Novel and Strange Ideas in Antennas and Impedance Matching

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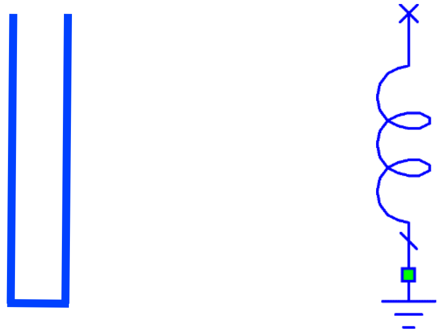
Outline

- **Ultimate terrain analysis – meshing Silicon Valley**
- **Antenna impedance models**
- **Fundamental limits**
- **Interesting impedance-matching methods**
  - Constant resistance networks
  - Active bilateral non-prf networks
- **Interesting antennas**
  - Antennas having curved elements
  - Antennas not made of metal
  - Stealth antennas
  - Non-stealth antennas
  - Antennas having extreme bandwidths
  - Antennas matched on the “space” side
- **The strange story of backward waves and metamaterials**
- **The final frontier – electromagnetic cloaking**

Antenna Questions for 2006

- **Q1: Consider the TL stub match of a J-pole or the tapped base-loading coil of a short monopole**

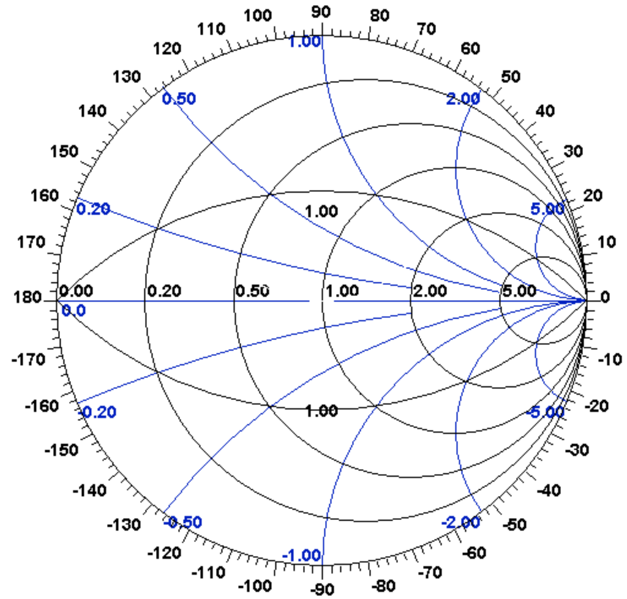


If the impedance is high at one end and zero at the other, then there is a 50-ohm match point somewhere along the line or coil. True or False?

- **Q2: If an the impedance of an antenna is inductive (positive reactance) on one side of resonance, then it is capacitive (negative reactance) on the other side of resonance. True or False?**

Answer to Q1

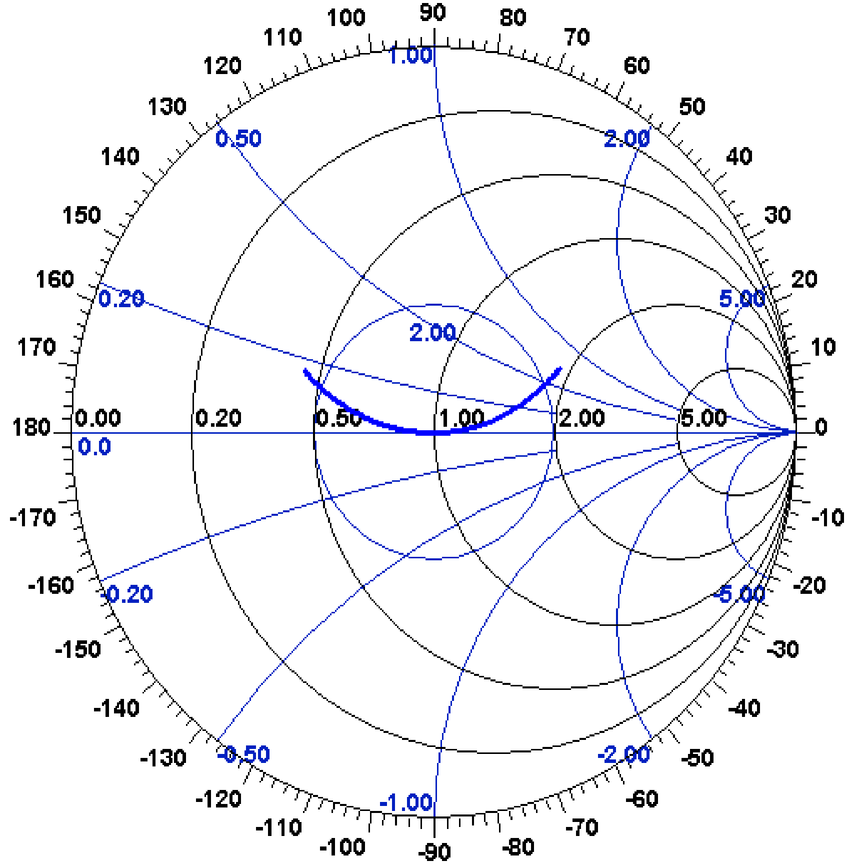
- False. There are many paths on the Smith Chart between zero and infinity that do not pass through the point in the center (50 + *j*0).



- The statement is an incorrect application of the Intermediate Value Theorem of Calculus, which applies only to real-valued continuous functions.

Answer to Q2

- **False. The feedpoint impedance of a correctly matched J-pole is inductive on both sides of its resonant frequency.**

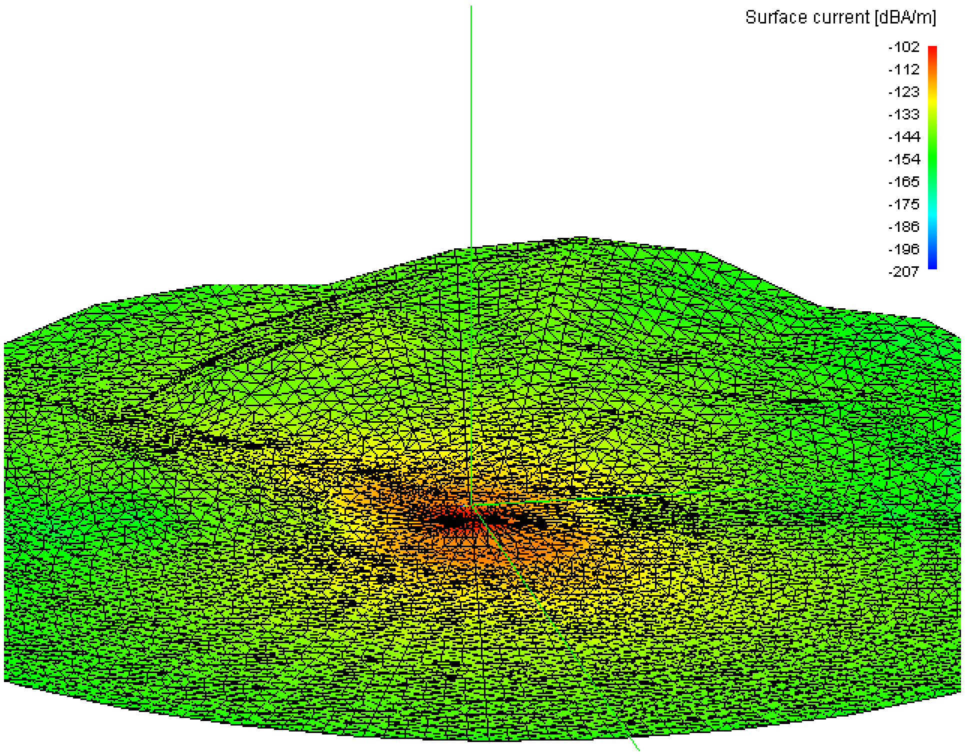


Meshing Silicon Valley

Terrain Effects

courtesy Keith Snyder, KI6BDR

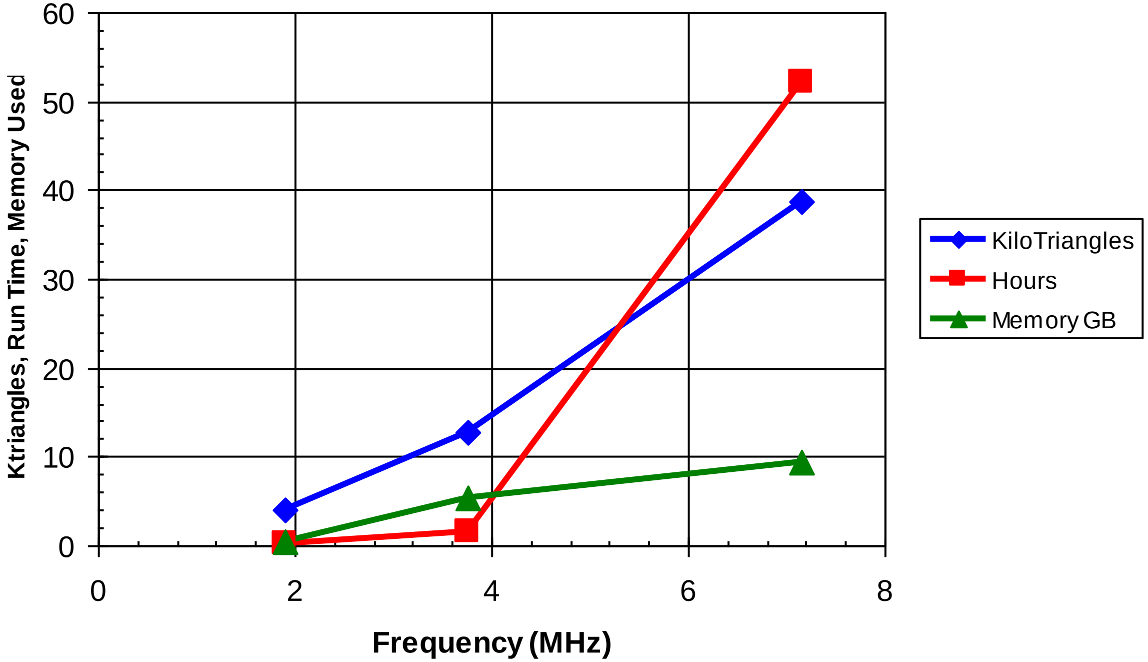
Earth Currents and Hills Looking South West



