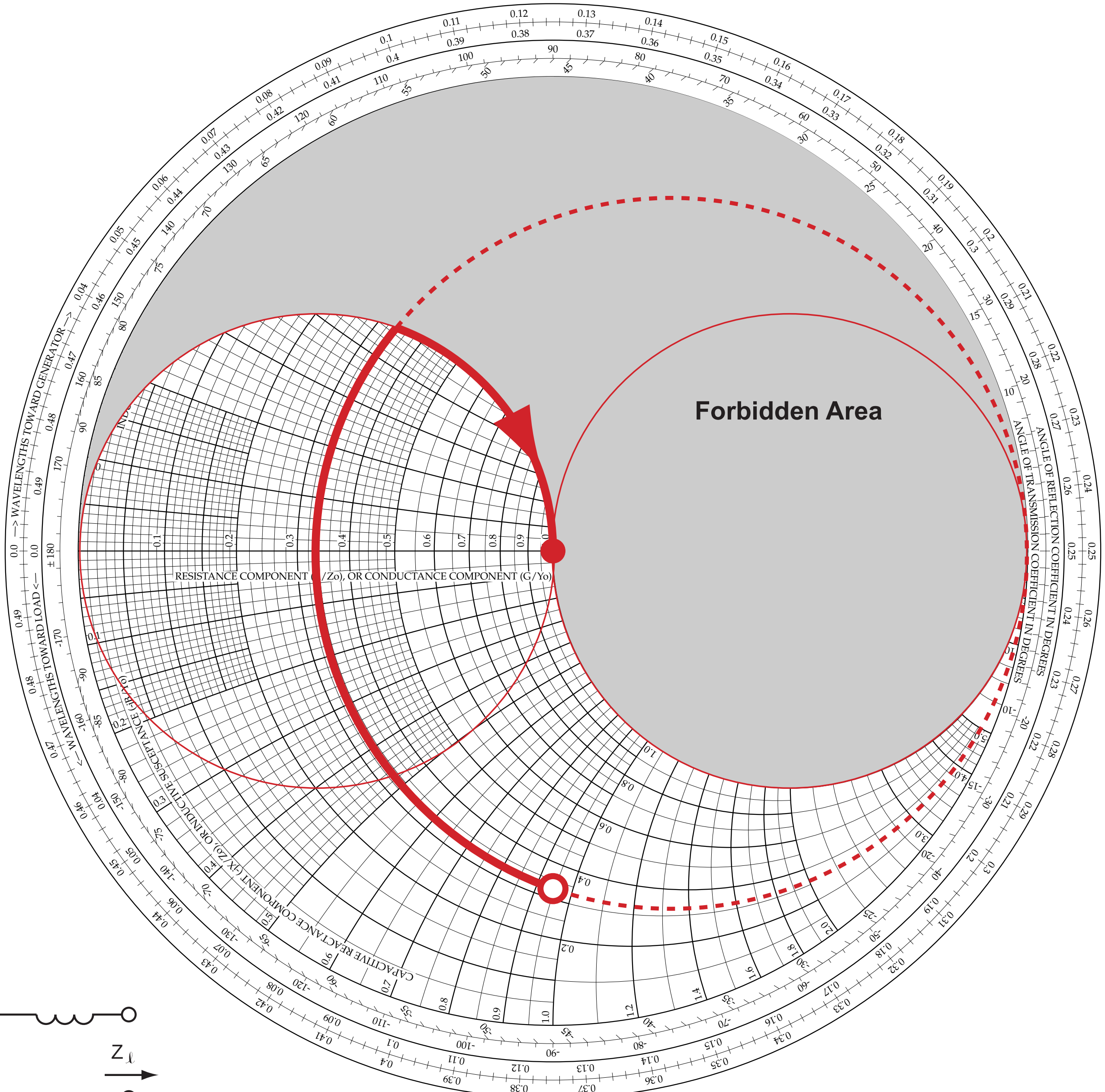


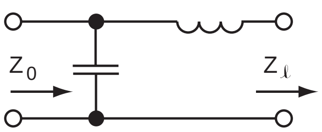

Forbidden Area
WAVELENGTHS TOWARD GENERATOR
WAVELENGTHS TOWARD LOAD
ANGLE OF REFLECTION COEFFICIENT IN DEGREES
ANGLE OF TRANSMISSION COEFFICIENT IN DEGREES
Z_0
Z_ℓ

(a)

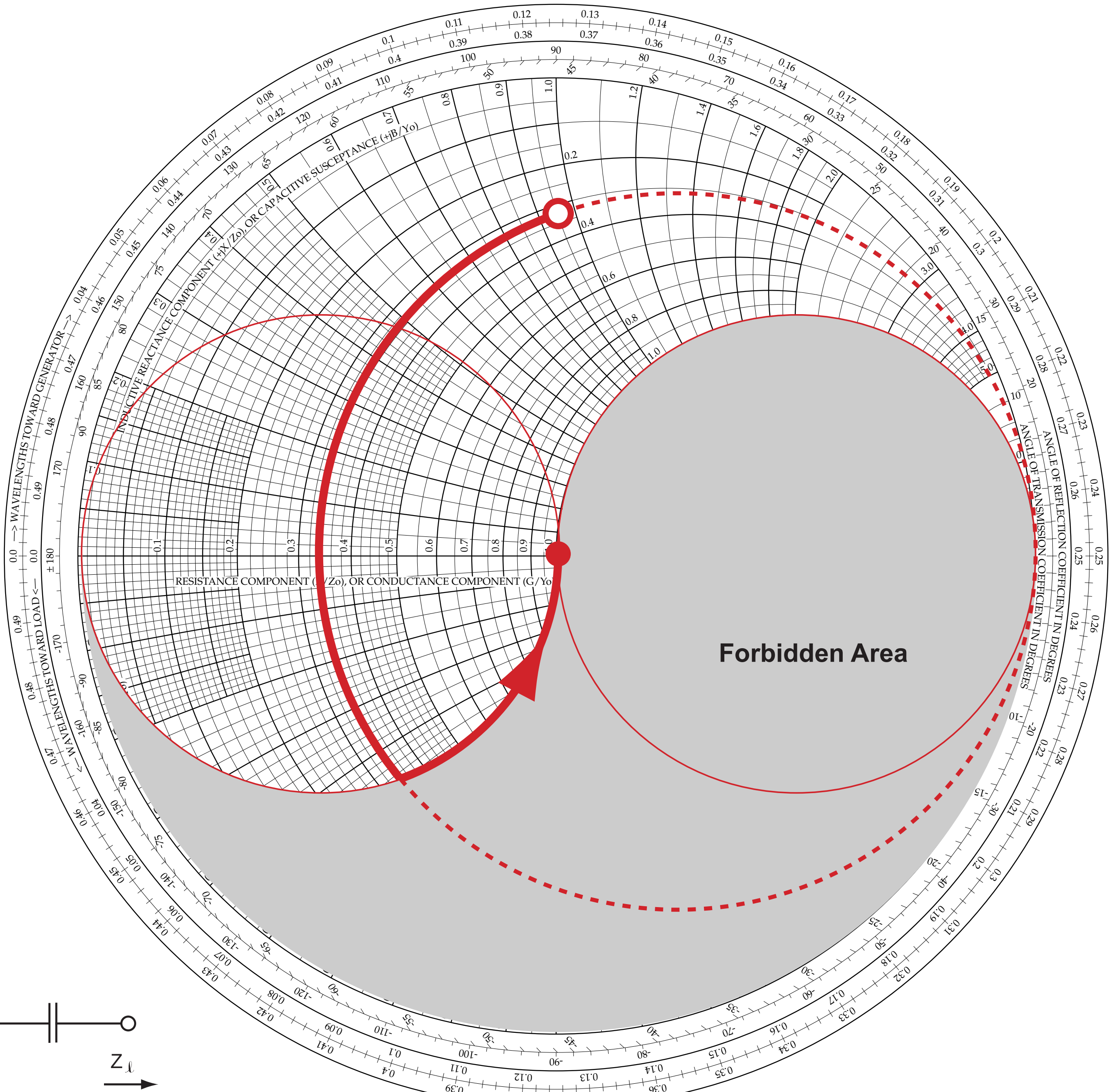


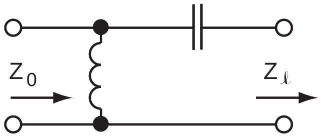
(b)


Forbidden Area
RESISTANCE COMPONENT (R/Zo), OR CONDUCTANCE COMPONENT (G/Yo)
ANGLE OF REFLECTION COEFFICIENT IN DEGREES
ANGLE OF TRANSMISSION COEFFICIENT IN DEGREES
—> WAVELENGTHS TOWARD GENERATOR —>
<— WAVELENGTHS TOWARD LOAD <—
CAPACITIVE REACTANCE COMPONENT (-jX/Zo) OR INDUCTIVE SUSCEPTANCE (-jB/Yo)

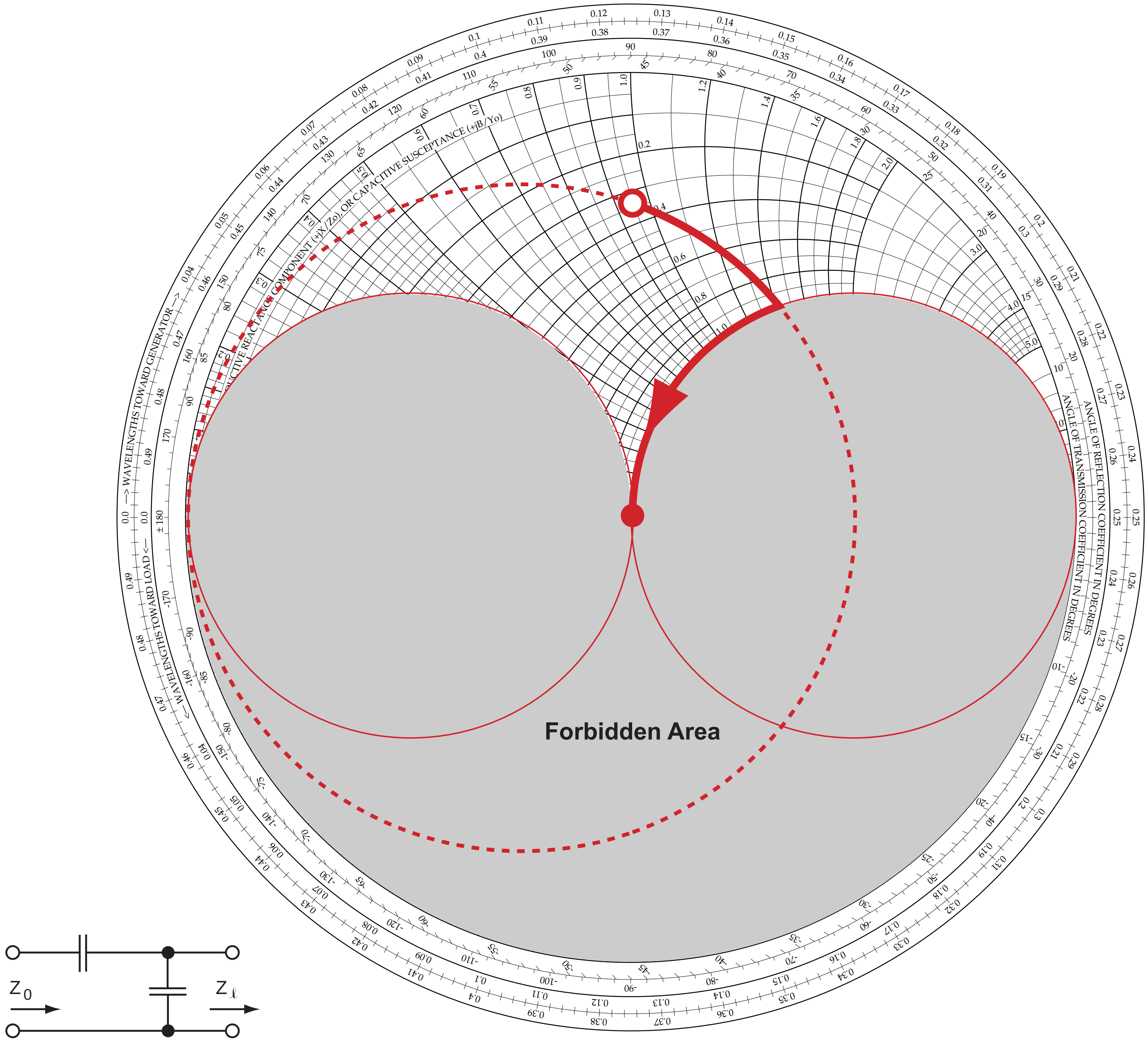

Z_0
Z_ℓ

(c)

