New Results on Antenna Impedance Models and Matching

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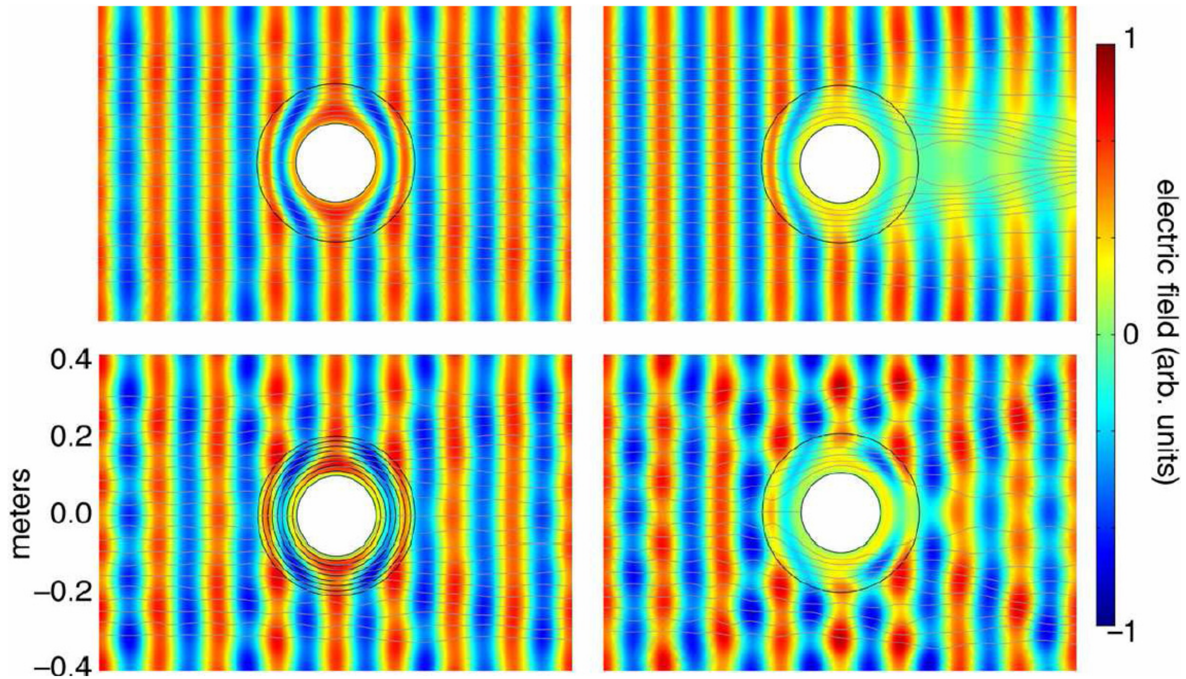
Electromagnetic Cloaking

- Idea introduced in the *Star Trek* television series, episode 9, on December 15, 1966, which featured a Romulan Bird Of Prey
- Practical technique presented at Pacificon Antenna Seminar, October 13, 2006
- Laboratory proof announced by Duke University on October 17, 2006

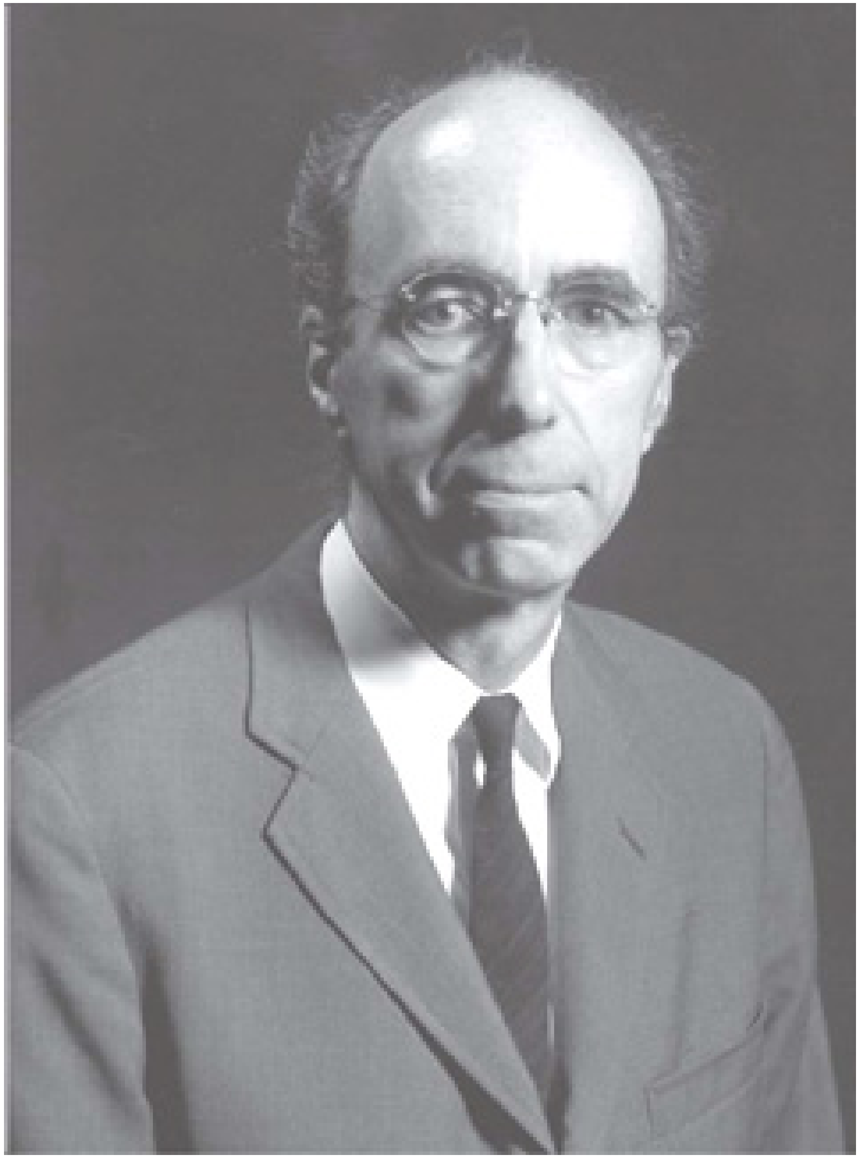


Outline

- **Antenna impedance models**
- **SWR basics**
- **Why not conjugate match?**
- **Impedance matching networks**
  - Multi-band match networks
  - Networks that give extremely broad match bandwidths
- **Interesting antennas**
- **Terrain effects by computational electromagnetics**
  - Meshing Silicon Valley

Antenna Impedance Models

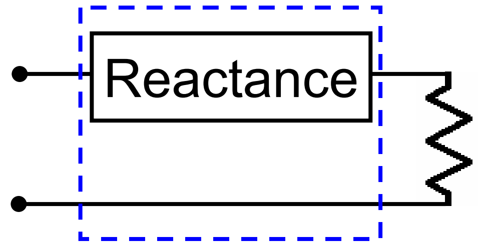
Sidney Darlington, 1906-1997



Darlington Forms (1939)

- **Every immittance function can be realized as a lossless two-port terminated by a resistor**
- **Every antenna impedance function has an equivalent circuit in Darlington form**

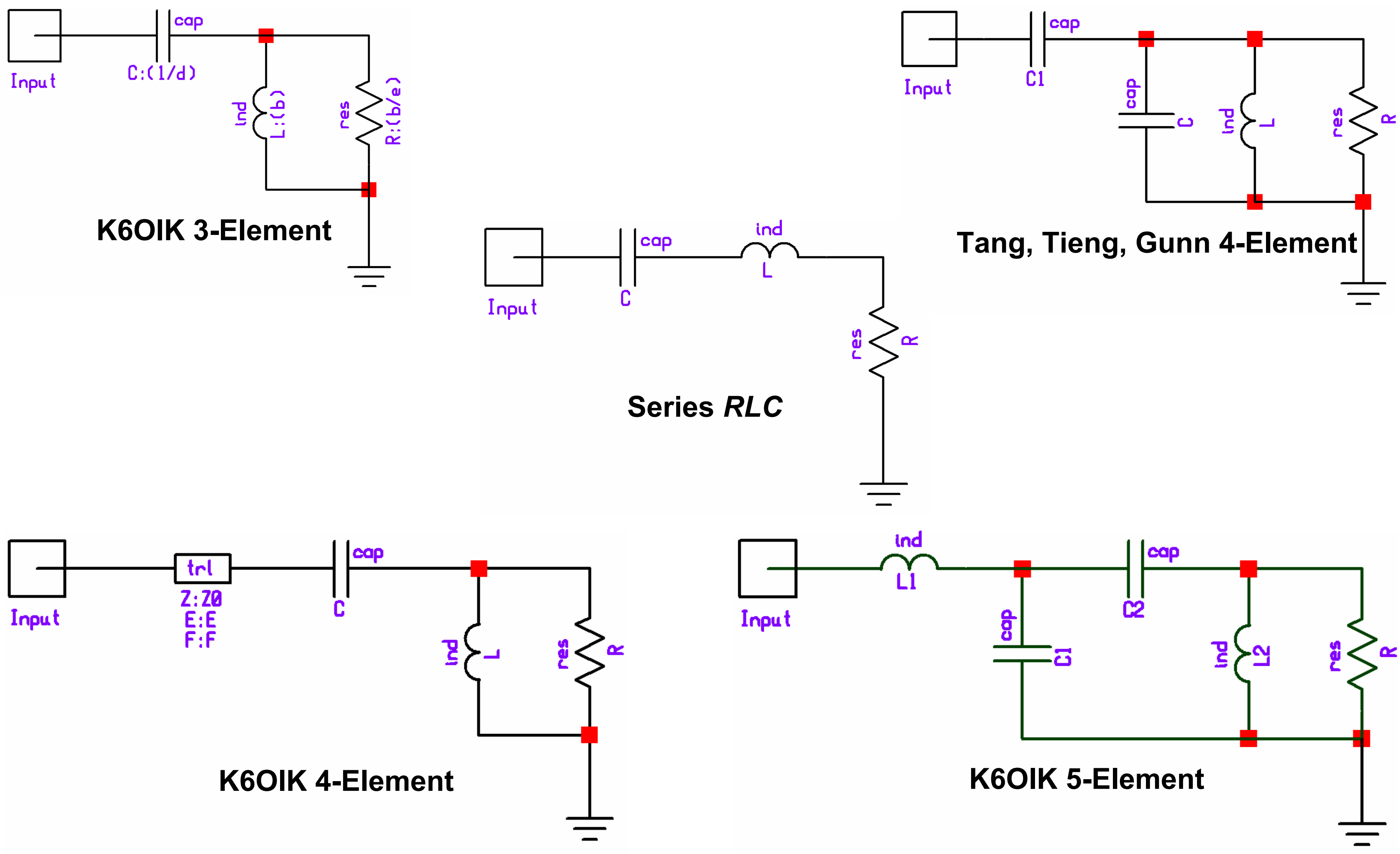
This……



Not This!

- **The Darlington form is the starting point for interesting results in network and matching theory**
  - The Fano (1947) and Carlin-LaRosa (1952) bounds on impedance matching
  - Constant resistance reflectionless impedance matching networks
  - Non-Foster active impedance matching networks

Impedance Models for Electrically-Small Dipoles & Monopoles

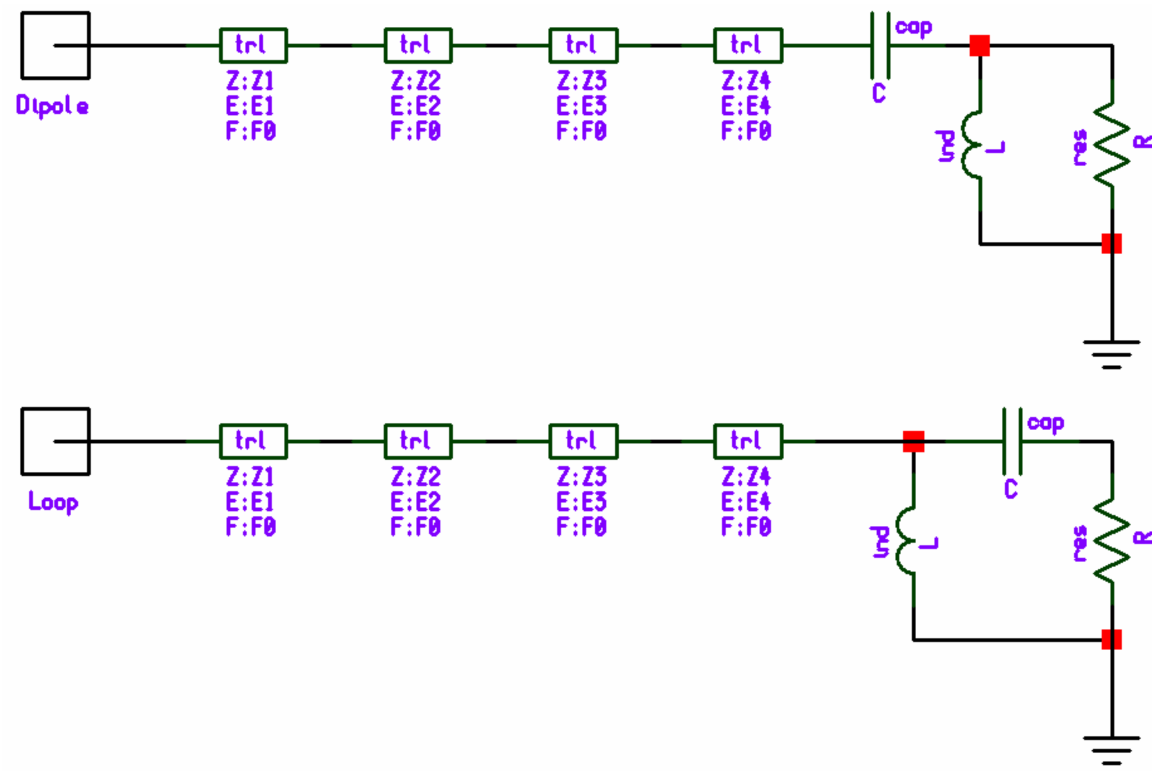


Broadband Models of Dipole Impedance

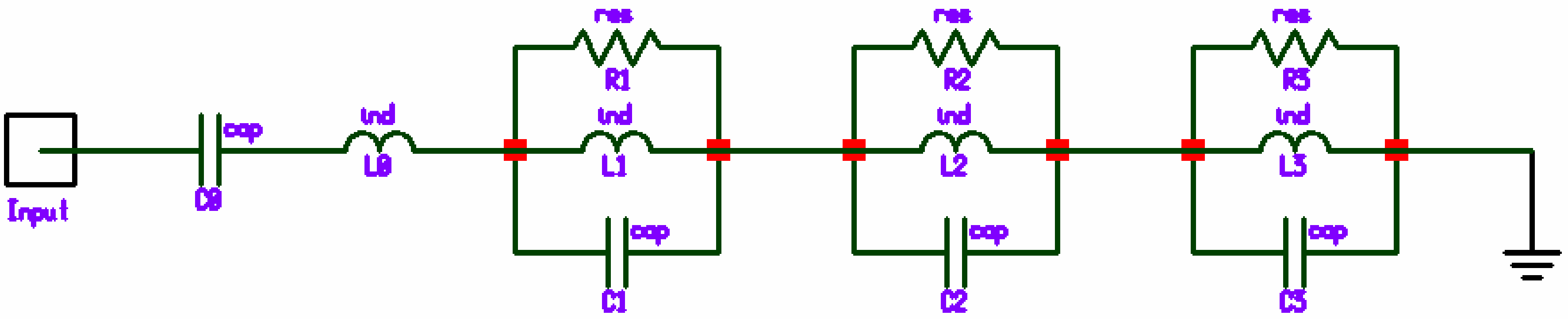
That Span Multiple Resonances

Schelkunoff's Universal Antenna Impedance Models

- Schelkunoff (1941) gave universal impedance models for a two broad classes of antennas
- Cascaded transmission lines terminated by a TE_{10} or TM_{10} mode impedance (e.g. loops or dipoles)



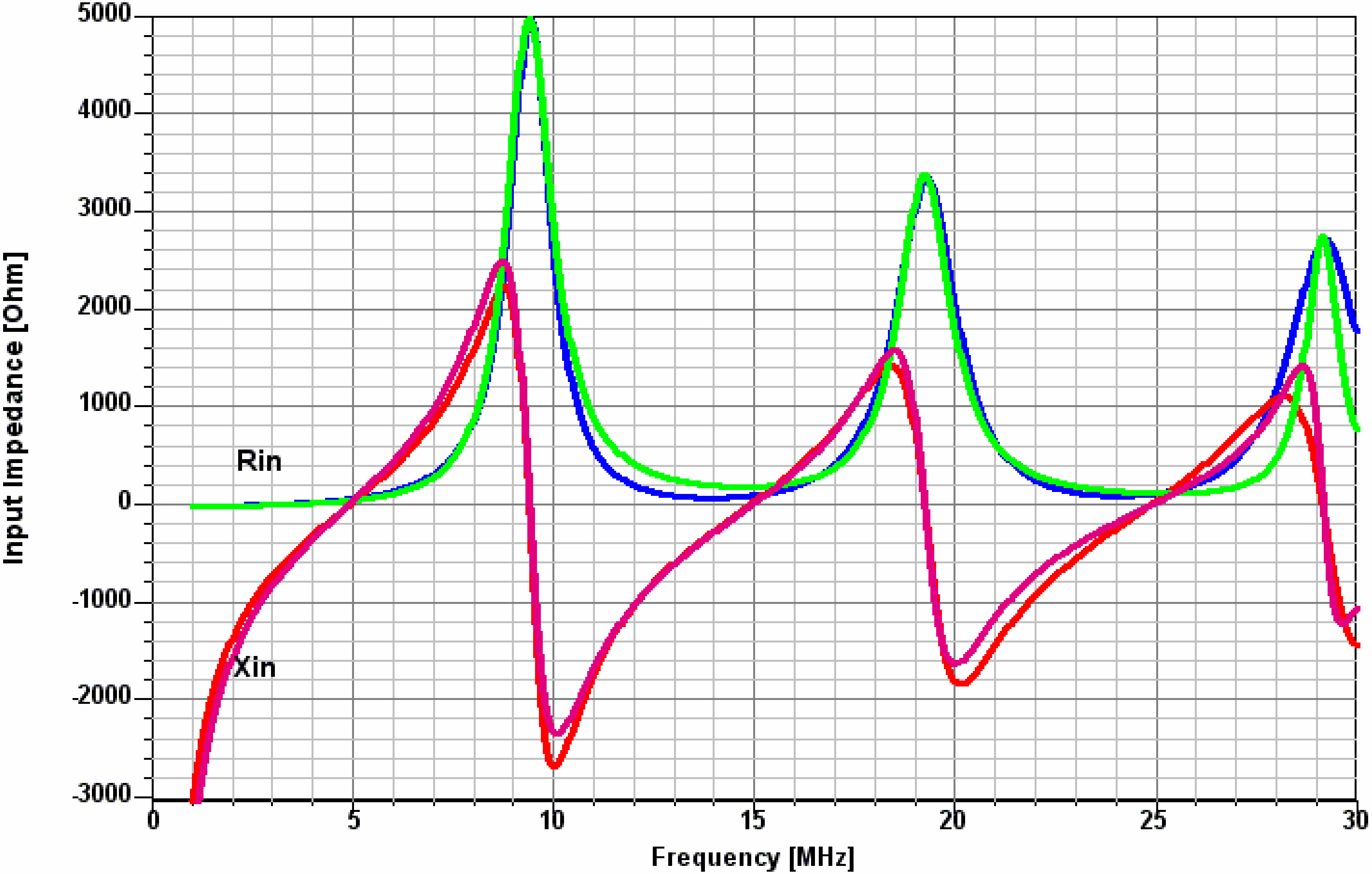
Foster's 1st Canonical Form with Small Losses Added



$C0$ = 43.9 pF	$C1$ = 22.9 pF	$C2$ = 30.3 pF	$C3$ = 57.1 pF
$L\infty$ = 4.49 mH	$L1$ = 12.5 μH	$L2$ = 2.26 μH	$L3$ = 522 nH
	$R1$ = 4,970 Ω	$R2$ = 3,338 Ω	$R3$ = 2,702 Ω

- **Ramo, Whinnery, and Van Duzer, *Fields and Waves in Communication Electronics*, Wiley, 1965, Section 11.13**
- **Was applied to antennas by Tang-Tieng-Gunn (1993), Hamid-Hamid (1997), Rambabu-Ramesh-Kalghatgi (1999)**
- **Fits dipole impedance best near antiresonances**

Accuracy of Hamid & Hamid's Equivalent Circuit



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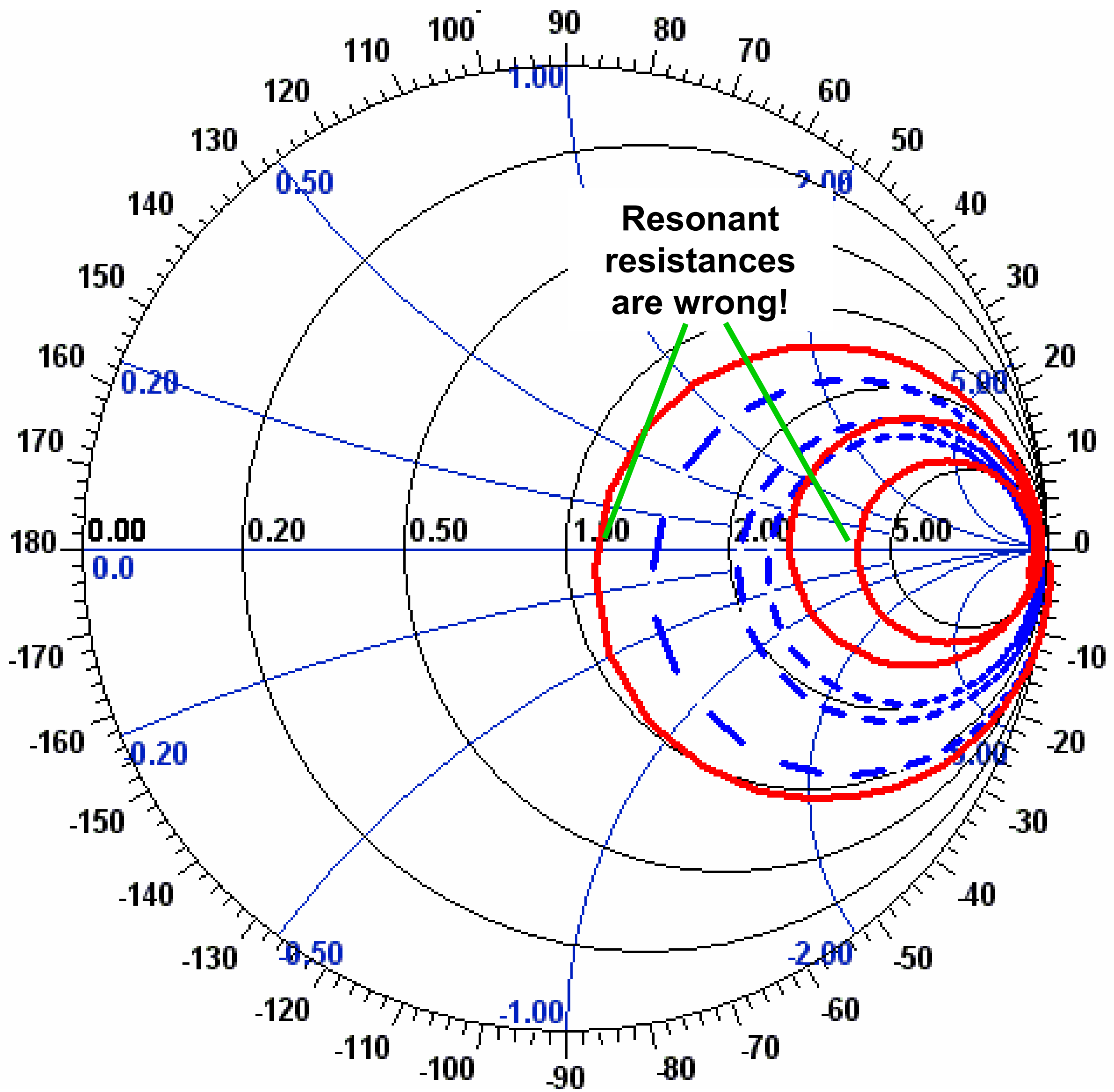
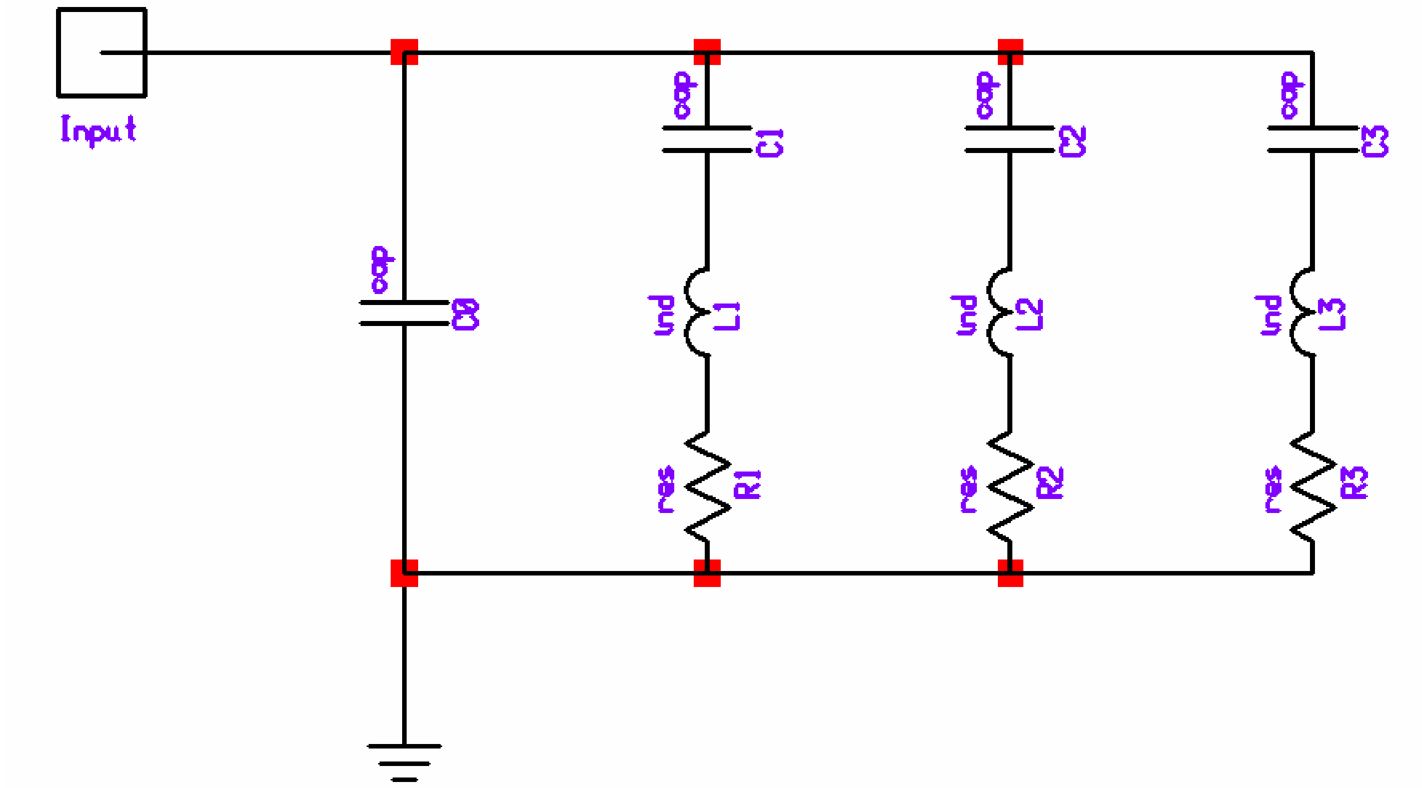


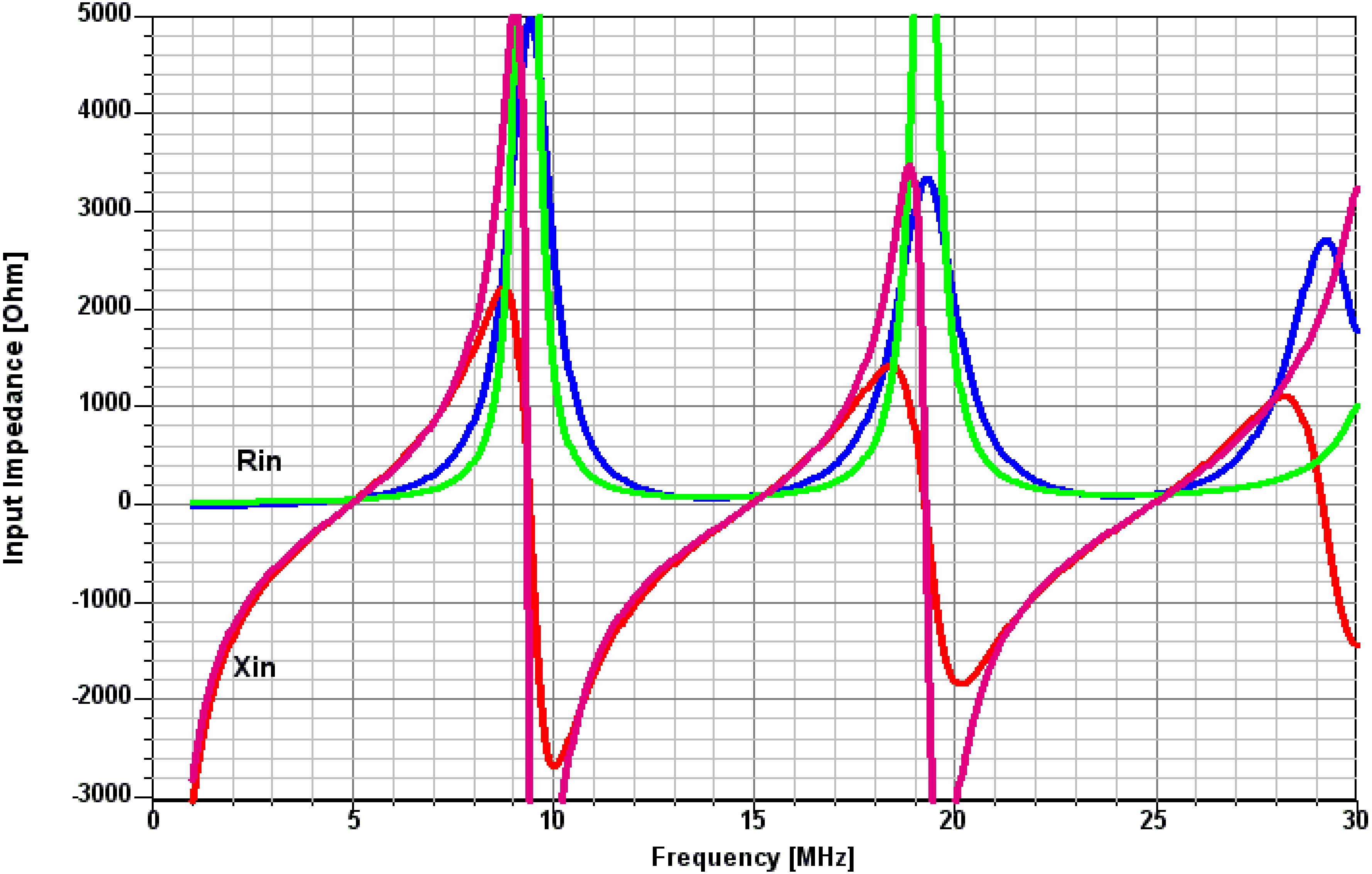
Foster's 2nd Canonical Form with Small Losses Added