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

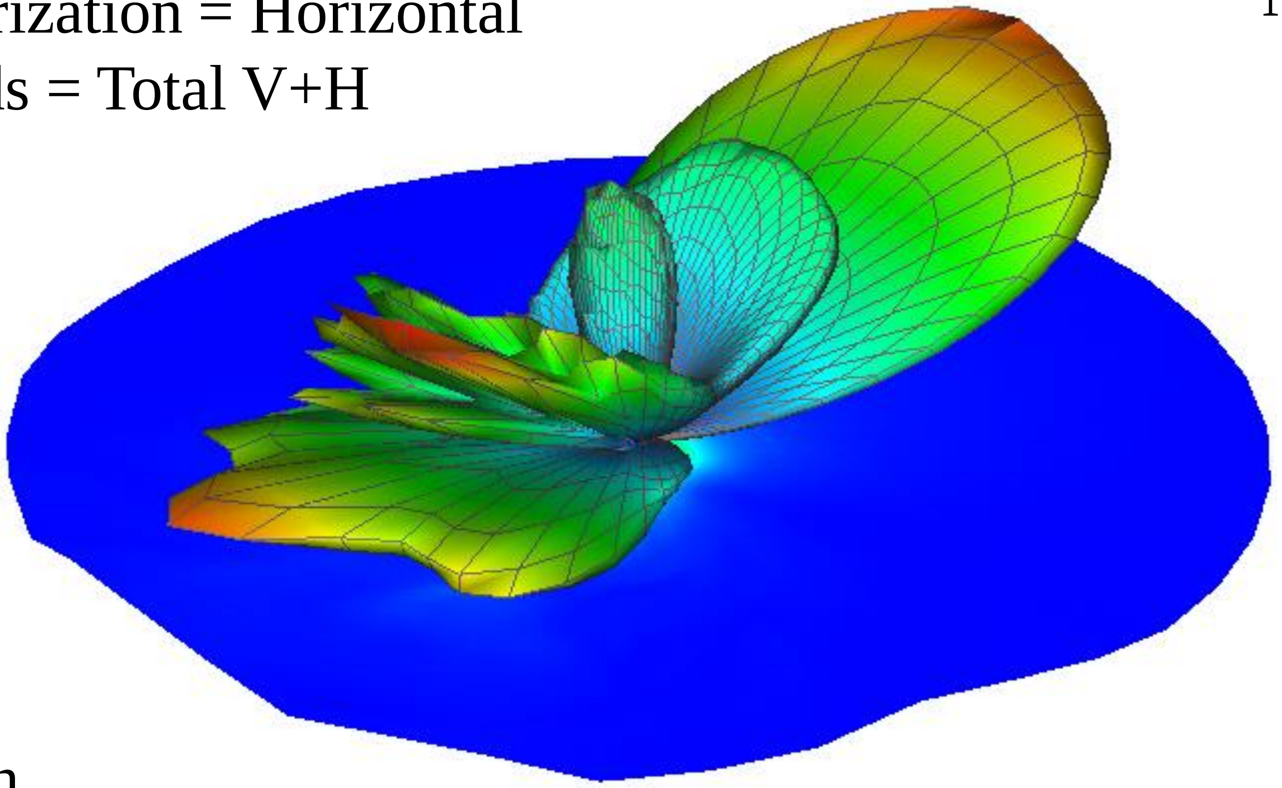


Frequency (kHz)	Triangles	Hours	Memory (GB)
1,900	3,928	0.125	0.53
3,750	12,834	1.54	5.48
7,150	38,717	52.1	9.38

3D Antenna Pattern

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

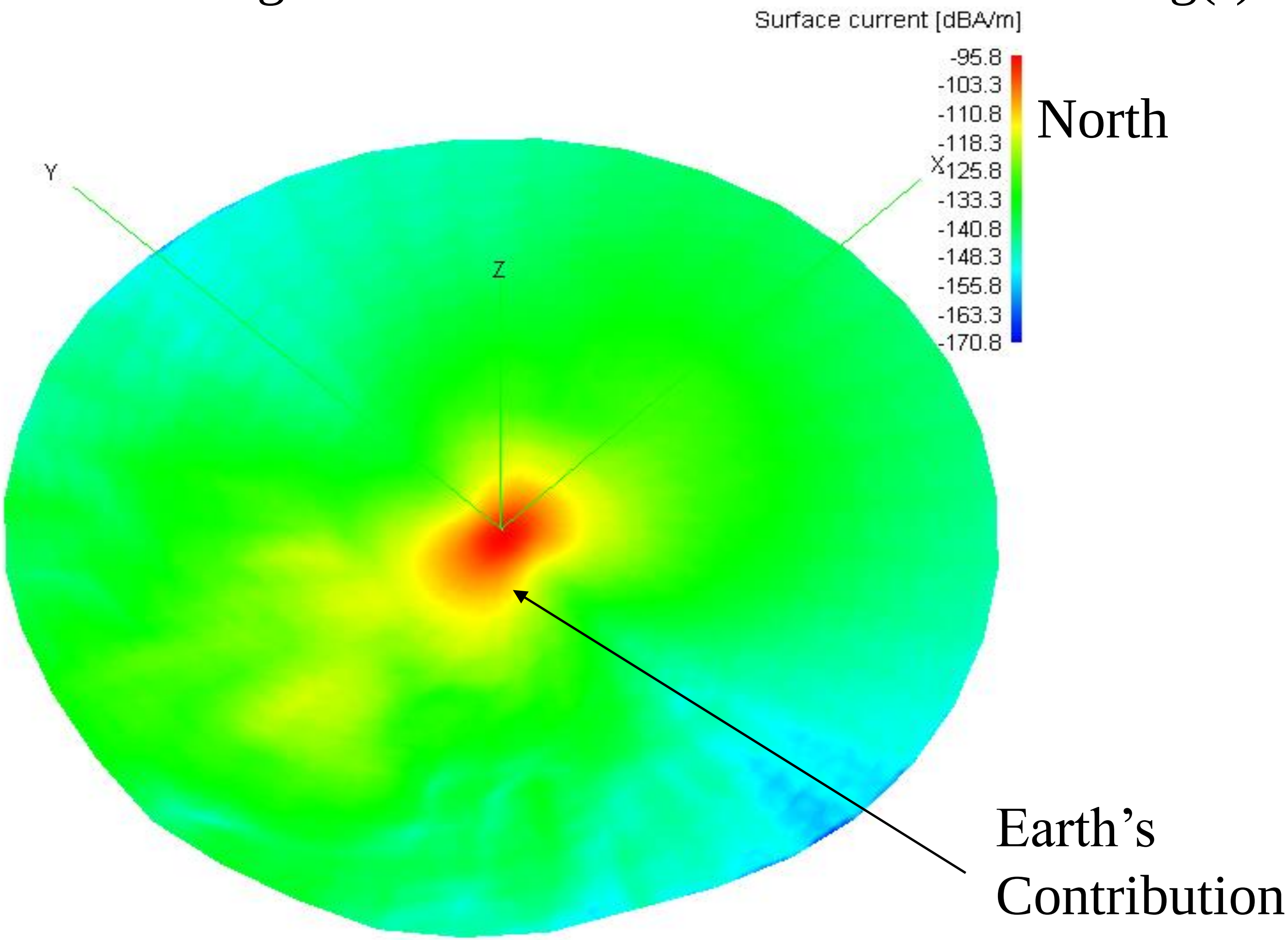
North



South

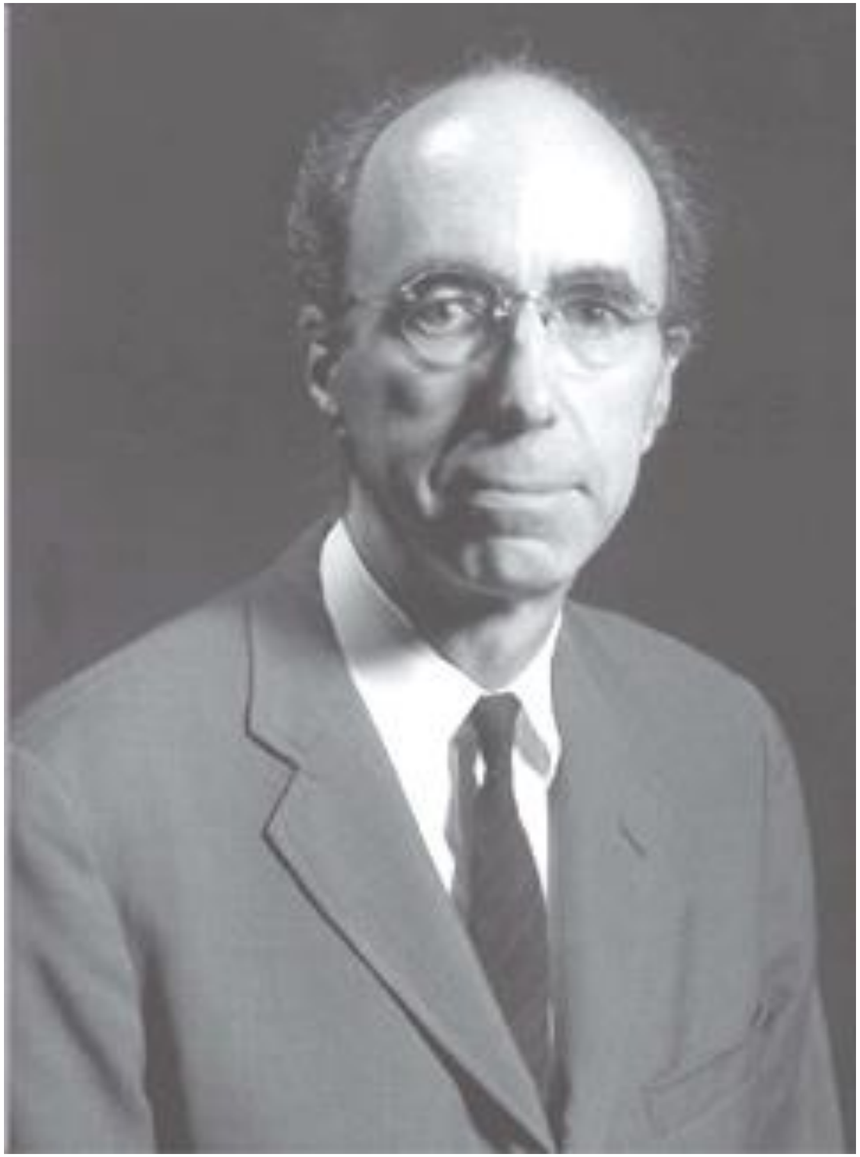
Ground Currents

7.15 MHz Antenna Height = 50 m Polarization = Horizontal Log(I)



Antenna Impedance Models

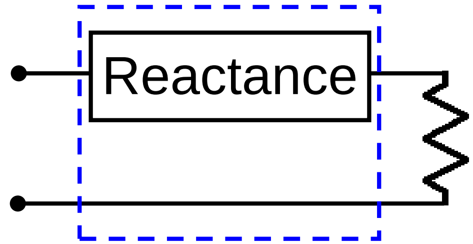
Sidney Darlington, 1906-1997



Darlington Forms (1939)

- **Every immittance function can be realized as a lossless two-port terminated by a resistor**
- **A resistor in series or shunt with a lossless one-port lacks generality – antennas don't act like this**