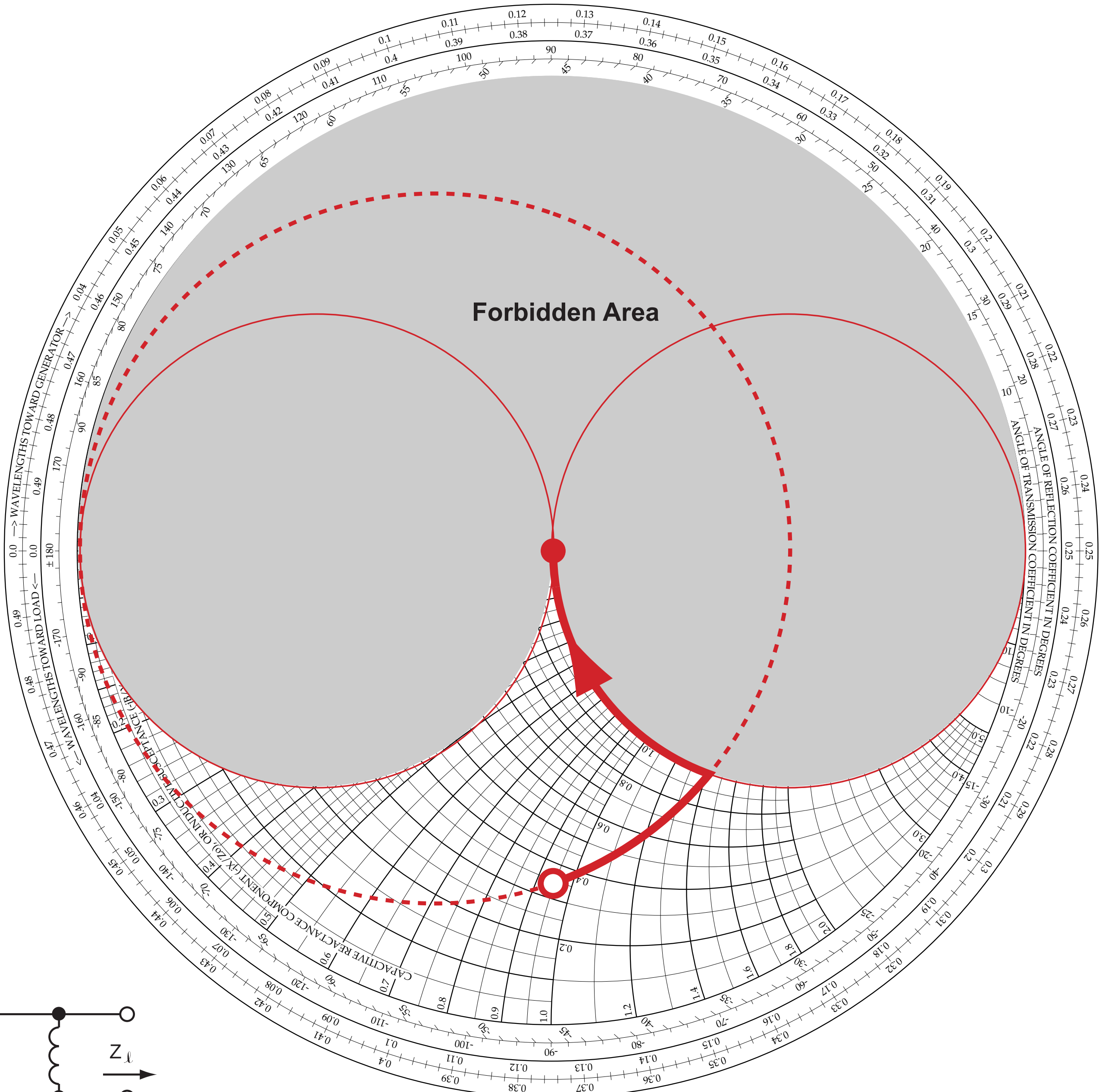


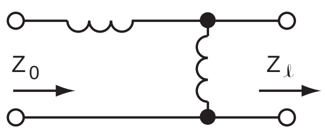


(d)

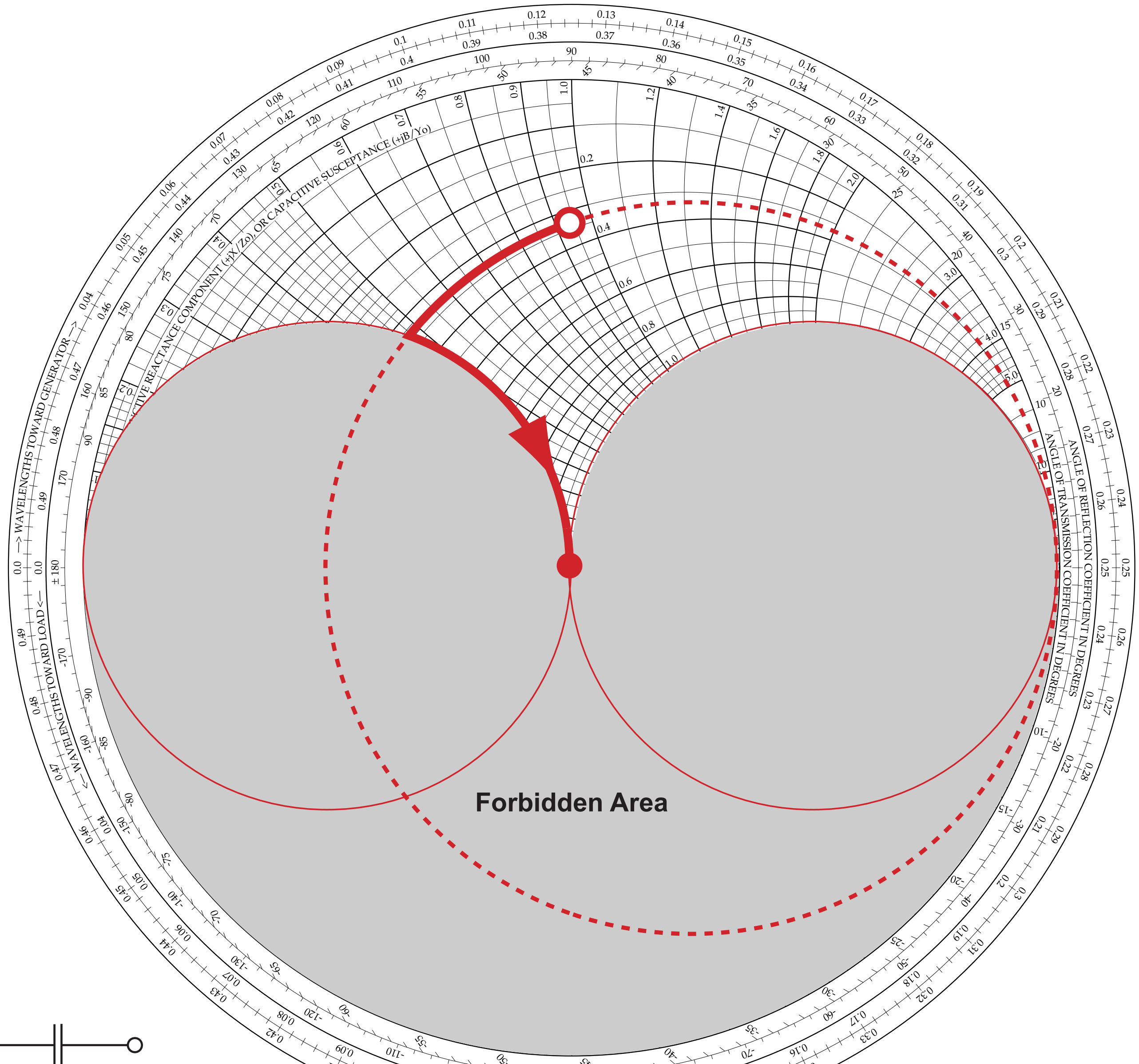


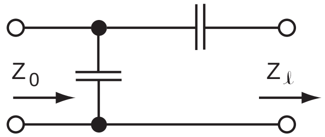
(e)



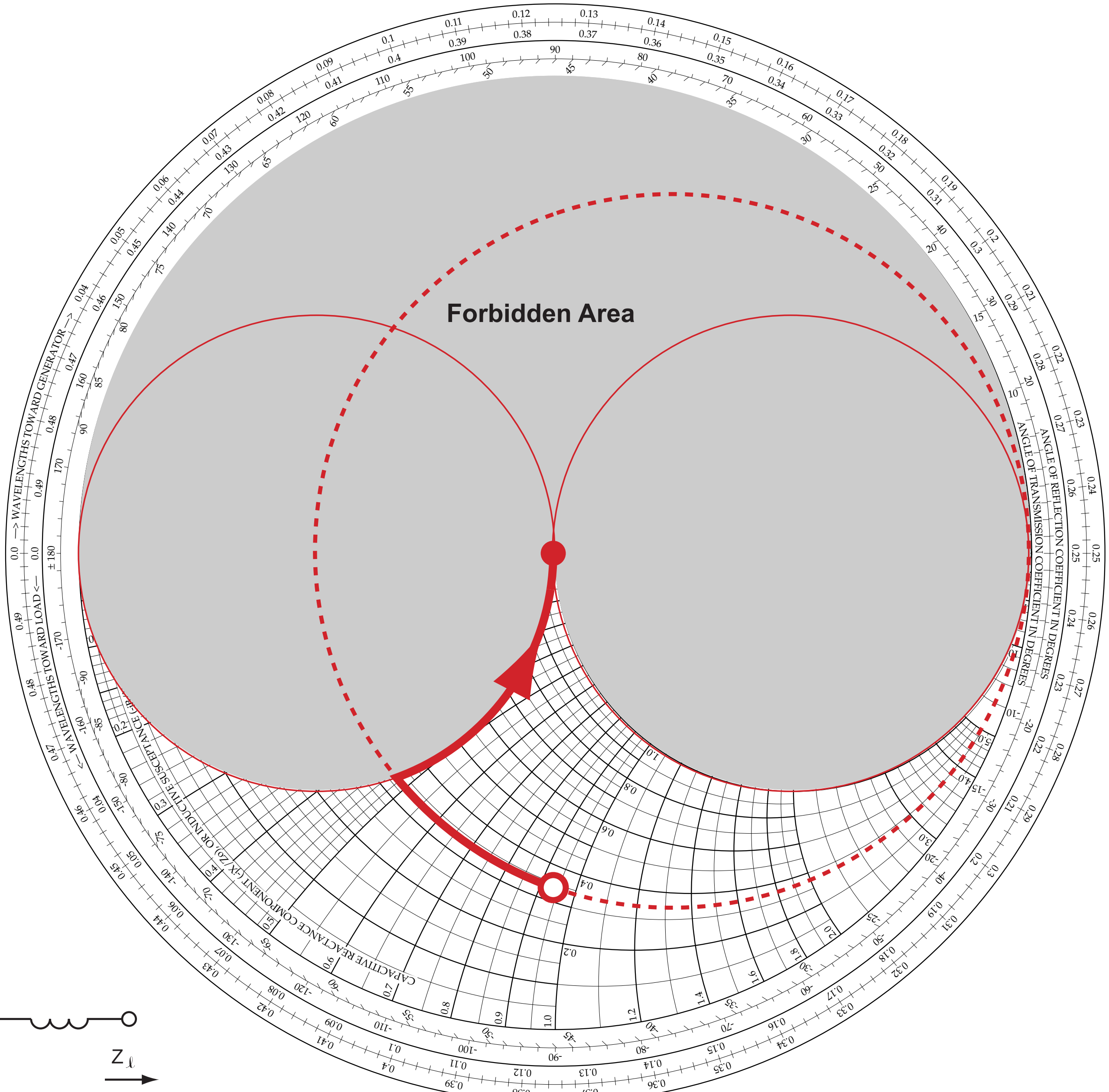


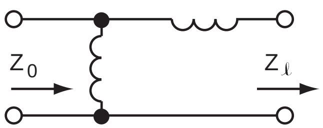
(f)