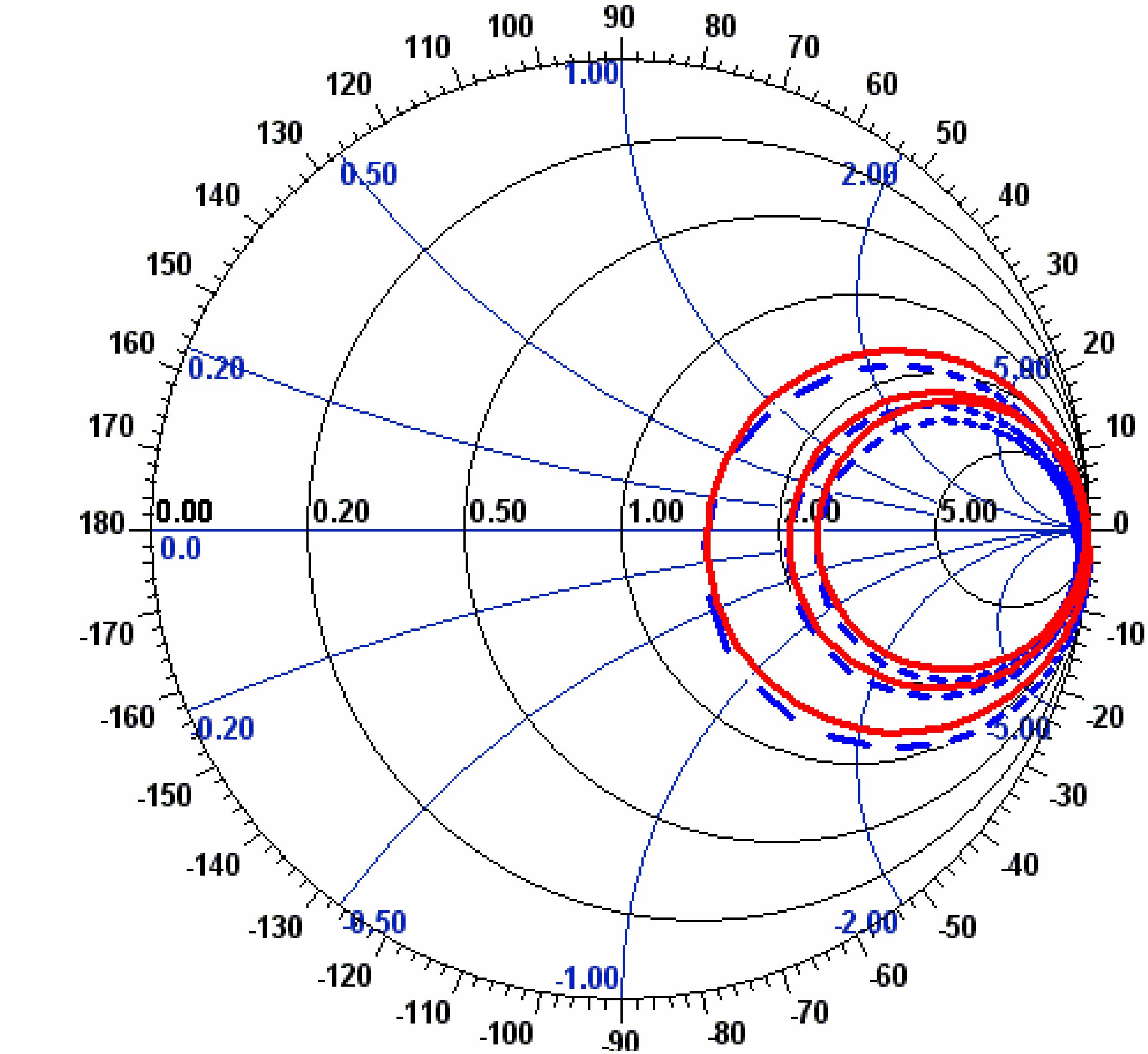
Example Dipole
C_∞ = 5.44 pF
$C1$ = 42.9 pF
$C2$ = 5.05 pF
$C3$ = 1.92 pF
$L0 = \infty$
$L1$ = 24.9 μH
$L2$ = 22.8 μH
$L3$ = 21.4 μH
$R1$ = 72.2 Ω
$R2$ = 106 Ω
$R3$ = 122 Ω

- **Ramo, Whinnery, and Van Duzer, *Fields and Waves in Communication Electronics*, Wiley, 1965, Section 11.13**
- **Fits dipole impedance best near resonances**

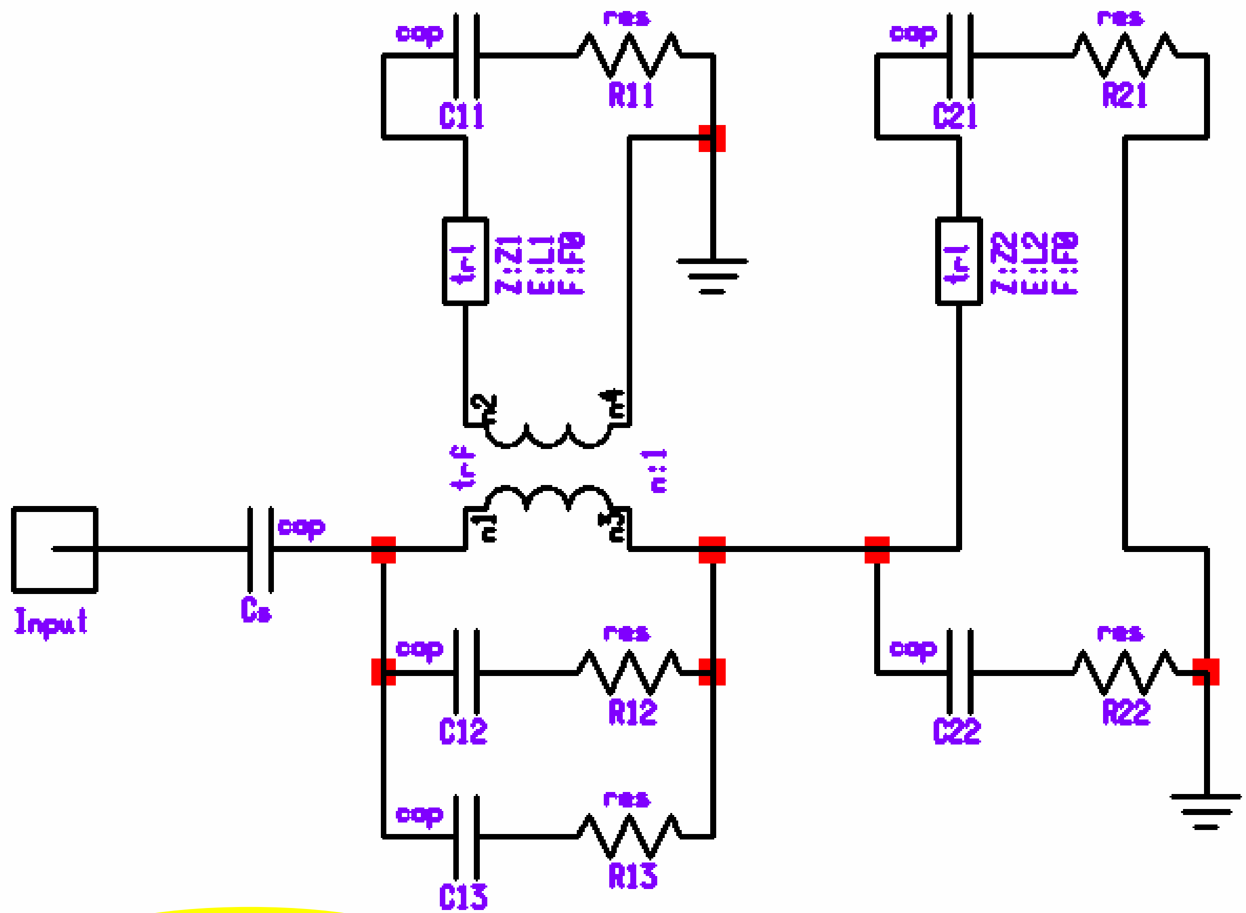
Accuracy of Foster's 2nd Form With Small Losses



Accuracy of Foster's 2nd Form With Small Losses

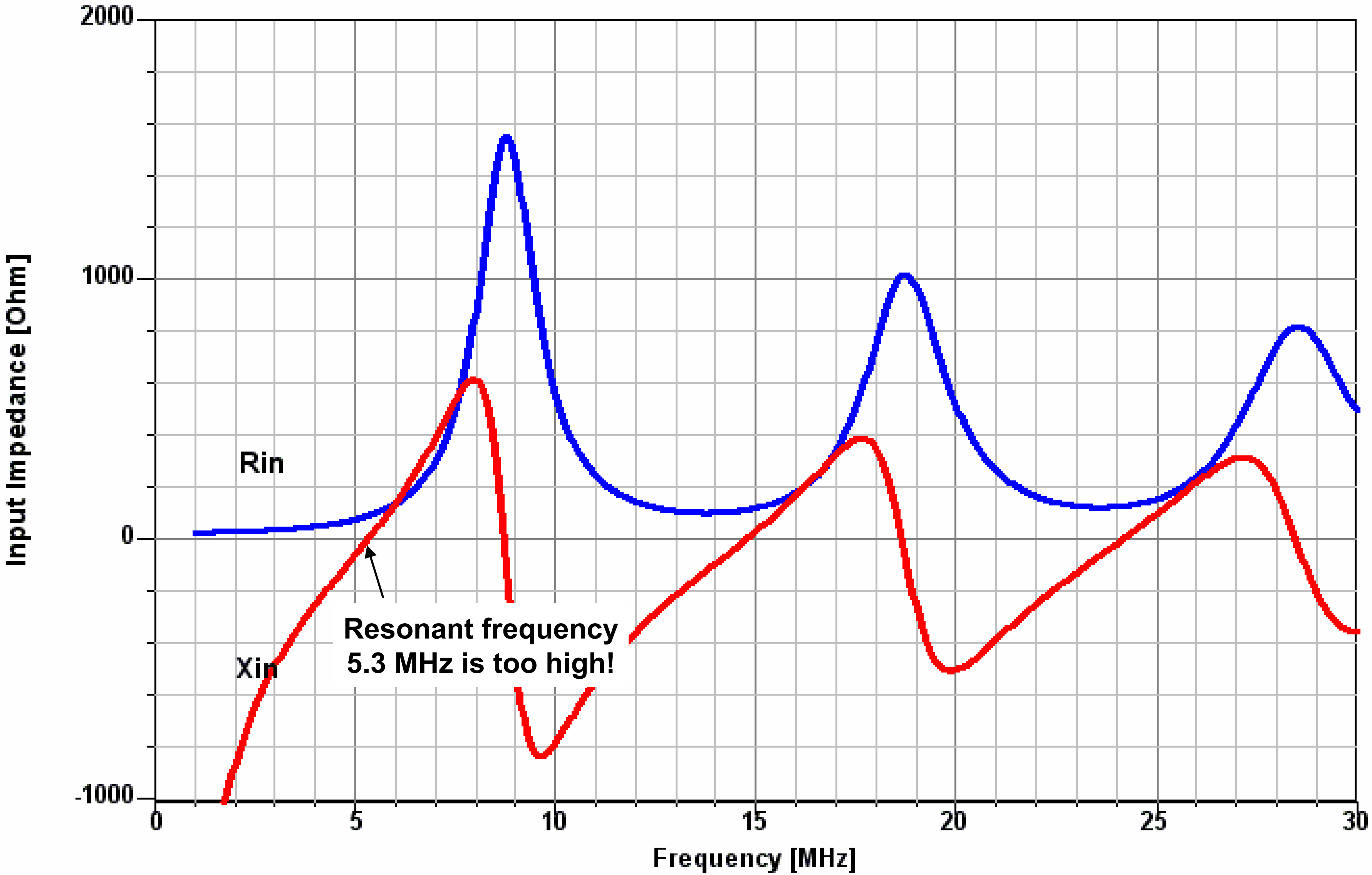


Long, Werner, & Werner's Broadband Model (2000) Frequency Scaled to f_0 = 5 MHz, Ω' = 7.8

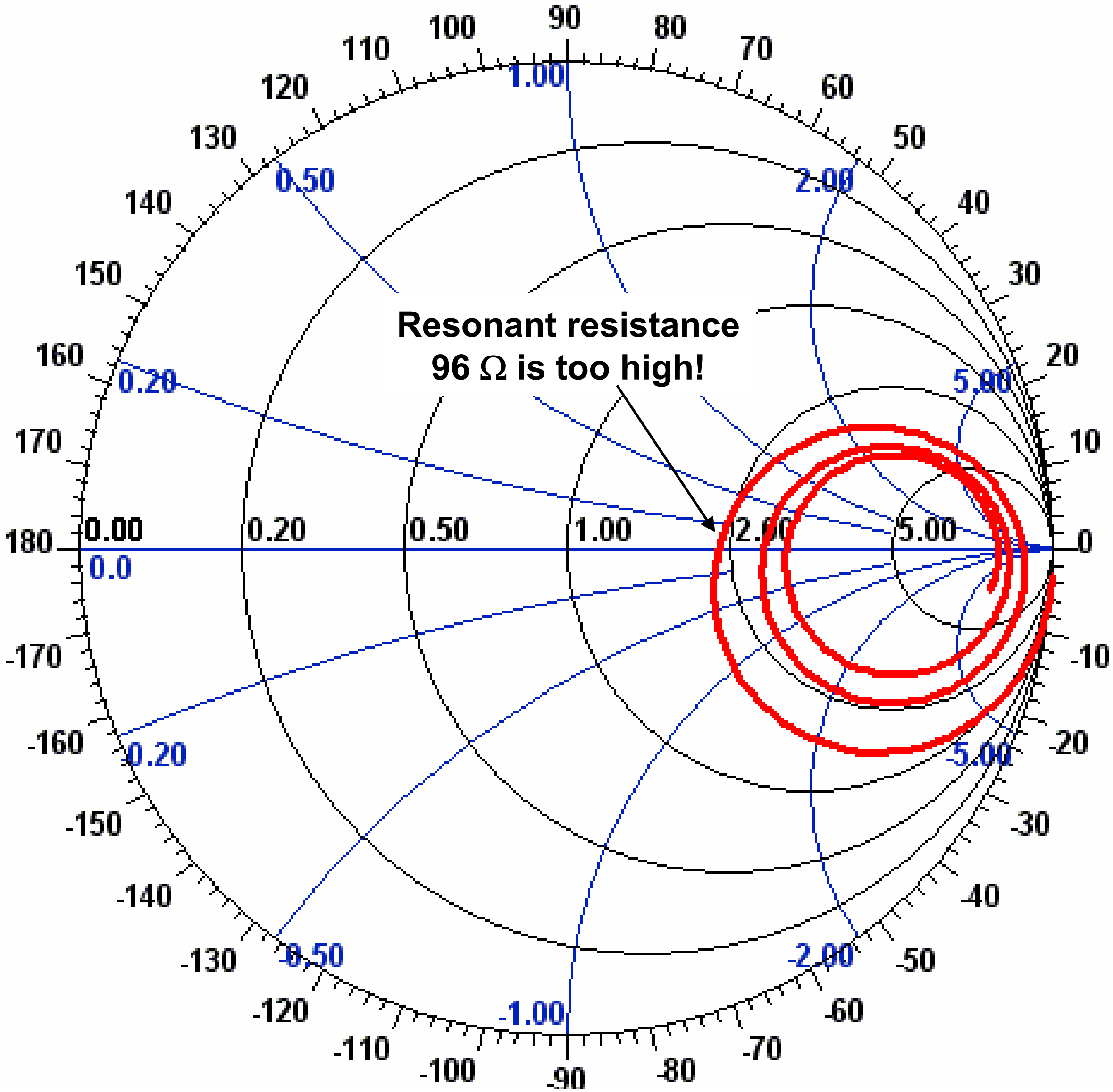


*C*s = 150 pF	*C*11 = -975 pF	*R*11 = 13.1 Ω	*C*21 = 17.6 pF	*R*21 = 700 Ω
	*Z*1 = 215 Ω	*E*1 = 44.9 deg	*Z*2 = 195 Ω	*E*2 = 46.9 deg
	*C*12 = 24.0 pF	*R*12 = 3,600 Ω	*C*22 = -3.00 pF	*R*22 = 295 Ω
	*C*13 = 8.33 pF	*R*13 = 500 Ω		

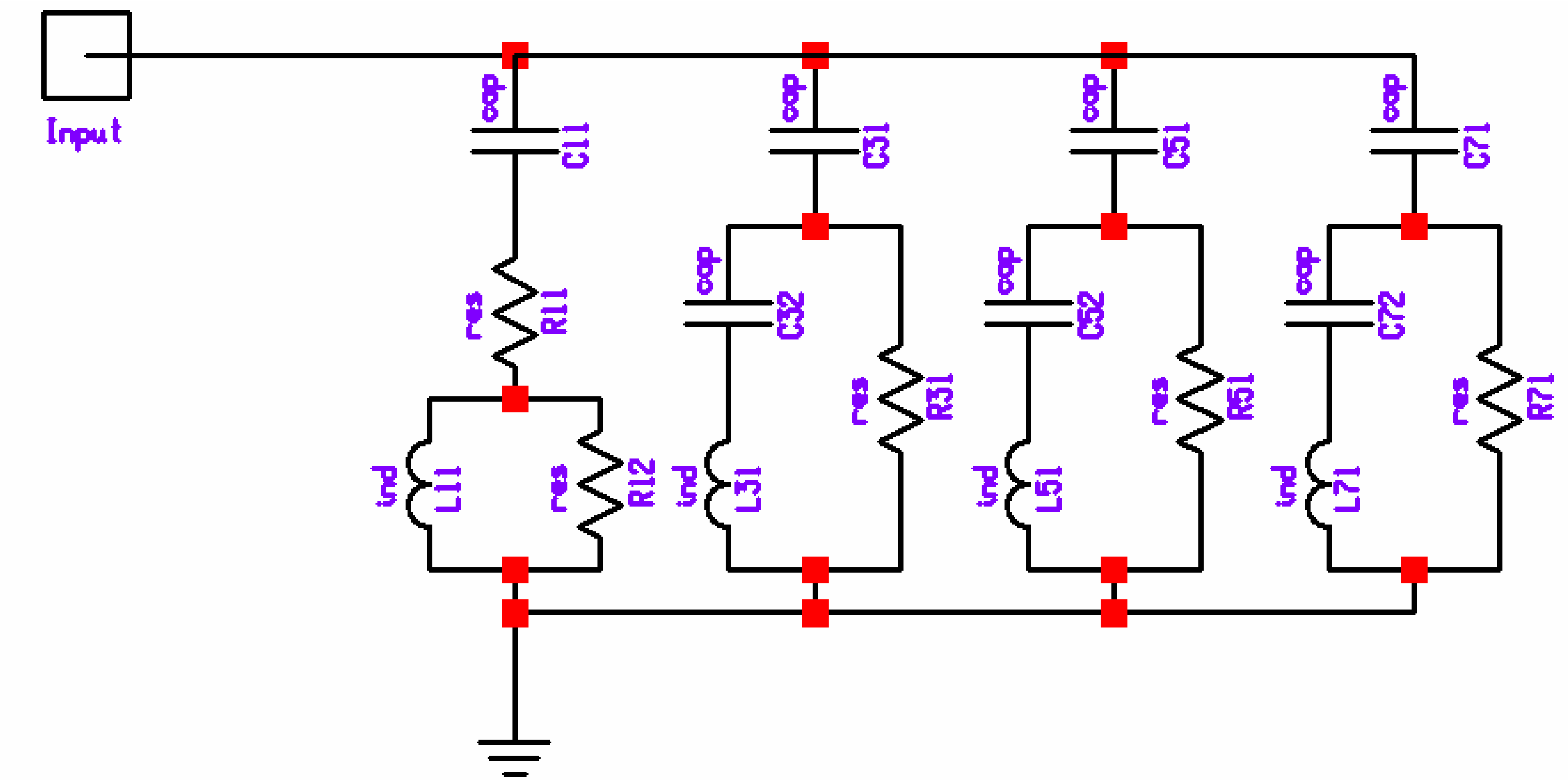
Accuracy of Long, Werner, & Werner's Model



Accuracy of Long, Werner, & Werner's Model

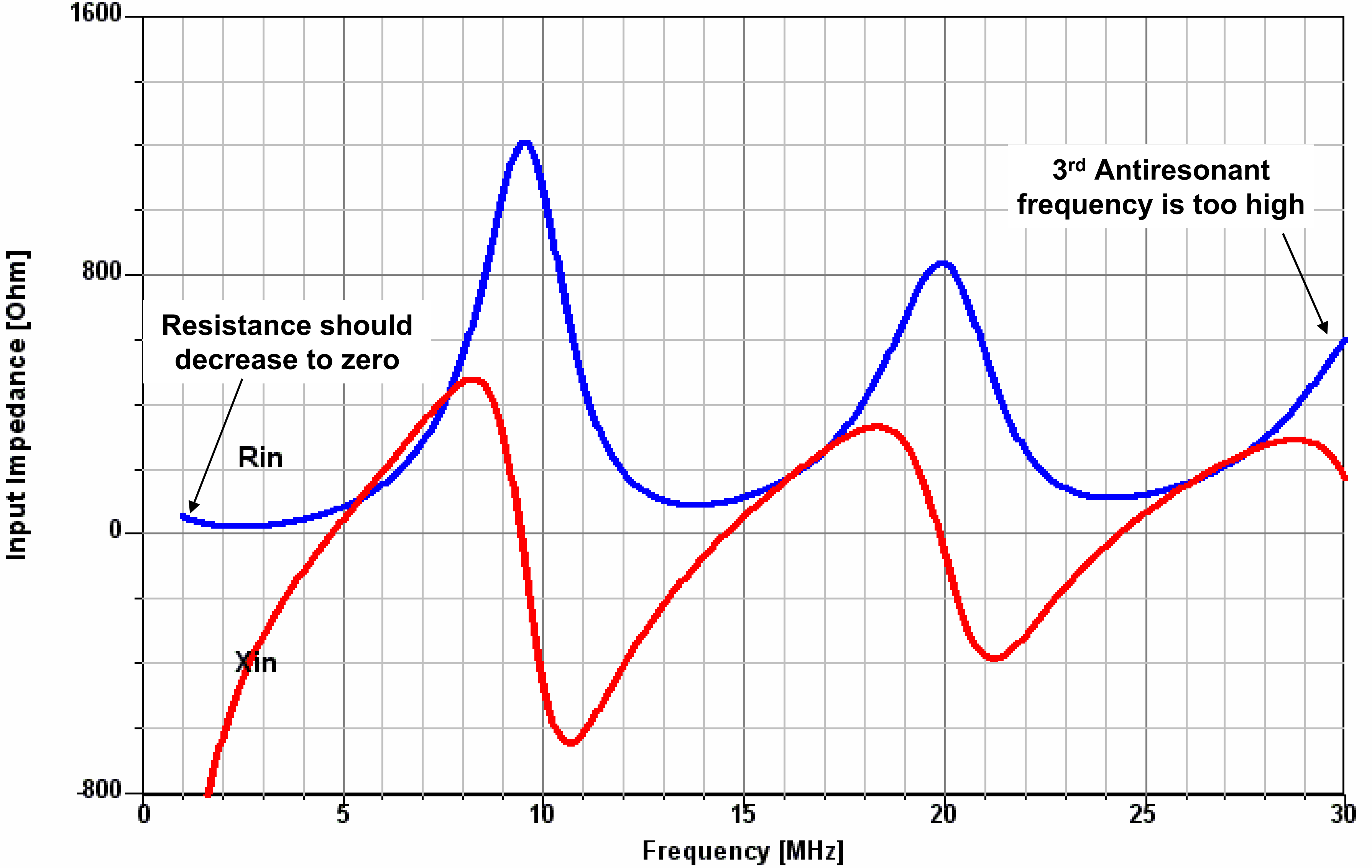


Streable & Pearson's Broadband Equivalent Circuit Frequency Scaled to f_0 = 5 MHz, Ω' = 10.6

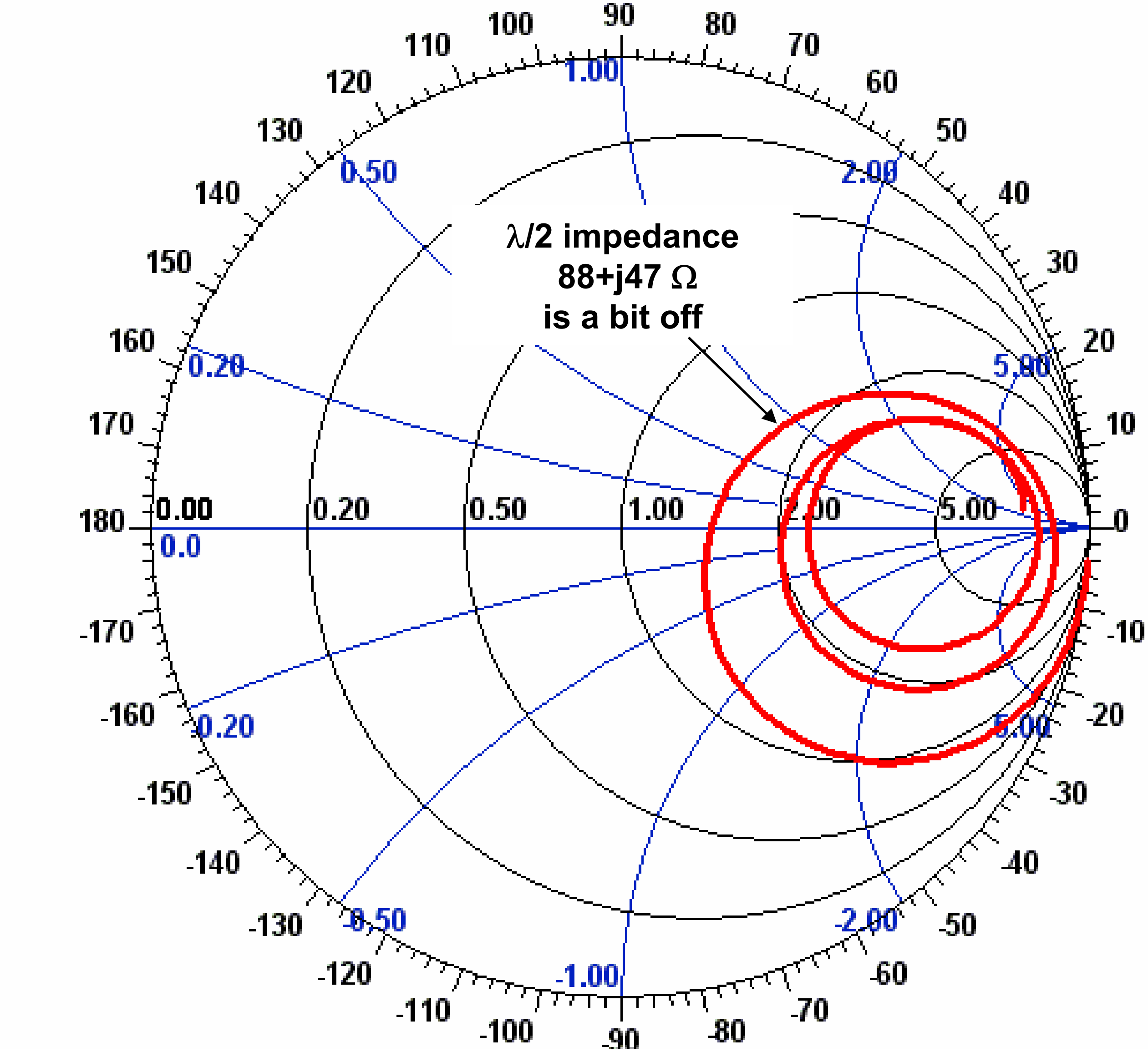


*C*11 = 86.6 pF	*C*31 = 15.0 pF	*C*51 = 7.17 pF	*C*71 = 4.51 pF
*L*11 = 13.8 μH	*C*32 = 33.8 pF	*C*52 = 8.87 pF	*C*72 = 3.98 pF
*R*11 = 0.663 Ω	*L*31 = 11.7 μH	*L*51 = 10.9 μH	L71 = 10.3 μH
*R*12 = 2,201 Ω	*R*31 = 4,959 Ω	*R*51 = 6,514 Ω	*R*71 = 7,542 Ω