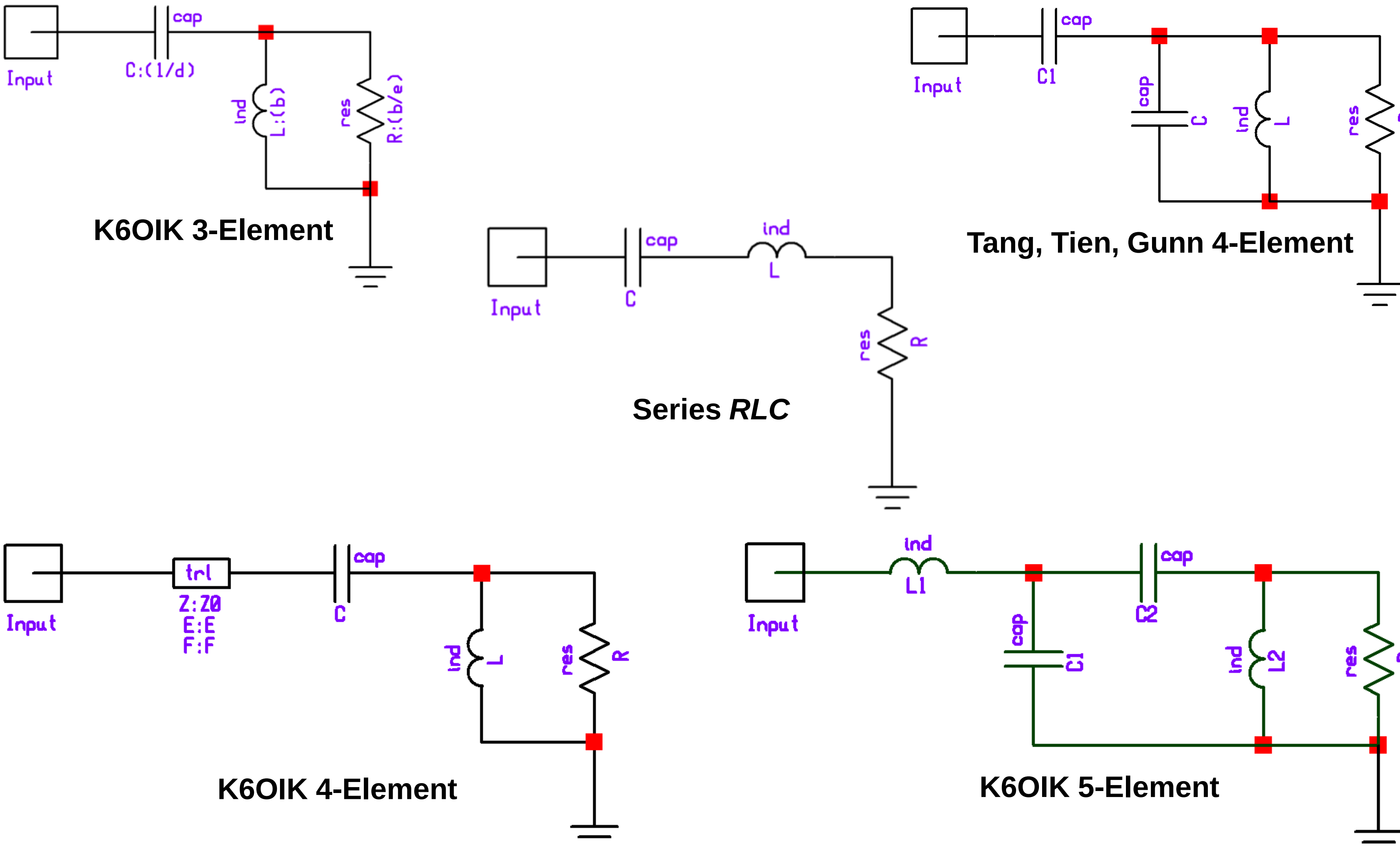
This……



Not This!

- **Every antenna impedance function has an equivalent circuit in Darlington form**
- **The Darlington form is the starting point for understanding the Fano bound on impedance matching**

Impedance Models for Small Dipoles & Monopoles



K6OIK 3-Element

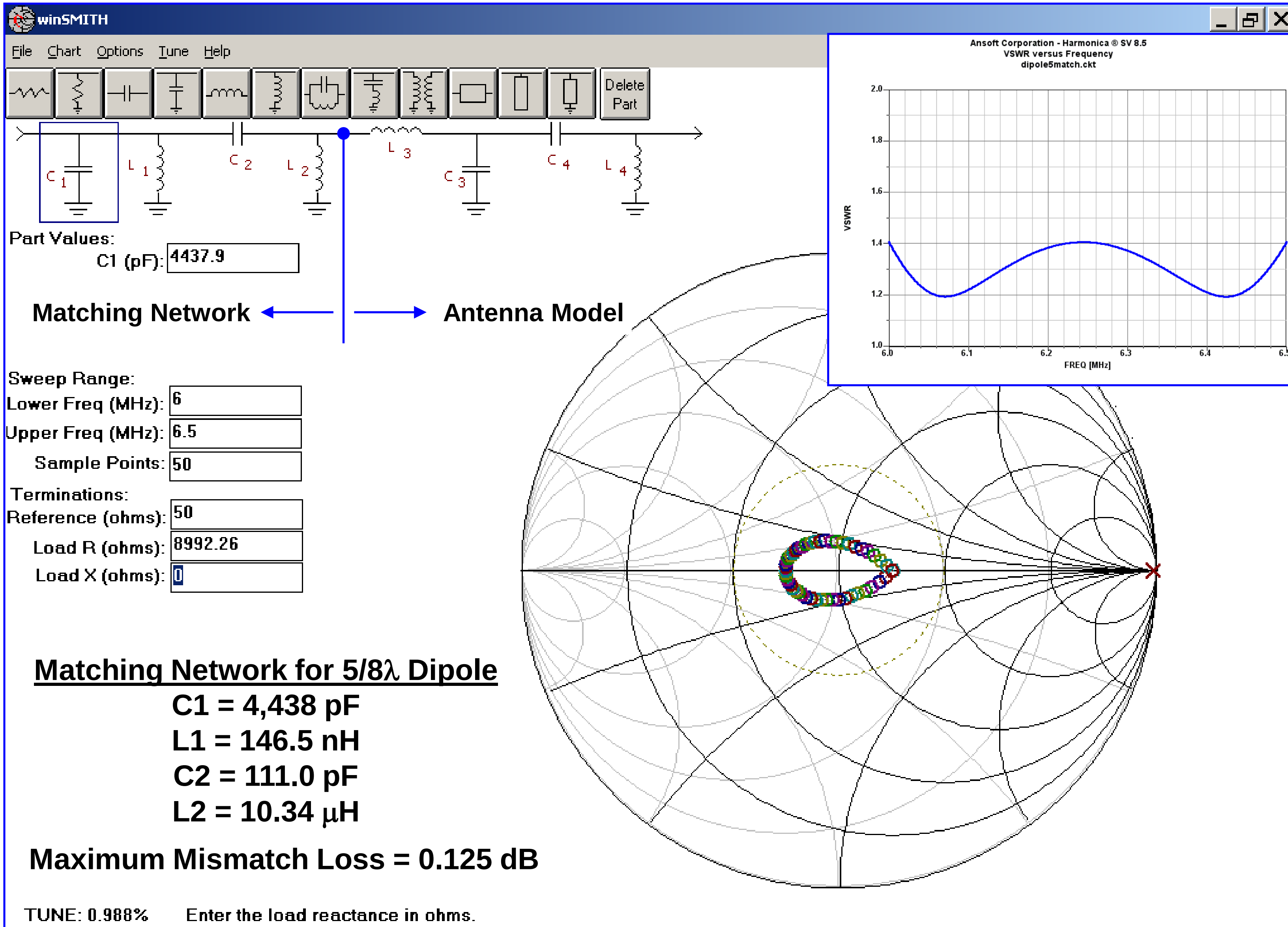
Tang, Tien, Gunn 4-Element

Series *RLC*

K6OIK 4-Element

K6OIK 5-Element

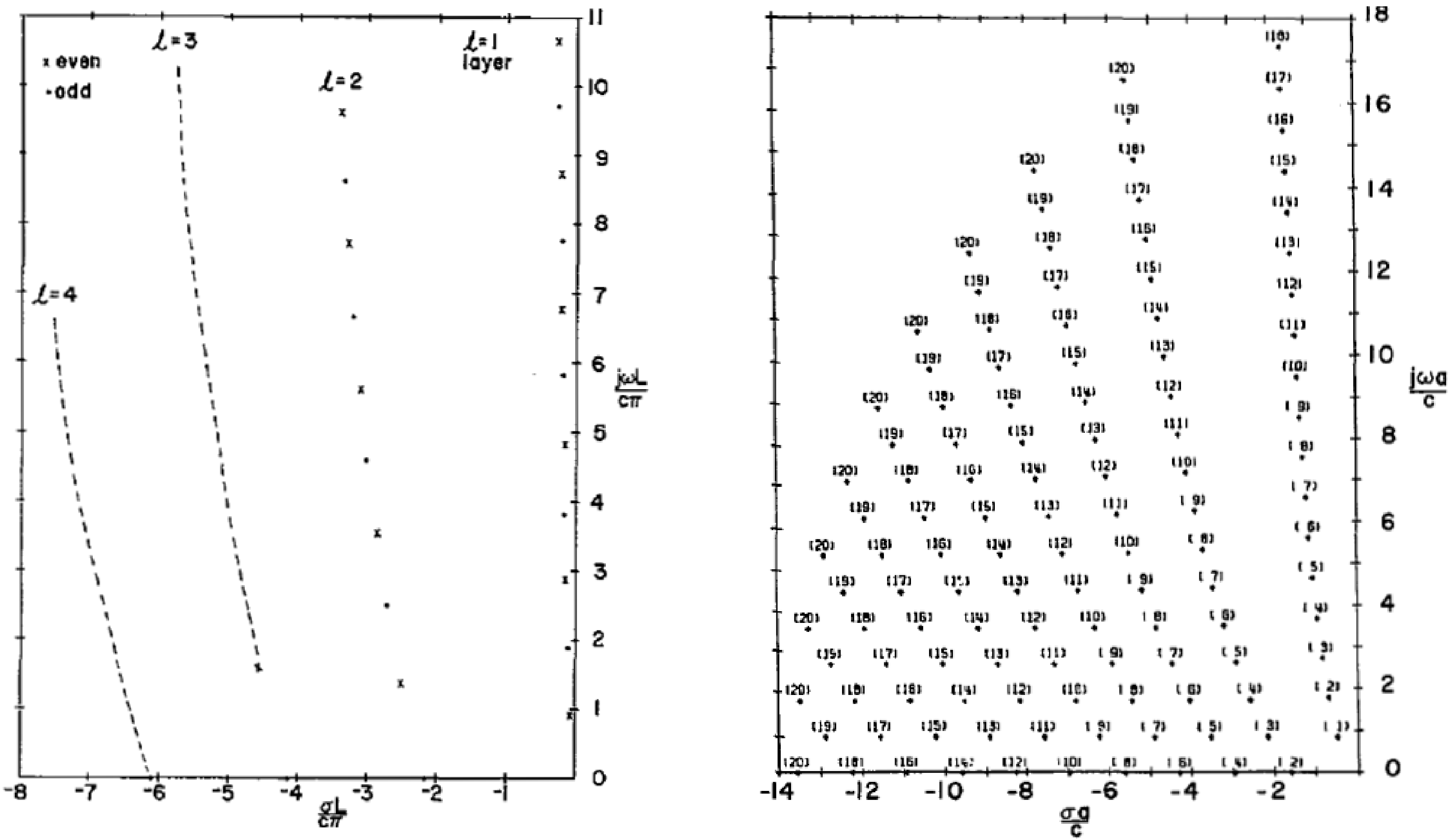
Matching Network Design in winSMITH
5/8λ Dipole, Gain = 0.25 dBd, Bandwidth = 8%, VSWR < 1.41



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
Hamid-Hamid and Rambabu et al.	poor	yes	no	*R*, *L*, *C*	no limit
Fosters 2nd Form with small losses	fair, best near resonances	yes	no	*R*, *L*, *C*	no limit
Long-Werner-Werner	fair	no	no	*R*, *C*, TL	5 octaves
Streable-Pearson	excellent	yes	no	*R*, *L*, *C*	no limit