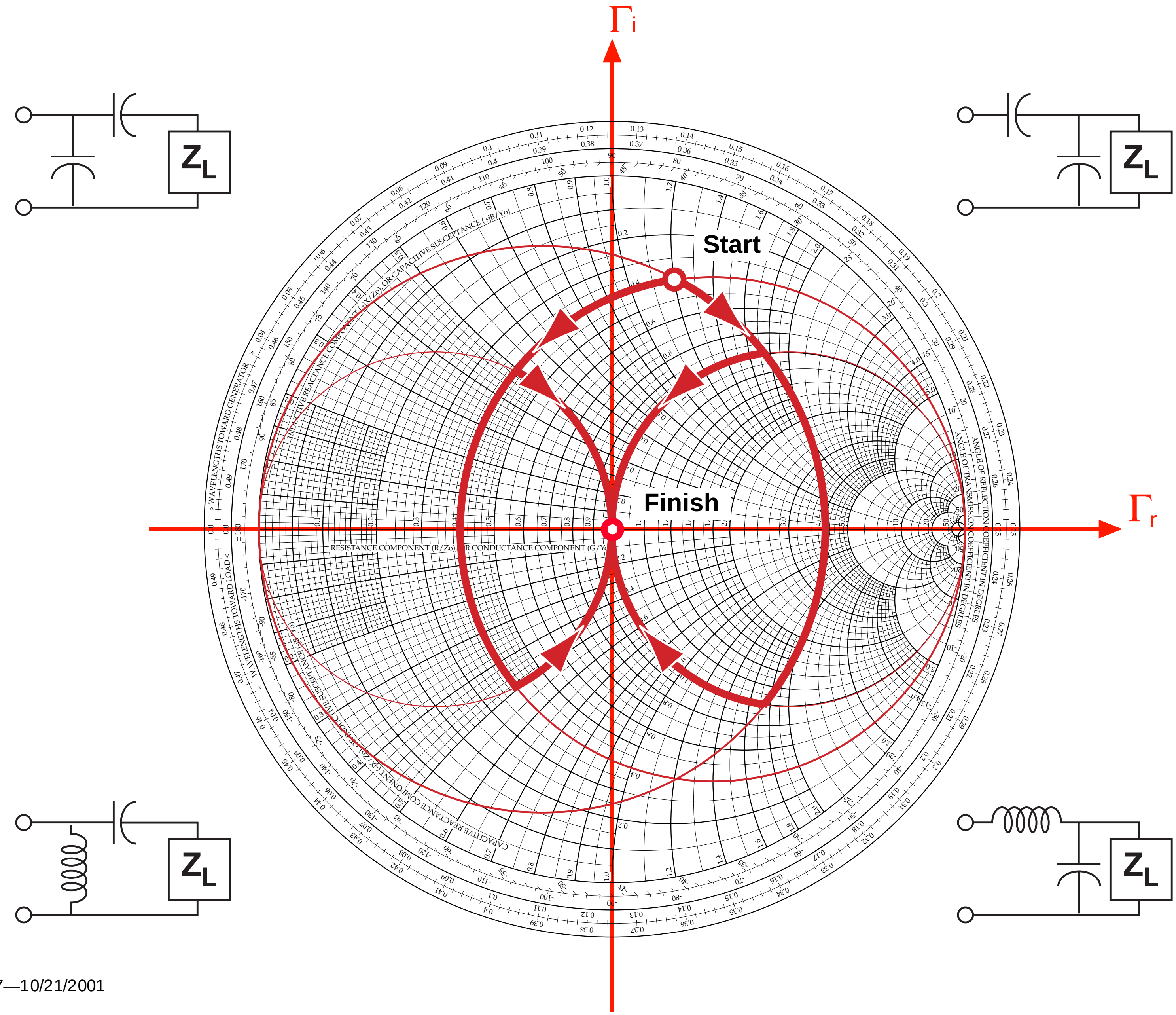
(g)


Forbidden Area
WAVELENGTHS TOWARD GENERATOR
WAVELENGTHS TOWARD LOAD
ANGLE OF REFLECTION COEFFICIENT IN DEGREES
ANGLE OF TRANSMISSION COEFFICIENT IN DEGREES
CAPACITIVE REACTANCE COMPONENT (-jX/Zo) OR INDUCTIVE SUSCEPTANCE

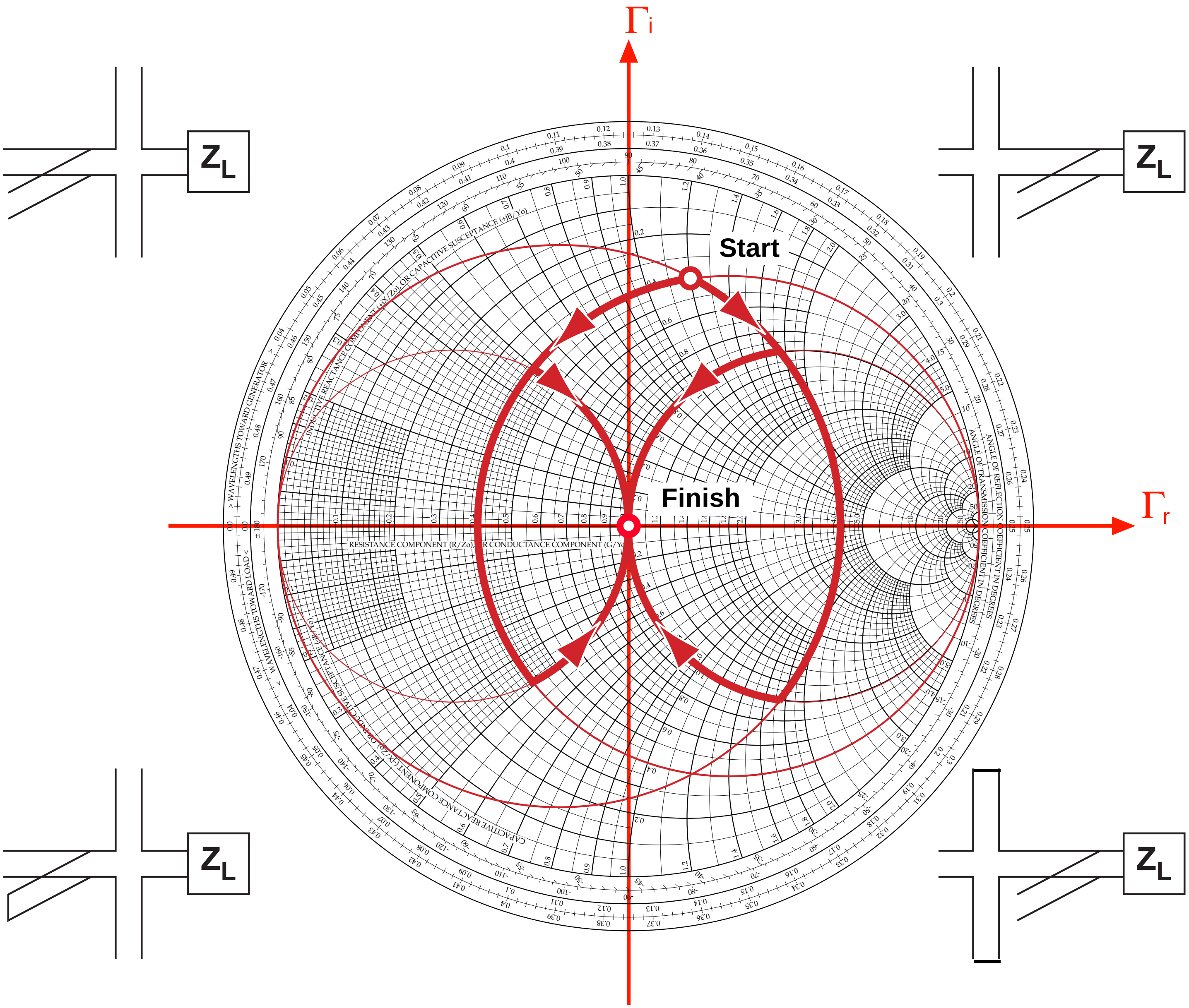

Z_0
Z_ℓ

(h)

Matching: Four L-Networks Using Lumped Elements



Matching: Four L-Networks Using Stubs



Reactance & Susceptance of Lumped Elements

Inductors

$$X_L = 2\pi fL \qquad B_L = \frac{-1}{2\pi fL}$$

Capacitors

$$X_C = \frac{-1}{2\pi fC} \qquad B_C = 2\pi fC$$

Reactance & Susceptance of Stubs

- ***Assuming Zo is real, then***
- ***Shorted Stubs***

$$X_{shorted} = Z_o \tan\left(\frac{2\pi l f}{v_f c}\right) \qquad B_{shorted} = \frac{-1}{Z_o \tan\left(\frac{2\pi l f}{v_f c}\right)}$$

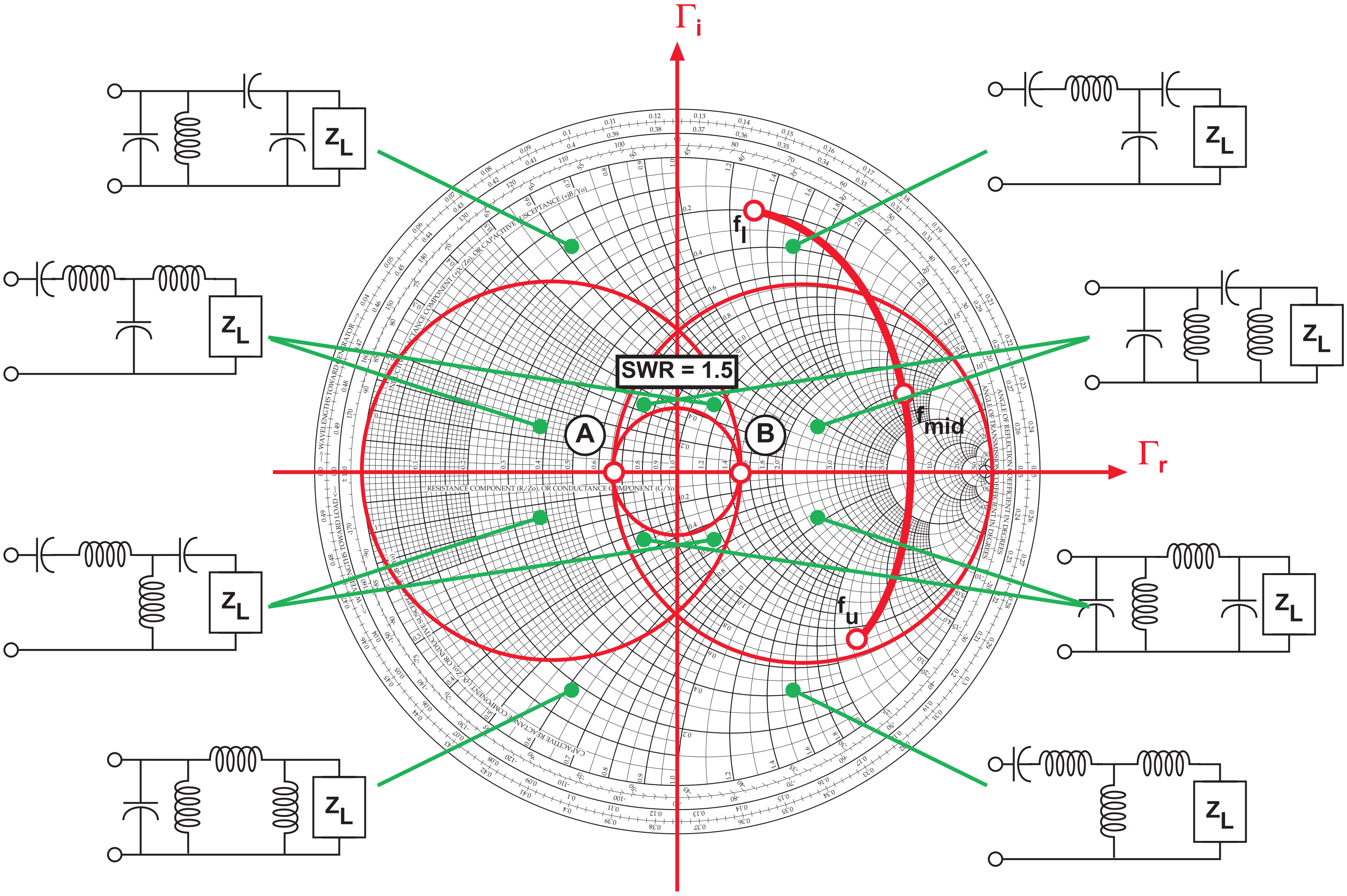
- ***Open Stubs***

$$X_{open} = \frac{-Z_o}{\tan\left(\frac{2\pi l f}{v_f c}\right)} \qquad B_{open} = \frac{1}{Z_o} \tan\left(\frac{2\pi l f}{v_f c}\right)$$