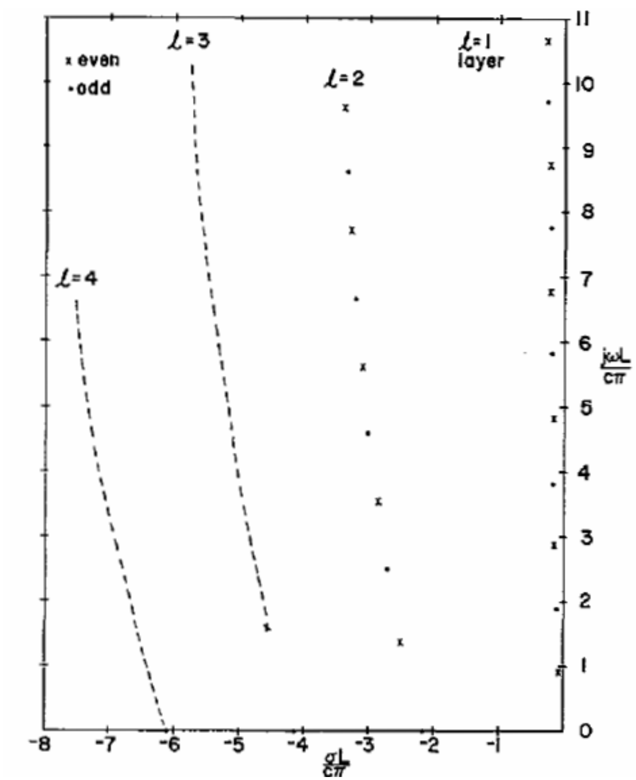
Accuracy of Streable & Pearson's Equivalent Circuit

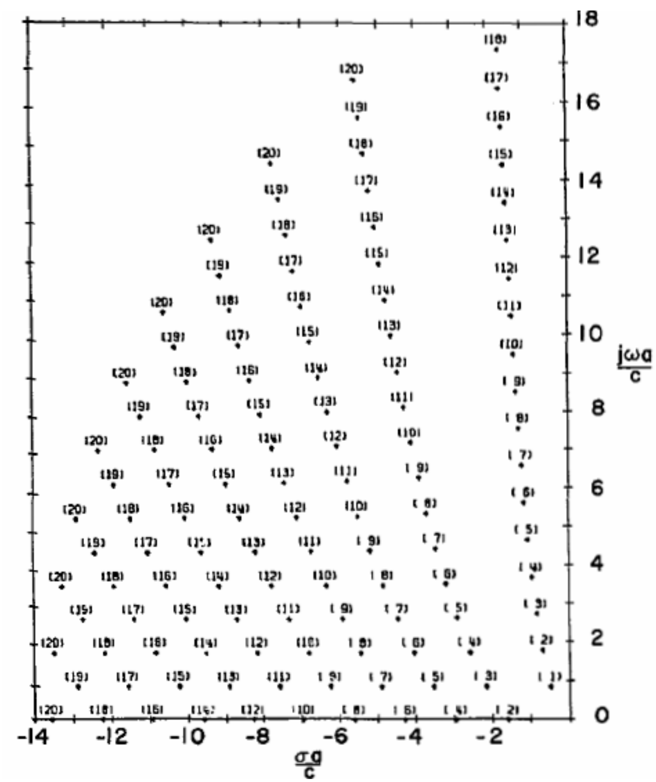


Accuracy of Streable & Pearson's Equivalent Circuit



Antennas Ring at Many Frequencies (Like Bells)

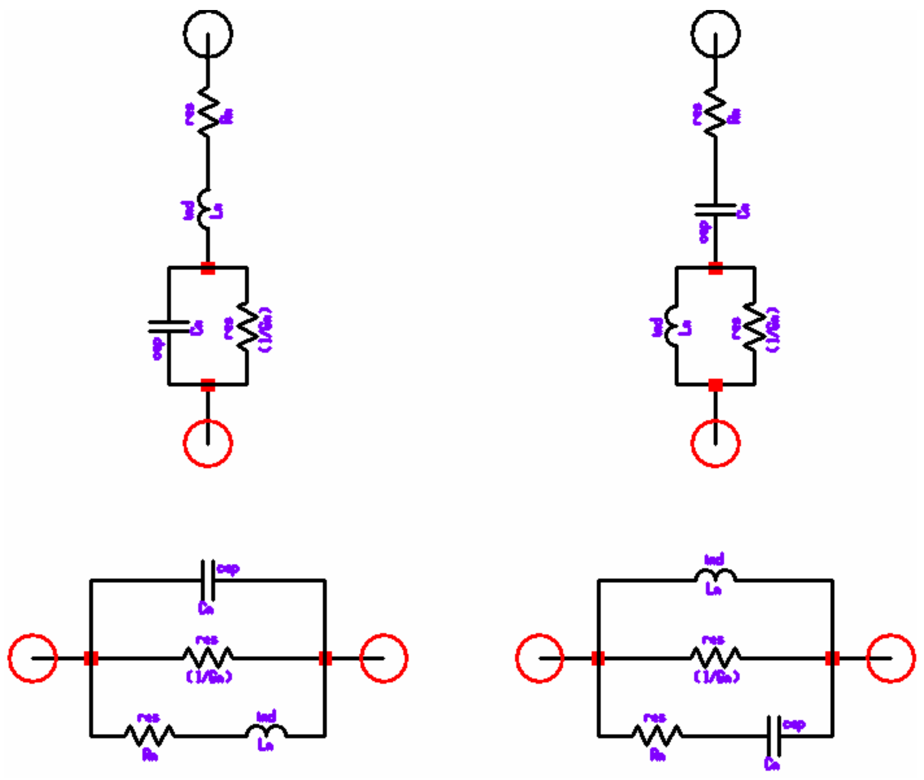




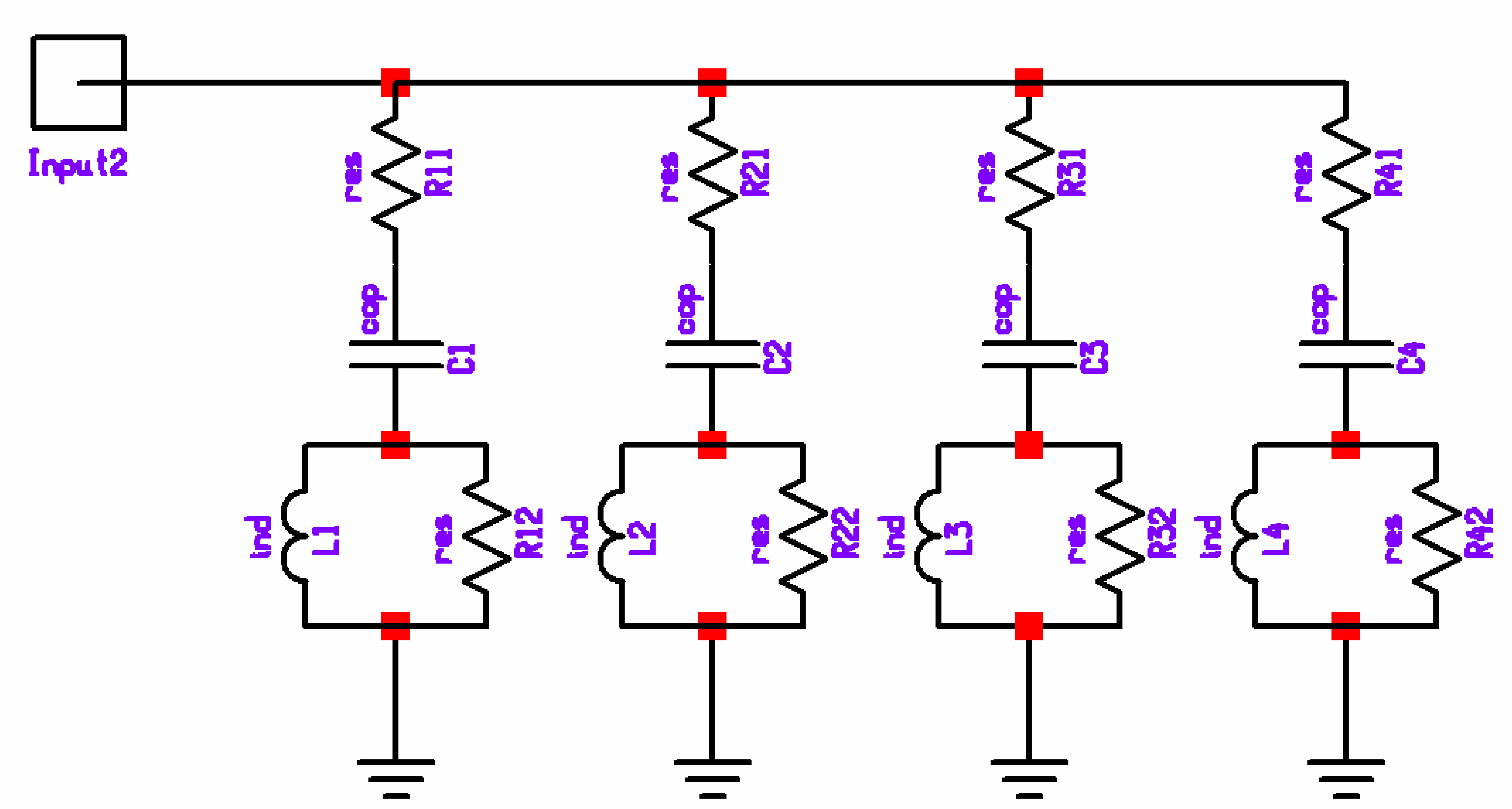
- Tesche (1973) derived antenna TM modes by SEM
- Distributed and electromagnetic systems are infinite-dimensional linear systems

Equivalent Circuits for Transcendental Immittances

- **Schelkunoff (1944), Zinn (1952): Transcendental immittances of continuous electromagnetic structures can be represented by ladder networks made of one of four subcircuits**

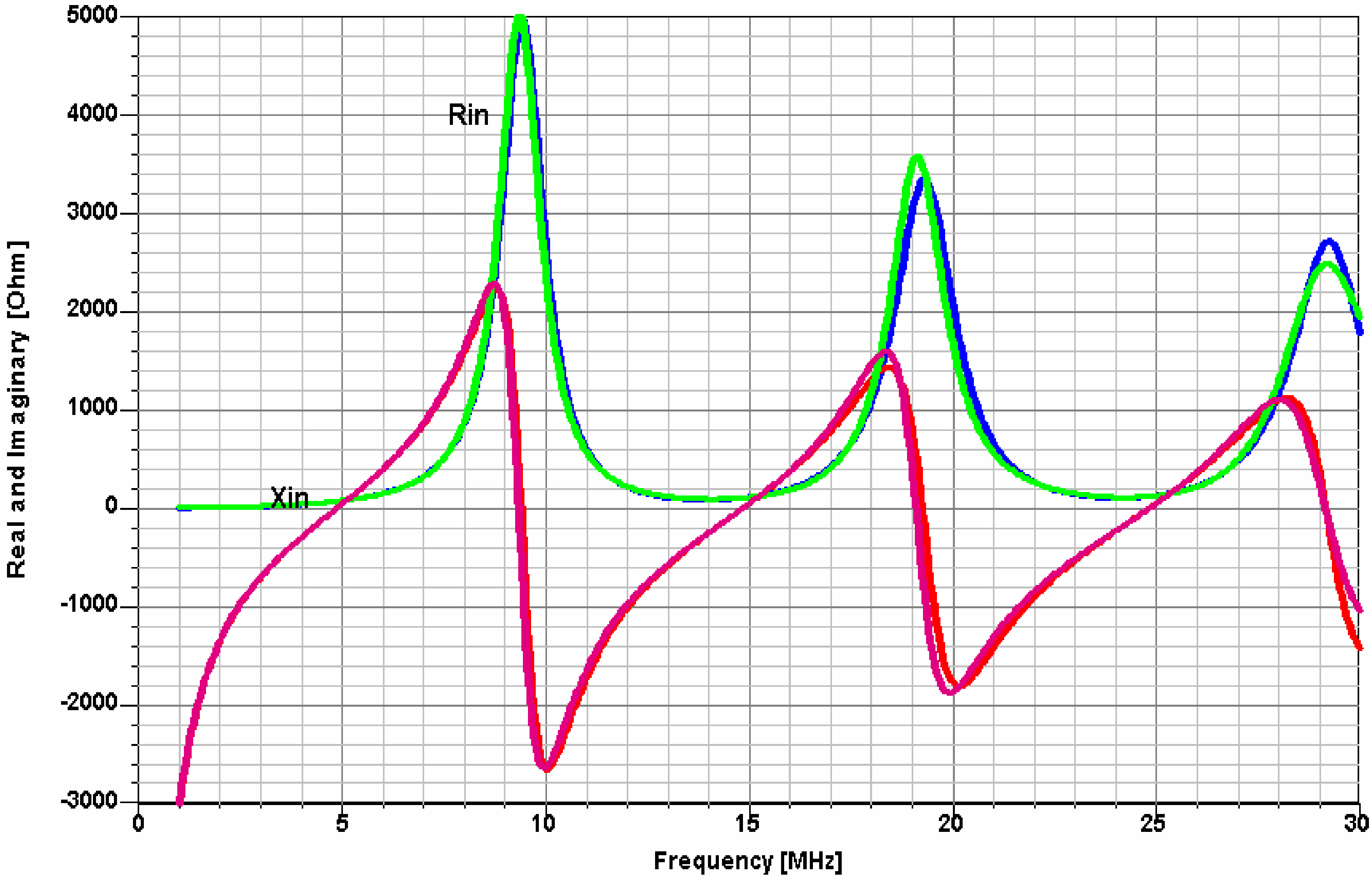


K6OIK's Broadband Equivalent Circuit

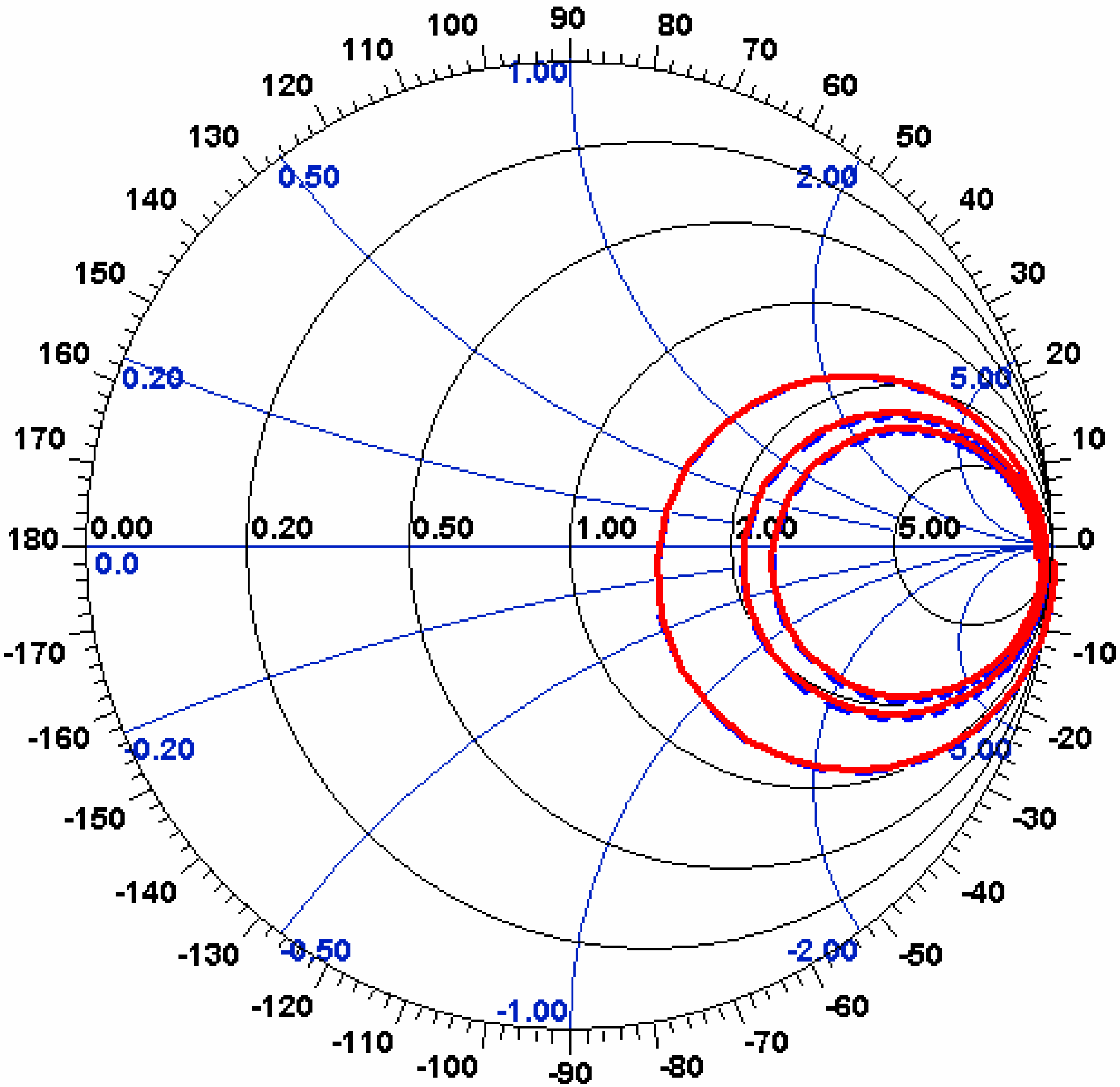


$R11 = 5.06\ \Omega$	$R21 = 0\ \Omega$	$R31 = 25.5\ \Omega$	$R41 = 0\ \Omega$
$C1 = 39.9$ pF	$C2 = 4.64$ pF	$C3 = 4.69$ pF	$C4 = 1.68$ pF
$L1 = 27.1\ \mu$H	$L2 = 24.9\ \mu$H	$L3 = 2.26\ \mu$H	$L4 = 24.5\ \mu$H
$R12 = 10.1$ kΩ	$R22 = 50.1$ kΩ	$R32 = 2.68$ kΩ	$R42 = 116$ kΩ

Accuracy of K6OIK's Broadband Equivalent Circuit



Accuracy of K6OIK's Broadband Equivalent Circuit

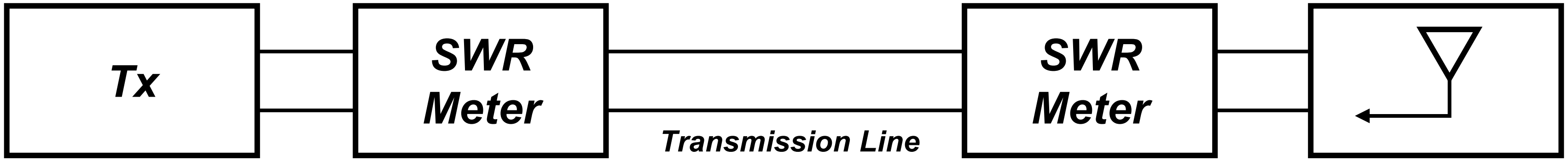


Comparison of Antenna Impedance Models

Antenna Impedance Model	Approximation Accuracy	Realizable Equivalent Circuit	Darlington Form	Element Types	Maximum Frequency Range
Series RLC	fair	yes	yes	*R, L, C*	0.94 f_0 to 1.05 f_0
Witt model	good	no	yes	*R*(*f*) and TL stub	0.6 f_0 to 1.2 f_0
K6OIK 3-Element	good	yes	yes	*R, L, C*	0.90 f_0 to 1.08 f_0
Tang-Tien-Gunn 4-Element	excellent	yes	yes	*R, L, C*	DC to 1.4 f_0
K6OIK 4-Element	excellent	yes	yes	*R,L,C*,TL	DC to 1.4 f_0
K6OIK 5-Element	excellent	yes	yes	*R, L, C*	DC to 1.4 f_0
Fosters 1st Form with small losses	poor, best near antiresonances	yes	no	*R, L, C*	no limit
Fosters 2nd Form with small losses	poor, best near resonances	yes	no	*R, L, C*	no limit
Long-Werner-Werner	fair	no	no	*R, C*, TL	5 octaves
Streable-Pearson	good	yes	no	*R, L, C*	no limit
K6OIK Broadband	excellent	yes	no	*R, L, C*	no limit

Standing Wave Ratio Basics

Question – Do the Meters Read the Same SWR?

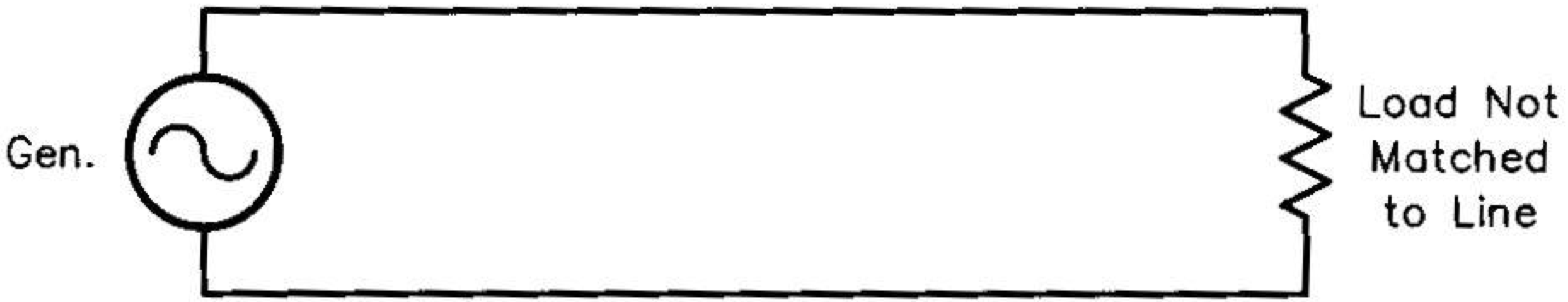


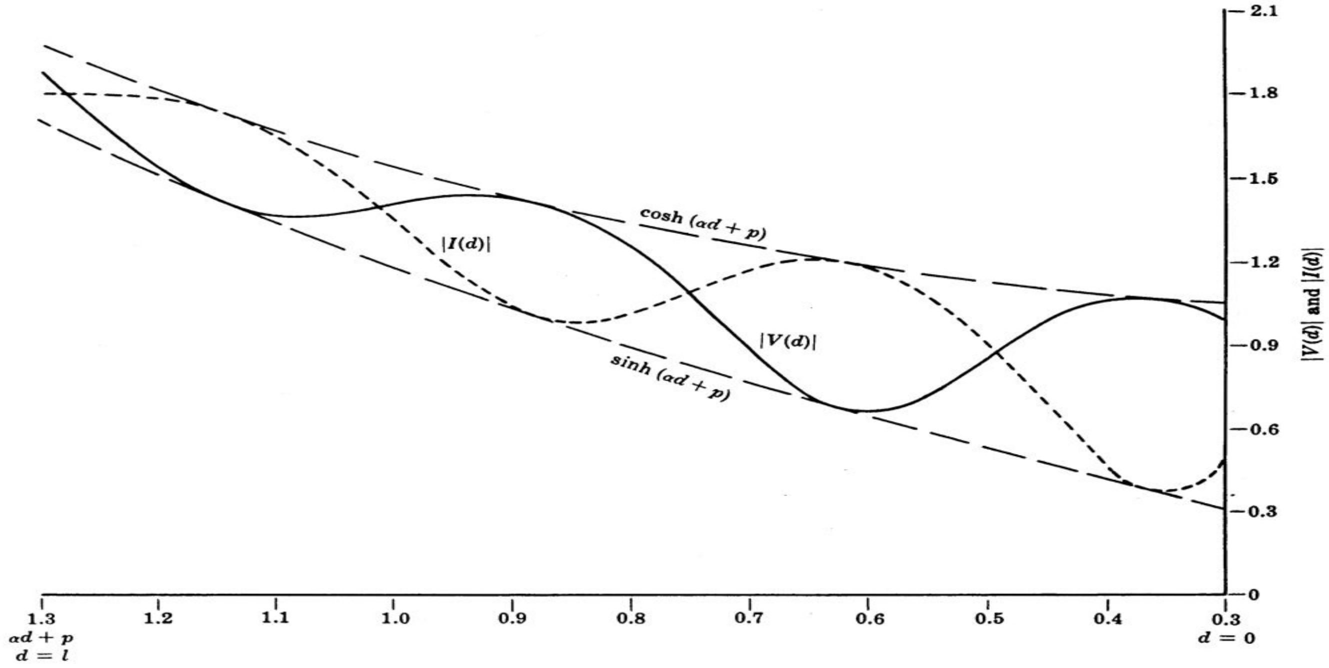
Answer

- **For lossless lines:**
  - Forward and reverse wave amplitudes are the same everywhere along the line
  - SWR is the same everywhere along the line
  - SWR is the ratio of max to min voltage (or current)
- **For lossy lines**
  - Forward and reverse wave amplitudes vary along the line
  - SWR is maximum at the load and decreases gradually to a minimum at the source
  - The “max / min” definition of the lossless case doesn’t work
  - Best definition is

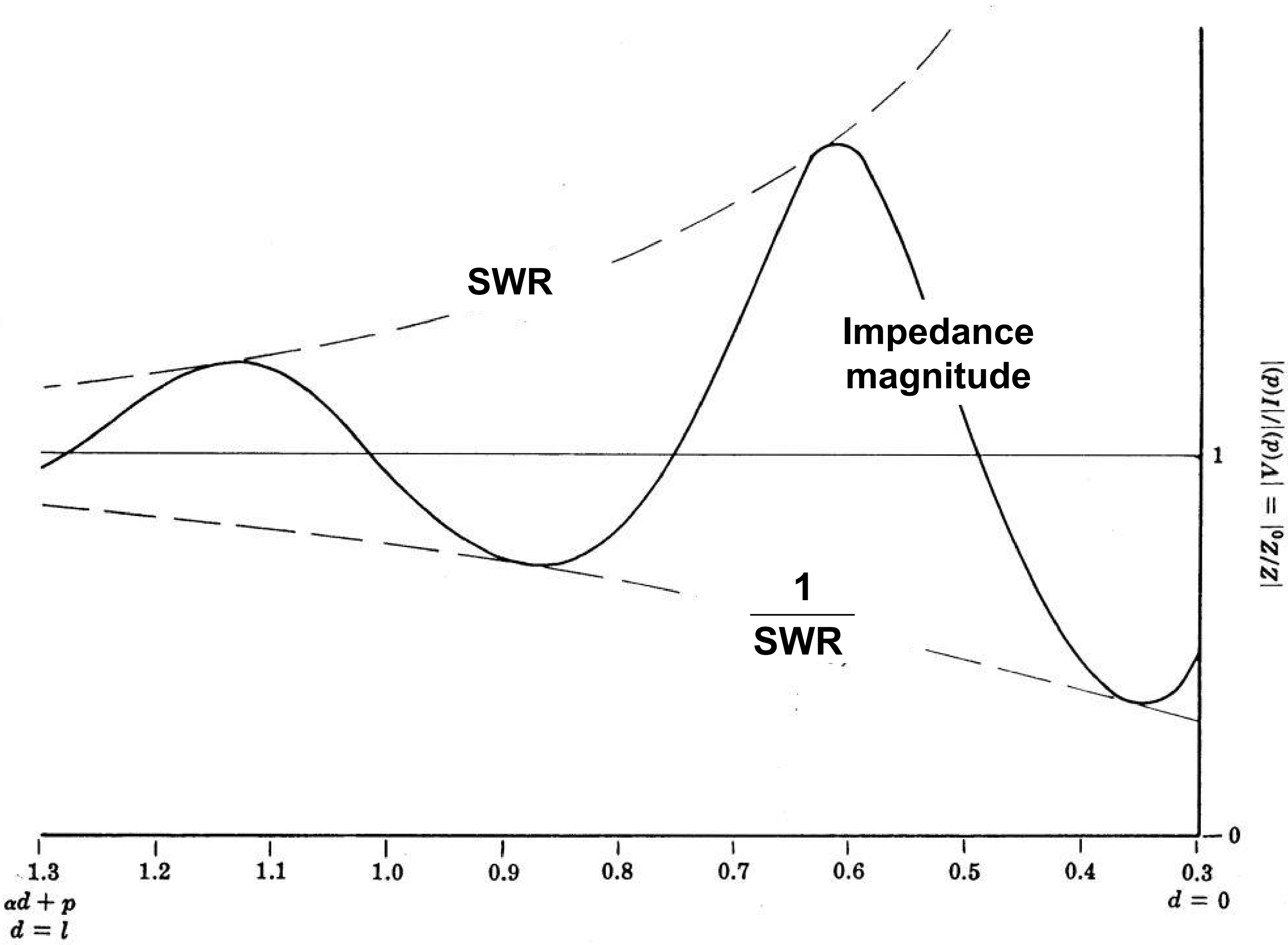
$$SWR = \frac{1 + \sqrt{\dfrac{P_R}{P_F}}}{1 - \sqrt{\dfrac{P_R}{P_F}}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