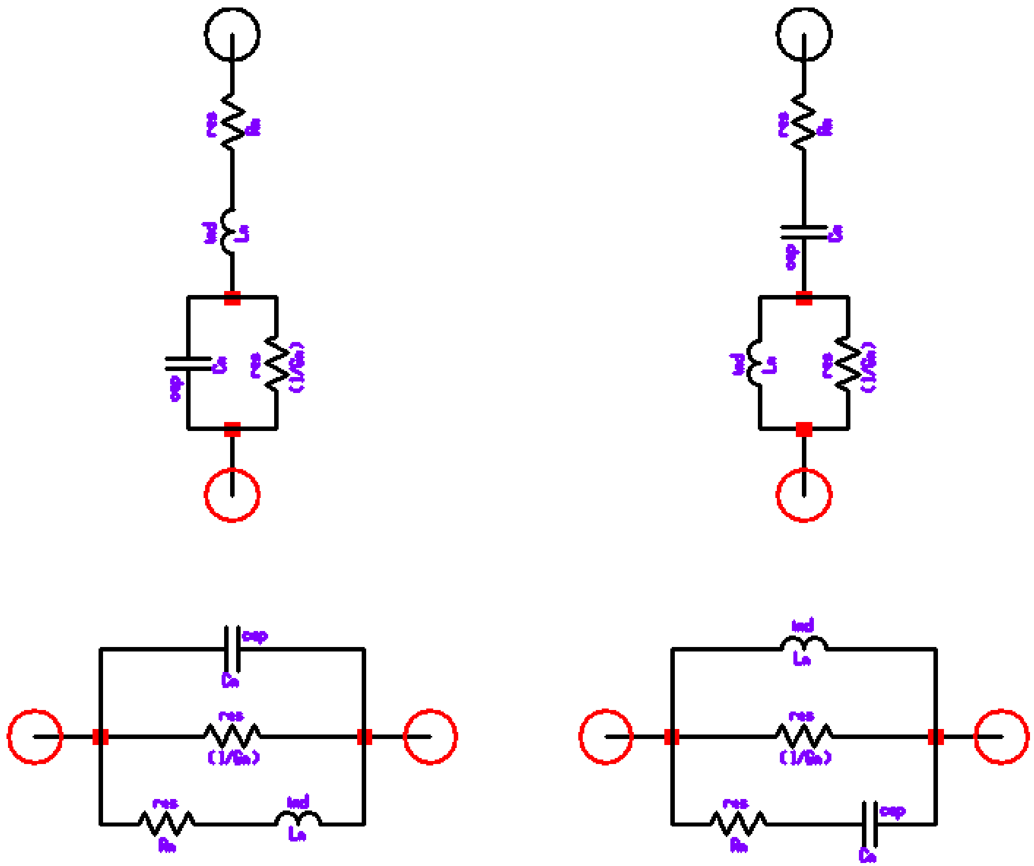
Tesche (1973) Antenna TM Modes by SEM



- **Distributed and electromagnetic systems are infinite-dimensional linear systems**

Synthesizing Transcendental Immittances

- **Zinn (1952) showed only four forms are needed to expand *f*(*s*) into series or shunt ladder form, the choice depending on *f*(0)**



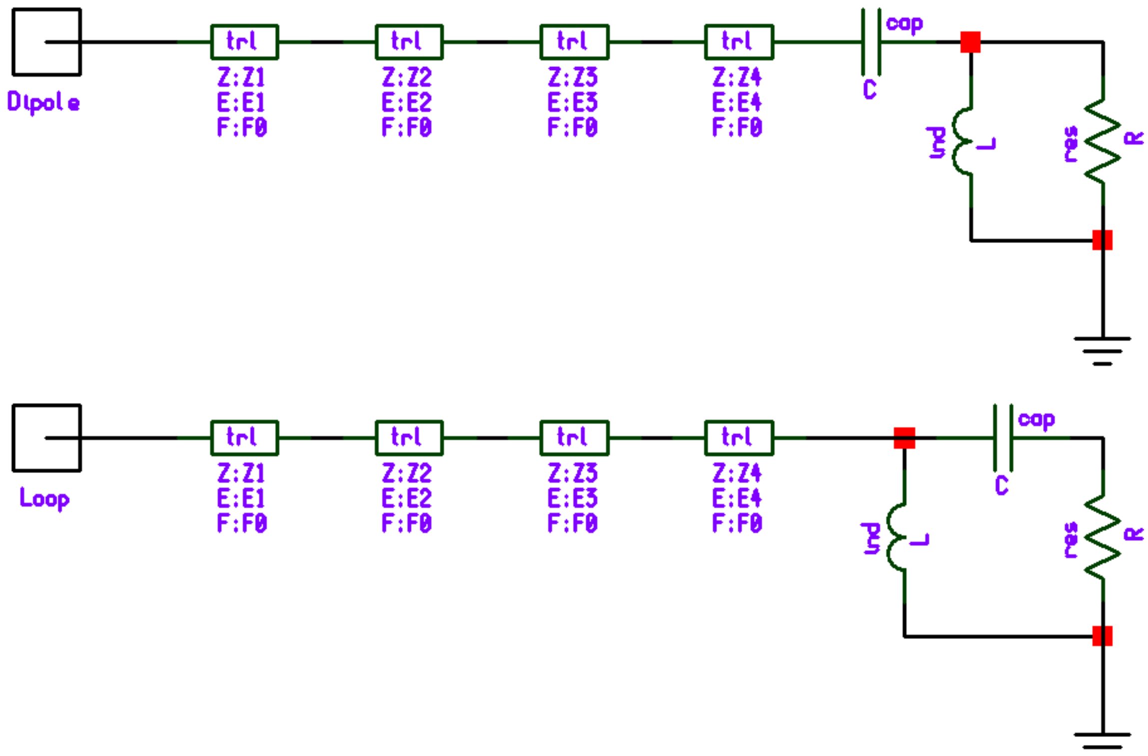
Ronold Wyeth Percival King, 1905-2006

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

Sergei Alexander Schelkunoff, 1897-1992

Schelkunoff's Universal Antenna Impedance Models

- Schelkunoff (1941) published universal impedance models for almost all antennas
- Cascaded transmission lines terminated by a TE_{10} or TM_{10} mode impedance (e.g. loops or dipoles)



Fundamental Limits

Chu

Fano

Carlin-LaRosa

L.J. Chu's Bound (1948)

- **Applies to electrically-small lossless antennas**
- **As antenna size shrinks, bandwidth shrinks faster**
    - Cubic relation
- **Limits the minimum *Q* and maximum bandwidth for a given antenna size**
- **Limits the smallest antenna size for a given bandwidth or *Q***
- **The Chu bound assumes that electrically small antennas can excite only the lowest order spherical mode(s)**
- **The bound is presumed true but could be overcome by an ingenious designer**
- **It is not a fundamental bound**

Chu Bound on Antenna *Q* and Bandwidth

- **The Chu bound states that for "electrically-small" lossless antennas**

$$Q_{Ant} \geq Q_{Chu}$$

$$BW_{VSWR\,2:1} \leq \frac{f}{3.17 \times Q_{Chu}}$$

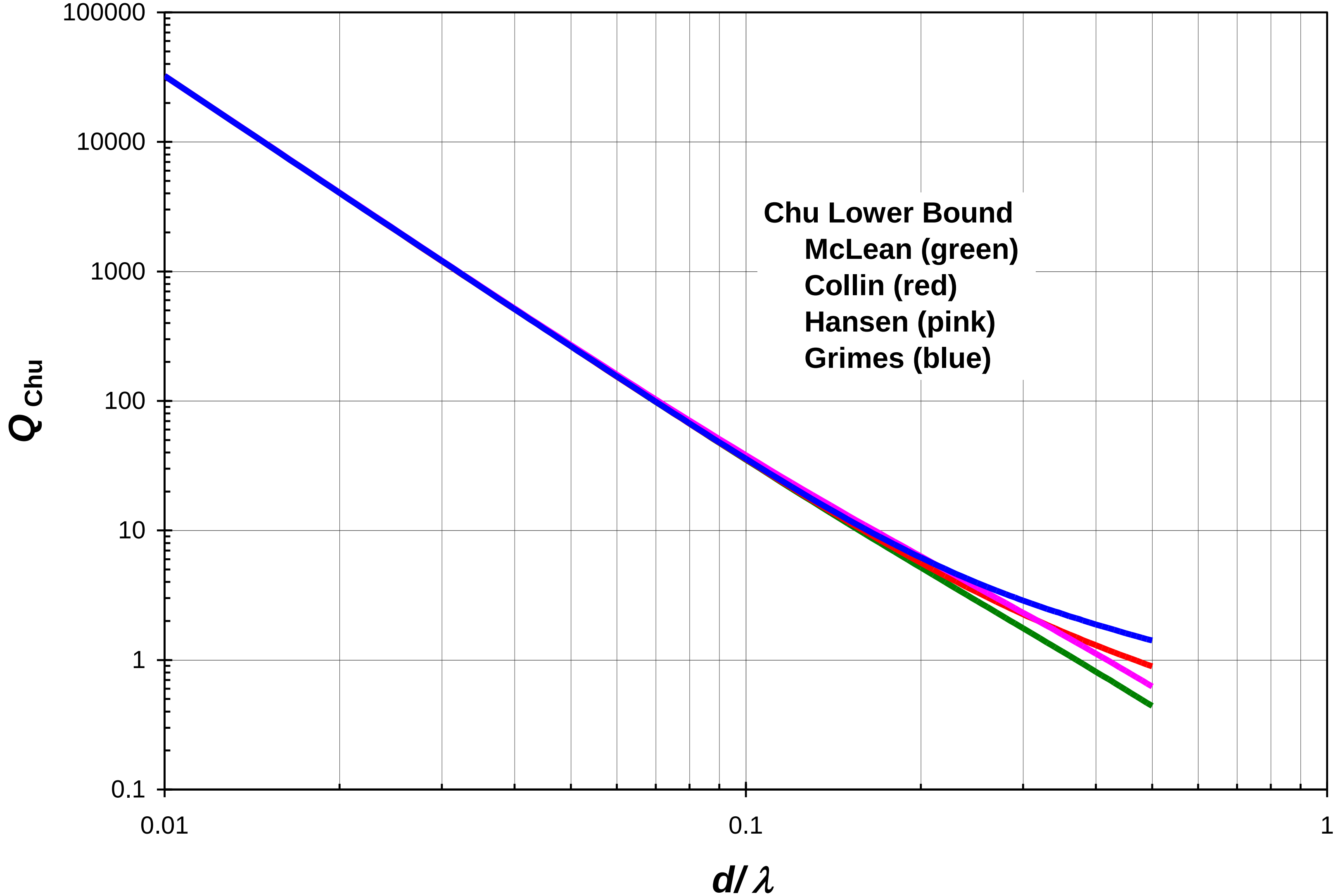
$$BW_{VSWR\,1.5:1} \leq \frac{f}{4.64 \times Q_{Chu}}$$

Bandwidth formulas assume a basic L-match network. Higher-order networks give match bandwidths up to the Fano limit.

where Q_{Chu} is given by

$$Q_{Chu} = \frac{1}{2(ka)^3}\left[1 + \sqrt{1 + 4(ka)^4}\right] + \frac{1}{ka}$$