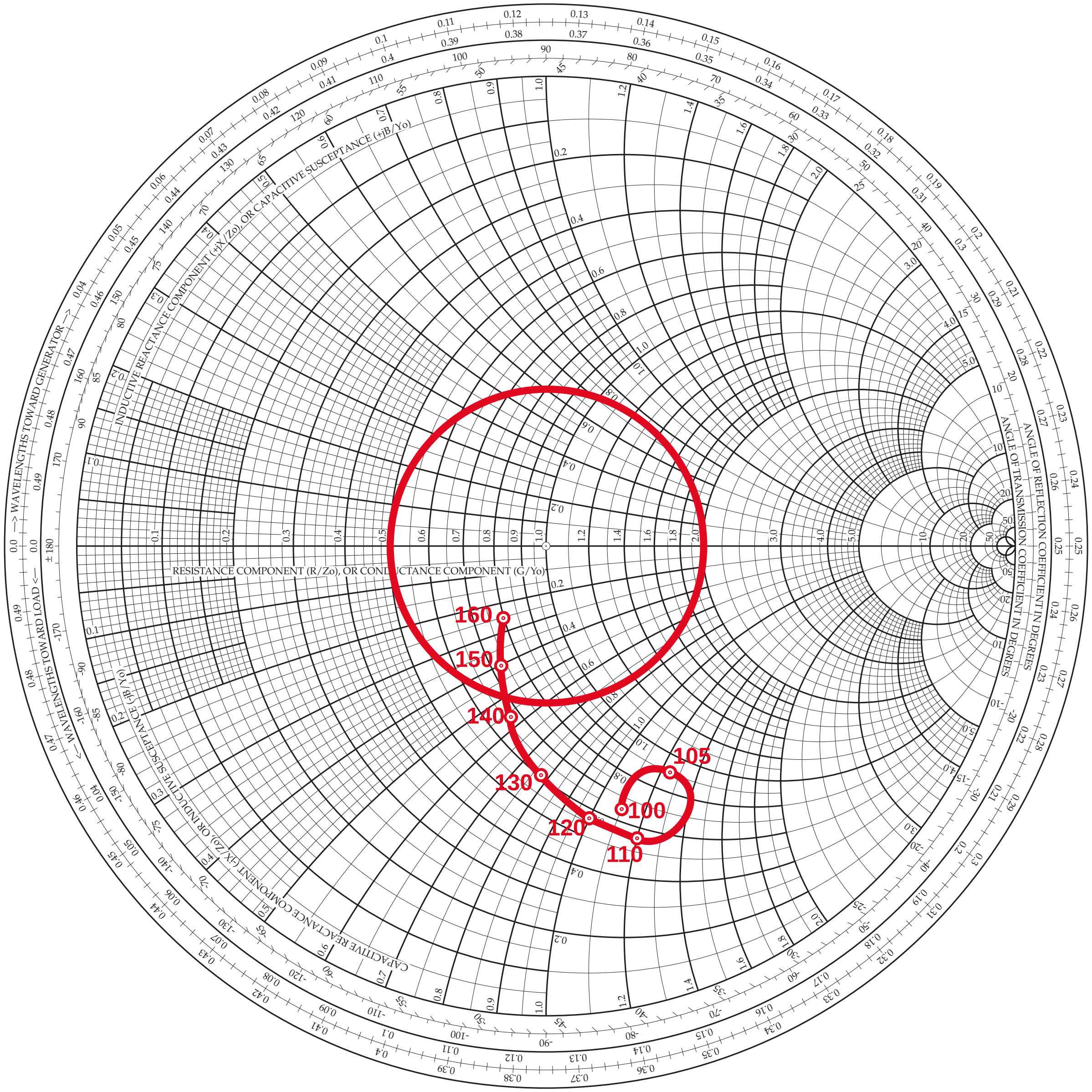
Broadband Matching Network Design Recipe
Using 4-Element π-Resonant and T-Resonant Networks

- ***Putting network insertion point close to load (antenna) gives greatest SWR bandwidth***
- ***Step 1: Using an L-network, move the midband impedance point to prime point A or B. Bandwidth will be maximized if the minimum reactance or susceptance L-network is chosen in this step.***
- ***Step 2: Wrap the impedance locus into the SWR circle by adding a series or parallel resonant circuit as required to complete the π-resonant or T-resonant network***

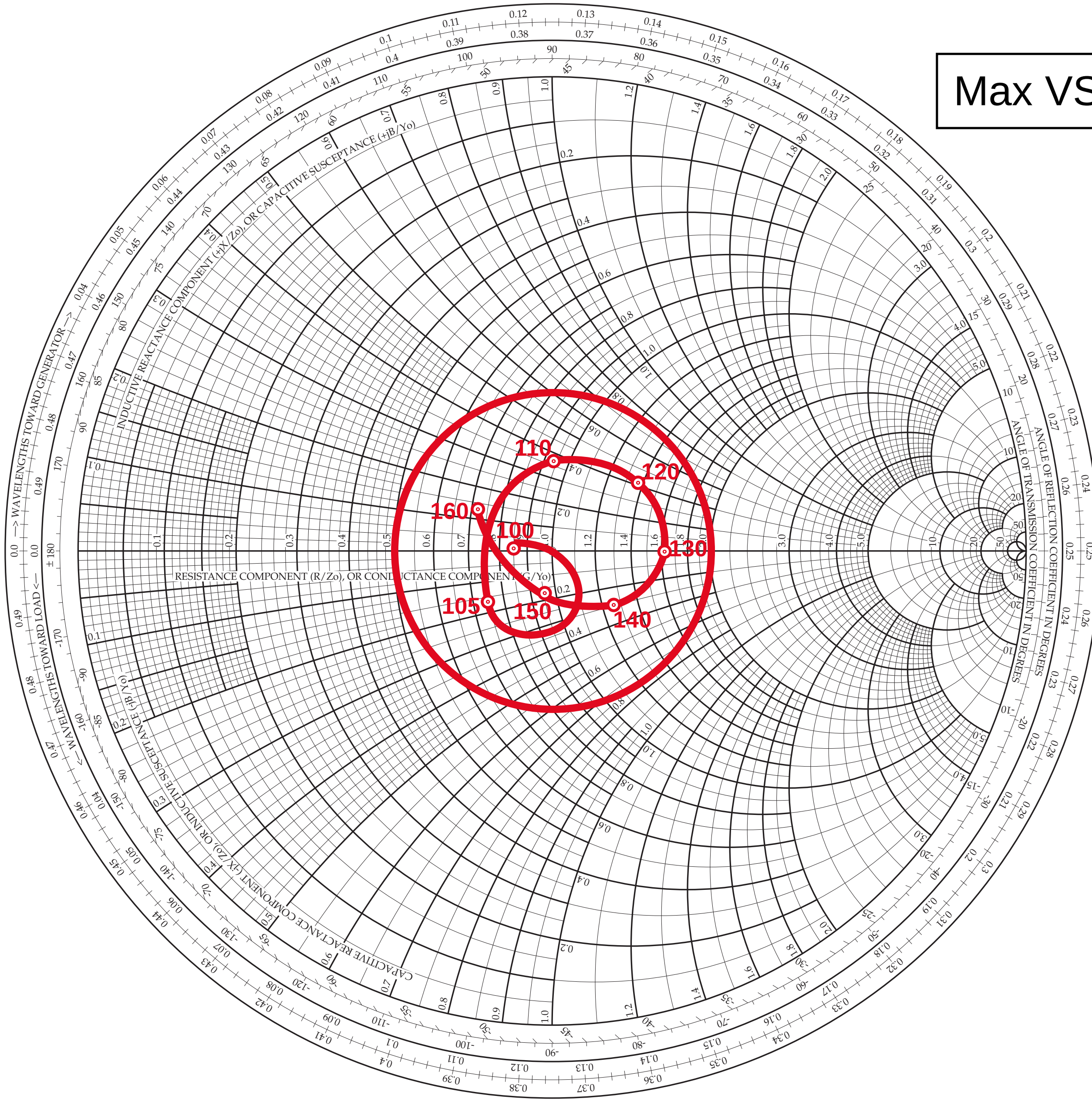
Π-Resonant and T-Resonant Network
For Moderate and Broadband Matching