Voltage and Current Standing Waves

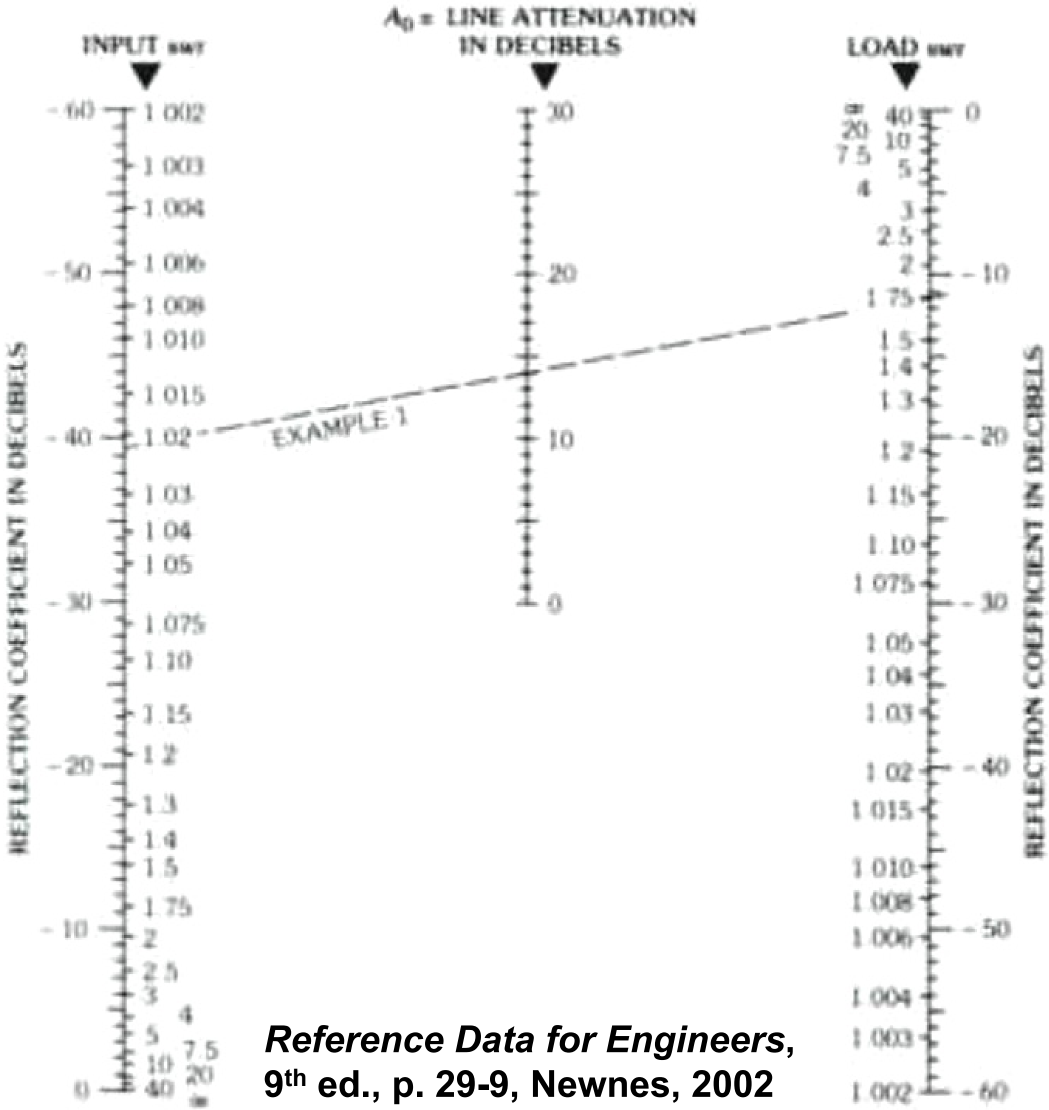




Impedance and SWR Along a Line

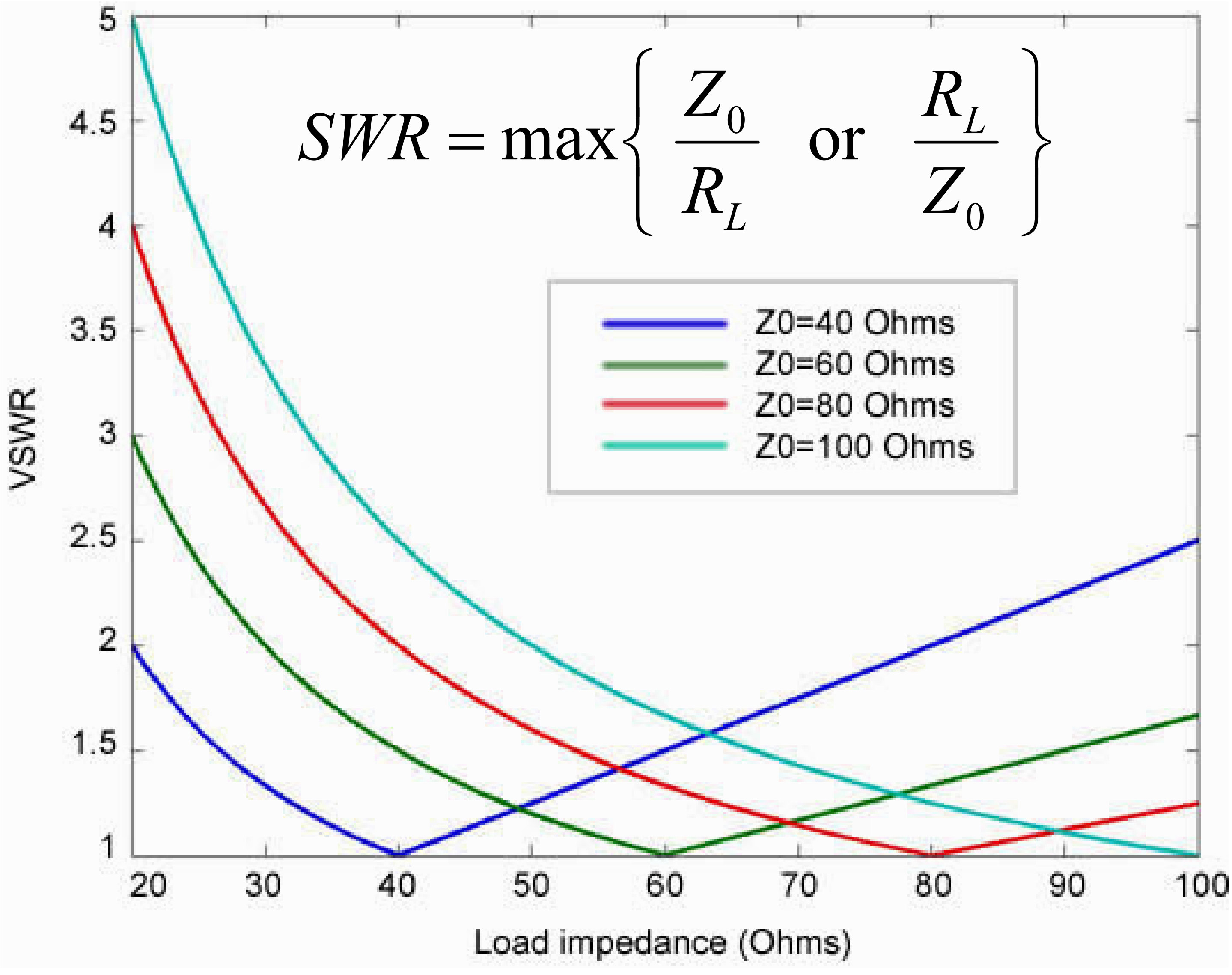


A Nomogram Relating Input and Output SWR



***Reference Data for Engineers*, 9th ed., p. 29-9, Newnes, 2002**

Standing Wave Ratio at a Resistive Load



Losses Are Due to Reflection and Dissipation

$$IL_{dB} = ML_{dB} + DL_{dB}$$

Lossless networks

$$DL_{dB} = 0$$

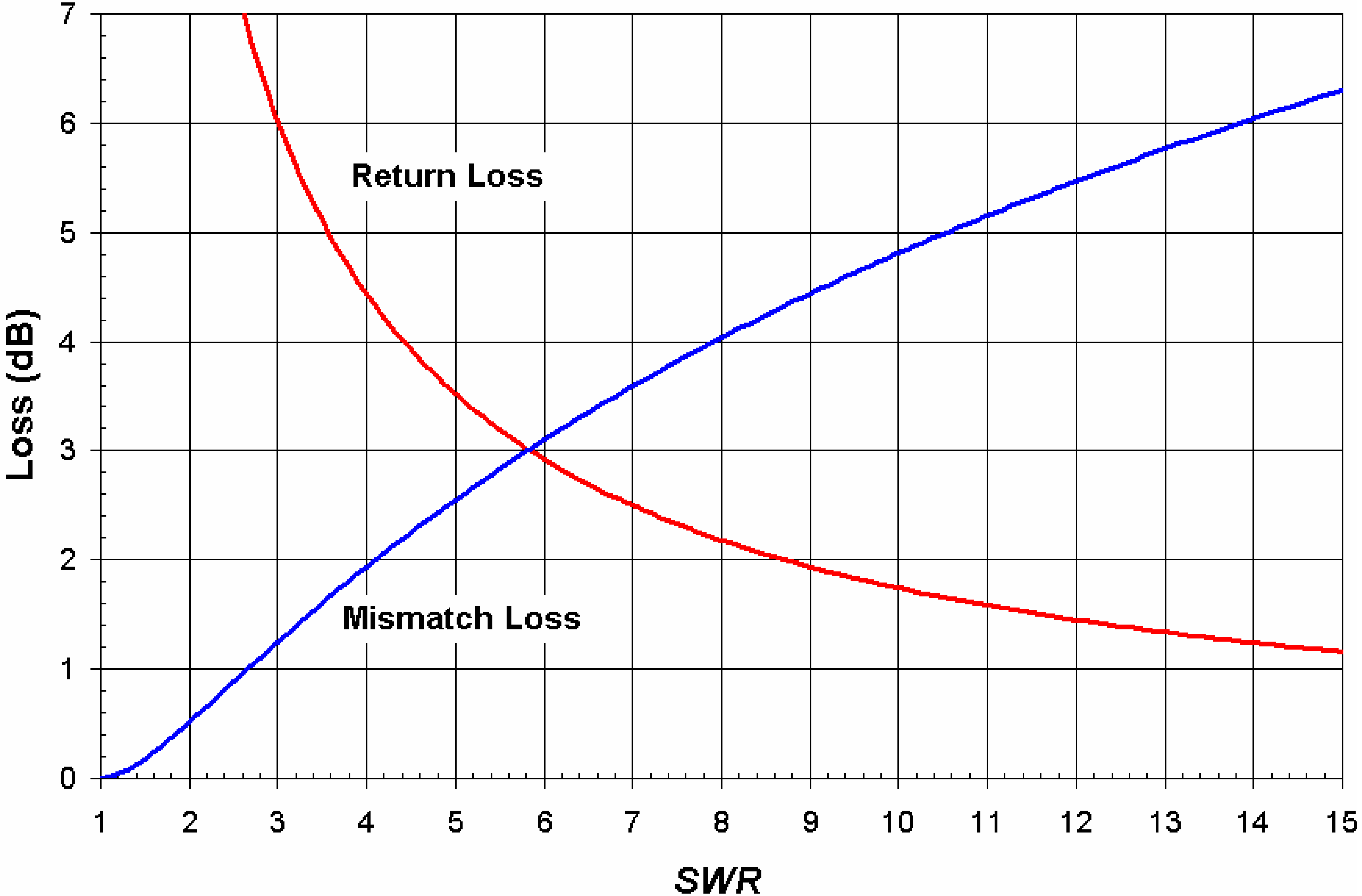
$$IL_{dB} = ML_{dB}$$

Reflectionless networks

$$ML_{dB} = 0$$

$$IL_{dB} = DL_{dB}$$

Reflection Loss of a Terminated Line vs Input SWR



Dissipation Loss of a Terminated Transmission Line

$$\text{Dissipation Loss} = 10\log\left(\frac{\frac{1}{A} - A\left|\Gamma_{Load}\right|^2}{1-\left|\Gamma_{Load}\right|^2}\right) \quad \text{dB}$$

where

$$A = 10^{-\alpha l/1000} < 1 = \text{power attenuation ratio}$$

$$\alpha = \text{line attenuation rate in dB/100 ft}$$

$$l = \text{line length in feet}$$

$$\left|\Gamma_{Load}\right| = \frac{SWR_{Load} - 1}{SWR_{Load} + 1}$$

- **Reference: *ARRL Antenna Book*, 21st ed., p. 24-10, eq. 16 with *A* = 1/*a***

A More Useful Form in Terms of SWR at Transmitter

$$\text{Dissipation Loss} = 10\log_{10}\left(\frac{1-\left|\Gamma_{Tx}\right|^2}{A-\frac{1}{A}\left|\Gamma_{Tx}\right|^2}\right) \quad \text{dB}$$

where

$$A = 10^{-\alpha l/1000} < 1 = \text{power attenuation ratio}$$

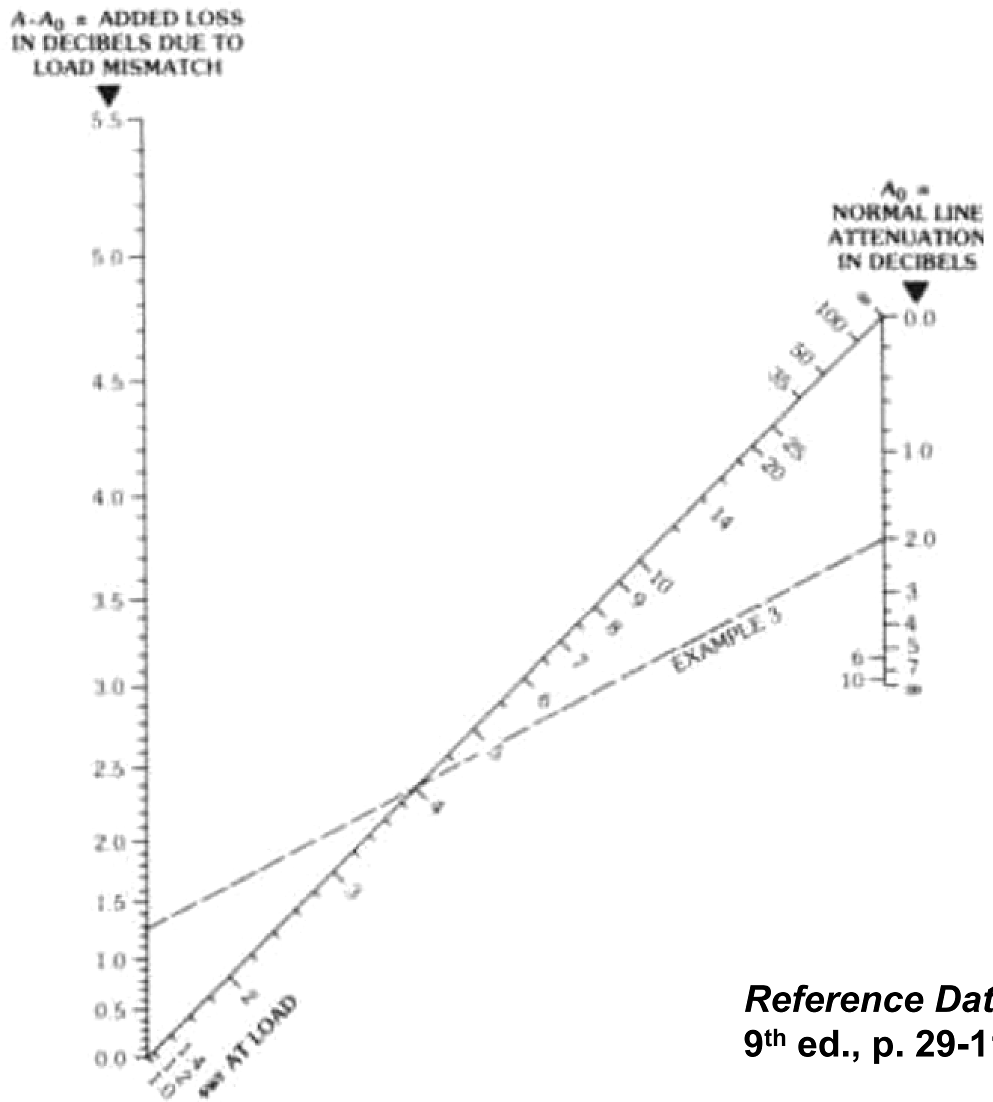
$$\alpha = \text{line attenuation rate in dB/100 ft}$$

$$l = \text{line length in feet}$$

$$\left|\Gamma_{Tx}\right| = \frac{SWR_{Tx}-1}{SWR_{Tx}+1}$$

- **Reference:** ***ARRL Antenna Book*, 22nd ed. ?**

A Nomogram for Finding Additional Loss Due to SWR

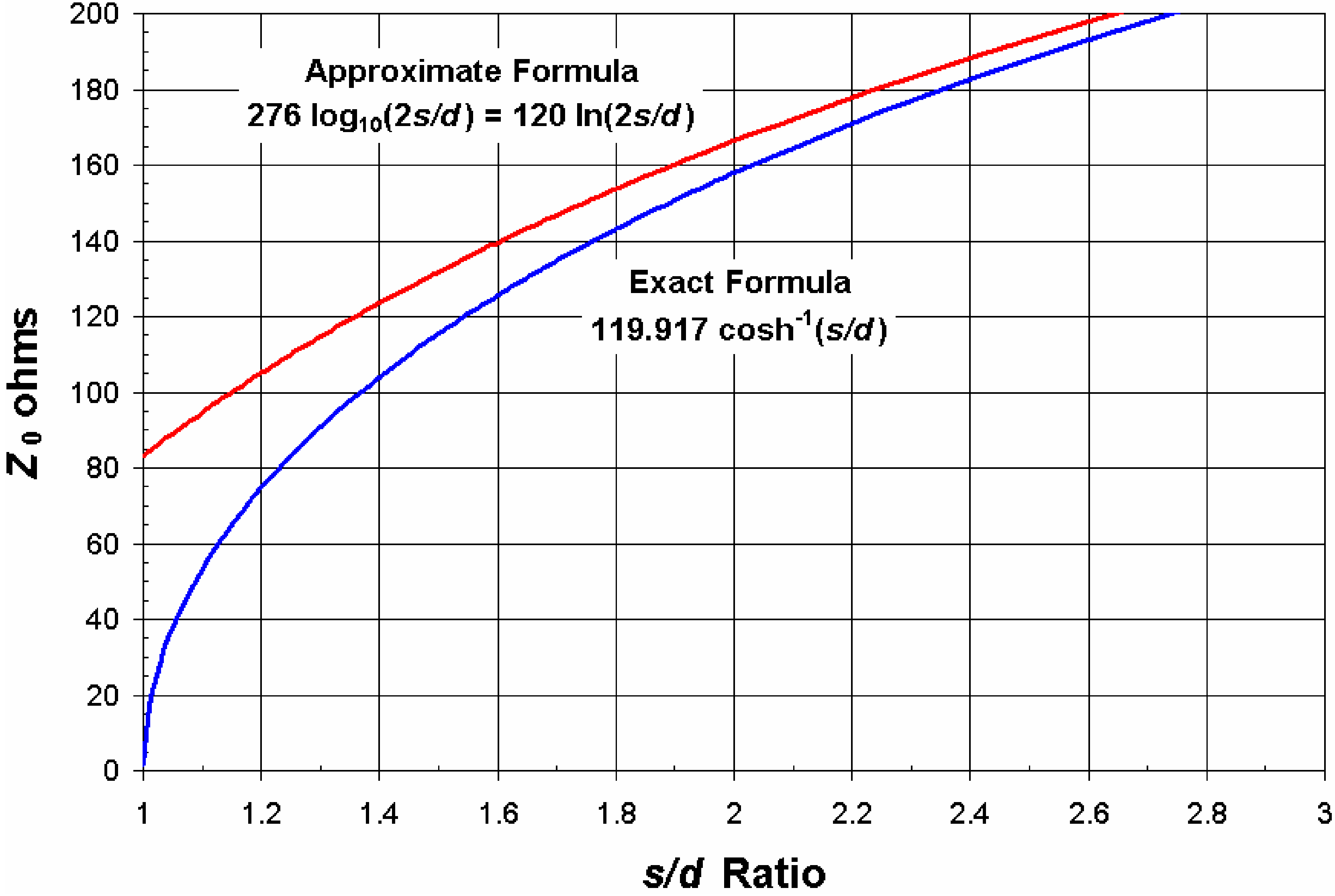


Reference Data for Engineers, 9th ed., p. 29-11, Newnes, 2002

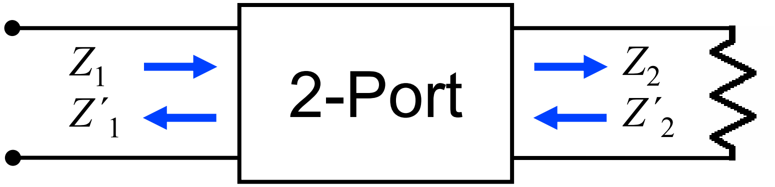
Myths and Bloopers

- **Impedance formula for open wire line**
  - Z_0 = 276 $\log_{10}(2s/d)$ = 120 $\log_e(2s/d)$ versus 120 $\cosh^{-1}(s/d)$
  - "Z_0 approaches 83 ohms as s/d approaches unity."
    George Murphy, VE3ERP, *CQ*, Nov. 2000
- **Return loss**
  - "Return Loss is 20 times the reflection coefficient."
    Kurt N. Sterba, *World Radio*, Jan, 2007
  - "Return Loss is not a commonly used quantity."
    Brice Wightman, VE3EDR, VA2BW, *World Radio*, May 2007
  - "Return Loss is 20 times the reciprocal of the reflection coefficient." Kurt N. Sterba, *World Radio*, June 2007
- **Conjugate match**
  - Numerous theorems of circuit theory incorrectly stated
  - Poor reasoning and incorrect conclusions at every turn

Impedance Formulas for Open-Wire Line



Why Not Conjugate Match?



- A conjugate match at the input does not imply a conjugate match at the output (load) and vice versa unless the 2-port is lossless
- Conjugate matching in long transmission line systems leads to reduced system bandwidth – not good for communication except for narrowband signals, and poor for digital modulations
- The goal of communication is information transmission, not power transmission. Digital modulations hate distortion caused by echoes, multipath, and reflections
- Solid state amplifiers are designed for stability by various methods, e.g. unilateralization, load-pull, source-push – to prevent oscillation !
- Conjugate matching plays no particular role in output impedance selection

Transducer Power Gain

- **Maximum power delivery from a given source through a general 2-port to a load is achieved by maximizing "Transducer Power Gain," not by conjugate matching at input or output**

$$G_T = \frac{\text{Power delivered to load}}{\text{Power available from source}}$$

$$= \frac{|S_{21}|^2 \left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_L|^2\right)}{\left|(1 - S_{11}\Gamma_S)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_L\Gamma_S\right|^2}$$

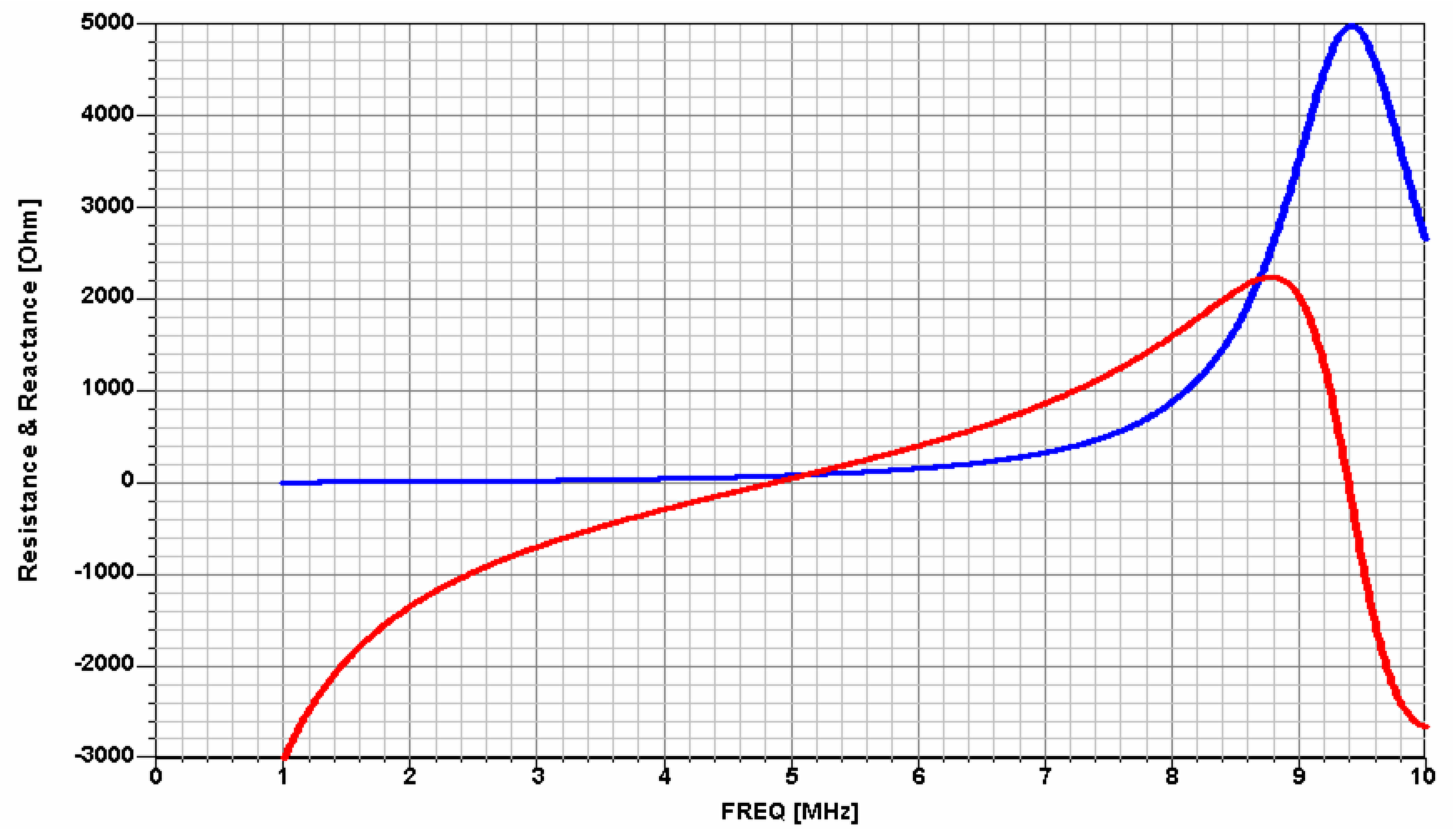
- **Don't use this fact to match a solid state amplifier to a load, unless you want an oscillator !**

Multi-Band Match Networks

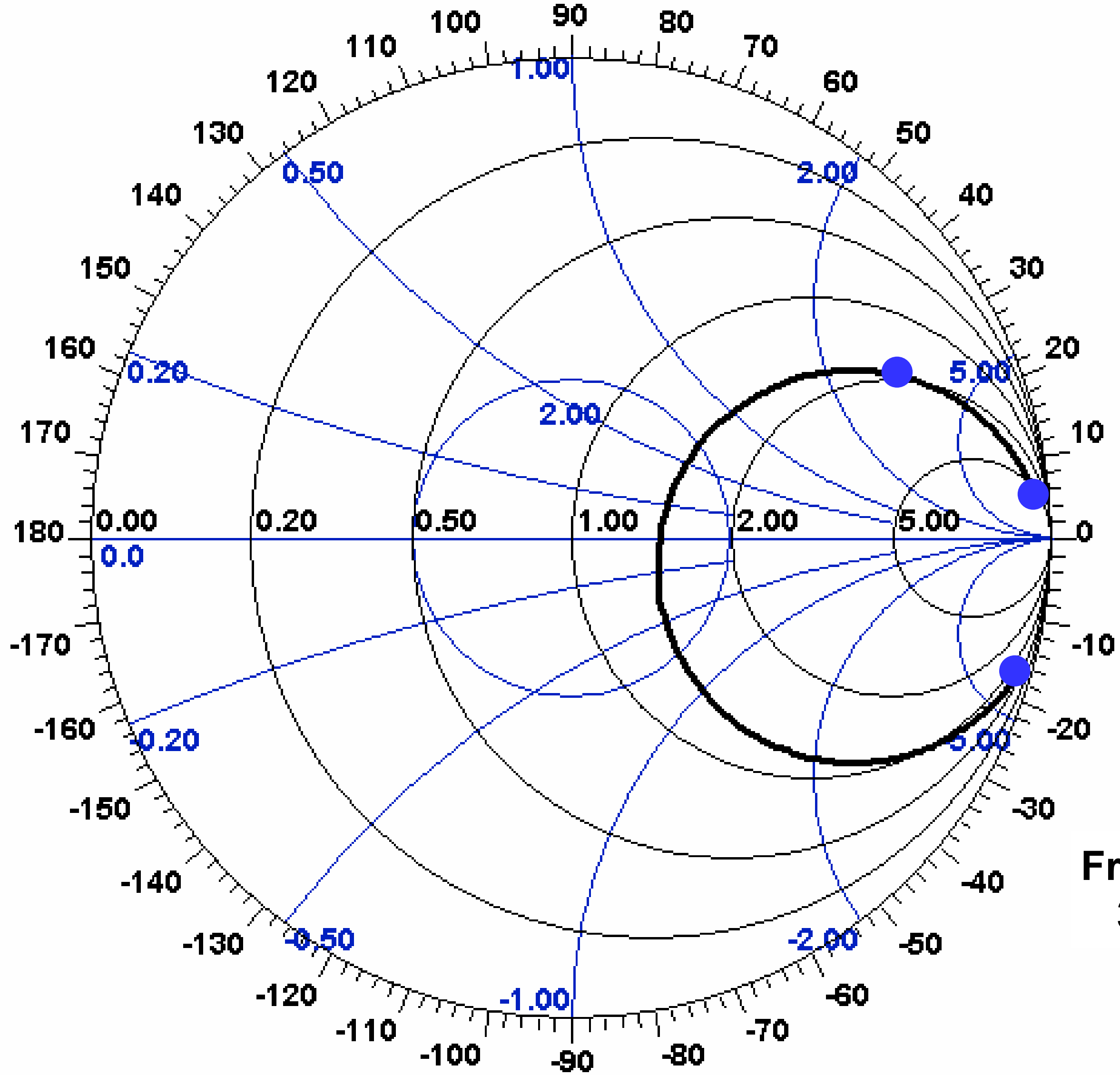
Three-Band Match Network

- Ward Silver (N0AX) proposed to design an antenna for the 75, 60, and 40 meter bands
- K6OIK's easy solution: Take an existing antenna and design a feedpoint match network for the three bands
- Antenna: 98.4-foot wire dipole antenna resonant at 4.868 MHz – nothing special
- Frequencies: 3.9 MHz; 5.35 MHz; and 7.2 MHz
- Design goal: SWR = 1 at these three frequencies