Chu Bound versus Antenna Size



How to Compute Antenna *Q*

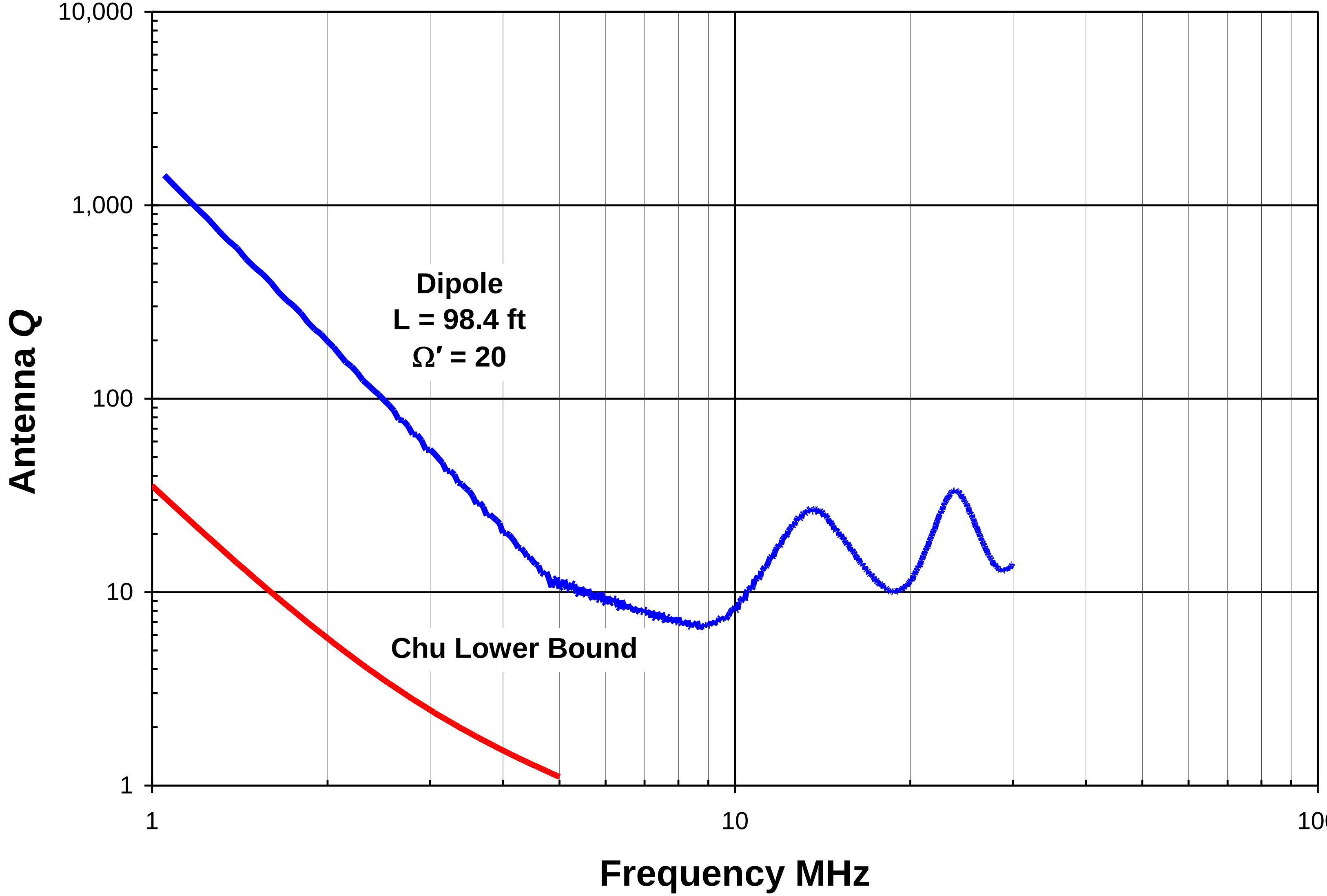
- **Basic definition for lossless antenna**

$$Q_A = 2\pi\left(\frac{\text{Maximum energy in induction fields}}{\text{Energy radiated per cycle}}\right)$$

- ***Q_A* can be computed directly from impedance data by**

$$Q_A(f) = \frac{f}{2R_A(f)}\sqrt{\left(R'_A(f)\right)^2 + \left(X'_A(f) + \frac{|X_A(f)|}{f}\right)^2}$$

Dipoles and Monopoles High *Q*s & Limited Bandwidths



Fractional Bandwidths of 16 U.S. Amateur Bands

Band	Frequencies (MHz)	Fractional Bandwidth
23 cm	1240 to 1300	4.72%
33 cm	902 to 928	2.84%
70 cm	420 to 450	6.90%
1.25 meters	219 to 225	2.70%
2 meters	144 to 148	2.74%
6 meters	50 to 54	7.69%
10 meters	28.0 to 29.7	5.89%
12 meters	24.890 to 24.990	0.40%
15 meters	21.000 to 21.450	2.12%
17 meters	18.068 to 18.168	0.55%
20 meters	14.000 to 14.350	2.47%
30 meters	10.100 to 10.150	0.49%
40 meters	7.0 to 7.3	4.20%
60 meters	5.3306 to 5.4064	1.41%
80 meters	3.5 to 4.0	13.33%
160 meters	1.8 to 2.0	10.53%

Robert Mario Fano, 1917-

R.M. Fano's Bound (1947)

- Applies to passive lossless impedance-matching networks
- Limits how well an arbitrary impedance can be matched by a passive lossless network of any complexity – even infinite
- Bounds the maximum possible return loss for a given match bandwidth
- Bounds the minimum possible VSWR for a given match bandwidth
- Bounds the maximum possible match bandwidth for a given VSWR
- The bound is fundamental; it cannot be overcome
- But it can be bypassed by an ingenious designer

Fano's Bound (1947)

- Bounds the area under the return loss curve of all lossless impedance-matching networks

$$\int_0^{\infty} \log\left(\frac{1}{\rho(\omega)}\right) d\omega \le \min\{A_1, A_2, \cdots, A_n\}$$

where

$$\rho(\omega) = |\Gamma(\omega)| = |s_{11}(\omega)|$$

and A_1, ... , A_n are constants that depend on the load impedance function $Z_L(f)$

- Proved in Fano's Ph.D. dissertation at MIT in 1947
- Published in summary form in the Journal of the Franklin Institute, 1950

Fano Bound for Matching Series RLC Loads

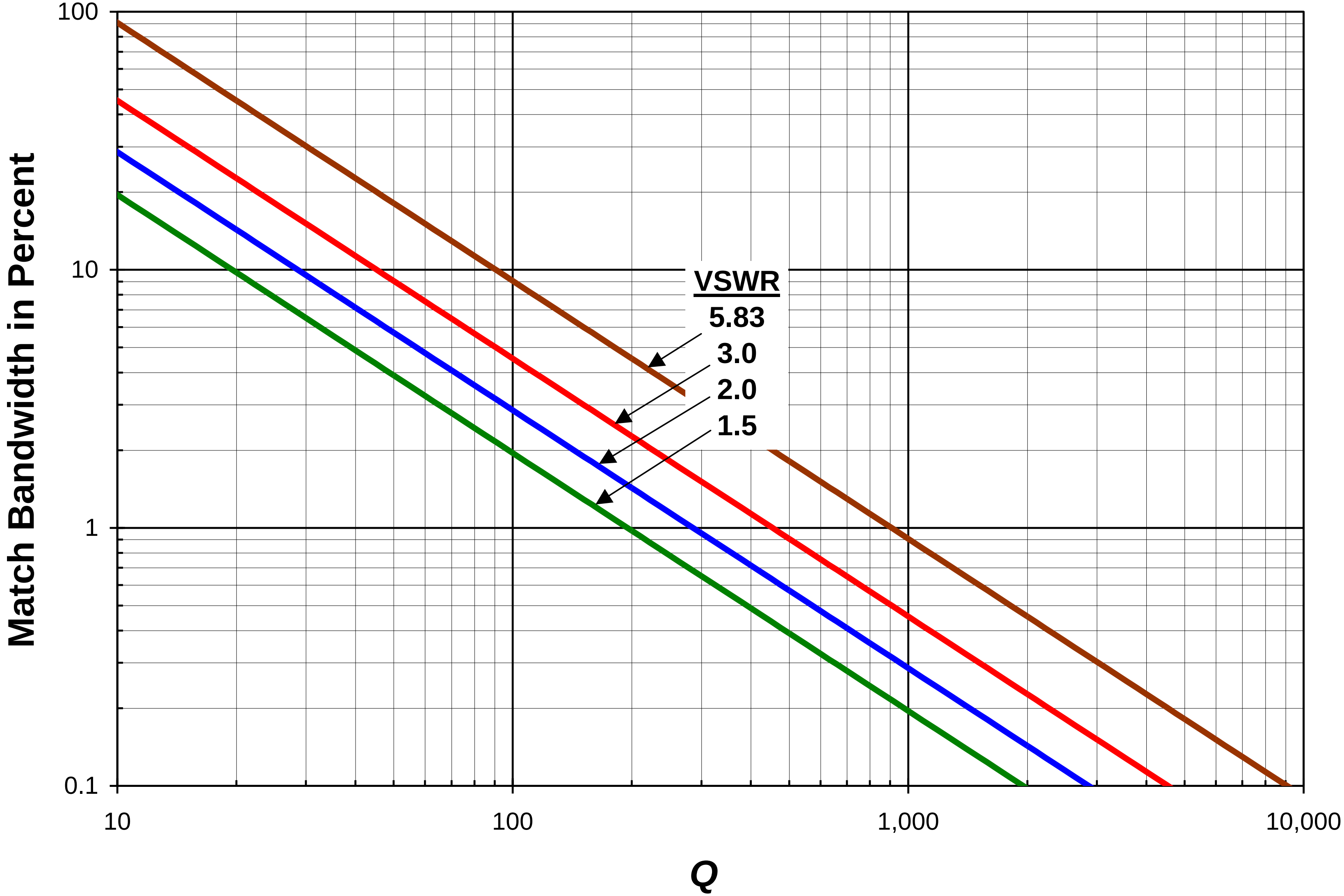
- **Worst-case *VSWR* for a given match bandwidth assuming lossless matching of a series *RLC* load**