Caron’s Example 10: VHF Folded Blade Antenna

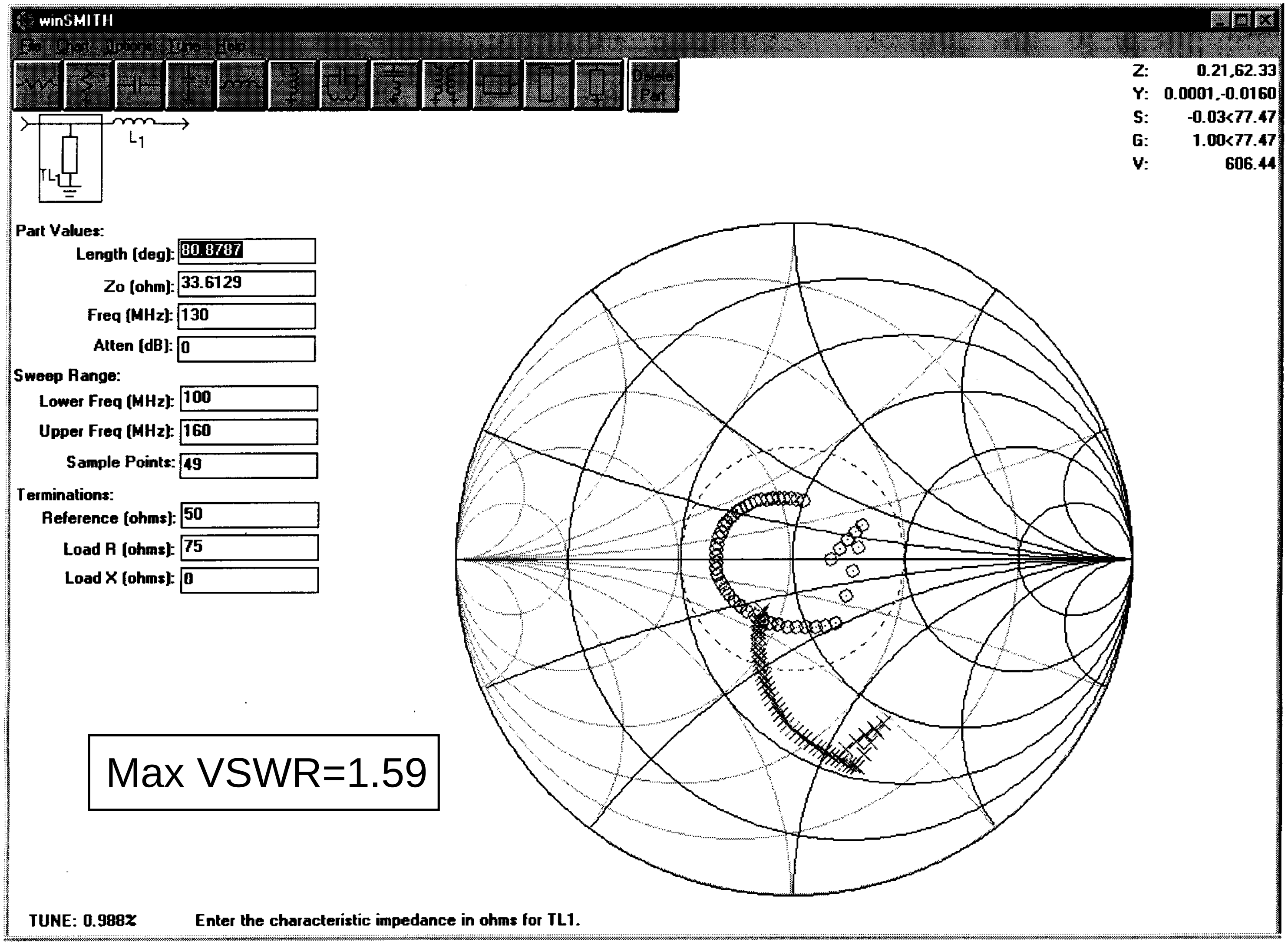


Caron’s Matching Solution

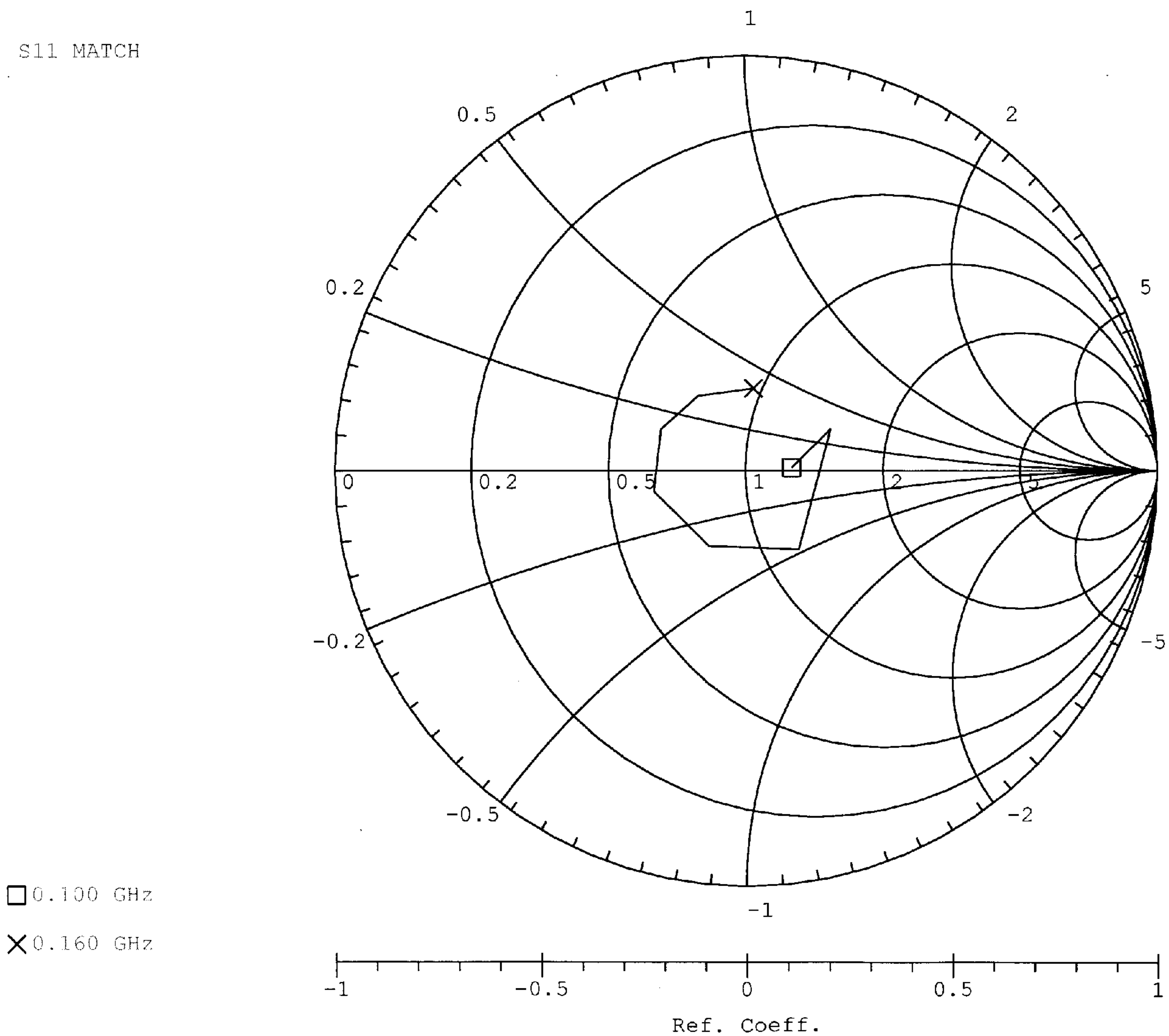


Max VSWR=1.67

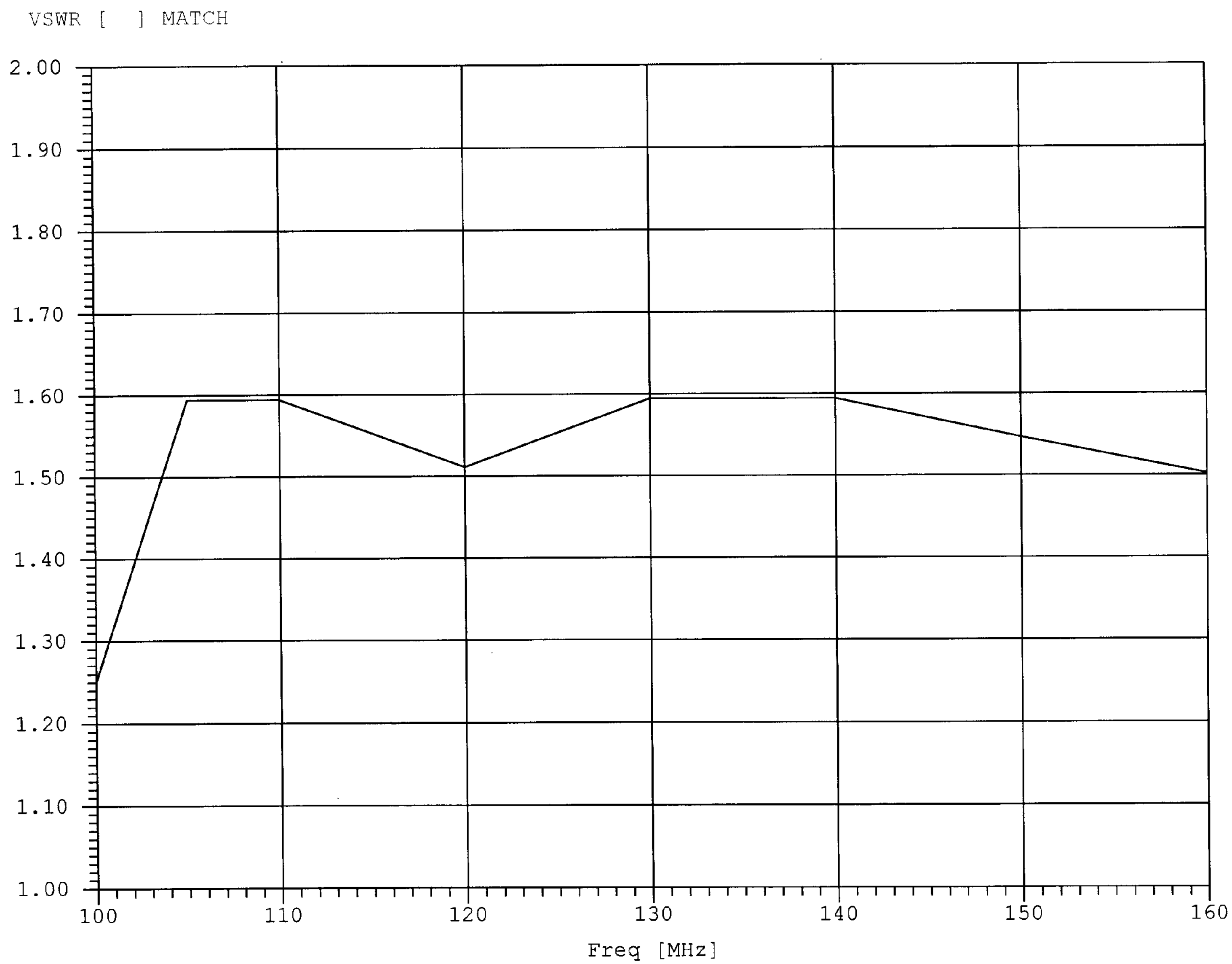
WinSmith Display



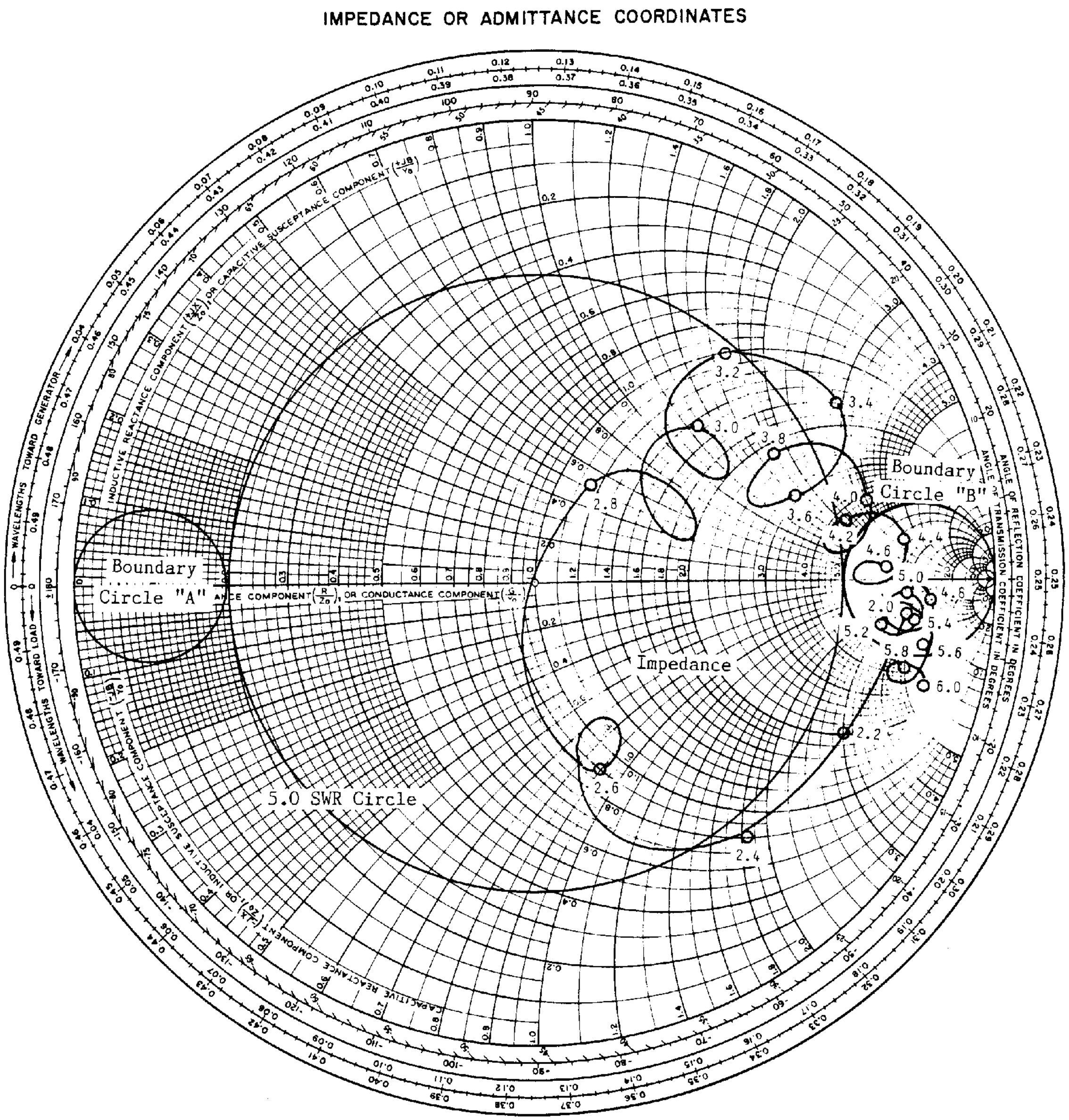
ARRL Radio Designer



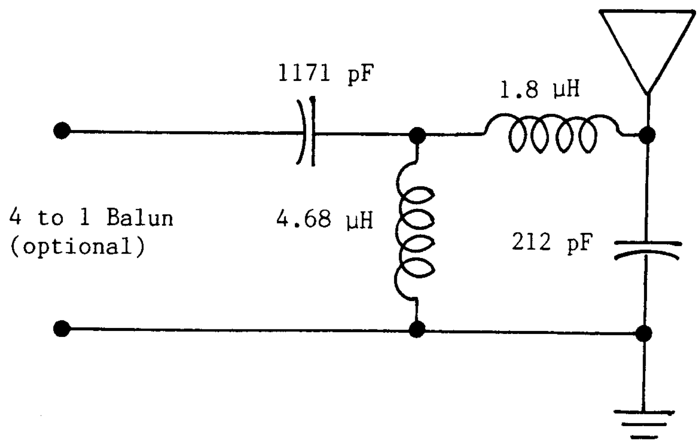
ARRL Radio Designer



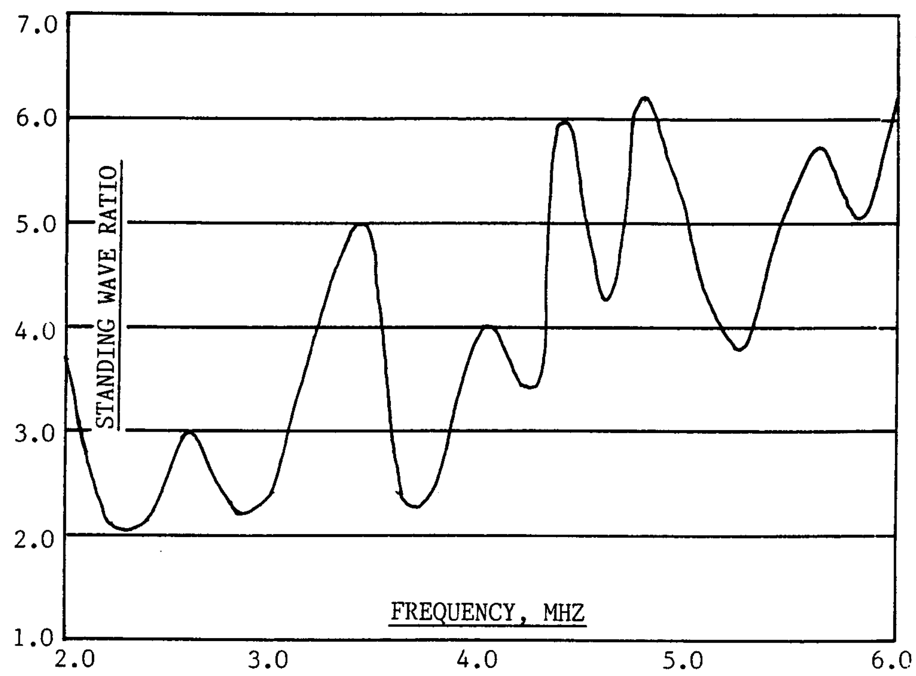
Caron's Example 11: Long Wire Receiving Antenna