Dipole Impedance

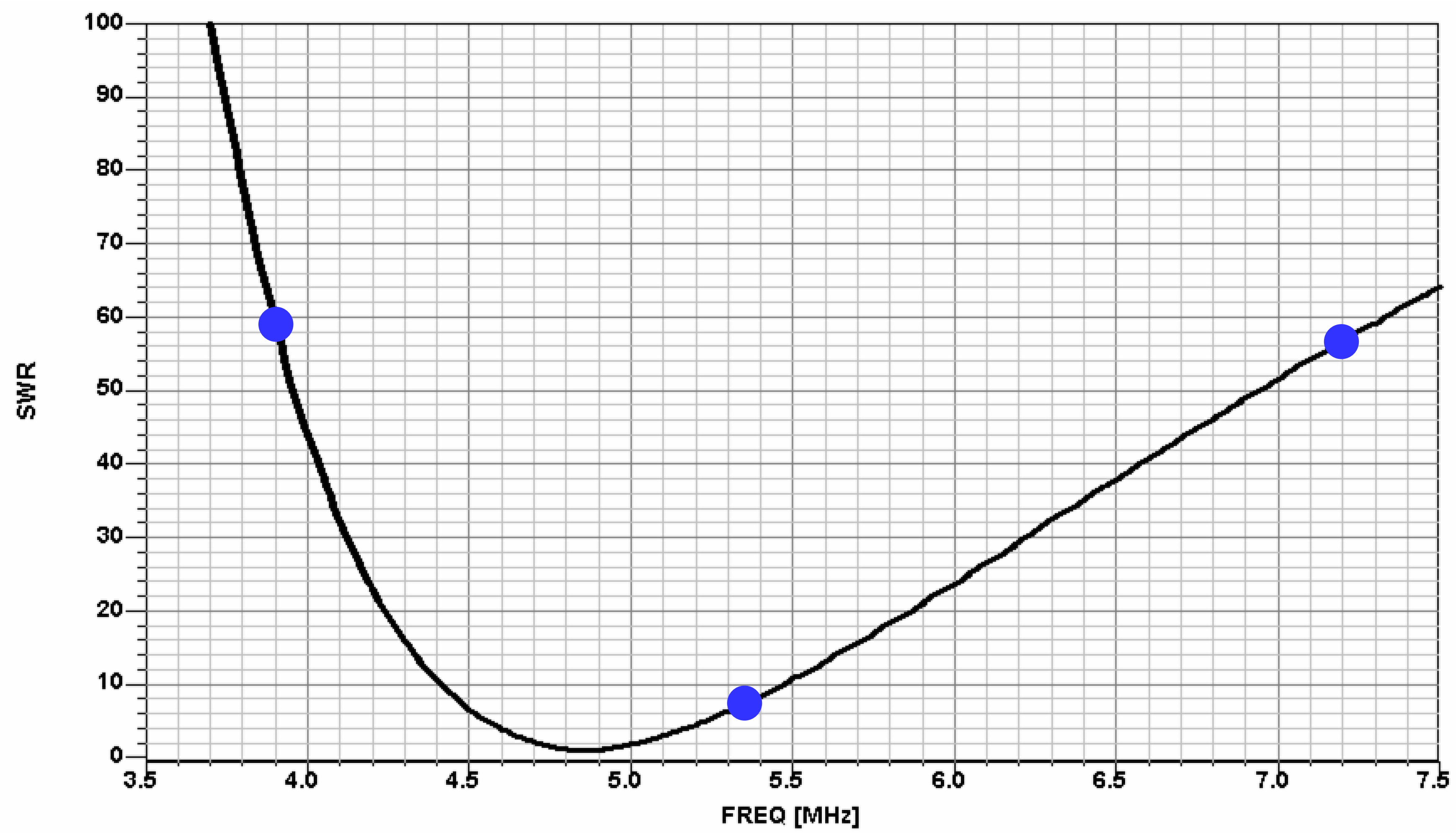


Dipole Impedance on the Smith Chart

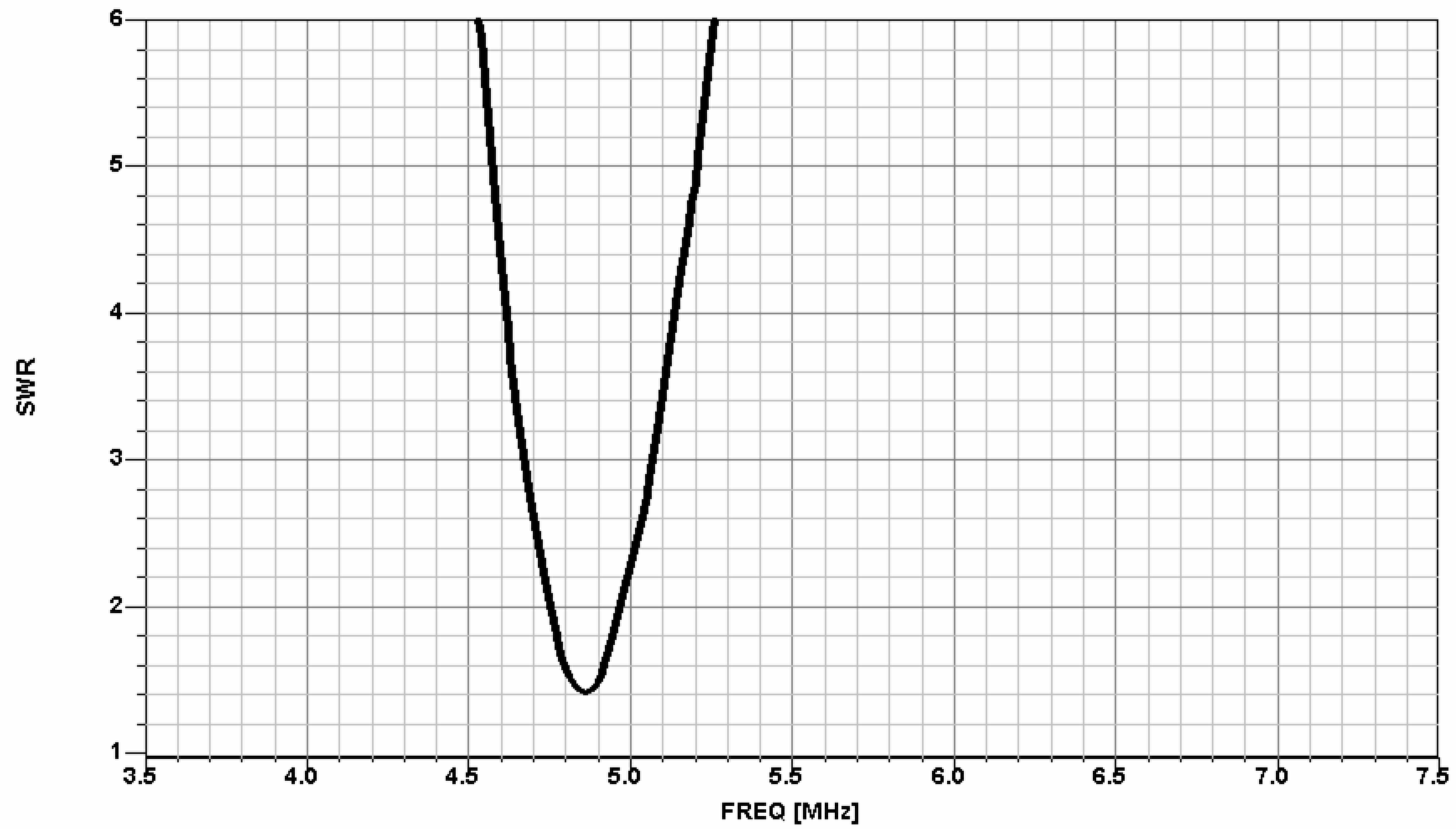


Frequency sweep
3.8 to 7.3 MHz

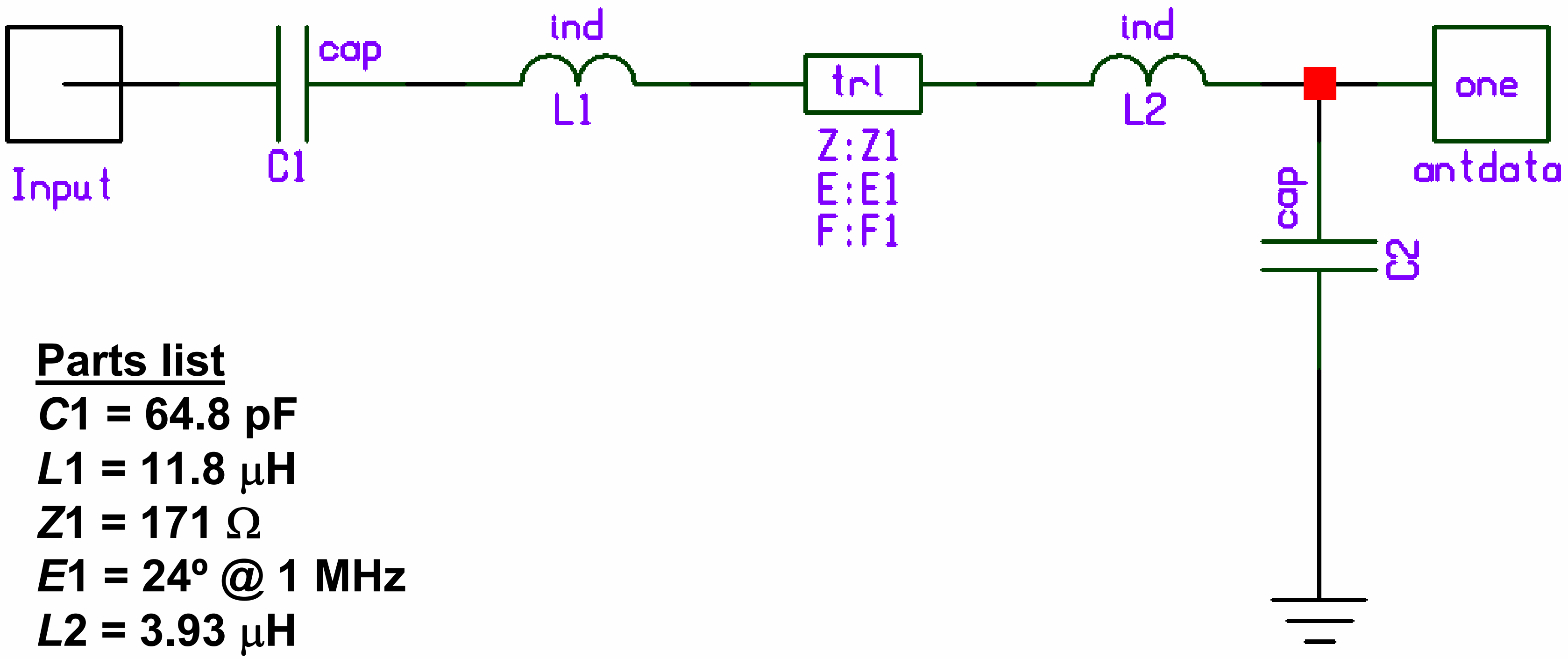
Dipole SWR Before Matching



Dipole SWR Before Matching



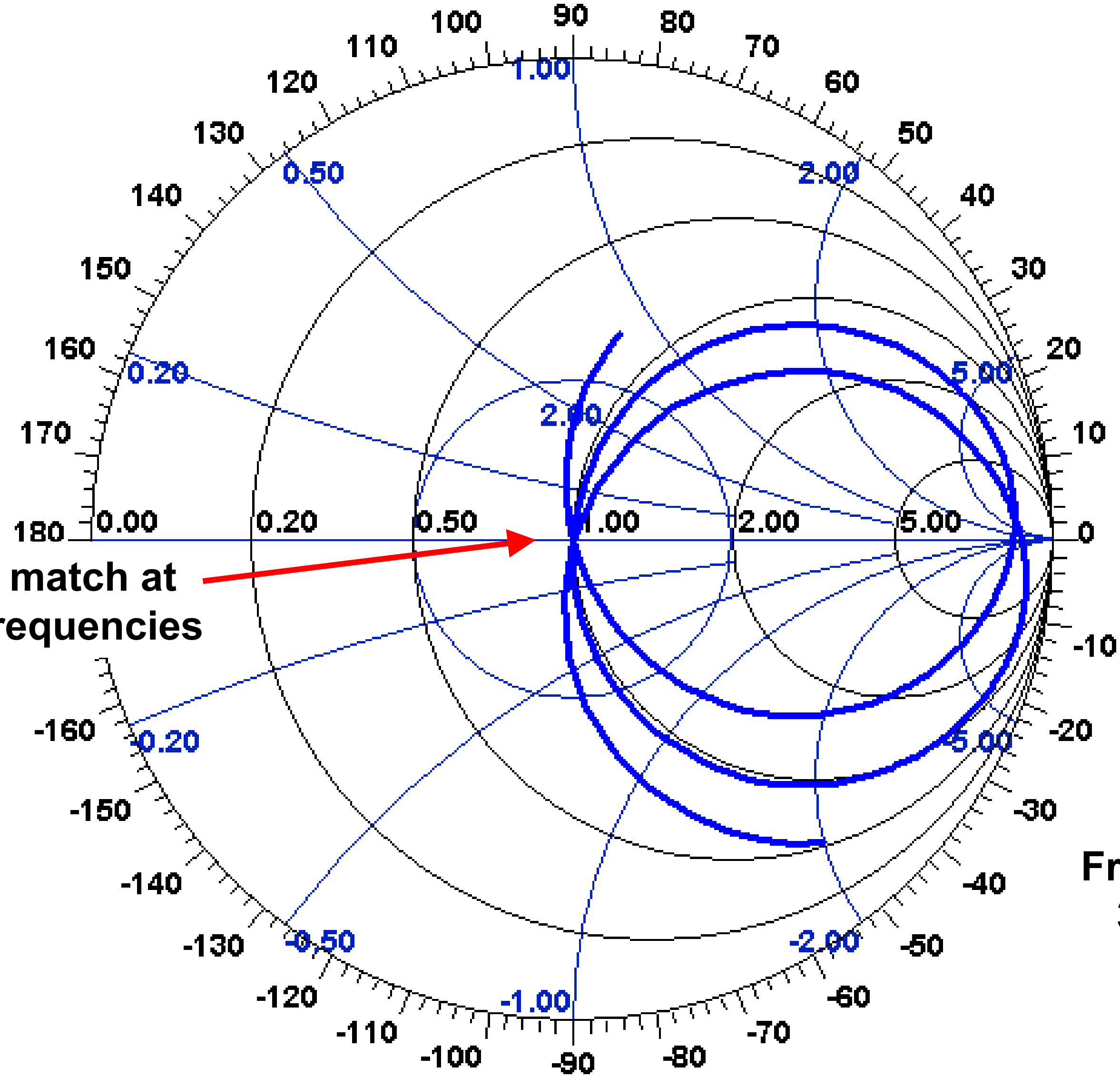
Circuit of Three-Band Match Network



Parts list

***C*1 = 64.8 pF**
***L*1 = 11.8 μH**
***Z*1 = 171 Ω**
***E*1 = 24° @ 1 MHz**
***L*2 = 3.93 μH**
***C*2 = 83.8 pF**

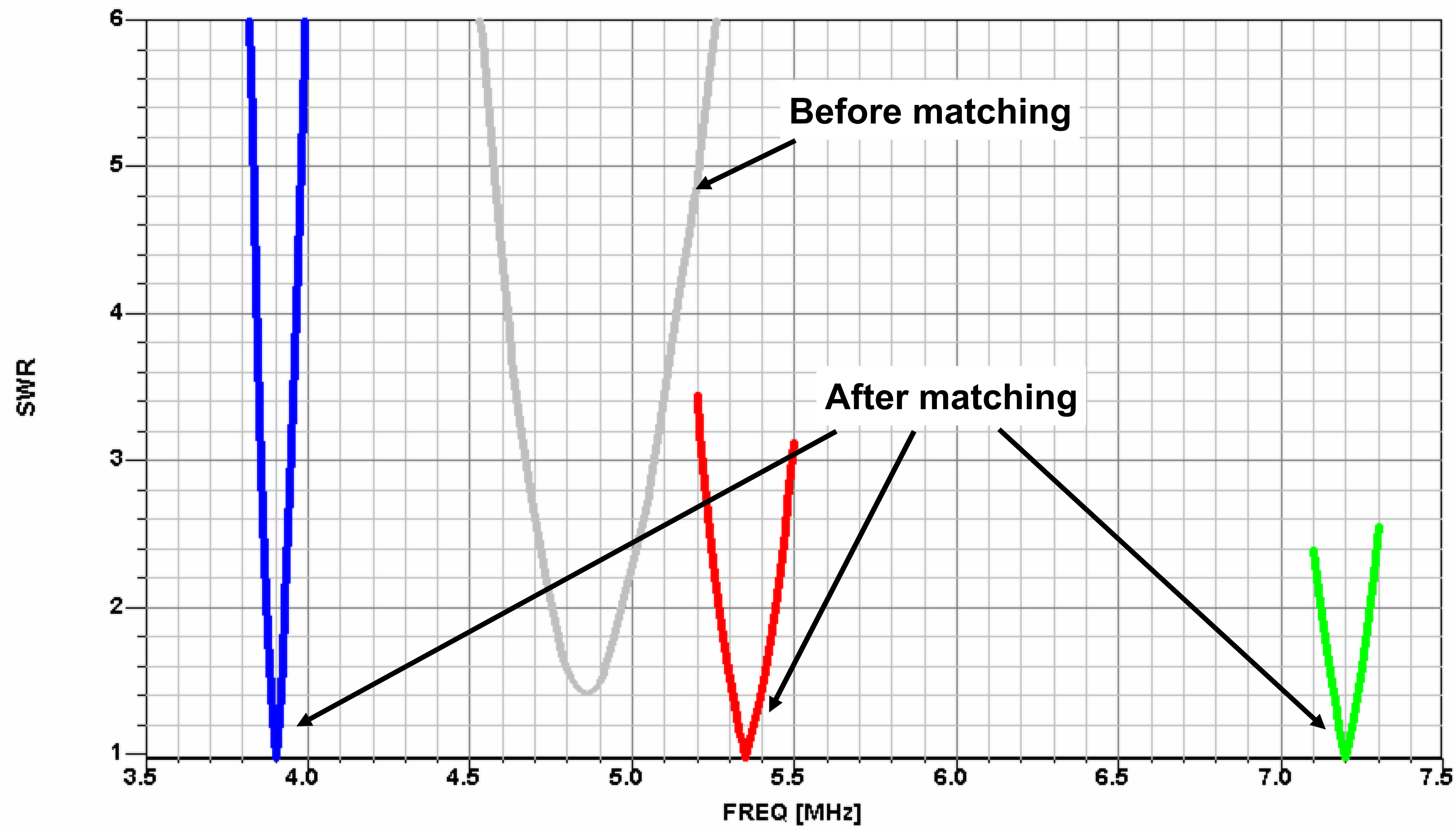
Impedance After Matching



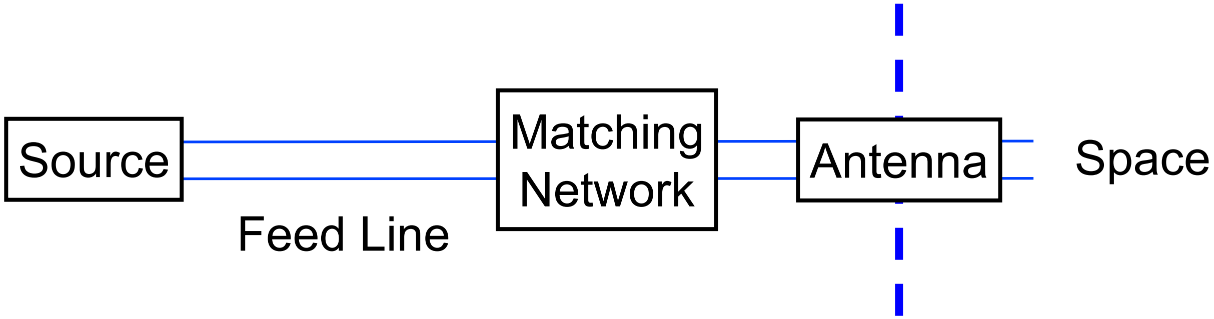
Perfect match at design frequencies

Frequency sweep 3.8 to 7.3 MHz

SWR After Matching



Question



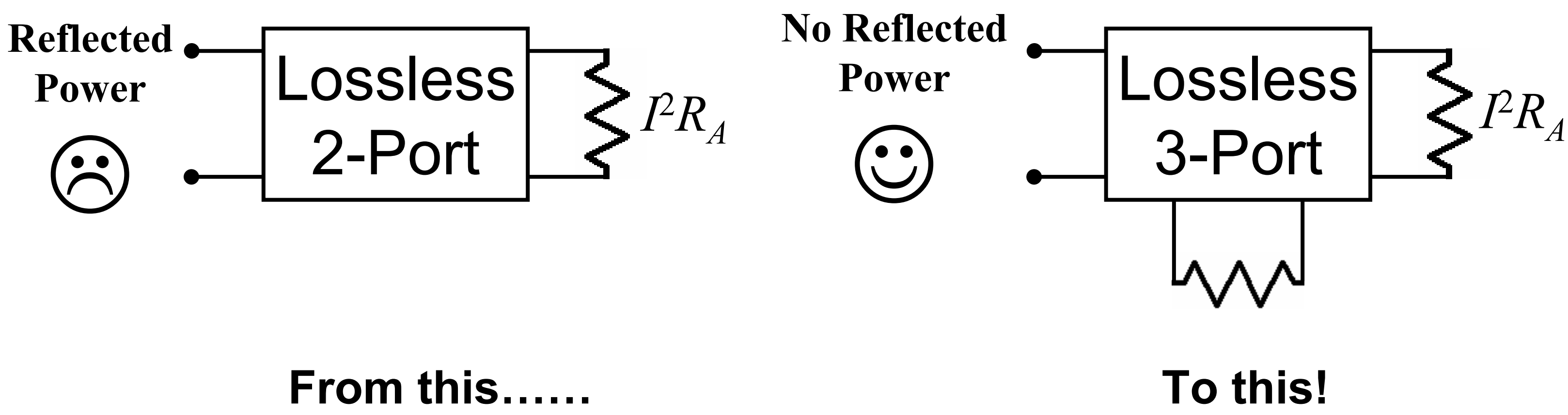
- **Can a fixed (non-tunable) impedance-matching network provide unity SWR at all frequencies?**

Reflectionless Broadband Impedance Matching

Constant-Resistance Networks
Non-Foster Active Networks

Edward Lawry Norton, 1898-1983, photo 1925

The Idea

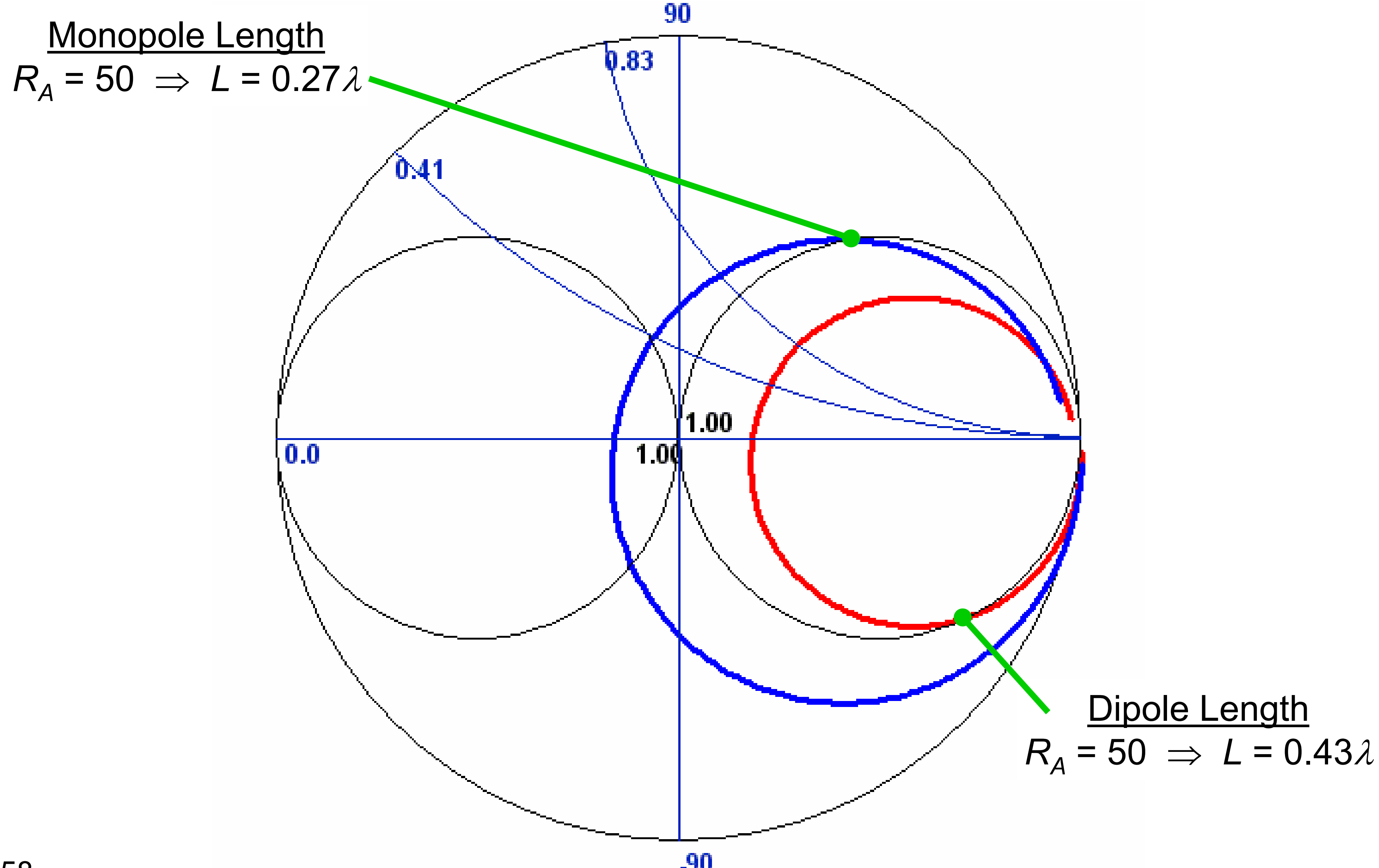


- **Traditional impedance-matching networks are "reflection" filters that create reflected waves**
  - Subject to the Fano bound
- **Constant-resistance reflectionless networks**
  - Developed by E.L. Norton (1937)
  - Have unity SWR over a wide band
  - Are "diplexers" that divide power between two loads
  - Rated by insertion-loss bandwidth instead of SWR bandwidth
  - Side-step the Fano bound but are subject to the Carlin-LaRosa bound

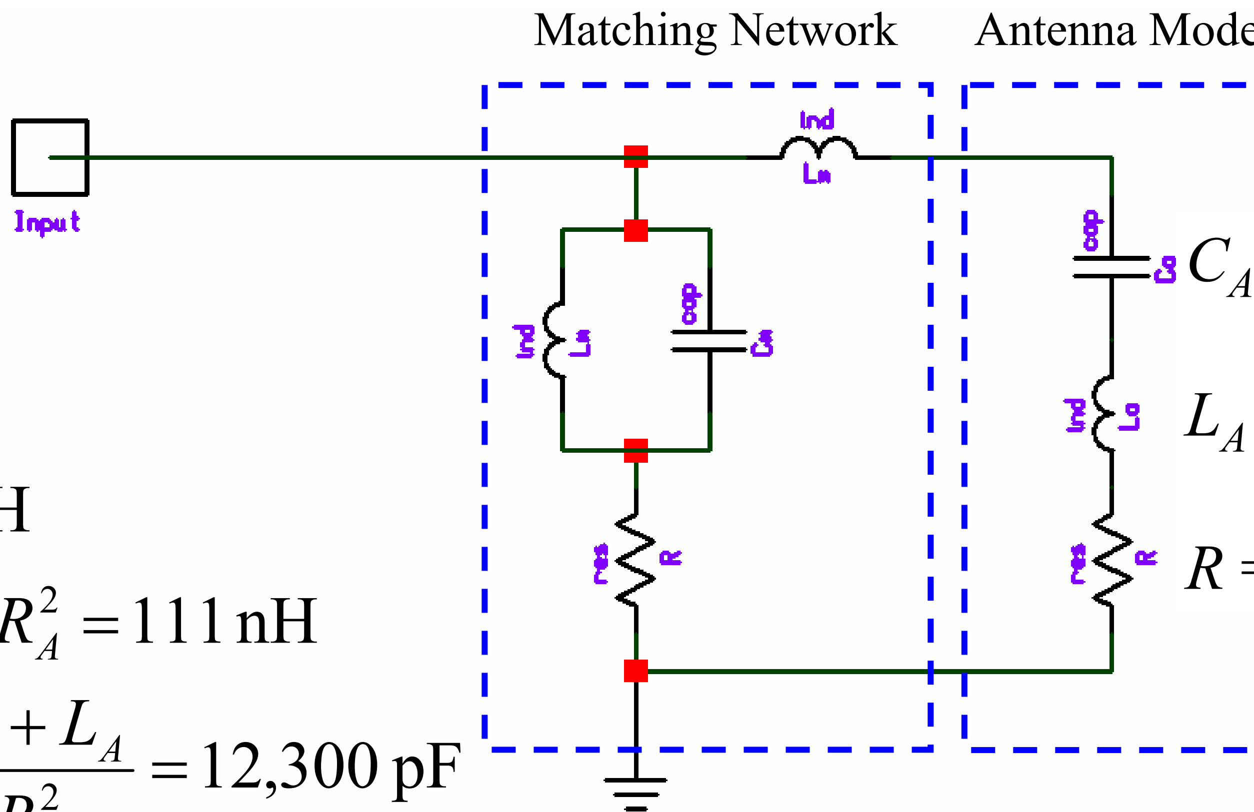
How to Do It

- **Step 1: Shorten "half-wave" dipoles or lengthen "quarter-wave" monopoles so that R_A = 50 ohms**
  - Dipoles: Use $K \approx 0.86$, or $L \approx 0.43\lambda$
  - Monopoles: Use $K \approx 1.07$, or $L \approx 0.27\lambda$
- **Step 2: Insert a series reactance to cancel feedpoint reactance**
  - Dipoles: Add a series inductor
  - Monopoles: Add a series capacitor
- **Step 3: Insert a shunt network to yield a 50-ohm constant-resistance network**