$$VSWR \geq \frac{1}{\tanh\left(\dfrac{\pi f}{2QB_{VSWR}}\right)}$$

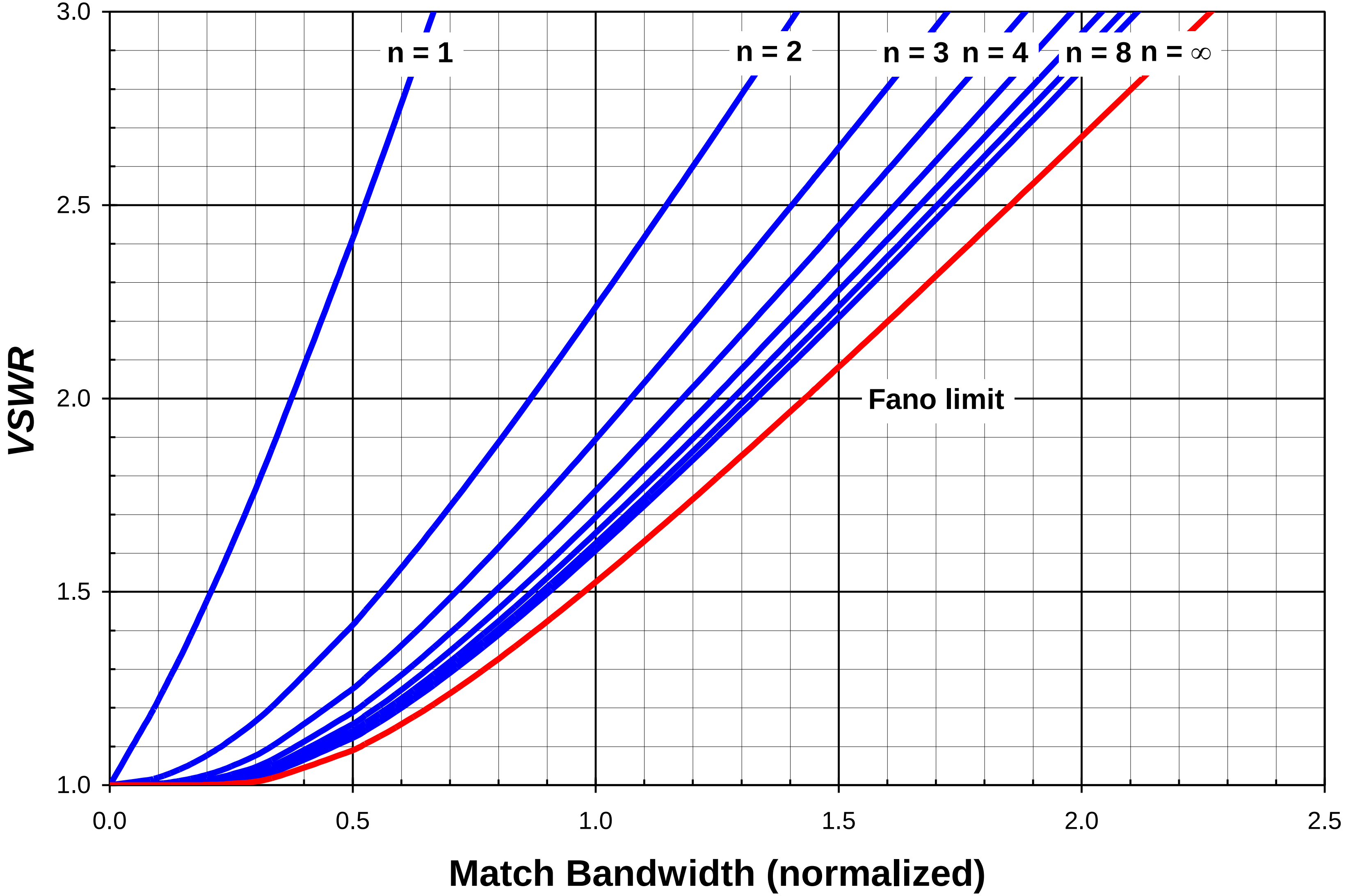
- **Match bandwidth limit in terms of maximum *VSWR***

$$B_{VSWR} \leq \frac{\pi f}{2Q\tanh^{-1}\left(\dfrac{1}{VSWR}\right)}$$

Fano Bound on Match Bandwidth vs *Q* at Resonance



Matching with Chebyschev Networks of Finite Order



Combined Chu-Fano Bound

- **Ultimate bandwidth of small antennas with infinite match complexity**

$$B_{VSWR} \le \frac{4\pi^4 f \left(\frac{h}{\lambda}\right)^3}{\tanh^{-1}\left(\frac{1}{VSWR}\right)}$$

- **where *h* is the monopole height or dipole half-length**
- **Bandwidth limit for λ/20 monopoles and λ/10 dipoles**

$$B_{VSWR} \le \frac{f}{20.53\tanh^{-1}\left(\frac{1}{VSWR}\right)}$$

H.J. Carlin and R. LaRosa's Bound (1952)

- Extends Fano's bound to passive networks that use loss to prevent reflection
- Applies to passive reflectionless impedance-matching networks
- Bounds the minimum possible insertion loss for a given bandwidth
- Bounds the maximum possible bandwidth for a given insertion loss
- The bound is fundamental like the Fano bound
- Covers one of the two paths that bypass Fano

The Situation

- **Dipoles and monopoles fall well short of the Chu bound**
  - 10× at $\lambda/2$
  - 50× at $\lambda/10$
  - Gets worse for smaller sizes
- **Problem is inherent to all monopoles and dipoles**
- **Amateur mobile antennas are more narrowband than need be**
  - Situation good for ATU manufacturers
  - Situation good for broadband matching network designers
  - Situation bad for radio amateurs
  - Limits bandwidth of modes that can be used
  - Limits the use of modern wideband digital communication modulations, e.g. all-band OFDM/CDMA
- **Better small antennas exist**

Interesting Impedance-Matching Methods

Why Impedance Match?

- Greater than unity VSWR means a reflected wave exists on the transmission line
- VSWR > 2 implies high loss (mismatch loss)
- High VSWR leads to high-voltage breakdown and heating by I^2R and dielectric losses
- Solid-state final amplifiers require low-VSWR loads
- Digital modulations don’t like phase distortion

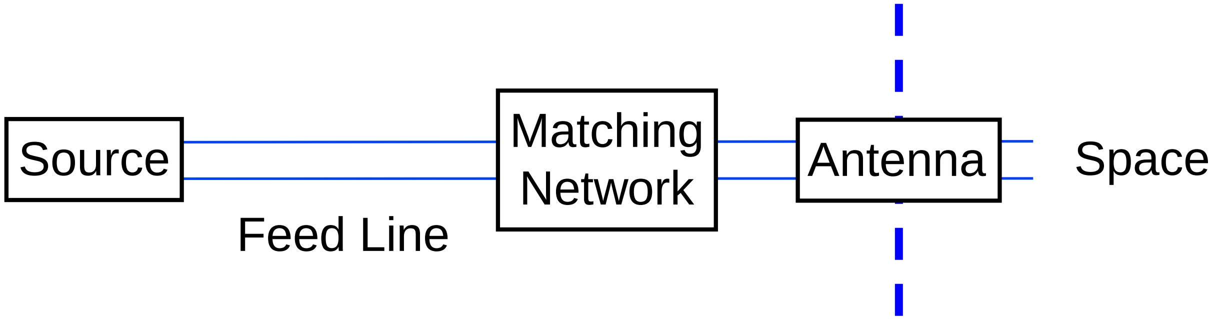
Traditional Impedance-Matching Techniques

- Gamma match
- T match
- Delta match
- Transmission line stubs
- Transmission line sections (quarter-wave transformers)
- Lumped-element L, Pi, and T networks
- High-order Chebyschev networks
- ATU’s
- Combinations of above

Facts or Myths?

- **Matching networks giving arbitrarily low VSWR over arbitrarily wide bandwidth do not exist?**
- **A reflection coefficient's magnitude is between zero and one?**
- **Impedance-matching devices and networks are always inserted either at an antenna's feedpoint or in its feedline?**
- **The goal of impedance matching is to maximize power delivery to a load?**
- **The goal of communication is to maximize power delivery?**
- **The goal of communication is to maximize information transmission?**

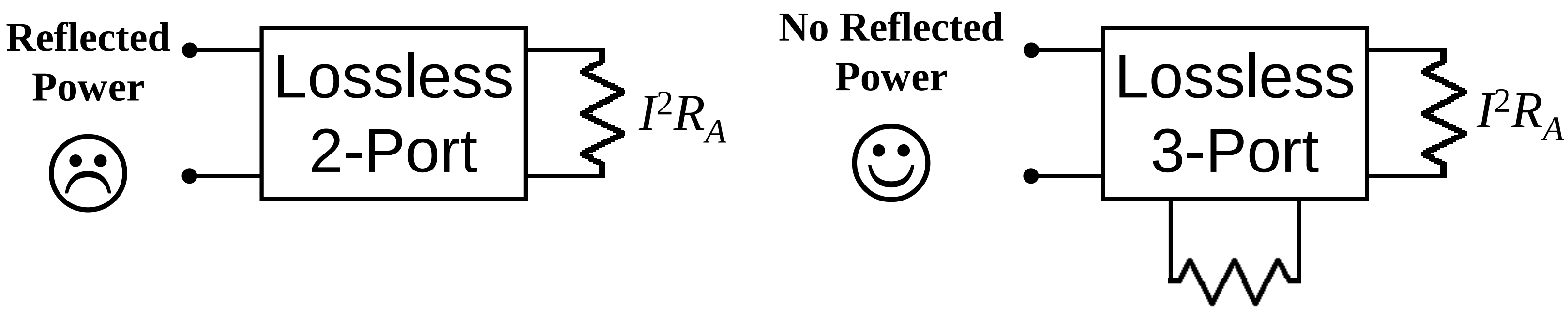
Three Questions



- **Q3: Can an antenna be matched on its "space" side instead of its feed side?**
- **Q4: Can a passive impedance-matching network be reflectionless (have unity VSWR) at all frequencies?**
- **Q5: Can a passive impedance-matching network have unity power transmission (have unity VSWR and zero insertion loss) at all frequencies?**

Edward Lawry Norton, 1898-1983, photo 1925

Answer to Q4: Yes
Constant-Resistance Reflectionless Networks

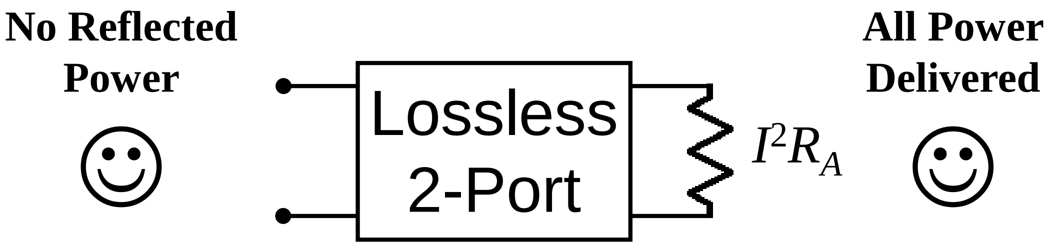


From this……

To this!