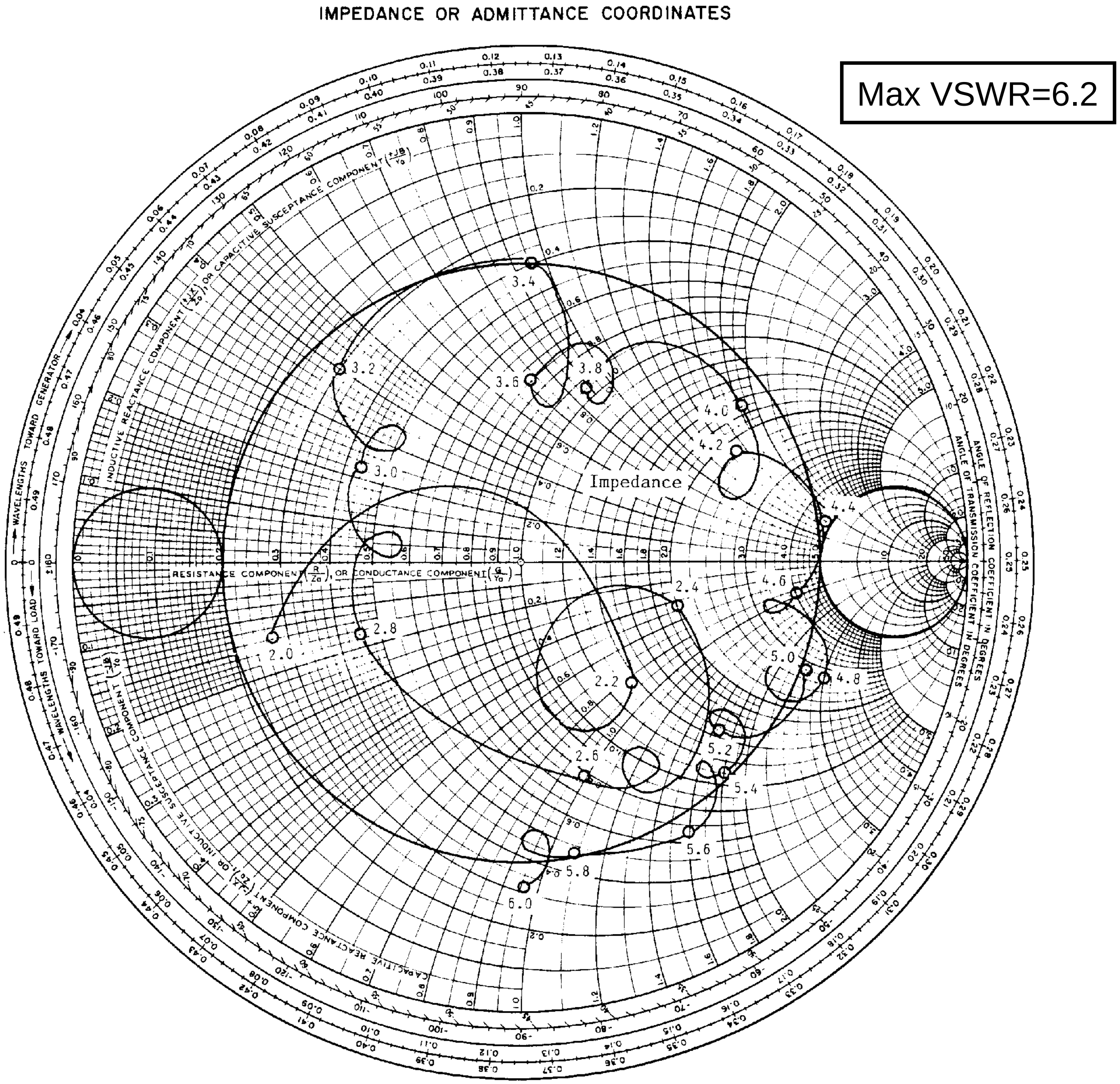
Caron's Solution



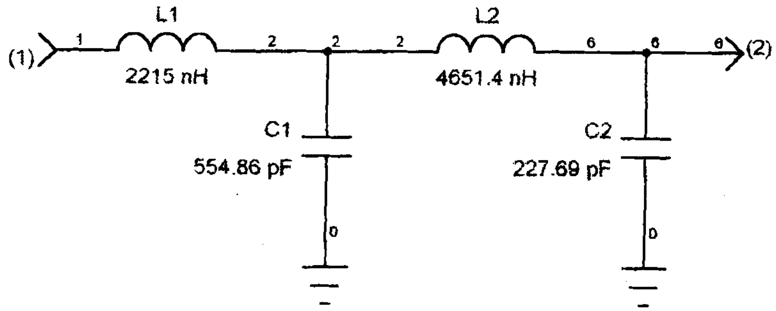
Max VSWR=6.2



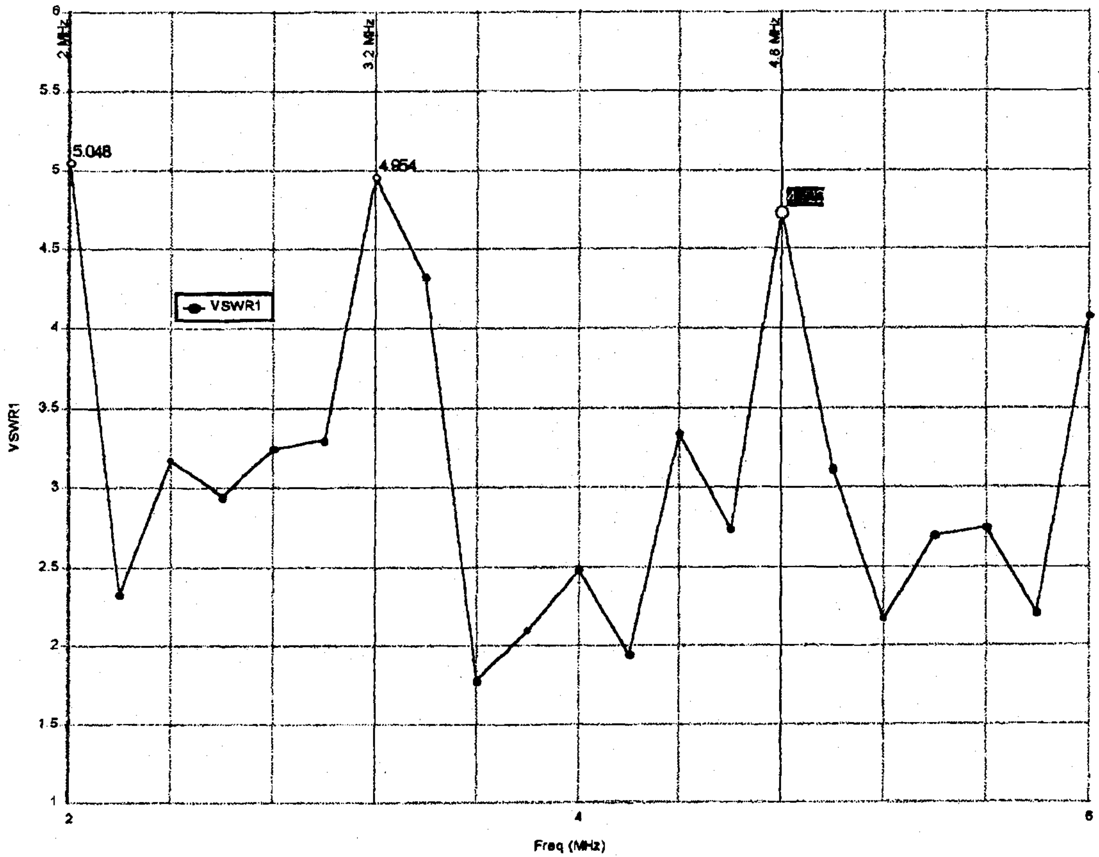
Caron's Solution



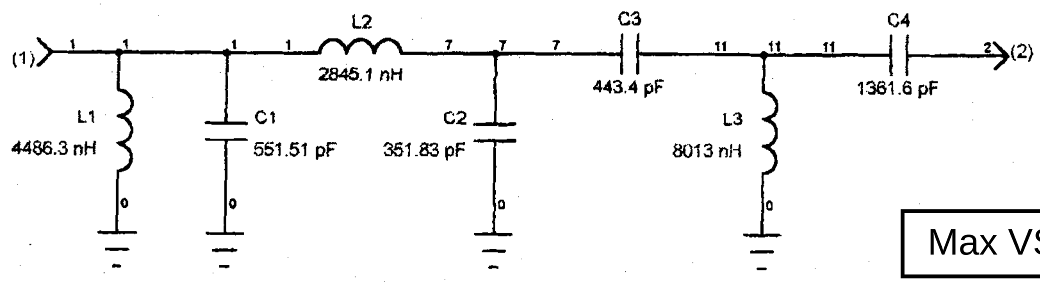
Eagleware's Solution 1



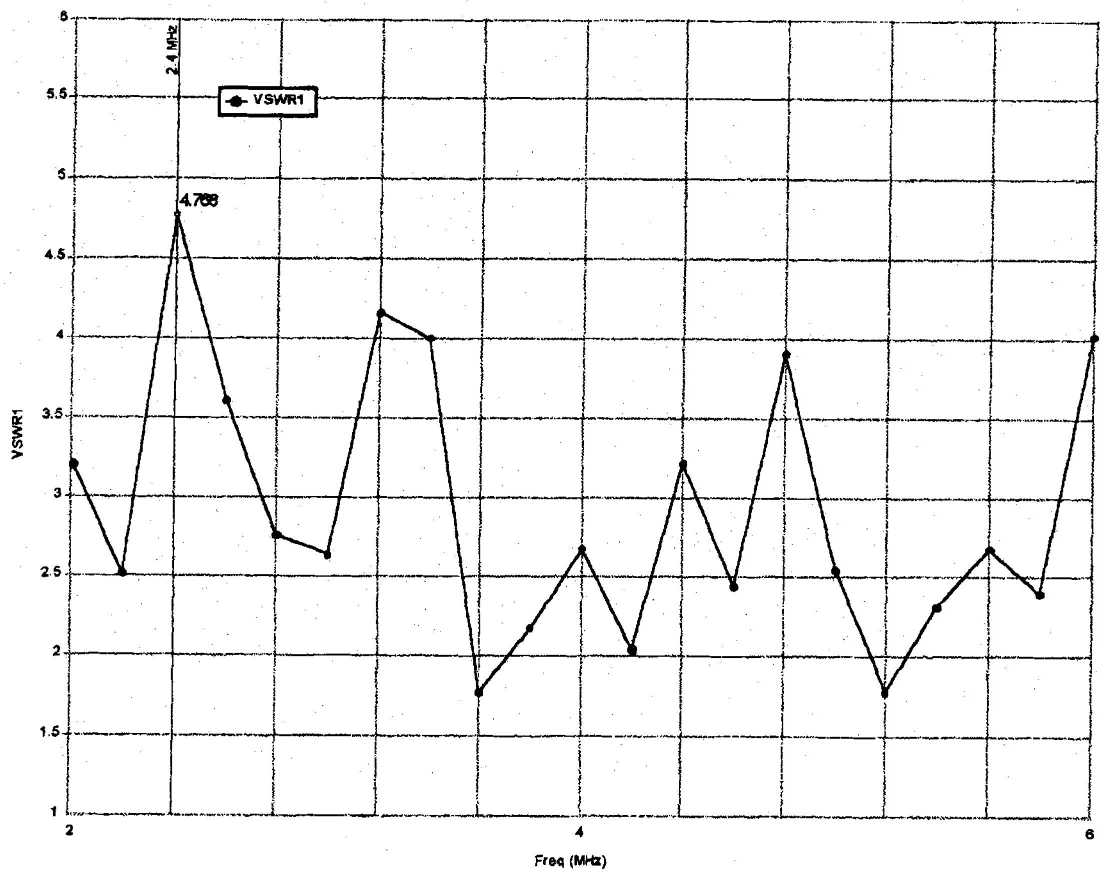
Max VSWR=5.05



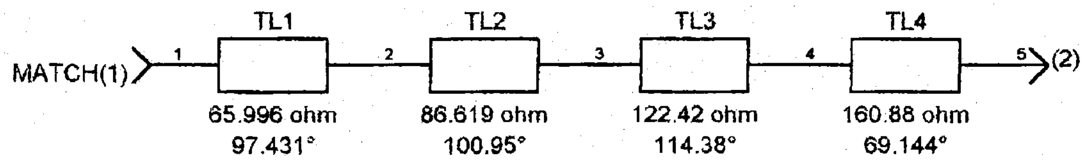
Eagleware's Solution 2

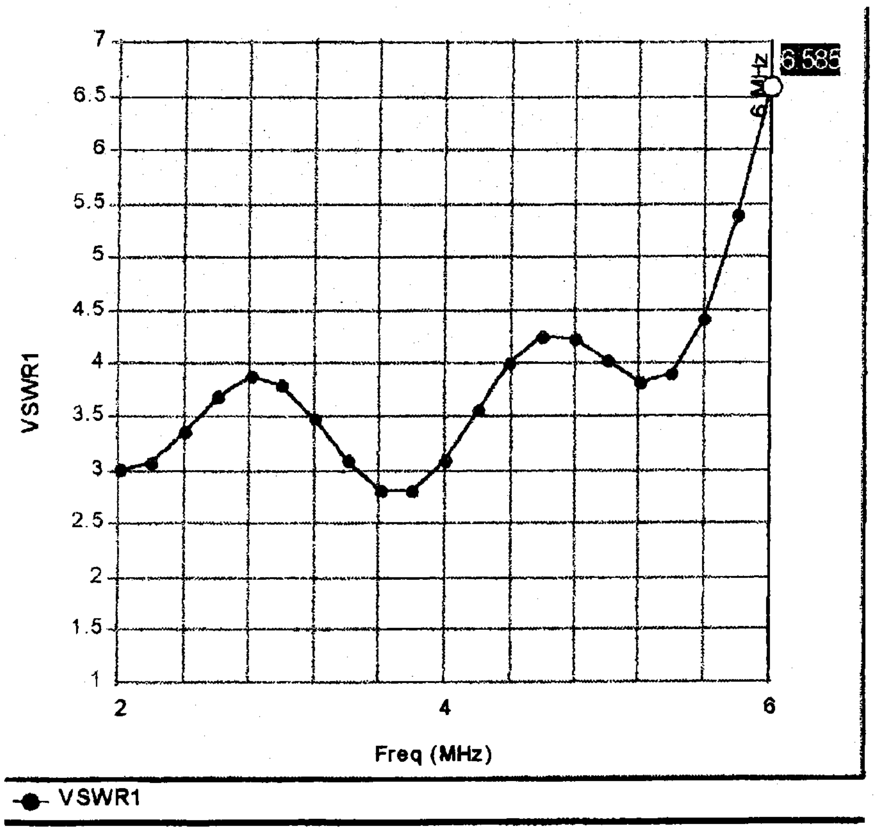


Max VSWR=4.77



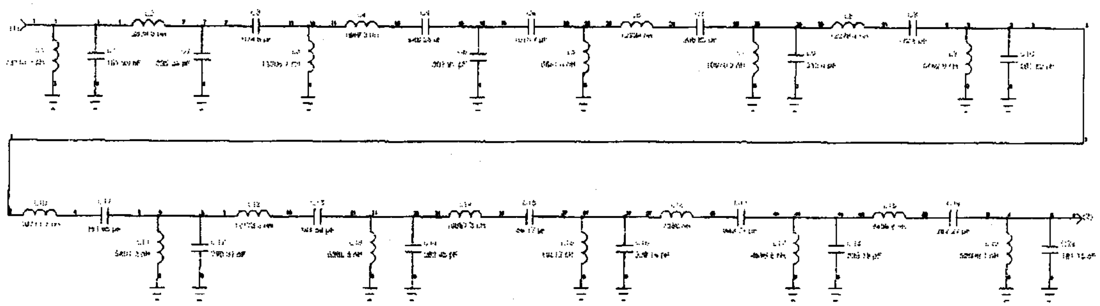
Eagleware's Solution 3

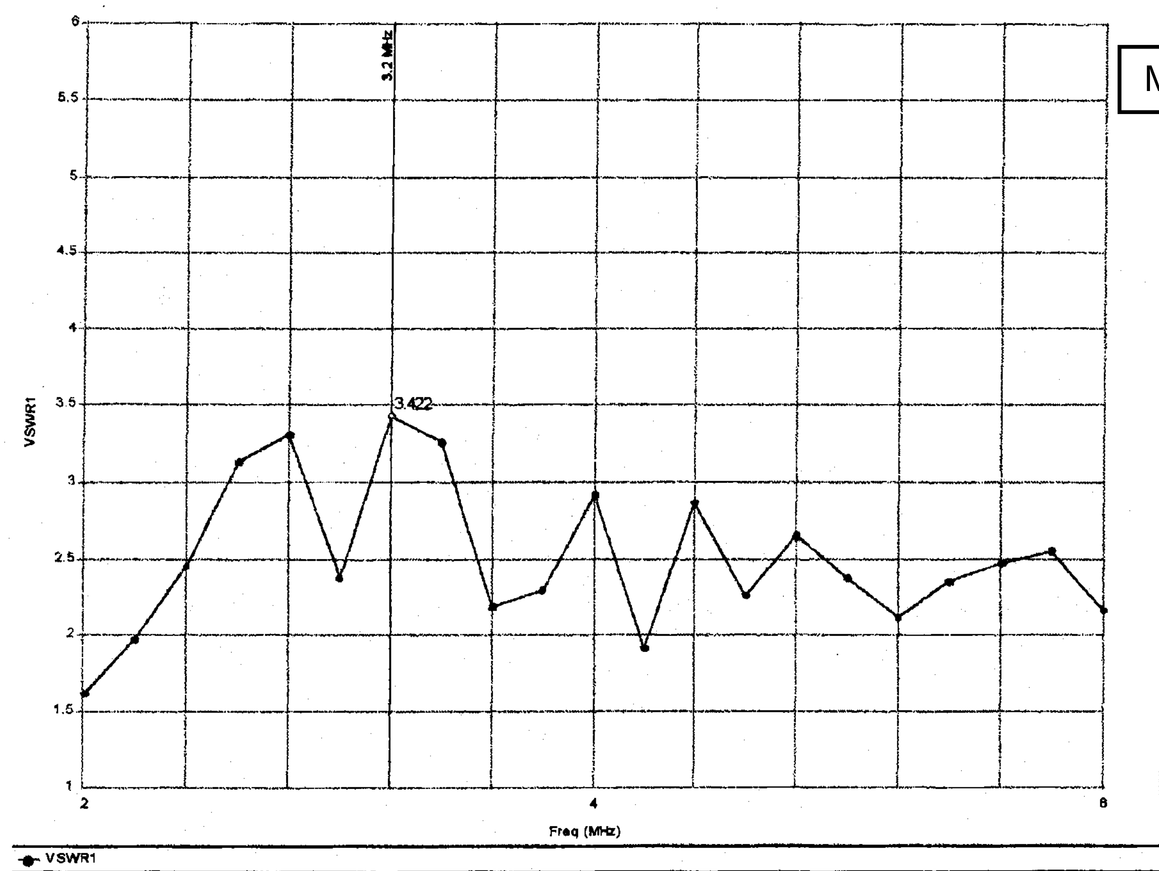




Max VSWR=6.59

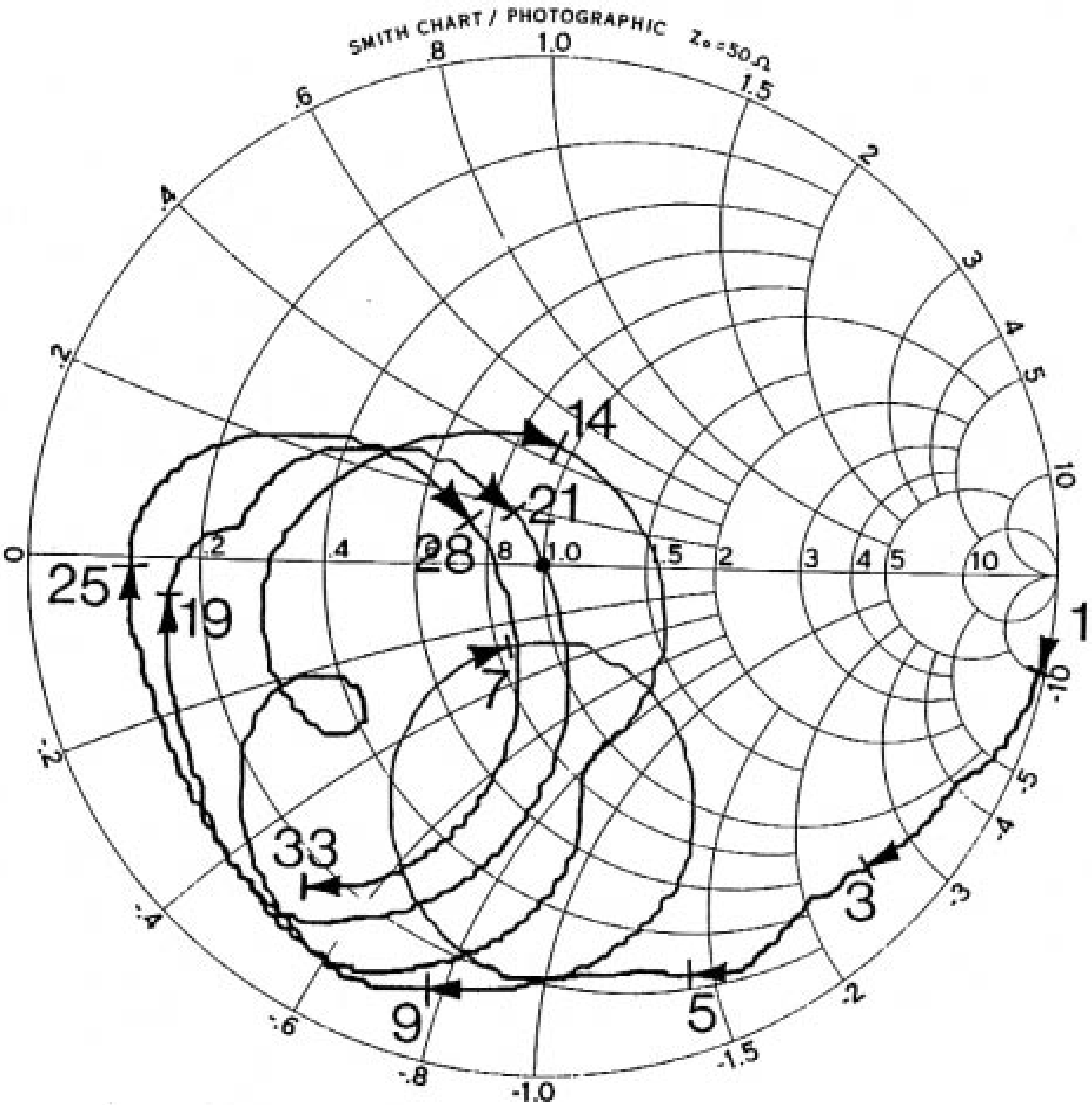
Eagleware's Solution 4: Fano Limit





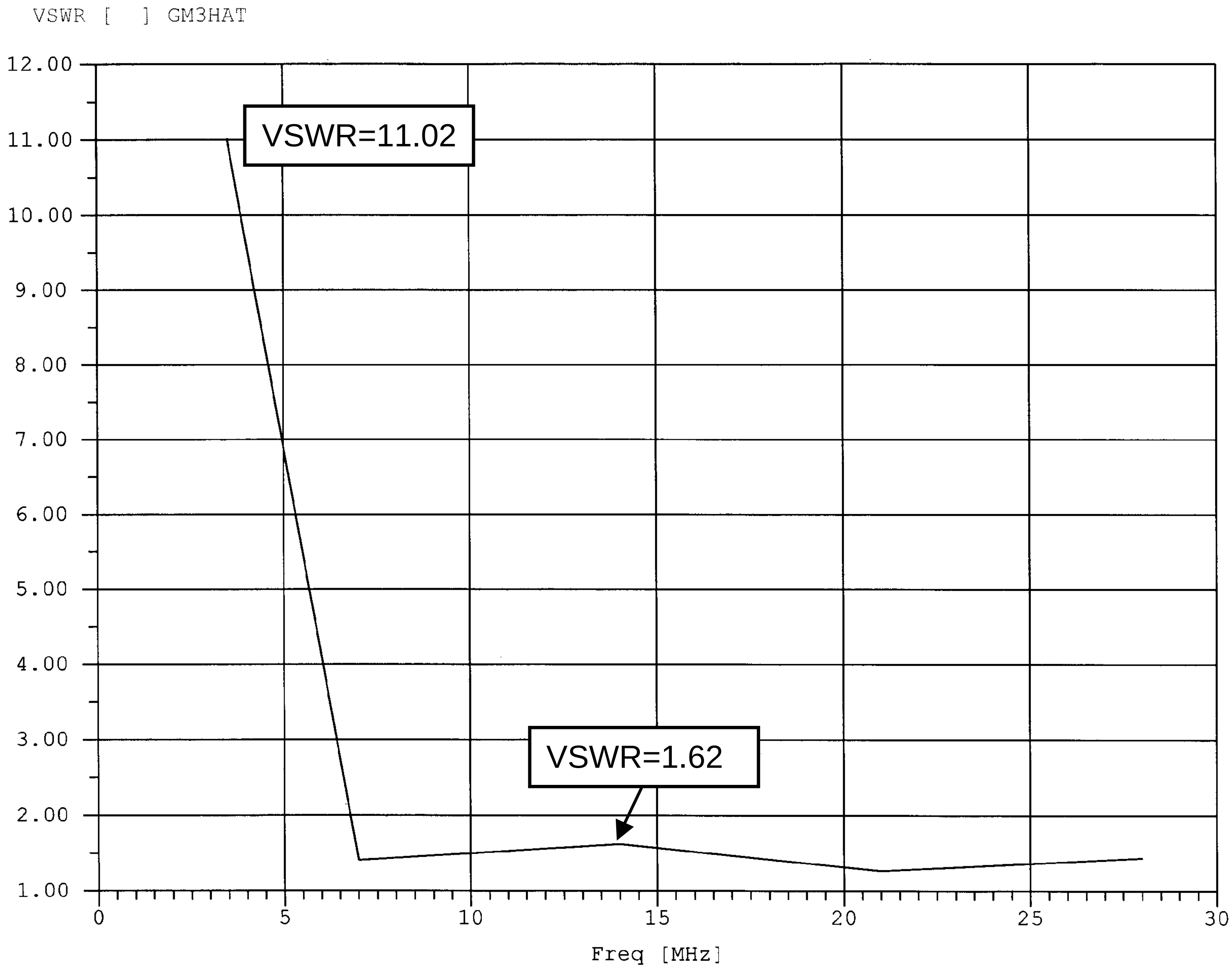
Max VSWR=3.42

GM3HAT 4-Band Dipole of Delight

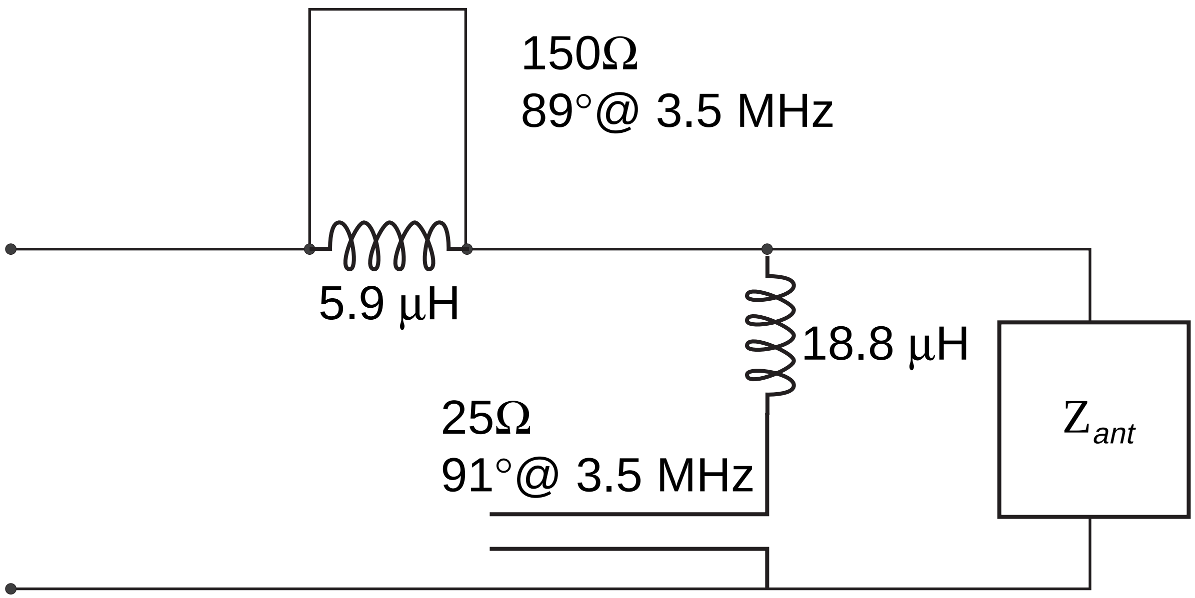


GM3HAT Feedpoint Impedance

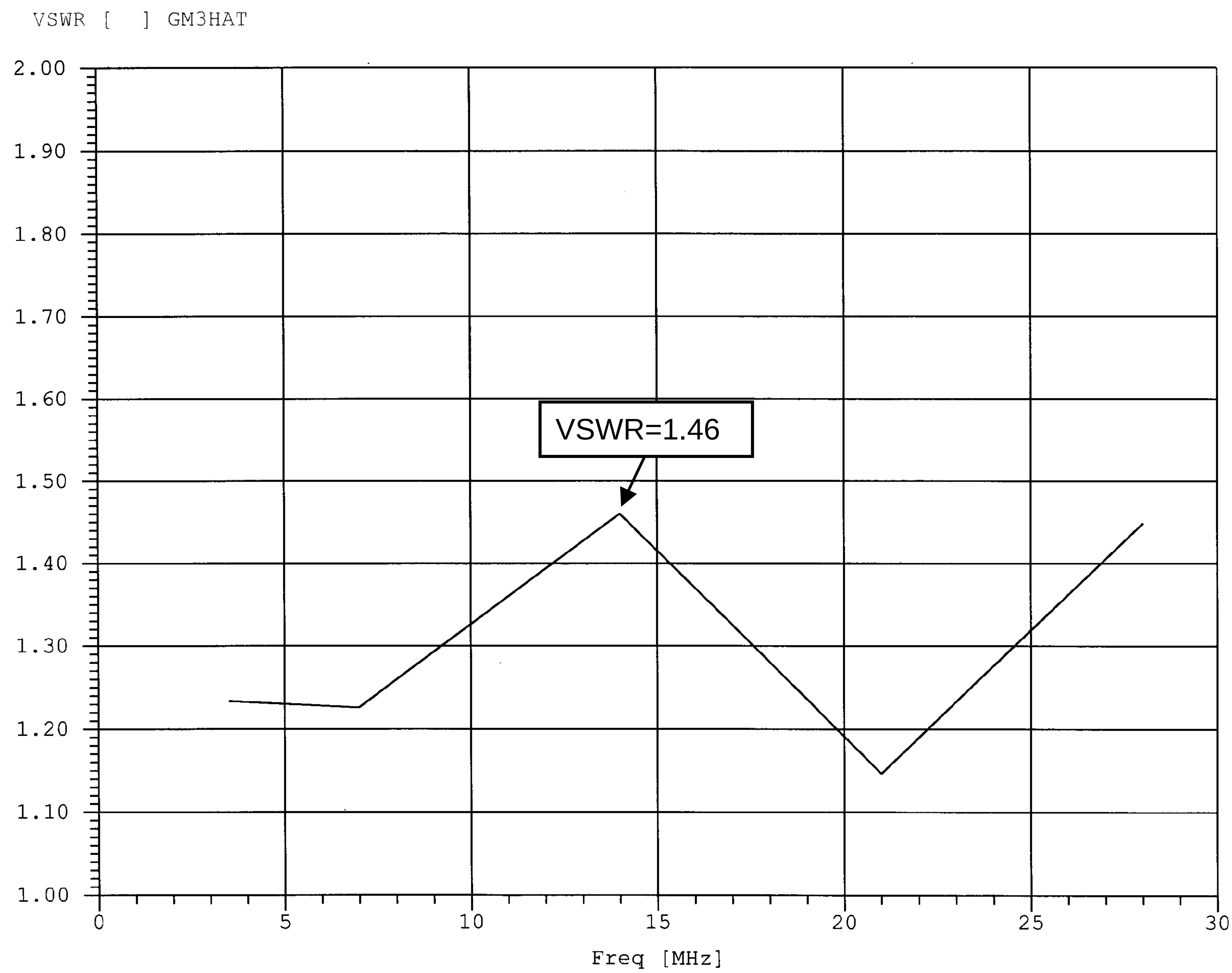
At Five Harmonic Frequencies



K6OIK 80m Suboctave Band Matching Network



K6OIK's Multiband Match Performance



Software for Smith Charting and Network Design

- ❑ ***Smith Chart Analysis & Display***
  - ➤ ***MicroSmith* 2.3, ARRL, 1992, $39**

    A primitive DOS program.
  - ➤ ***winSMITH* 2.0, Noble Publishing, 1995, $79**

    Written by Eagleware. Easy to use. Restricted to ladder networks. Doesn't have series stubs. Lacks an optimizer.
- ❑ ***Matching Network Optimization & Synthesis***
  - ➤ ***ARRL Radio Designer* 1.5, ARRL, 1995, $150**

    No longer sold. ARD's optimizer works with Serenade netlists and handles more variables than Serenade SV's optimizer.
  - ➤ ***Serenade SV* (student version), Ansoft, 2000, $0 (free)**

    Download (about 20 Mbytes) from: http://www.ansoft.com/about/academics/sersv/index.cfm
  - ➤ ***Advanced Automated Smith Chart* 3.0, Artech House, 1998, $395**
  - ➤ ***=MATCH=,* Eagleware, $699 (requires *GENESYS Basic*, $1997)**
  - ➤ ***Harmonica Linear Design Suite*, Ansoft, 2000, $6900**

References: Articles

- ❑ Robert L. Thomas, “Broadband Impedance Matching in High-Q Networks,” *EDN*, pp. 62–69, December 20, 1973.