Antenna Impedance on the Smith Chart



Example 1: Reflectionless Match to 0.43λ Dipole



$C_A = 44.5 \text{ pF}$

$L_A = 23.8 \ \mu\text{H}$

$R = 50 \ \Omega$

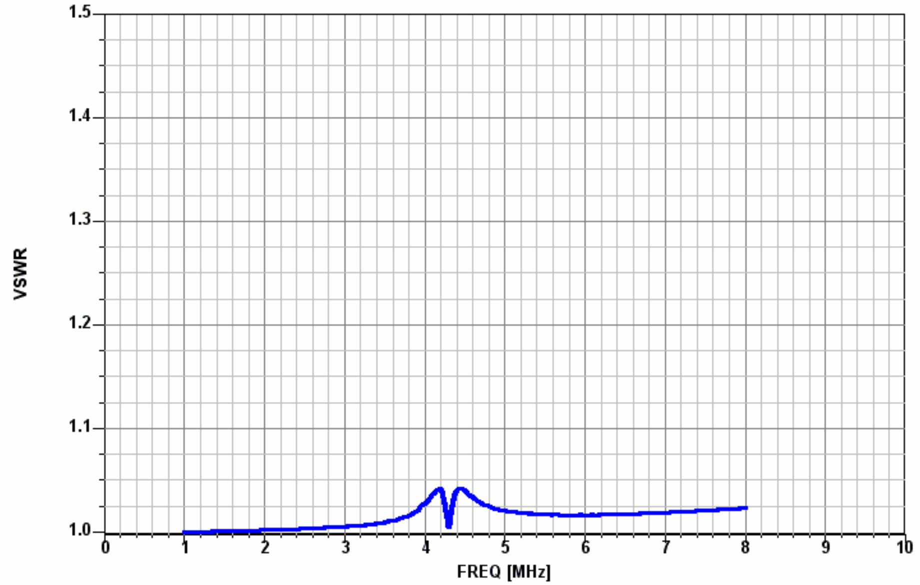
$$L_S = 7 \ \mu\text{H}$$

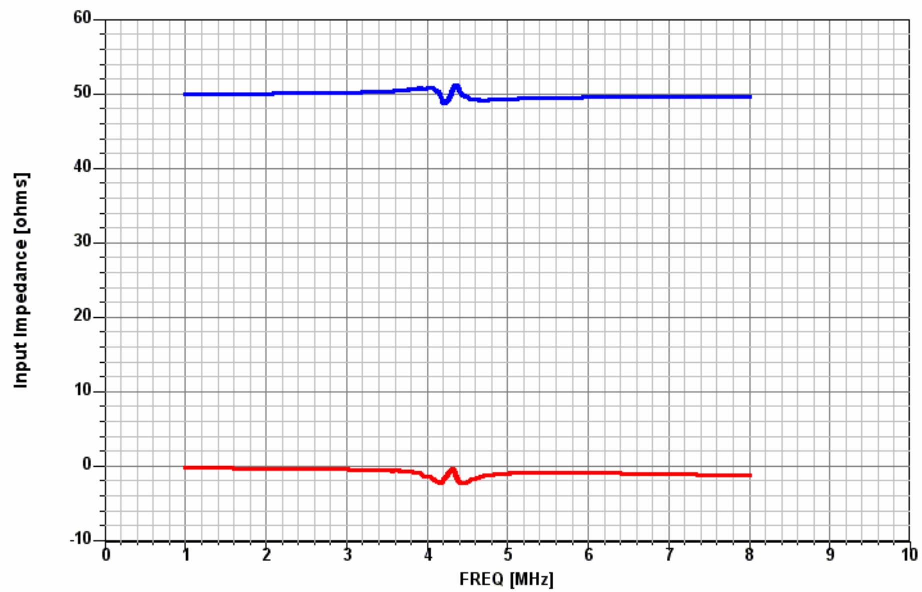
$$L_M = C_A R_A^2 = 111 \text{ nH}$$

$$C_M = \frac{L_S + L_A}{R_A^2} = 12{,}300 \text{ pF}$$

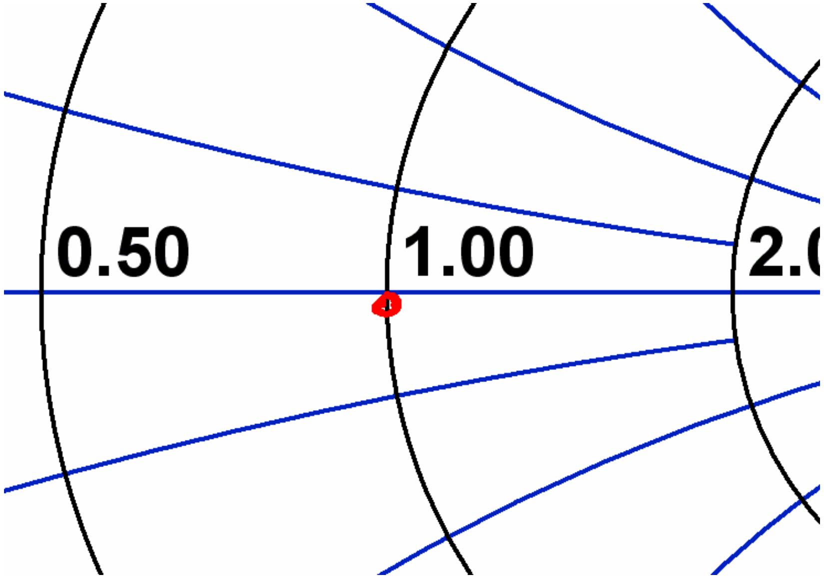
$$R = R_A = 50 \ \Omega$$

Network Performance on Dipole Impedance Data

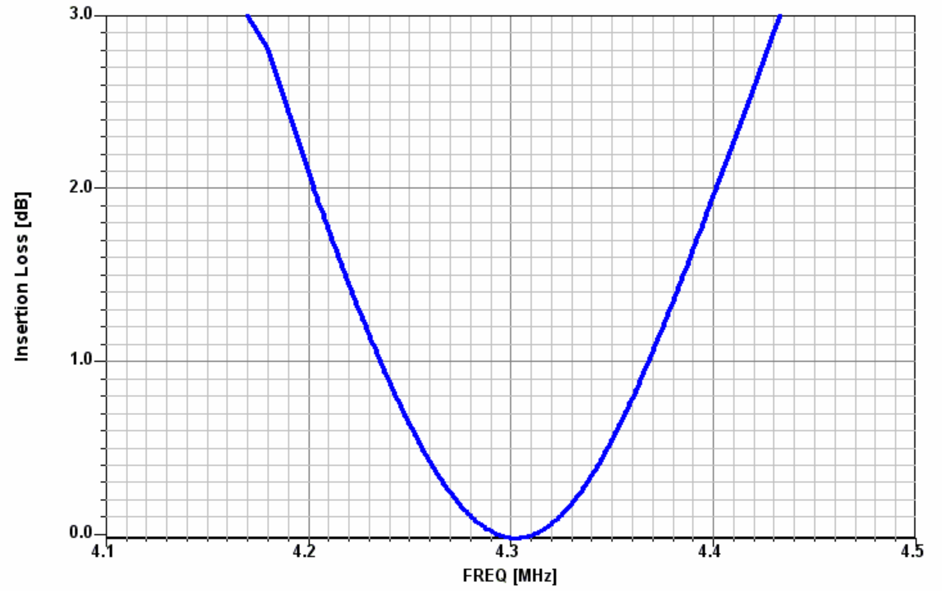




- Frequency sweep 1 to 8 MHz
- Maximum SWR = 1.04
- Input resistance: 48.8 to 51.2 ohms
- Input reactance: -2.1 to 0 ohms



Power Delivered to the 0.43λ Dipole



- **Pattern gain = - 0.11 dBd**
- **Minimum insertion loss = 0 dB**
- **100% power delivery at 4.3 MHz**
- **3-dB Bandwidth = 259 kHz (6.0%)**
- **0.51-dB Bandwidth = 91 kHz (2.1%)**

Bandwidths to Compare	
Lossless Networks	**Reflectionless Networks**
$BW_{VSWR\ 5.83:1}$ ⟷	$BW_{IL\ 3\text{-}dB}$
$BW_{VSWR\ 2:1}$ ⟷	$BW_{IL\ 0.51\text{-}dB}$

Interesting Antennas

John Daniel Kraus, 1910-2004

Chen-To Tai, 1915-2004

Ronold Wyeth Percival King, 1905-2006

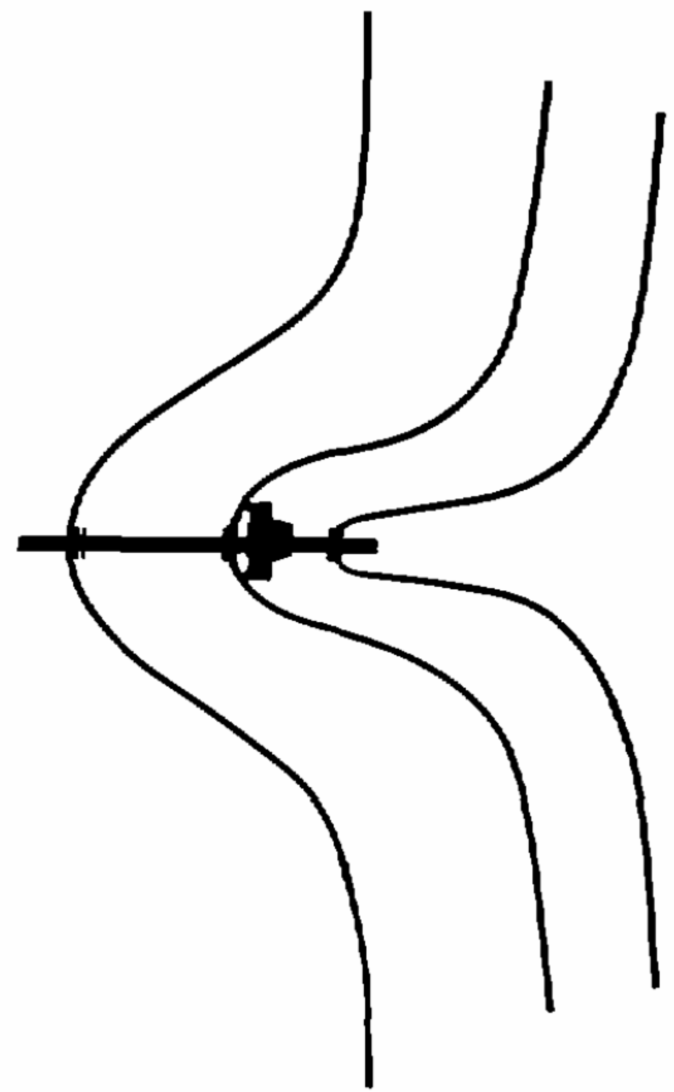
R.W.P. King speaking at his 100th birthday party, Oct. 2005.

Sergei Alexander Schelkunoff, 1897-1992

Amateur Antenna Paradigms

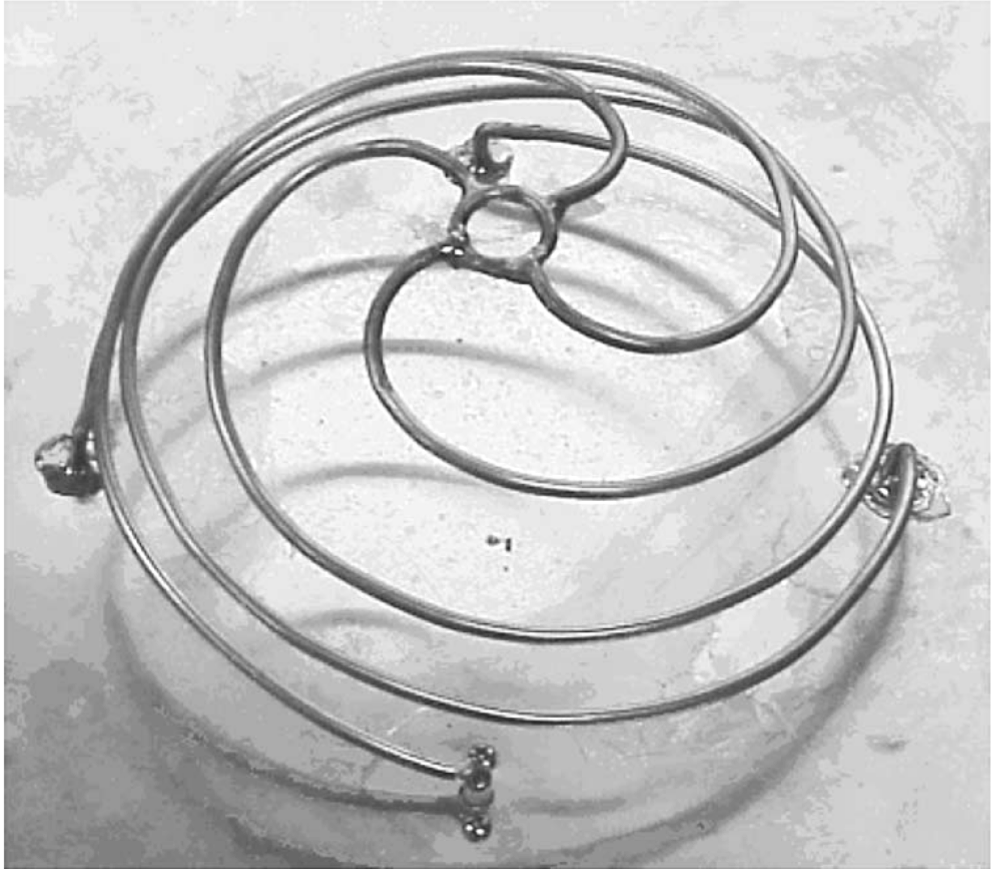
- Antennas made of straight elements (wires, rods, and tubes)
- Antennas made of conductors (metals)
- Resonant antennas
- Narrowband antennas
- But … many interesting and novel antennas break these rules!
- And some strange antennas don’t ...

Landstorfer Antenna (1976)



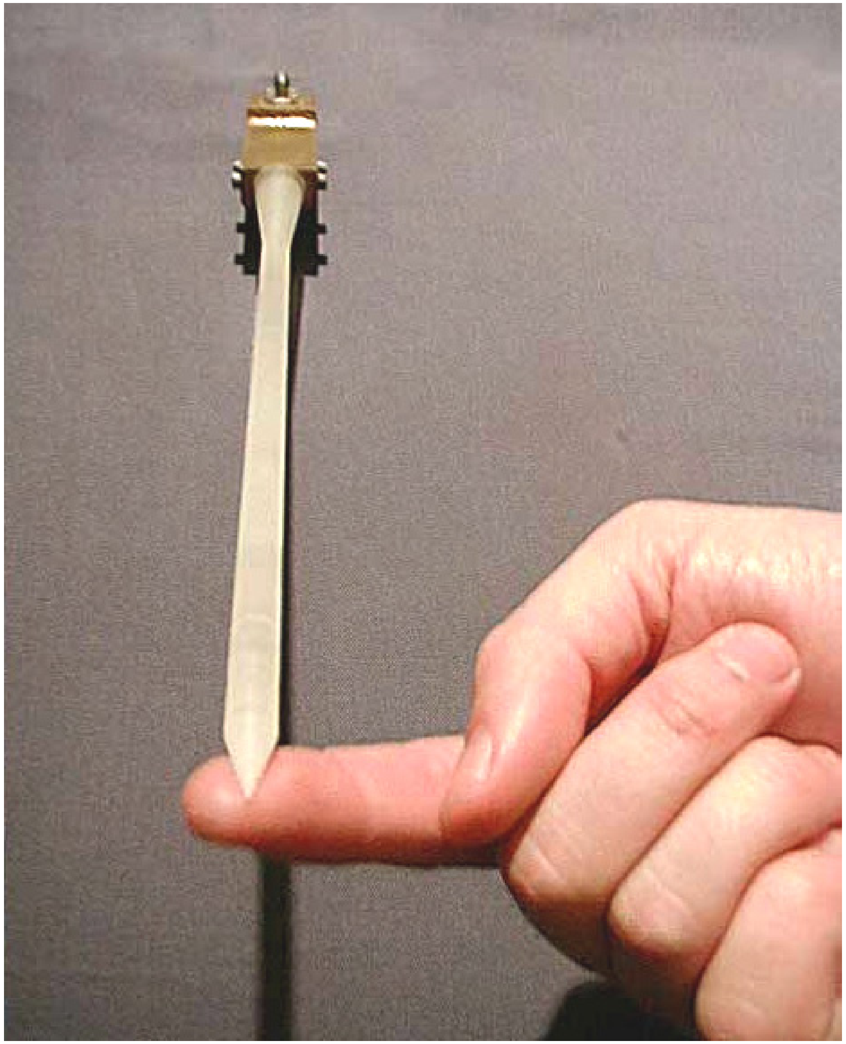
- Elements: 3
- Element shape: Optimized (approximately Gaussian)
- Gain: 11.5 dBi
- Sidelobes: < -20 dB
- F/B ratio: 26 dB
- Performance similar to 10-element Yagi – except…
- Bandwidth: > 3% (W4RNL)

Folded Hemi-Spherical Helix Over Ground Plane (2004)



- Helix: 4 arms, 1 turn
- Height (radius): $\lambda/16.5$
- Frequency: 300 MHz
- Polarization: vertical
- Z: 50 ohms real
- SWR: < 1.16
- Efficiency: > 94%
- Bandwidth: 22.8 MHz (7.6%)
- Q_A: 32 (Q_{Chu} = 22.8)

Polyrod Antenna (1947)



- **Material: Polystyrene**
- **Frequency: 11.6 GHz**
- **Gain: 20 dBi**
- **Bandwidth: 40%**

Dielectric rods made of ceramic or fused quartz can handle high power

Stealth Antennas

Saguaro Cactus (Carnegia giantea)?

Evergreen Trees?

Deciduous Tree?

Non-Stealth Antennas

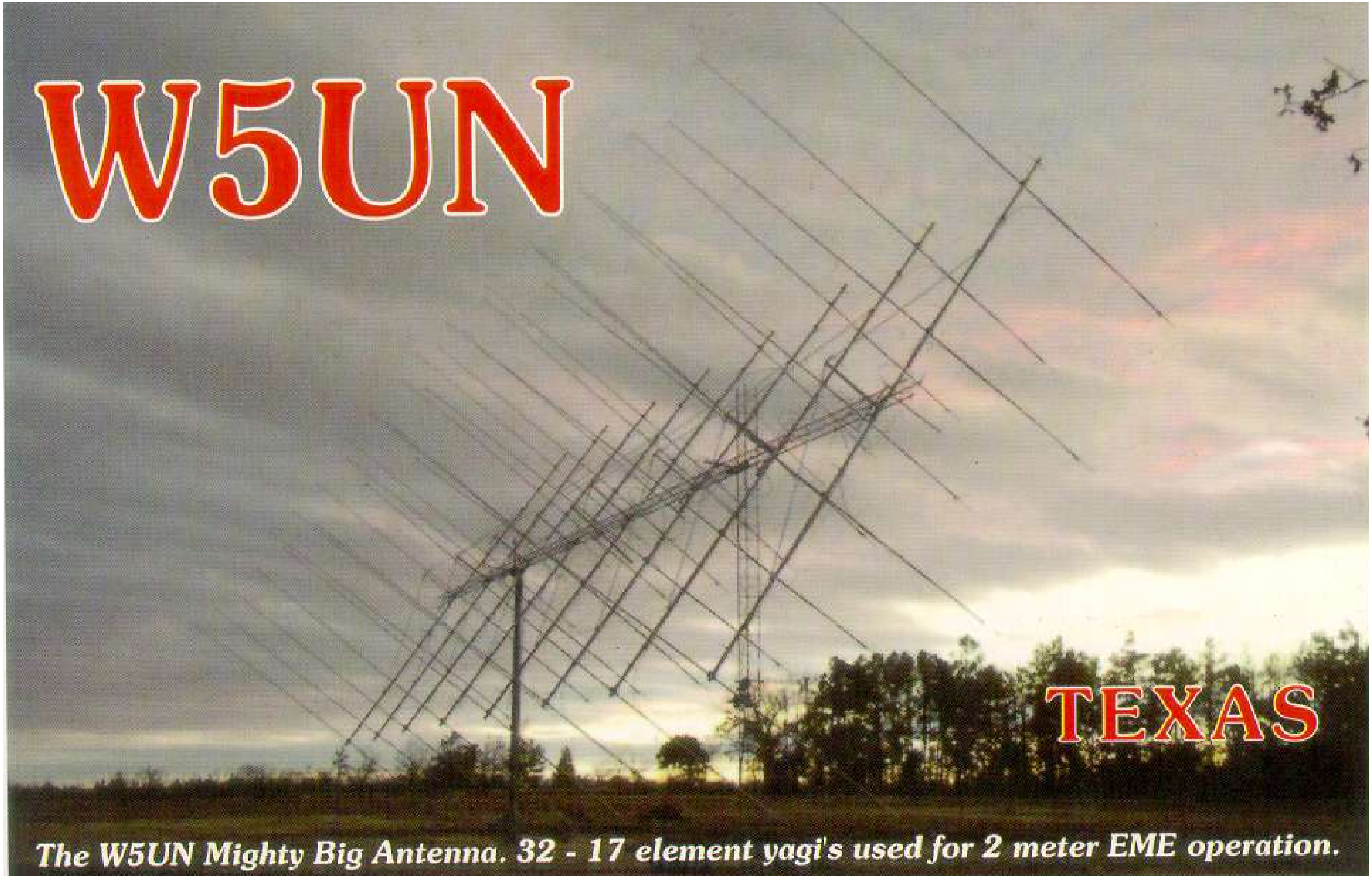
90-Foot Drive-Up Discone, Green Valley, Arizona

Why Little Transmitters Get Heard

K0DK in Boulder, Colorado

K4JA at Callao, Virginia

W5UN at Mount Pleasant, Texas

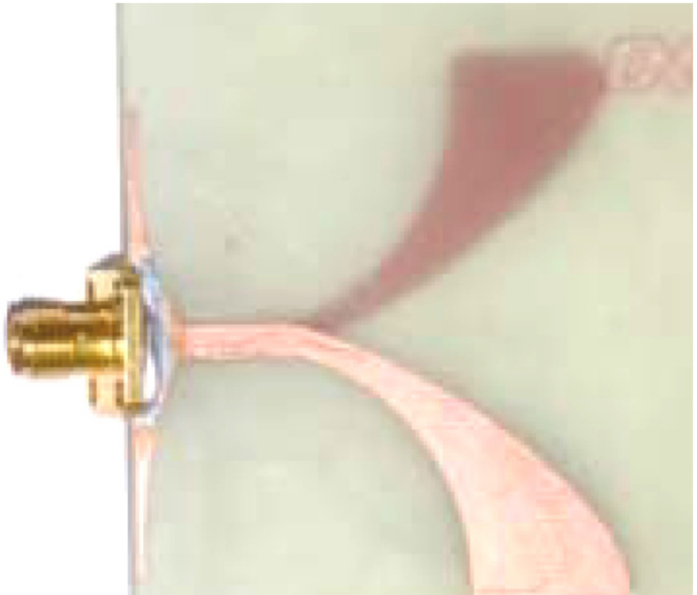


W6AM's Antennas As Seen from Space

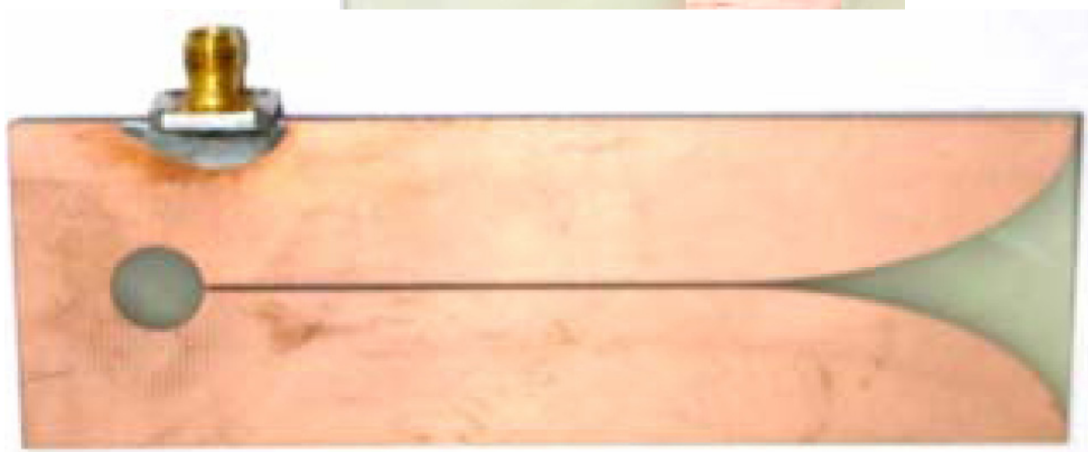
W6AM at Rancho Palos Verdes, California

Broadband Antennas

Vivaldi Antenna (1974)

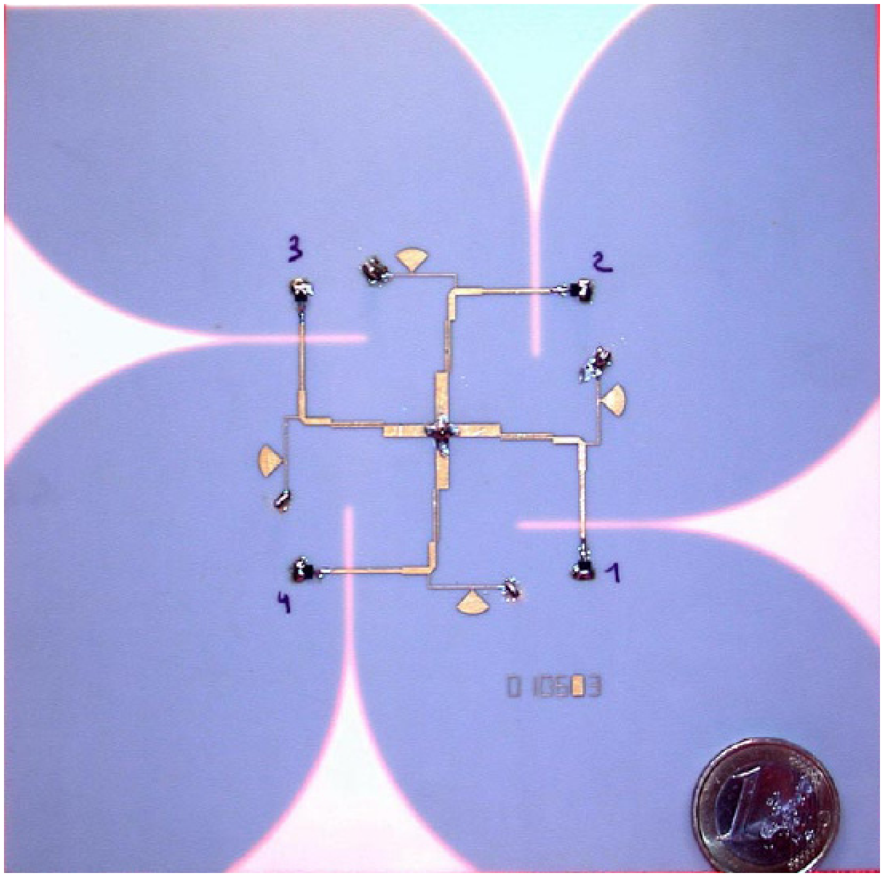


- Exponentially tapered slot antenna
- Gain: 8 to 9 dBi
- Bandwidth: no limit
- Arbitrary polarizations obtained by feeding two crossed antennas
- Construction: PC board



Bandwidths of one octave to one decade can be achieved

Four-Sector Vivaldi Antenna

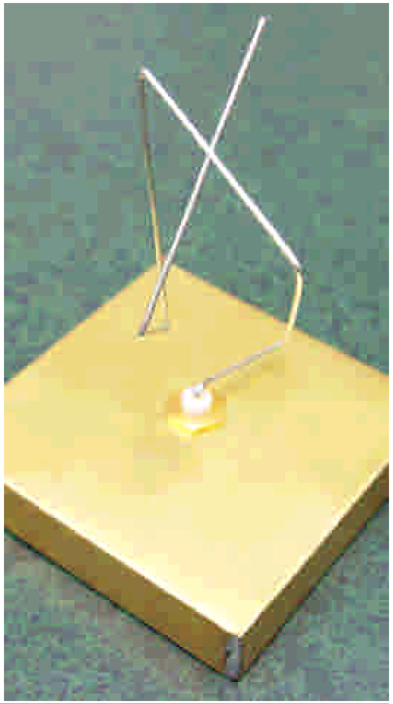


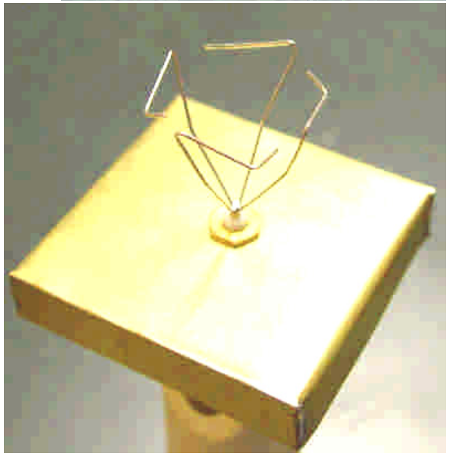
- **Antenna mounts horizontally**
- **Polarization: horizontal**
- **Four directional beams**
- **Beam selected by PIN diodes**
- **Gain: 8 to 9 dBi per sector**

Dual use! Could be mounted as a horizontal capacity hat on a short HF monopole to span all UHF bands

Or mount two vertically and crossed for vertical polarization in four sectors

Computer Evolved Antennas via Genetic Optimization

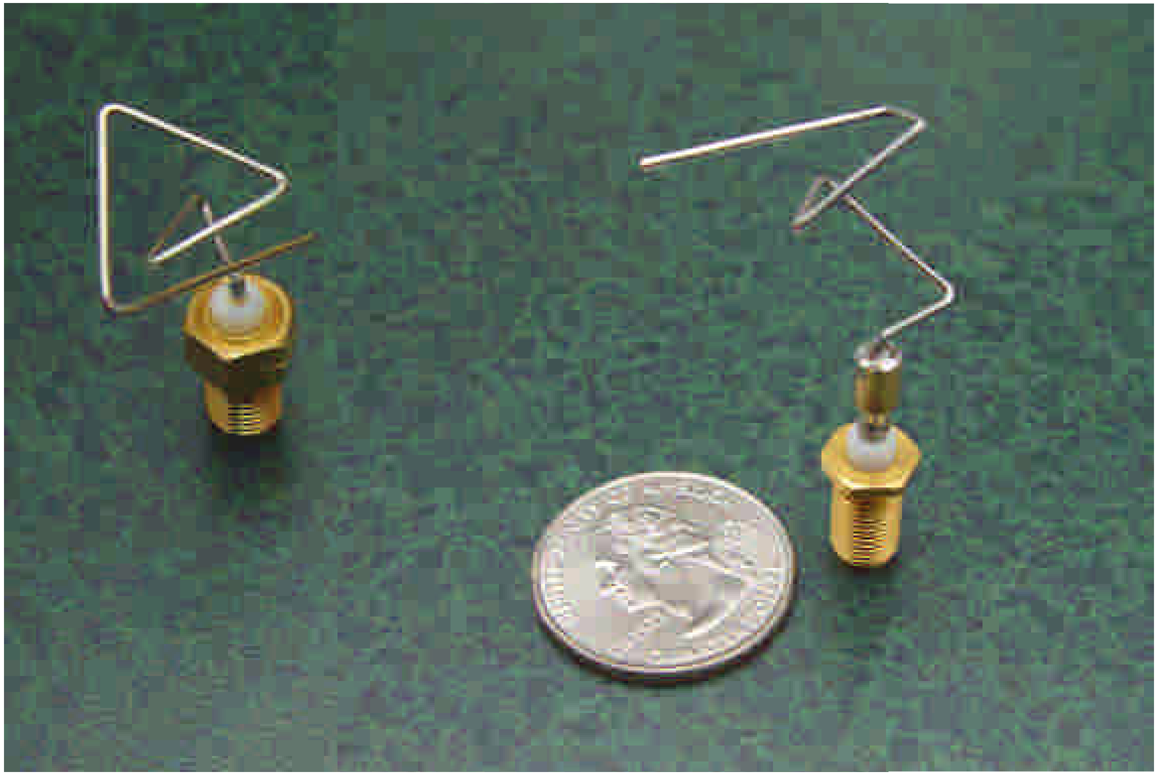




- Crooked Wire Genetic Antennas (CWGA)
- Types: 1 and 4 arms
- Frequencies: 2 to 18 GHz
- Pattern: Omni 10º above horizon