Will be covered tomorrow morning

Answer to Q5: Yes
Broadband Active Bilateral Non-PRF Match Networks



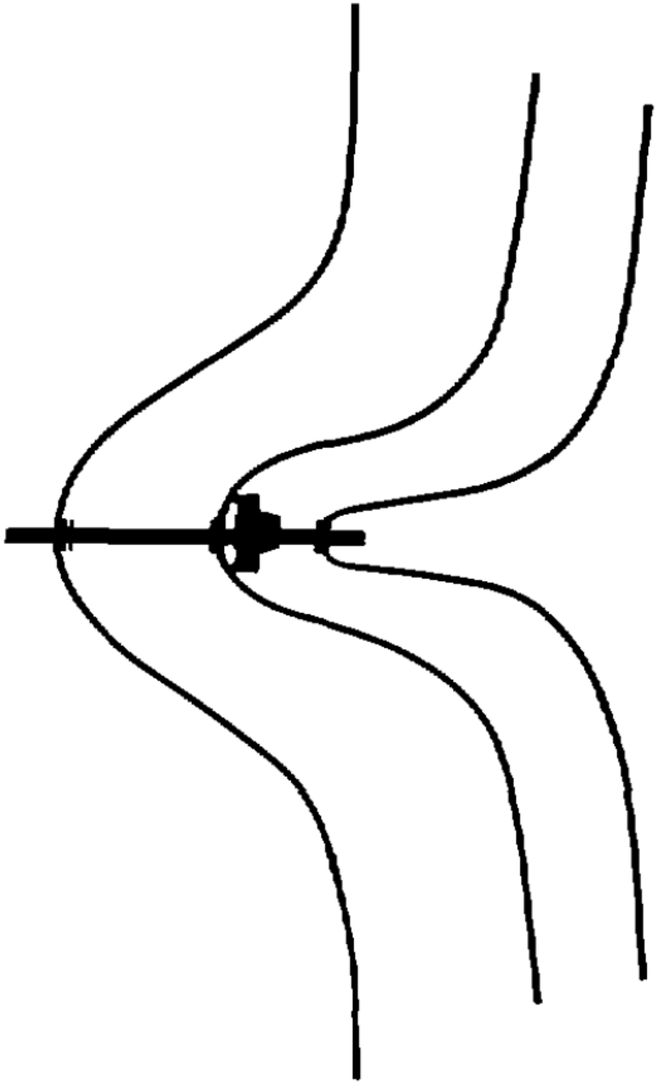
Will be covered tomorrow morning

Interesting Antennas

Amateur Antenna Paradigms

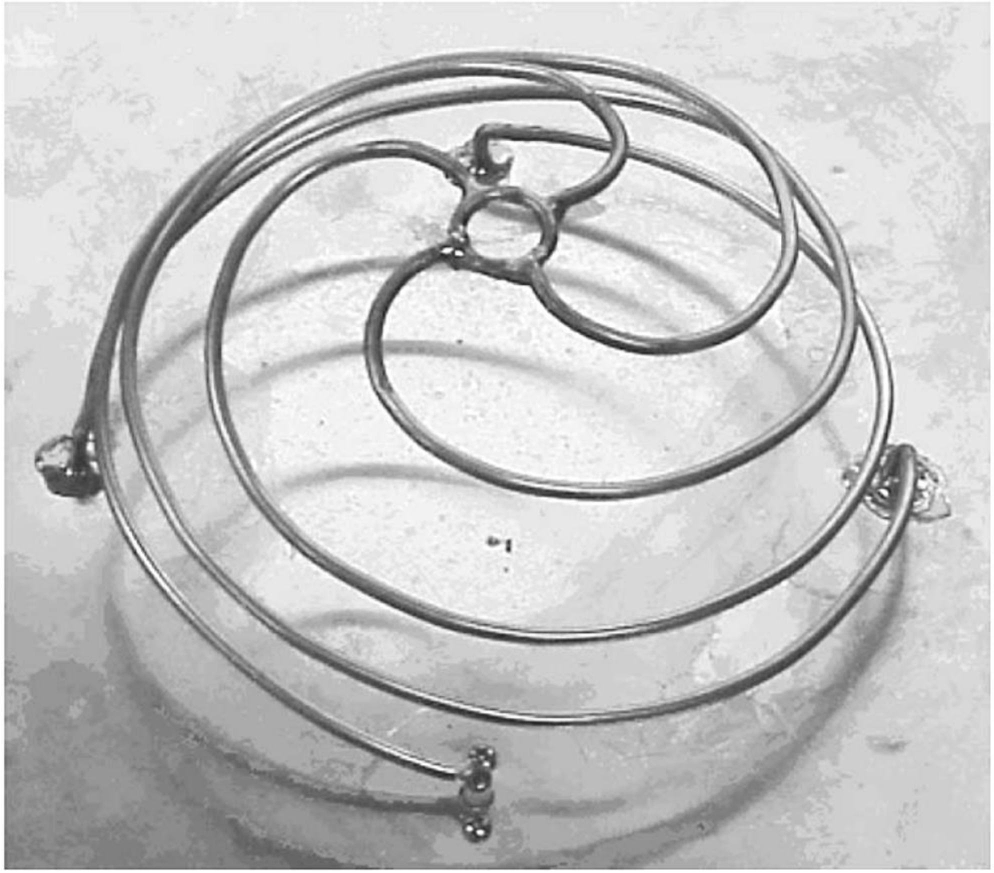
- Antennas made of straight elements (wires, rods, and tubes)
- Antennas made of conductors (metals)
- Resonant antennas
- Narrowband antennas
- But … many interesting antennas break these rules!

Landstorfer Antenna (1976)



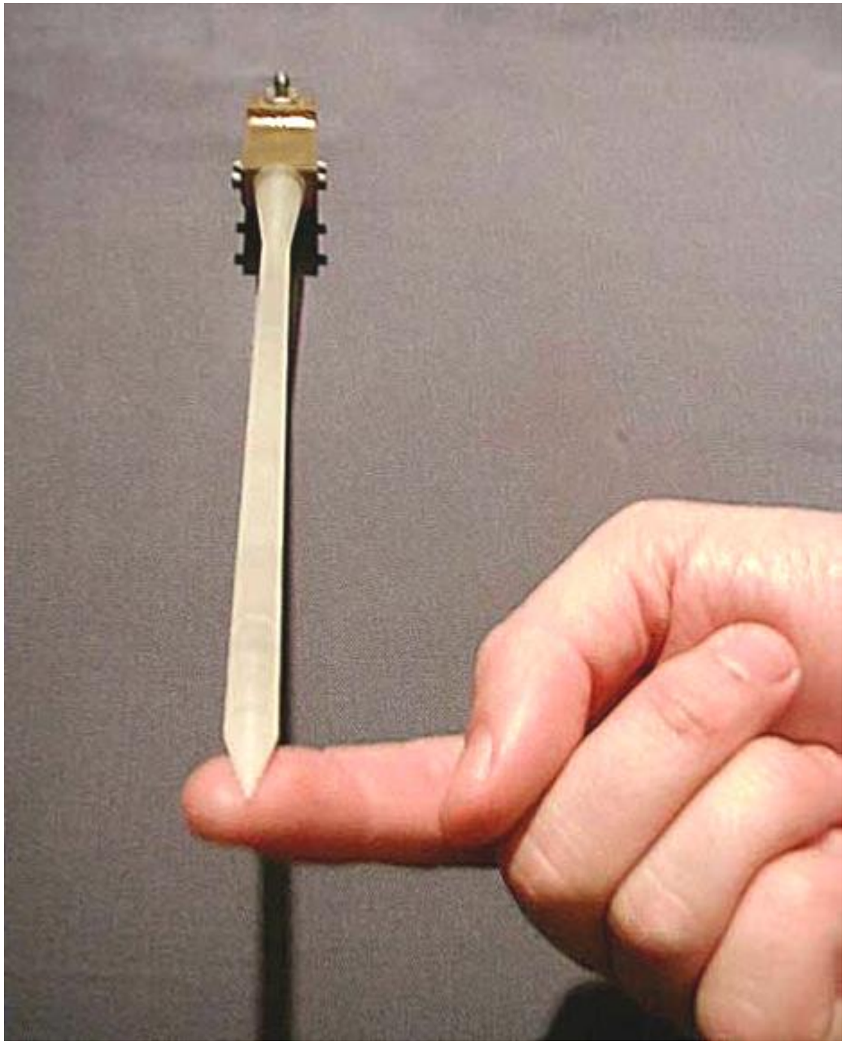
- Elements: 3
- Element shape: Optimized (approximately Gaussian)
- Gain: 11.5 dBi
- Sidelobes: < -20 dB
- F/B ratio: 26 dB
- Performance similar to 10-element Yagi – except…
- Bandwidth: > 3% (W4RNL)

Folded Hemi-Spherical Helix Over Ground Plane (2004)



- **Helix: 4 arms, 1 turn**
- **Height (radius): λ/16.5**
- **Frequency: 300 MHz**
- **Polarization: vertical**
- **Z: 50 ohms real**
- **VSWR: < 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?