- ❑ Neal C. Silence, “The Smith Chart and Its Usage in RF Design,” *RF Design*, pp. 85–88, April 1992.
- ❑ Thomas R. Cuthbert, Jr., “Broadband Impedance Matching Methods,” *RF Design*, pp. 64–91, August 1994.
- ❑ Thomas R. Cuthbert, Jr., “Broadband Impedance Matching - Fast and Simple,” *RF Design*, pp. 38–50, November 1994.
- ❑ William E. Sabin, “Broadband HF Matching with ARRL Radio Designer,” *QST*, pp. 33–36, August 1995.
- ❑ William E. Sabin, “ARRL Radio Designer and the Circles Utility, Part 1: Smith Chart Basics,” *QEX*, pp. 3–9, Sept/Oct 1998.
- ❑ William E. Sabin, “ARRL Radio Designer and the Circles Utility, Part 2: Small-Signal Amplifier Design,” *QEX*, pp. 3–11, Nov/Dec 1998.

References: Articles (Cont'd)

- **Steve Sparks, "A Practical Amateur Application of the Smith Chart," *Communications Quarterly*, pp. 102–106, Summer 1999.**
  - ➤ *This article contains serious Smith charting errors. See the comments by Garry Shapiro, NI6T, Communications Quarterly, p. 3, Fall 1999.*
- **K.C. Chan and A. Harter, "Impedance Matching and the Smith Chart – The Fundamentals," *RF Design*, pp. 52–66, July 2000.**

References: Books

- ❑ **Robert A. Chipman, *Transmission Lines*, Schaum Outline Series, McGraw-Hill, 1968.**
  - ➤ *Basic, mathematical. A classic, but out-of-print.*
- ❑ **Robert L. Thomas, *A Practical Introduction to Impedance Matching,* Artech House, 1976, ISBN 0890060509.**
  - ➤ *Intermediate, mathematical. A nice treatment of 4-element networks for wideband matching.*
- ❑ **Pieter L. D. Abrie, *The Design of Impedance-Matching Networks for Radio-Frequency and Microwave Amplifiers,* Artech House, 1985, ISBN 0890061726.**
  - ➤ *Advanced, mathematical.*
- ❑ **Wilfred Caron, *Antenna Impedance Matching*, ARRL, 1989, ISBN 0872592200.**
  - ➤ *Intermediate, non-mathematical. Caron illustrates manual Smith chart methods at their best, but which nonetheless have been completely replaced by computer-aided network design.*