Courtesy of JEM Engineering

NASA ST5 Satellite Antenna



- **Frequencies:**
  - Tx: 8.470 GHz
  - Rx: 7.209 GHz
- **Polarization: RHCP**
- **Gain:**
  - -5 dBi, 0º to 40º
  - 0 dBi, 40º to 90º
  - No null at zenith
- **SWR:**
  - Tx: 1.19
  - Rx: 1.22
- **Wire: 20 gauge**

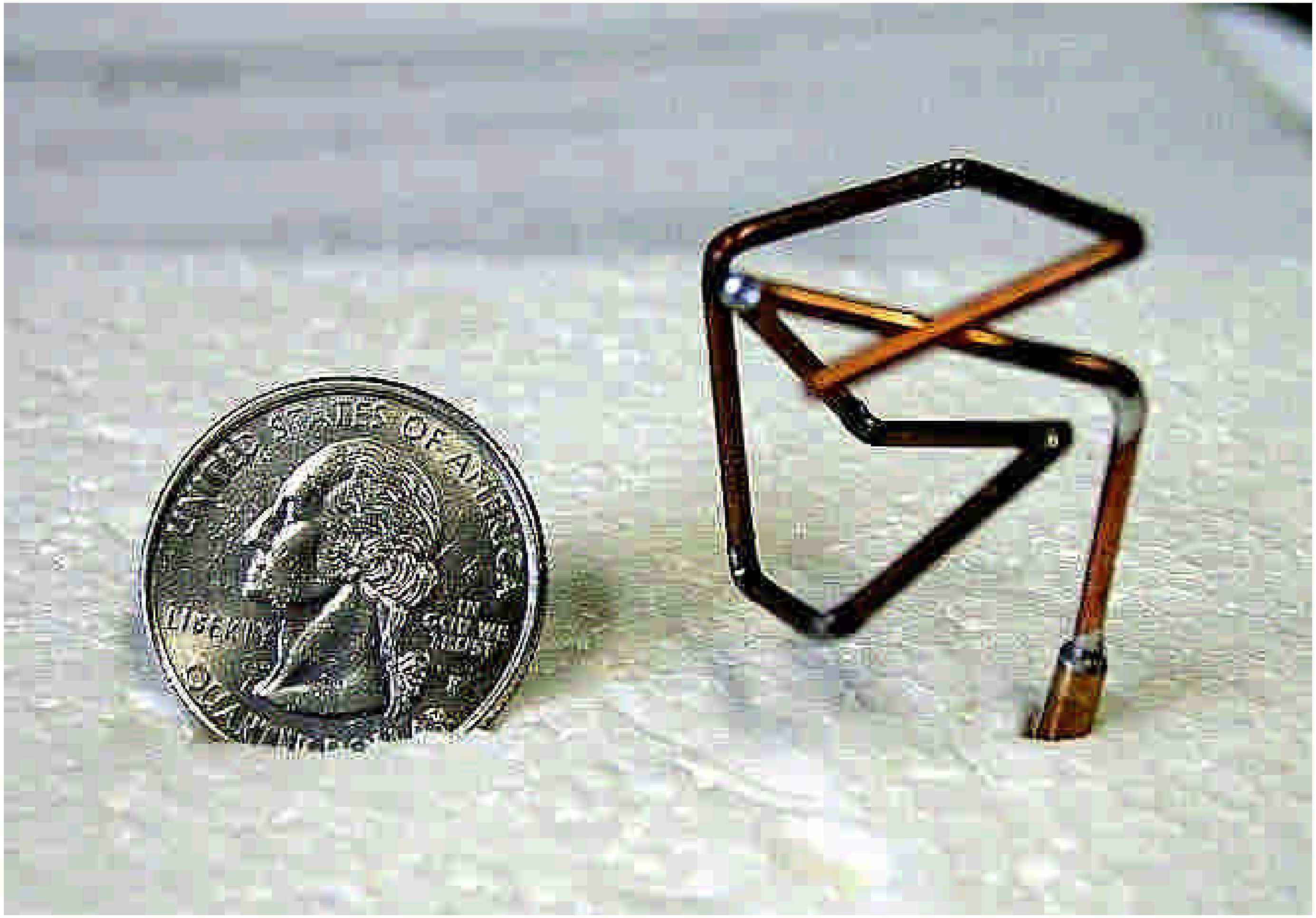
Courtesy of JEM Engineering

Loaded UWB Antenna for 1 to 15 GHz

SWR < 3 from 1 to 15 GHz

Courtesy of JEM Engineering

Air Force 10-Segment Resonant Antenna (0.03 λ)

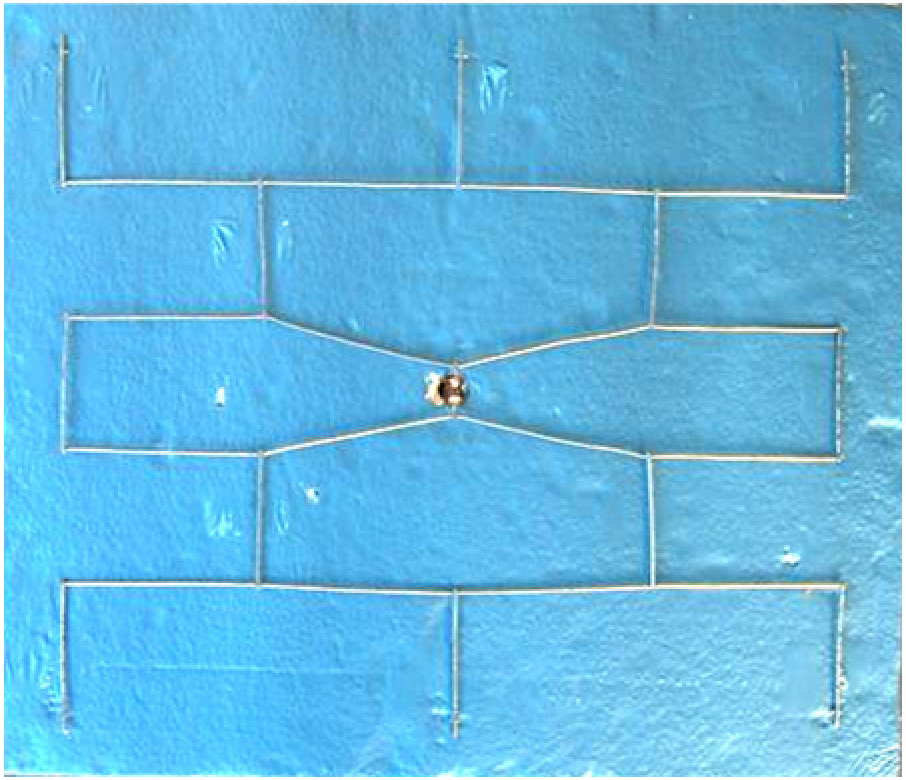


Courtesy of JEM Engineering

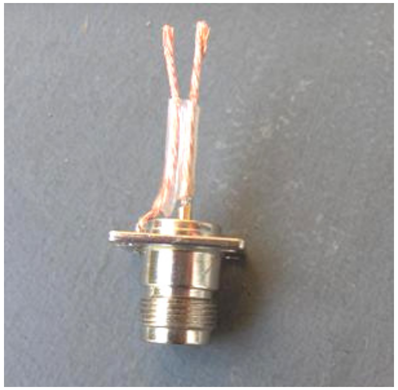
Inexpensive Curtain Quad Arrays

Courtesy of Ross Anderson, W1HBQ

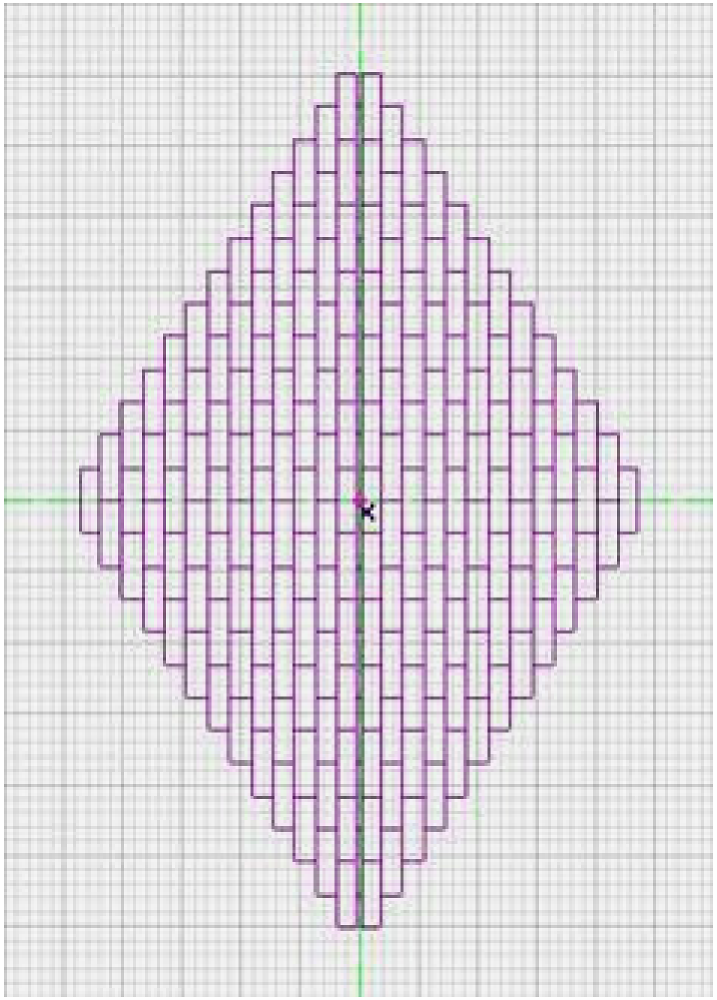
Ross Anderson W1HBQ's Curtain Quad for WiFi



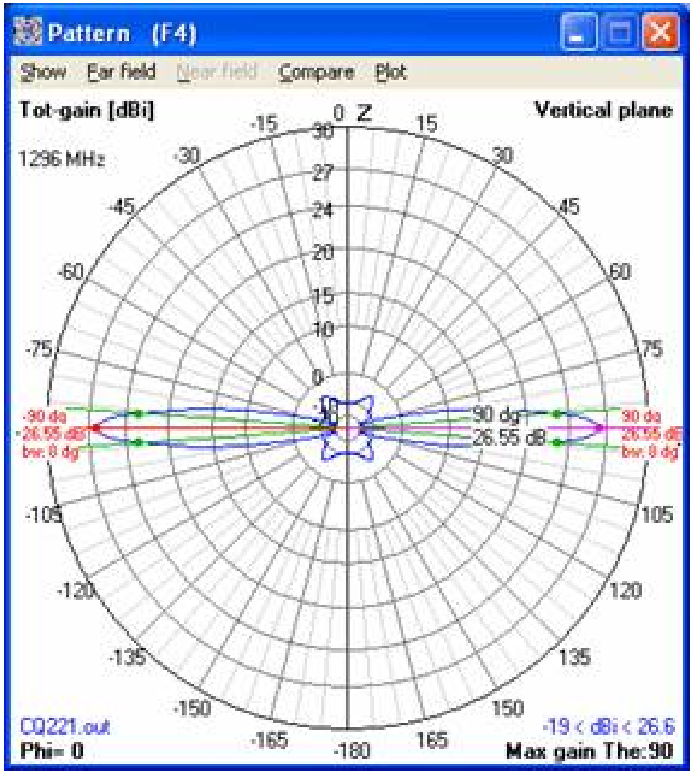
- Frequency 2.4 GHz IEEE 802.11
- Gain: 17 dBi
- Polarization: V (as shown)
- Material: 3 × 2 inch welded wire fence
- Wire: #16 steel wire, 0.031 in
- Backing: 1 inch foam board, backed with aluminum foil
- Feedpoint Z: 600 Ω
- Match device: ~1 in of 125 Ω speaker wire



W1HBQ's 221-Element Curtain Quad for 1296 MHz

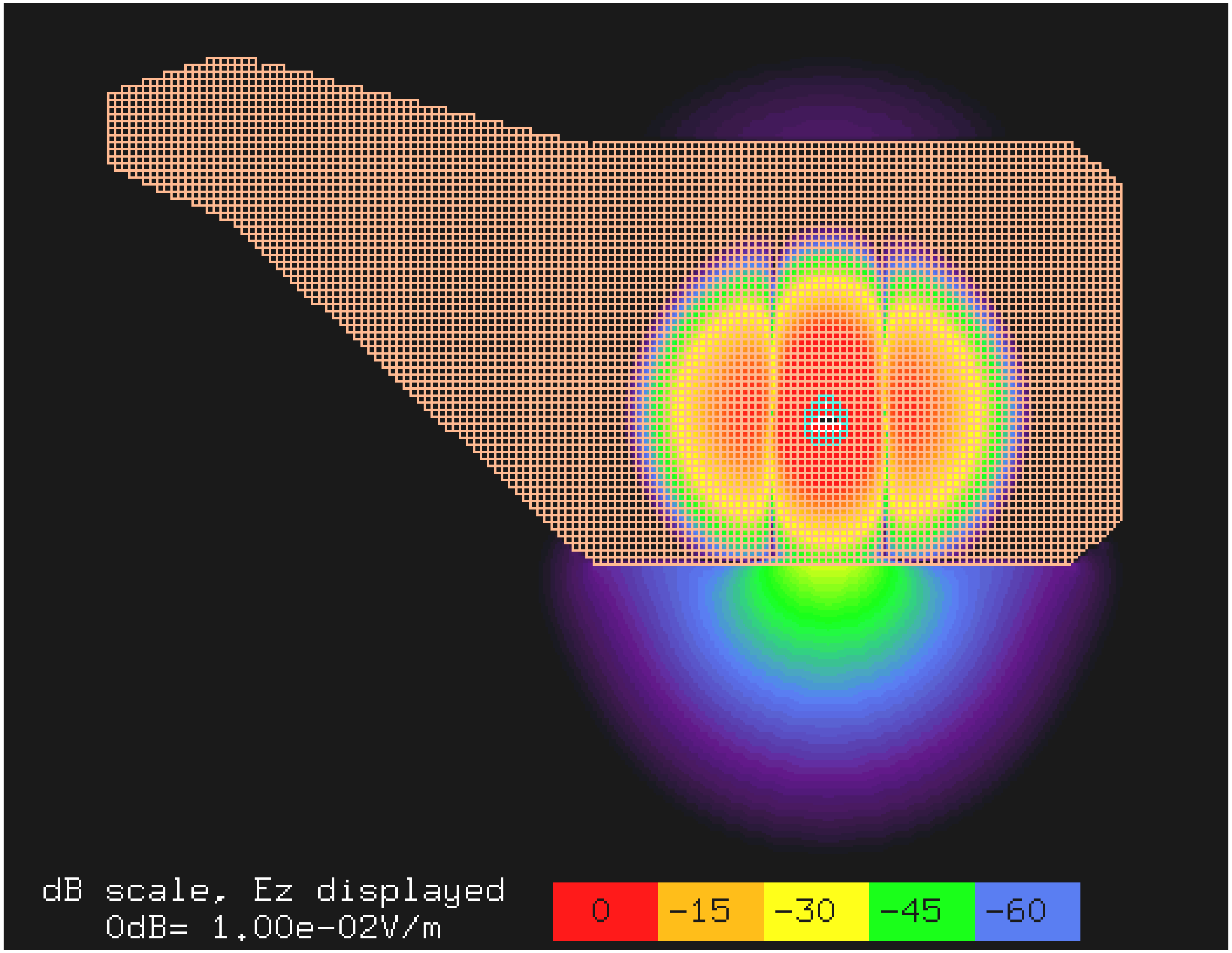


- Gain: 26 dBi
- Polarization: H (as shown)
- Feedpoint Z: 99 Ω

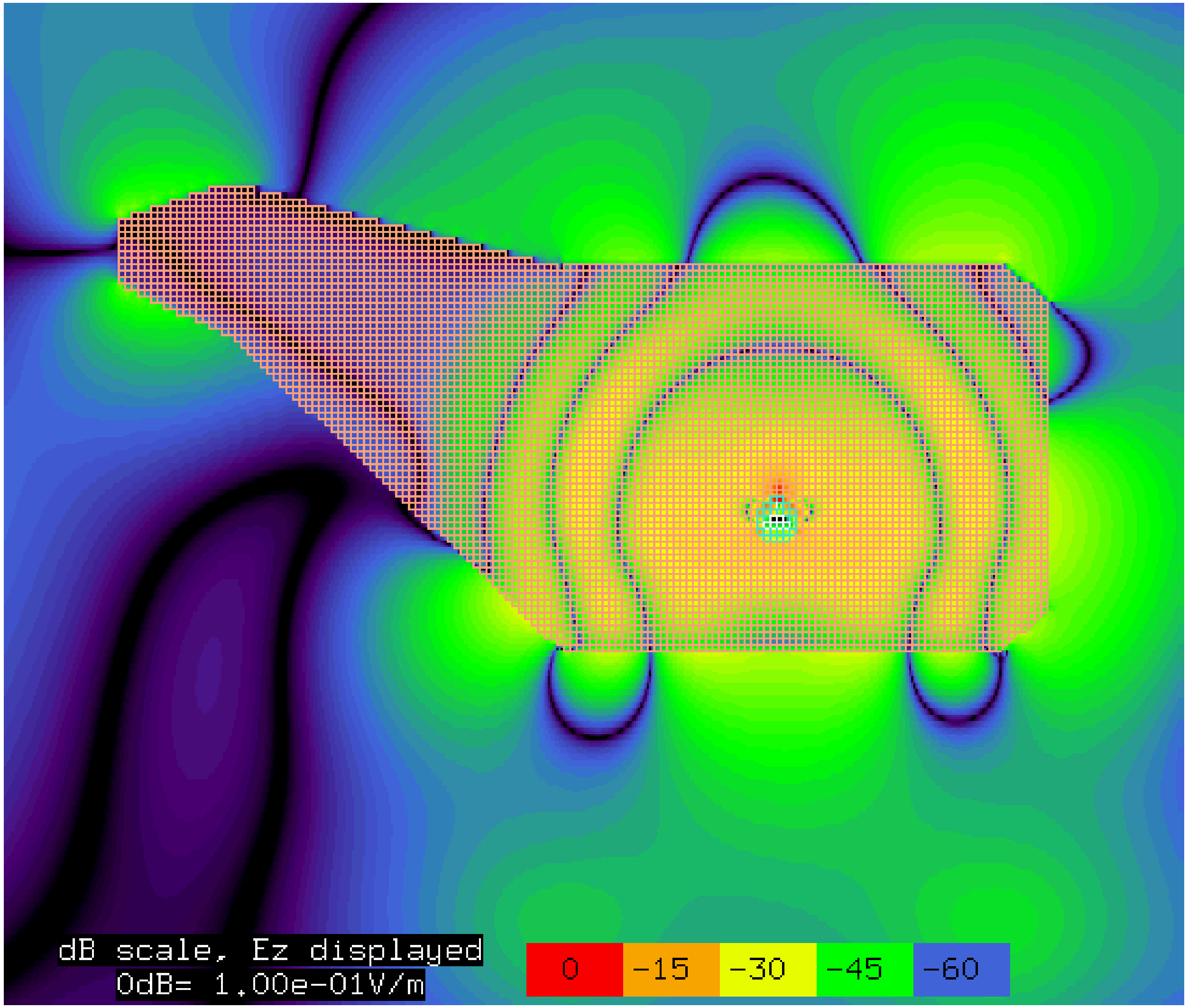


Metamaterial Radomes

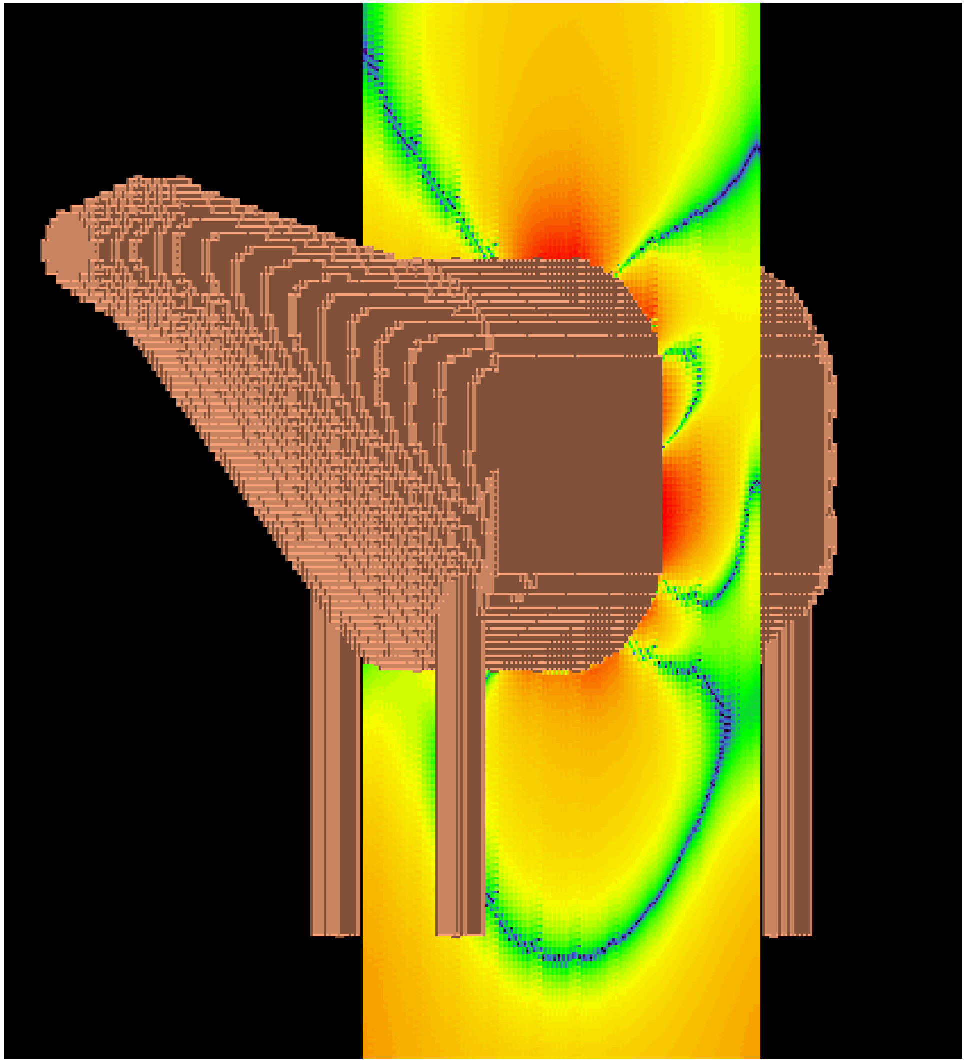
Transmitter Inside Cow



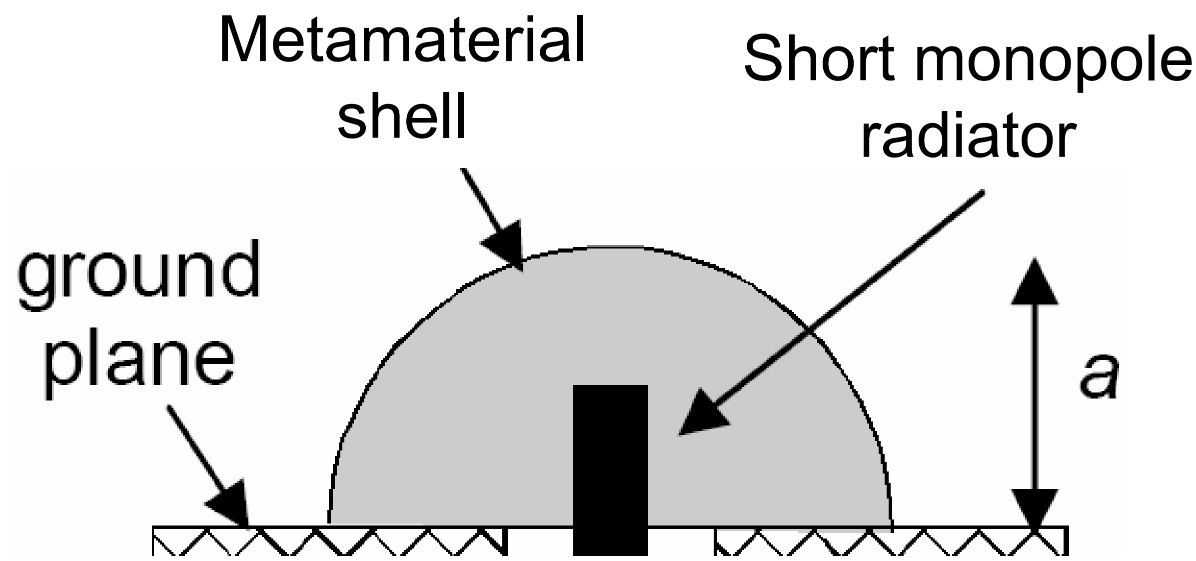
Performance of Cow Radome – Longitudinal Plane



Cow Radome – Transverse Plane

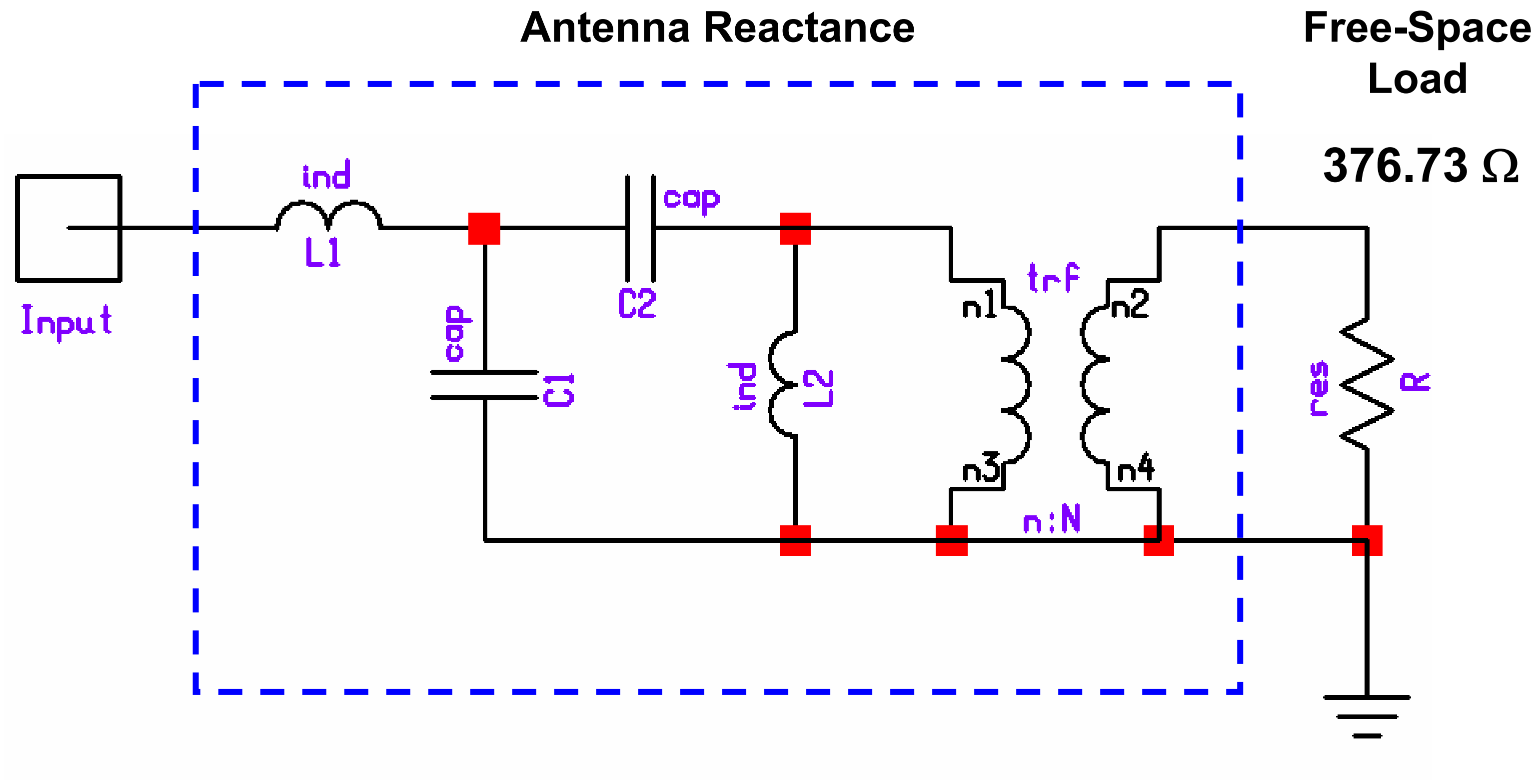


Bell Laboratories Monopole in Metamaterial Shell

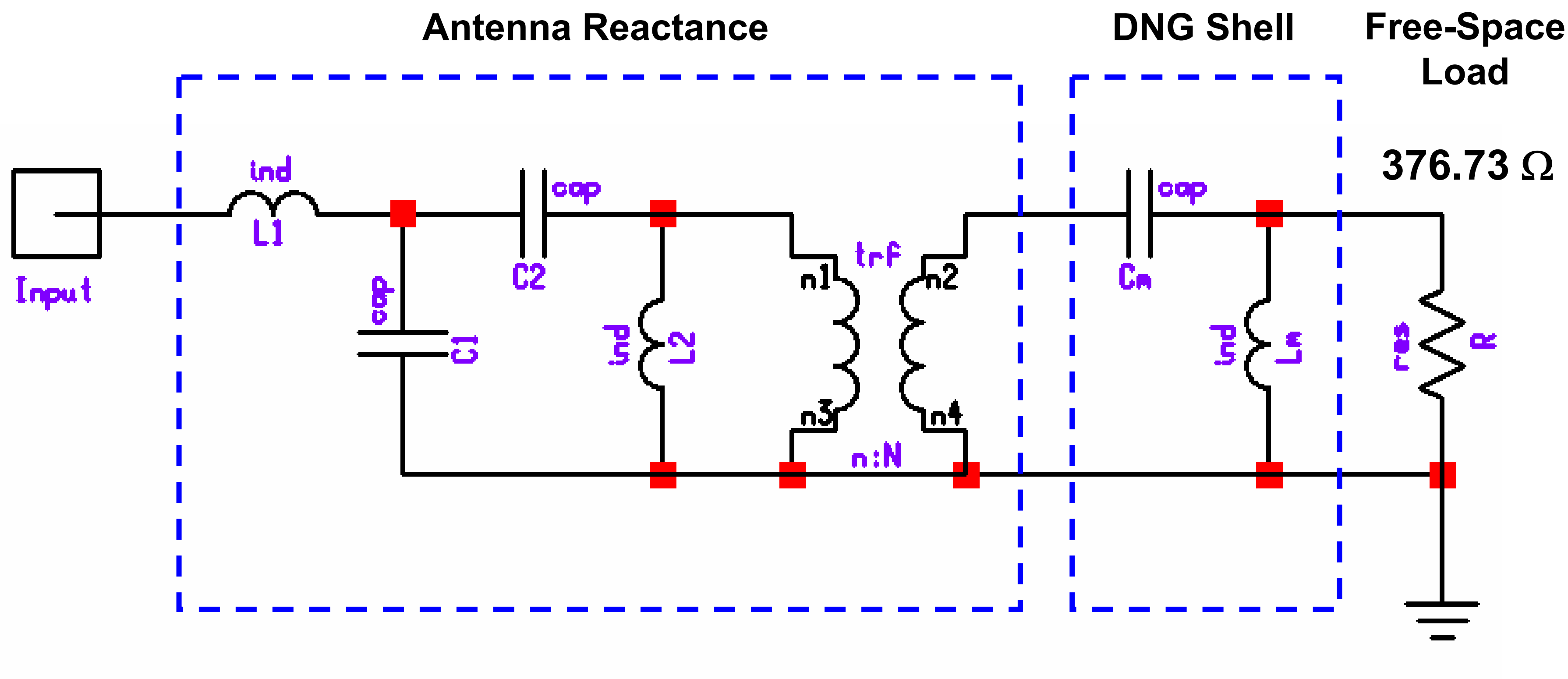


- Shell type: ENG
- Stub length: $\lambda/50$
- Shell radius: $\lambda/18.5$
- Frequency: 2.025 GHz
- Z: 50 ohms real
- VSWR: < 1.02
- Bandwidth: 4.76%
- Q_A: 42 (Q_{Chu} = 28.9)
- Polarization: vertical
- Efficiency: > 61%

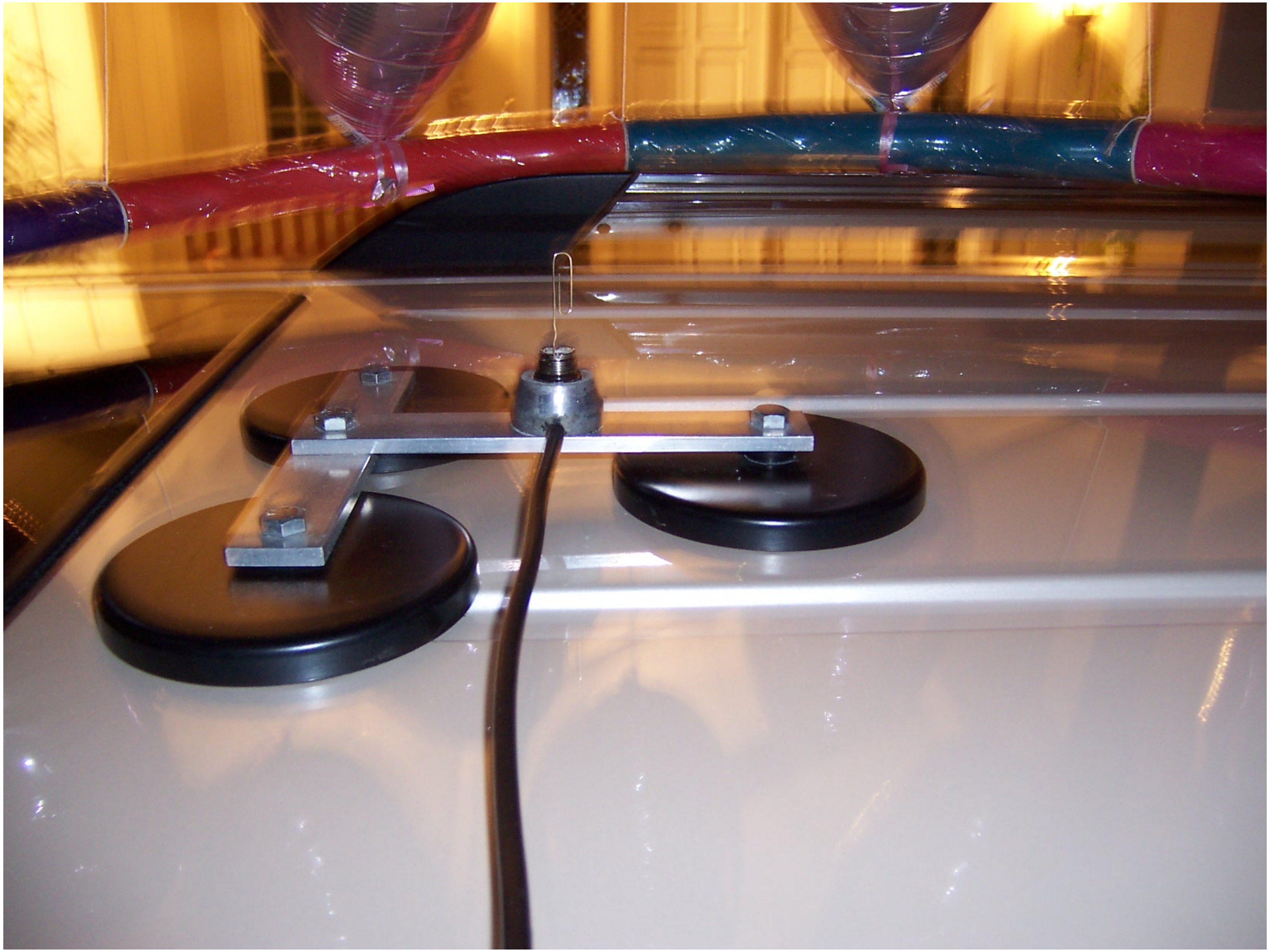
Two-Port Equivalent Circuit of Monopole Antenna



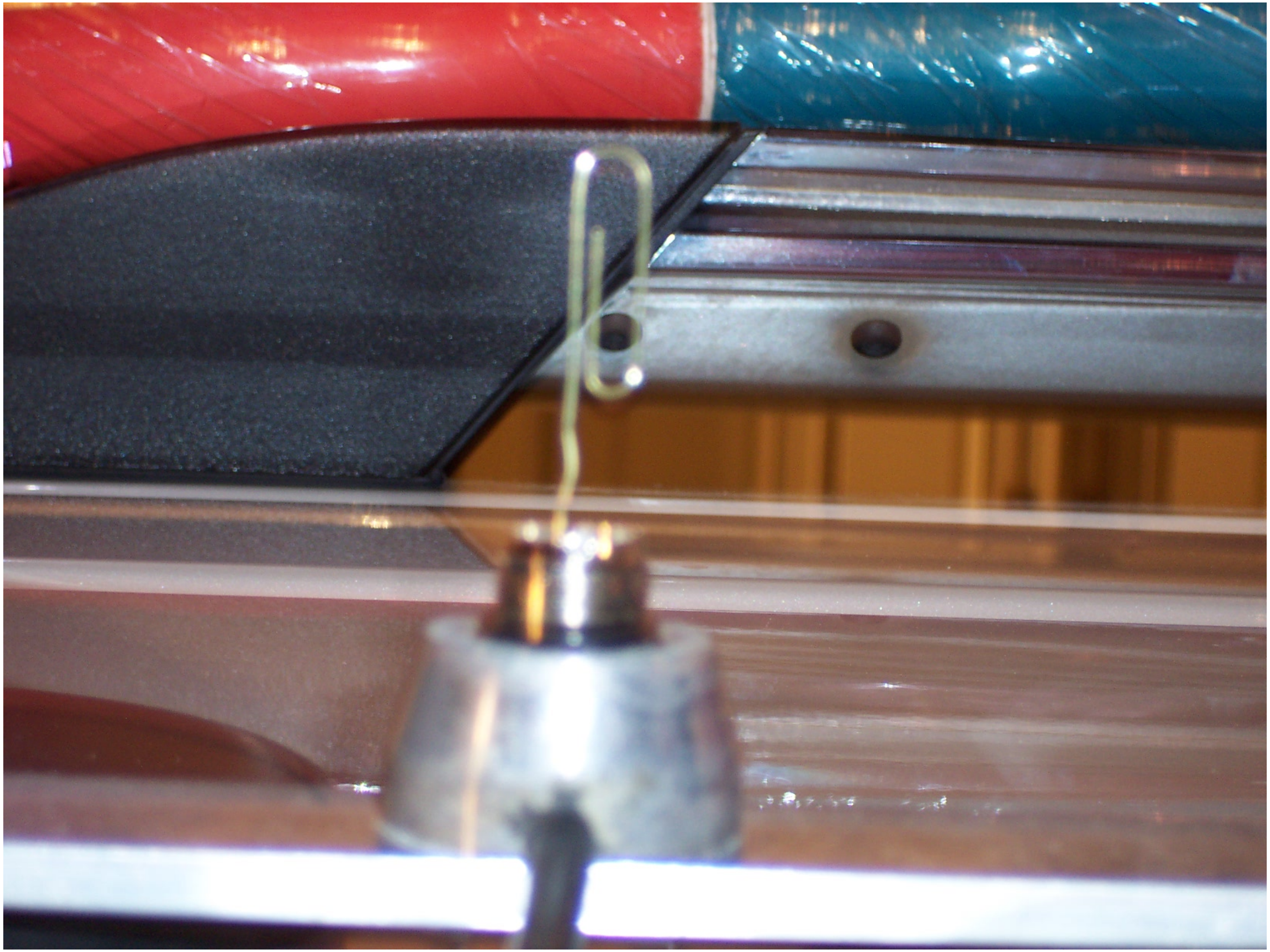
Monopole Space-Matched by Thin DNG Shell



K6OIK's Electrically-Small 2-Meter Antenna



Close Up View of the Radiator



Metamaterial Radome for Impedance Matching

Radome for Impedance Matching on 2 Meters

Analyzing Terrain Effects by Computational Electromagnetics

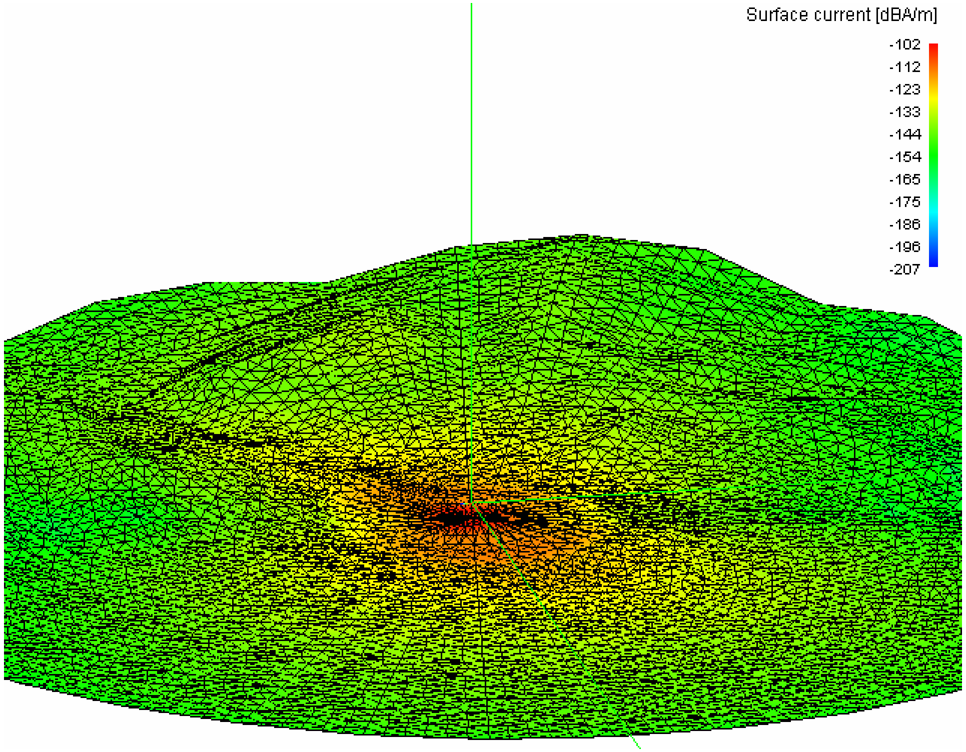
Meshing Silicon Valley

Courtesy of Keith Snyder, KI6BDR

Antenna Modeling Software for Radio Amateurs

- **EZNEC and EZNEC+ by Roy Lewallen, W7EL**
  - 500 and 1,500 segments respectively, $89 and $139
- **EZNEC-ARRL**
  - Included on *ARRL Antenna Book* CD, $45
- **MultiNEC by Dan Maguire, AC6LA, http://www.ac6la.com**
  - Low cost but currently unavailable
  - Puts EZNEC on autopilot for making a series of many runs
  - Doesn't work with EZNEC-ARRL
- **4nec2 by Arie Voors, http://home.ict.nl/~arivoors**
  - Free download
  - Runs under Windows 2000 and XP
  - Handles up to 11,000 segments
  - Optimizer included
- **Professional evaluation software**
  - FEKO LITE http://www.feko.info
  - WIPL-D Lite http://www.wipl-d.com

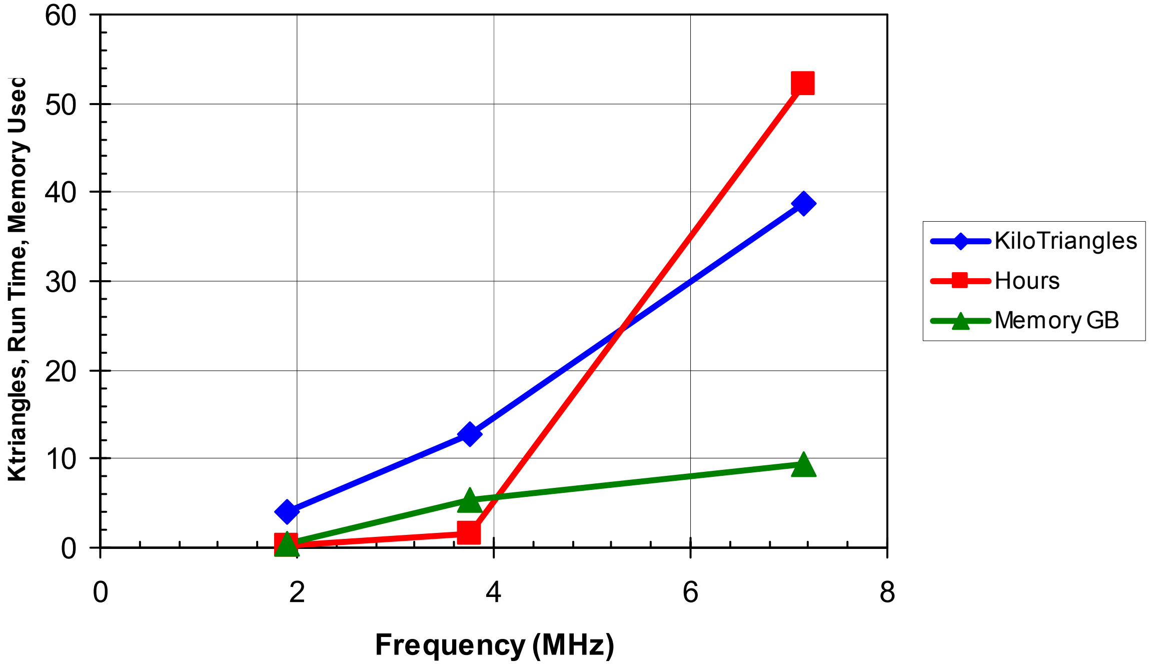
Earth Currents and Hills Looking South West



Computer Used For Antenna Design and Electromagnetic Systems Analysis

Description	6 Xi NetRAIDer network servers
Processors	12 AMD Opteron 64-bit
Memory	96 Gbytes
Disk storage	12 Tbytes
Compute speed	> 53 GFLOPs/sec

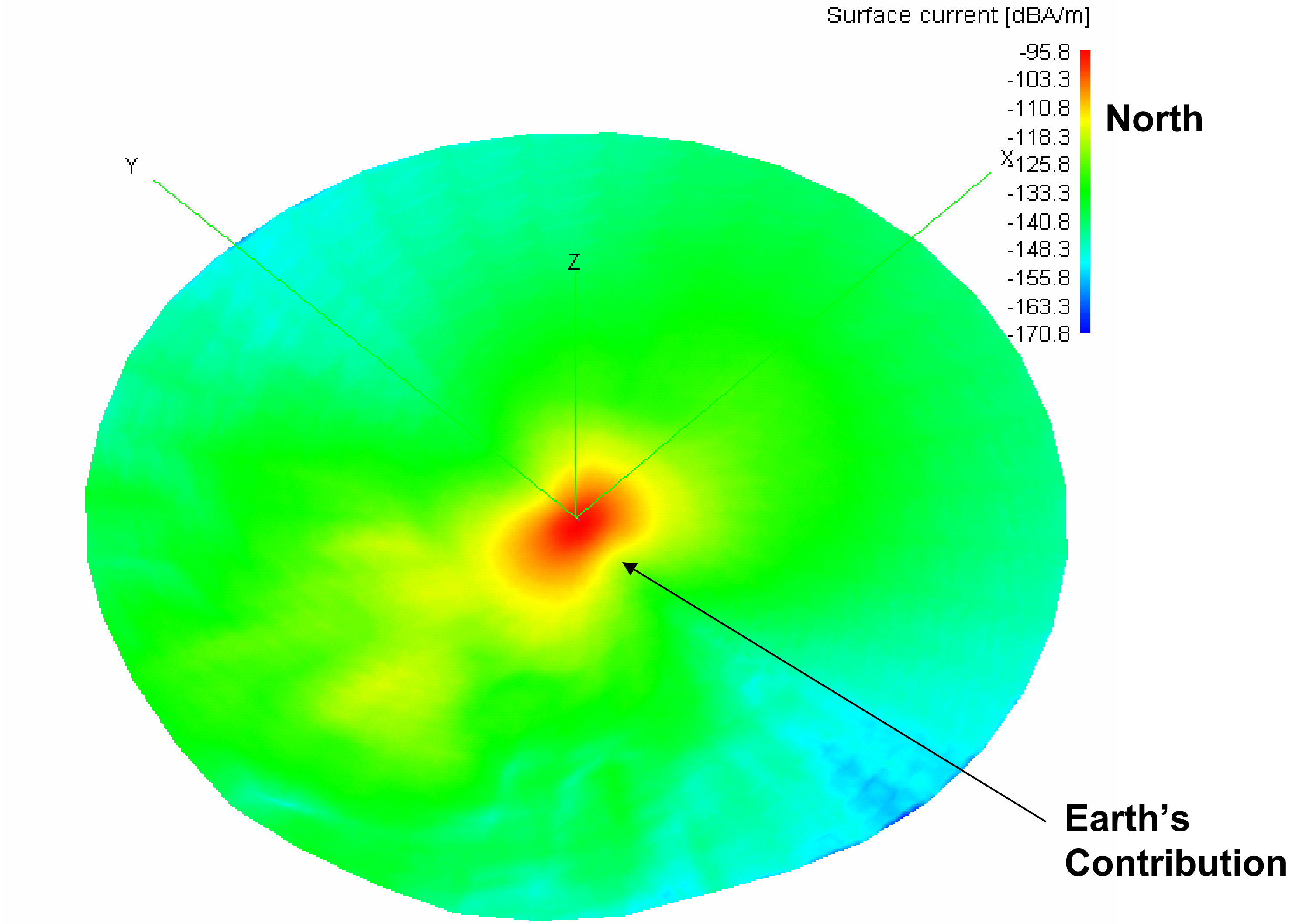
Required Computation



Frequency (kHz)	Triangles	Hours	Memory (GB)
1,900	3,928	0.125	0.53
3,750	12,834	1.54	5.48
7,150	38,717	52.1	9.38

Ground Currents

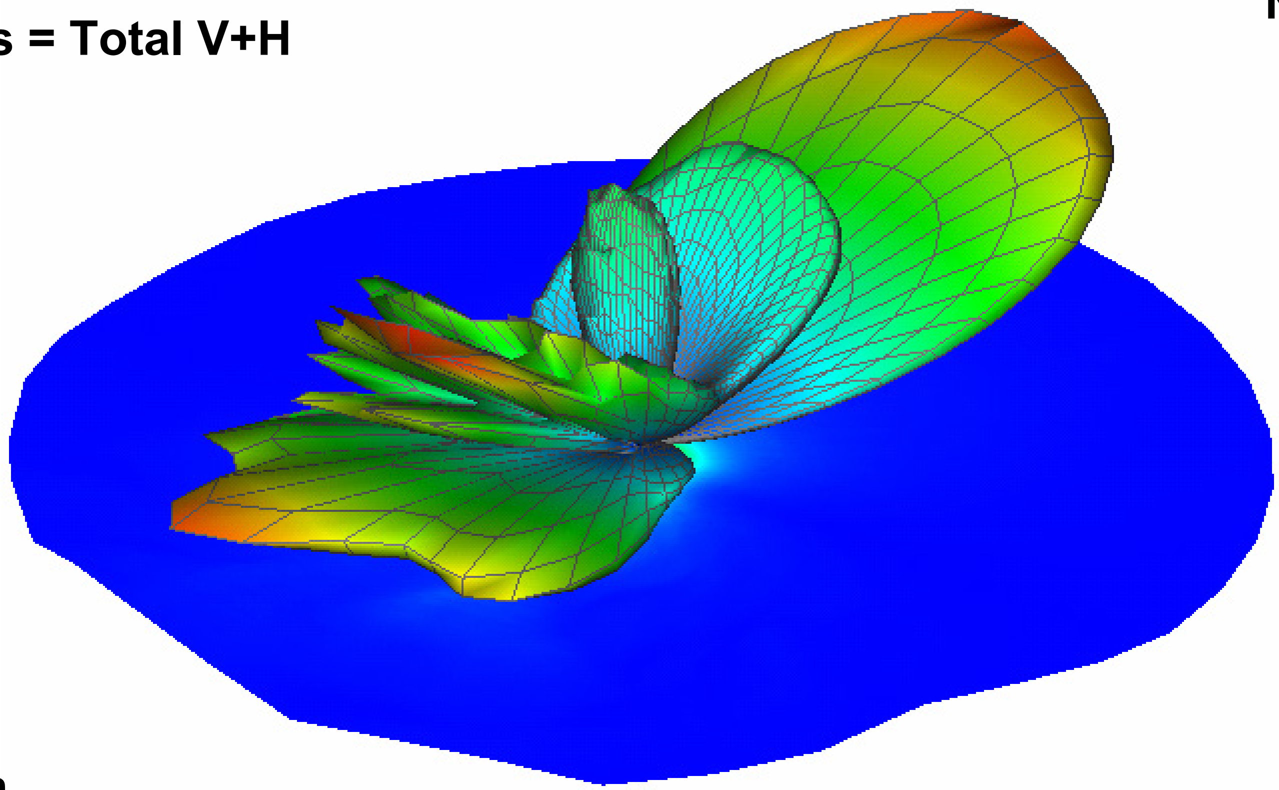
7.15 MHz Antenna Height = 50 m, Polarization = Horizontal



3D Antenna Pattern

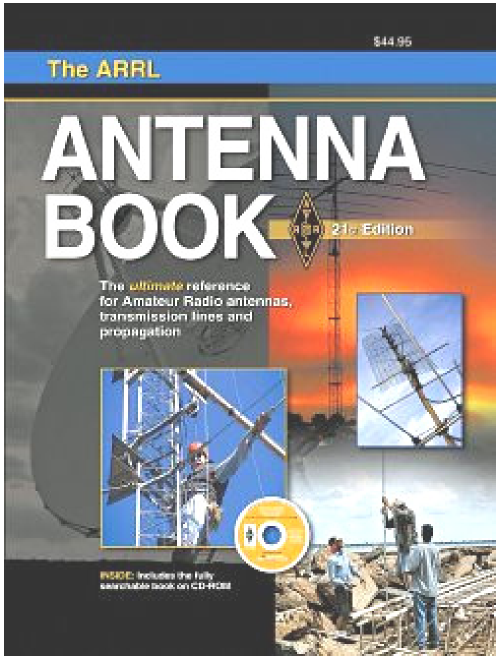
7.15 MHz
Antenna Height = 50 m
Polarization = Horizontal
Fields = Total V+H

North

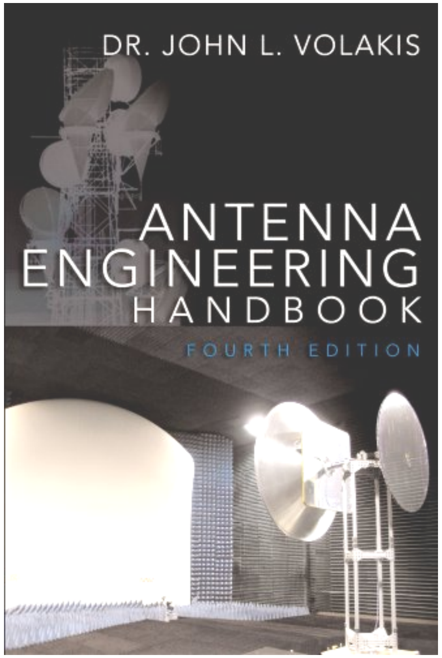


South

New Antenna Books for 2007

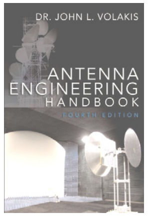


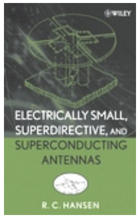
Amateur Reference

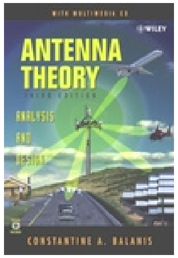


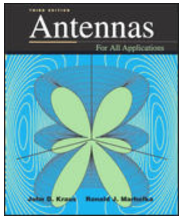
Engineering Reference

Favorite Antenna Books



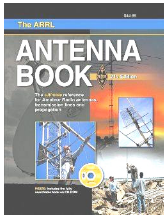


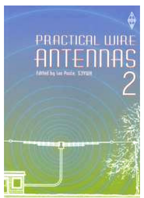


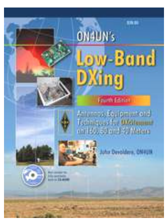


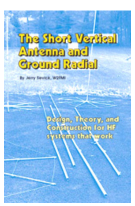
- **Books for antenna engineers and students**
  - *Antenna Engineering Handbook*, 4th ed., J.L. Volakis editor, McGraw-Hill, 2007, ISBN 0071475745. First published in 1961, Henry Jasik editor.
  - R.C. Hansen, *Electrically Small, Superdirective, and Superconducting Antennas*, Wiley, 2006, ISBN 0471782556.
  - C.A. Balanis, *Antenna Theory*, 3rd ed., Wiley, 2005, ISBN 047166782X. First published in 1982 by Harper & Row.
  - J.D. Kraus and R.J. Marhefka, *Antennas*, 3rd ed., McGraw-Hill, 2001, ISBN 0072321032. First published in 1950.
  - S.J. Orfanidis, *Electromagnetic Waves and Antennas*, draft textbook online at http://www.ece.rutgers.edu/~orfanidi/ewa/
  - E.A. Laport, *Radio Antenna Engineering*, McGraw-Hill, 1952. http://snulbug.mtview.ca.us/books/RadioAntennaEngineering
- **Antenna research papers**
  - IEEE AP-S Digital Archive, 1952-2000 (2 DVDs), JD0351.
  - IEEE AP-S Digital Archive, 2001-2003 (1 DVD), JD0301.

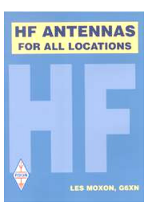
Favorite Antenna Books continued



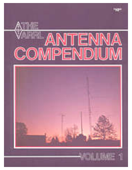


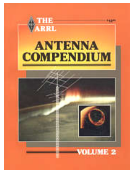


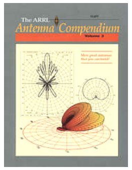


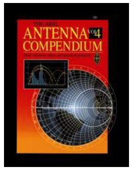


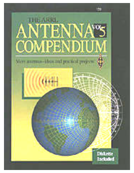
- **Books for radio amateurs**
  - *ARRL Antenna Book*, 21st ed., Dean Straw (N6BV) editor, American Radio Relay League, 2007, ISBN 0872599876.
  - *Practical Wire Antennas 2*, Ian Poole (G3YWX) editor, Radio Society of Great Britain, 2005, ISBN 1905086040.
  - J. Devoldere (ON4UN), *ON4UN's Low-Band Dxing*, 4th ed., American Radio Relay League, 2005, ISBN 0872599140.
  - J. Sevick (W2FMI), *The Short Vertical Antenna and Ground Radial*, CQ Communications, 2003, ISBN 0943016223.
  - L. Moxon (G6XN), *HF Antennas for All Locations*, 2nd ed., Radio Society of Great Britain, 1983, ISBN 1872309151.
- **ARRL Antenna Compendium series – Volumes 1 through 7**

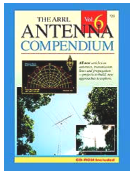


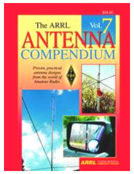




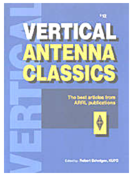


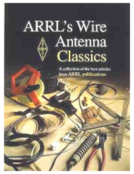


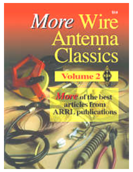


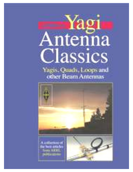


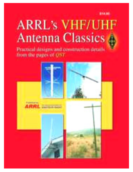
- **ARRL Antenna Classics series – five titles**











The End

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