- ❑ **Brian C. Wadell, *Transmission Line Design Handbook*, Artech House, 1991, ISBN 0890064369.**
  - ➤ *Analysis and formulas for many transmission lines. Comparable to M.A.R. Gunston or K.C. Gupta, et al., below.*

References: Books (Cont'd)

- **Phillip H. Smith, *Electronic Applications of the Smith Chart in Waveguide Circuit, and Component Analysis*, 2nd edition, Noble Publishing, 1995, ISBN 1884932398.**
  - *Originally published by McGraw-Hill, 1969, and reprinted by Krieger, 1983. Intermediate, mathematical.*
- **K.C. Gupta, R. Garg, I. Bahl, and P. Bhartia, *Microstrip Lines and Slotlines*, 2nd ed., Artech House, 1996, ISBN 089006766X.**
  - *Analysis and formulas for many transmission lines.*
- **M.A.R. Gunston, *Microwave Transmission-Line Impedance Data*, Noble Publishing, 1997, ISBN 1884932576.**
  - *Originally published by Van Nostrand Reinhold, 1972. Analysis and formulas for many transmission lines. Comparable to B. Wadell above.*
- ***ARRL Antenna Book*, 18th edition, chapters 24-28, ARRL, 1997, ISBN 0872596133.**
  - *Elementary, non-mathematical.*
- **M. Walter Maxwell, W2DU, *Reflections II: Transmission Lines and Antennas*, 2nd ed., Worldradio Books, 2001, ISBN 0970520603.**
  - *A non-mathematical treatment of transmission lines and matching that examines and corrects common misunderstandings.*

References: Application Notes, Videos, and Web Sites

- ***Application Notes***
  - **Times Microwave's *Complete Coaxial Cable Catalog & Handbook* Download from: http://www.timesmicrowave.com/products/military/TL14/TL14.htm**
- ***Videos***
  - **Glenn Parker, *Introduction to the Smith Chart*, Noble Publishing, 1996. 50 minutes, $99.**
- ***Useful Web Sites***
  - **http://www.timesmicrowave.com/calculators/index.htm**
  - **http://www.sss-mag.com/smith.html**
  - **http://www.ee.surrey.ac.uk/Personal/D.Jefferies/smith.html**
  - **http://www.scott-inc.com/html/smith.htm**
- ***This Presentation is at***
  - **http://www.fars.k6ya.org/docs/smithchart.html**