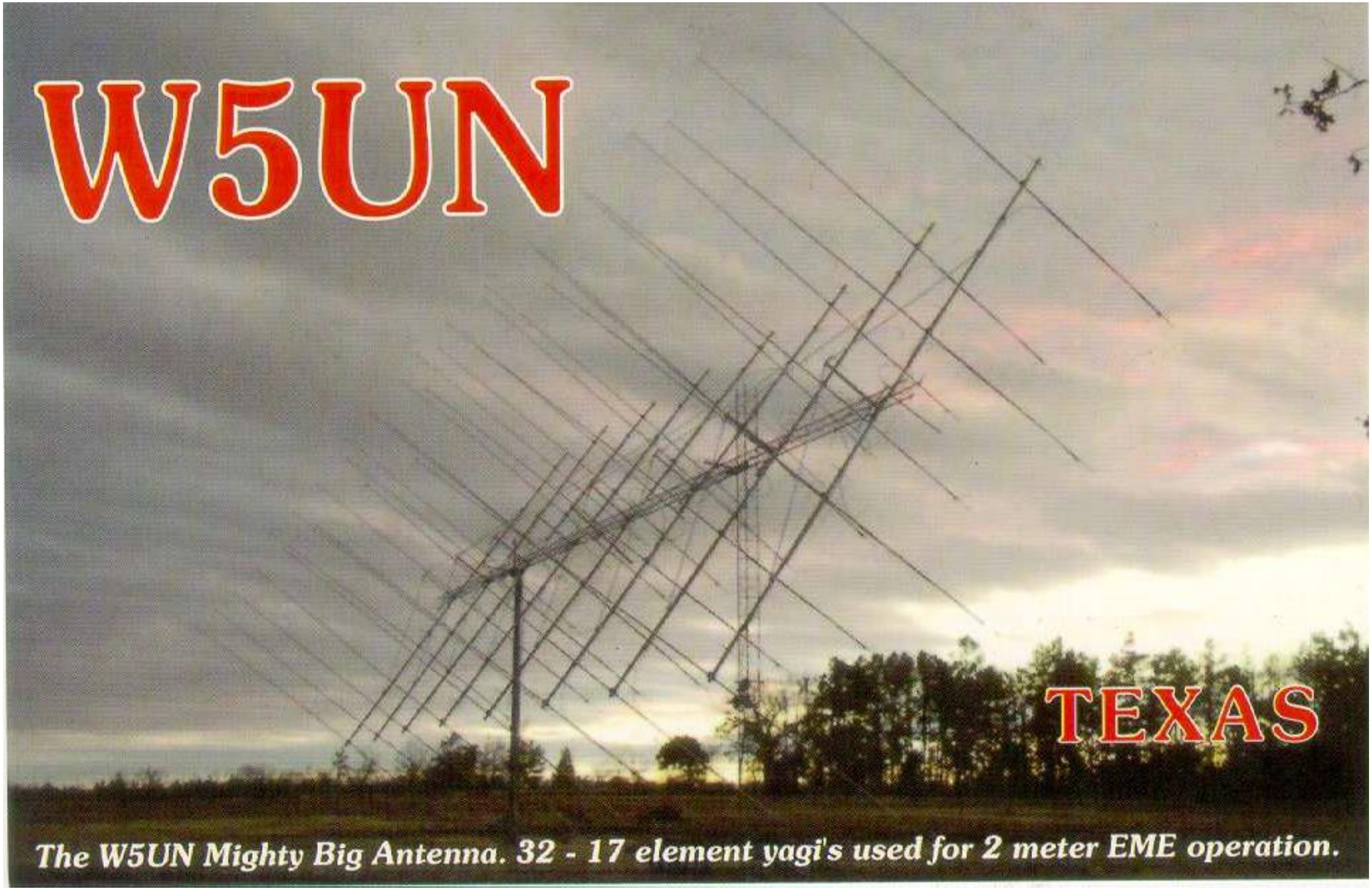
Non-Stealth Antennas

Why Little Transmitters Get Heard

K0DK in Boulder, Colorado

K4JA at Callao, Virginia

W5UN at Mount Pleasant, Texas

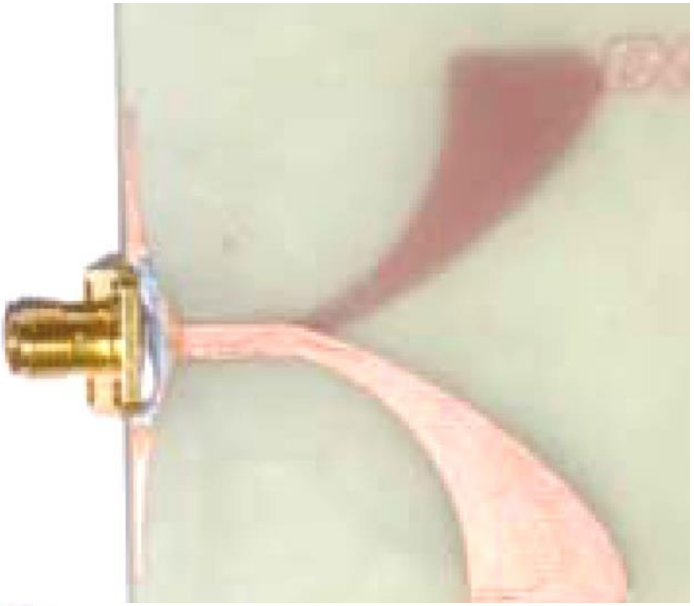


W6AM's Antennas As Seen from Space

W6AM at Rancho Palos Verdes, California

Broadband Antennas

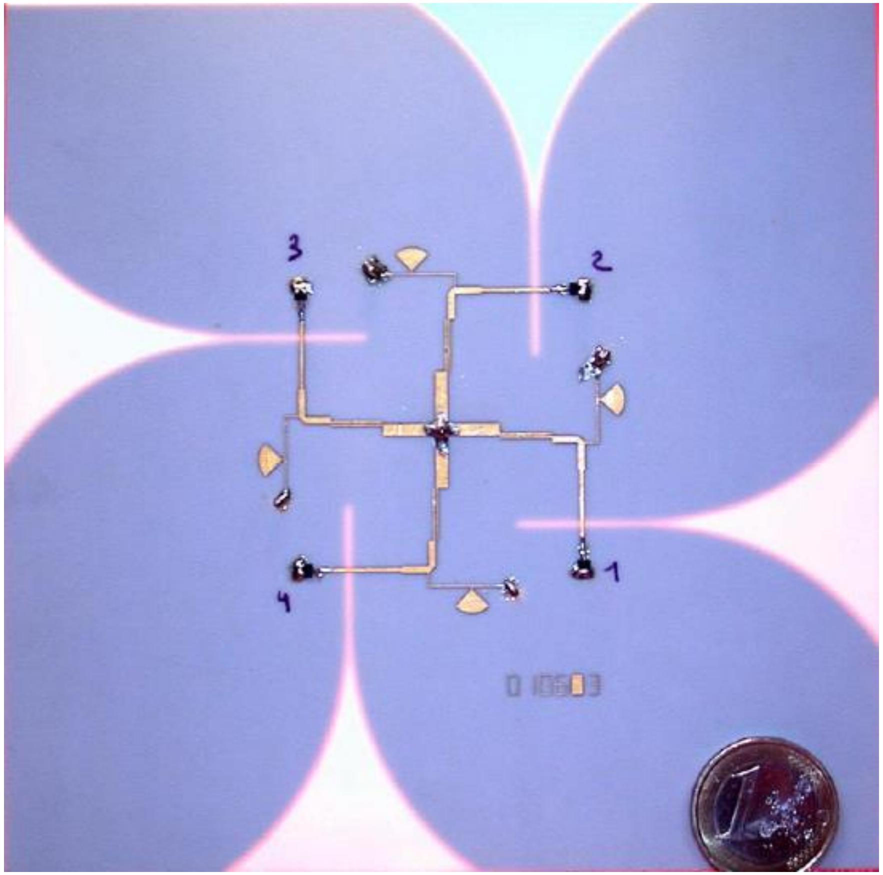
Vivaldi Antenna (1974)



- 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

Radomes

Good Stuff for Antennas

Greater gain

Very small VSWR

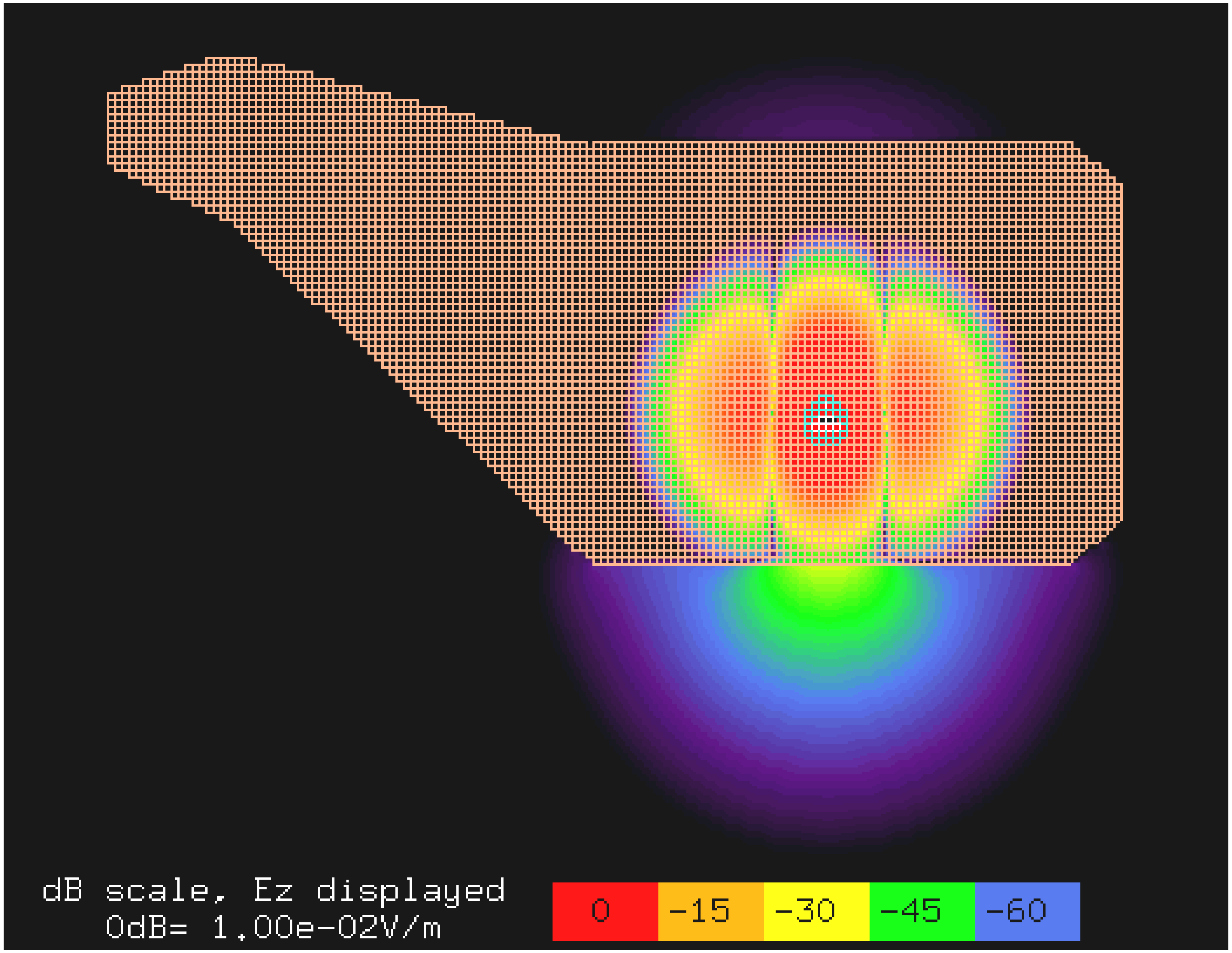
Higher directivity

Bigger bandwidth

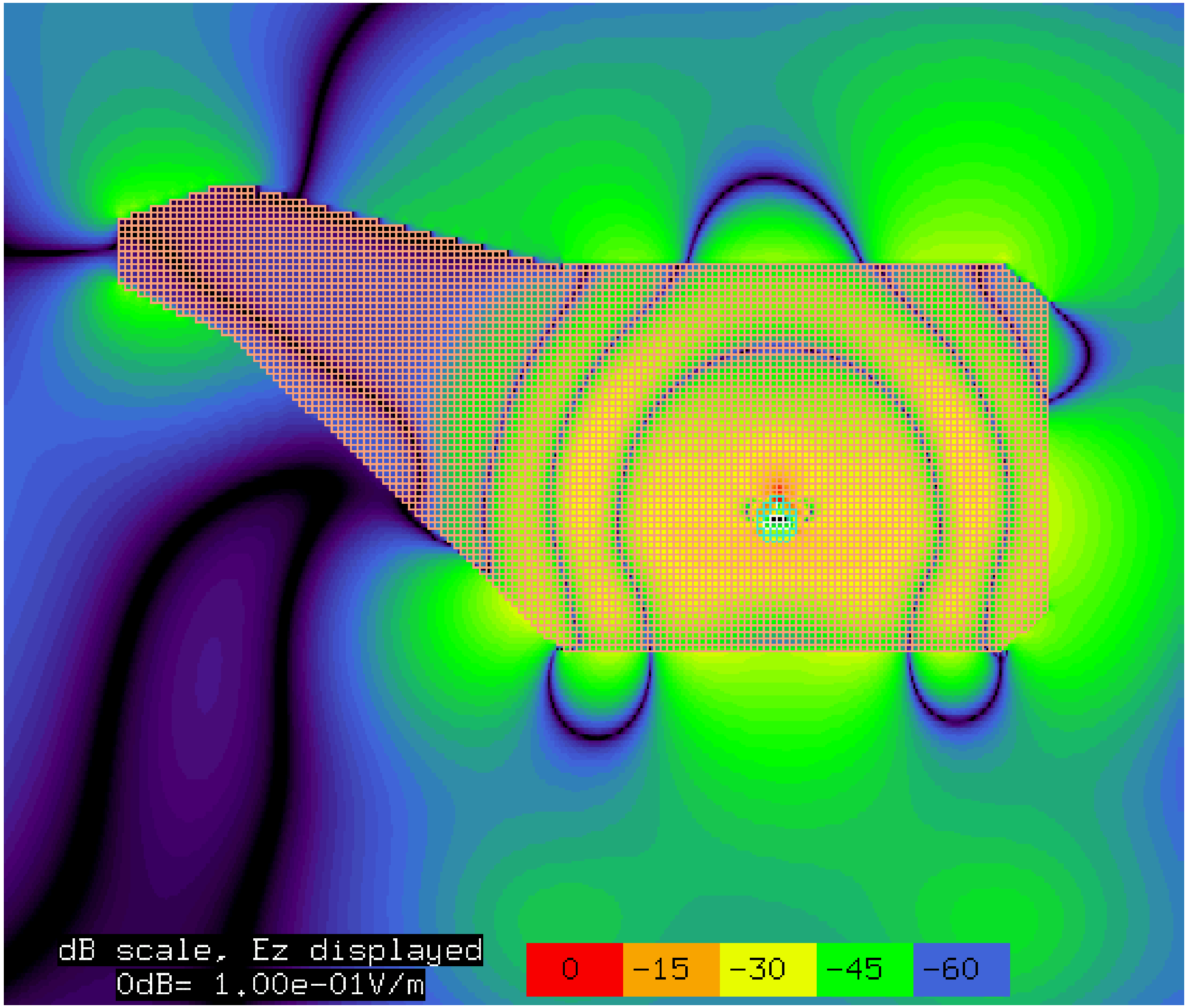
More radiation resistance

Improved efficiency

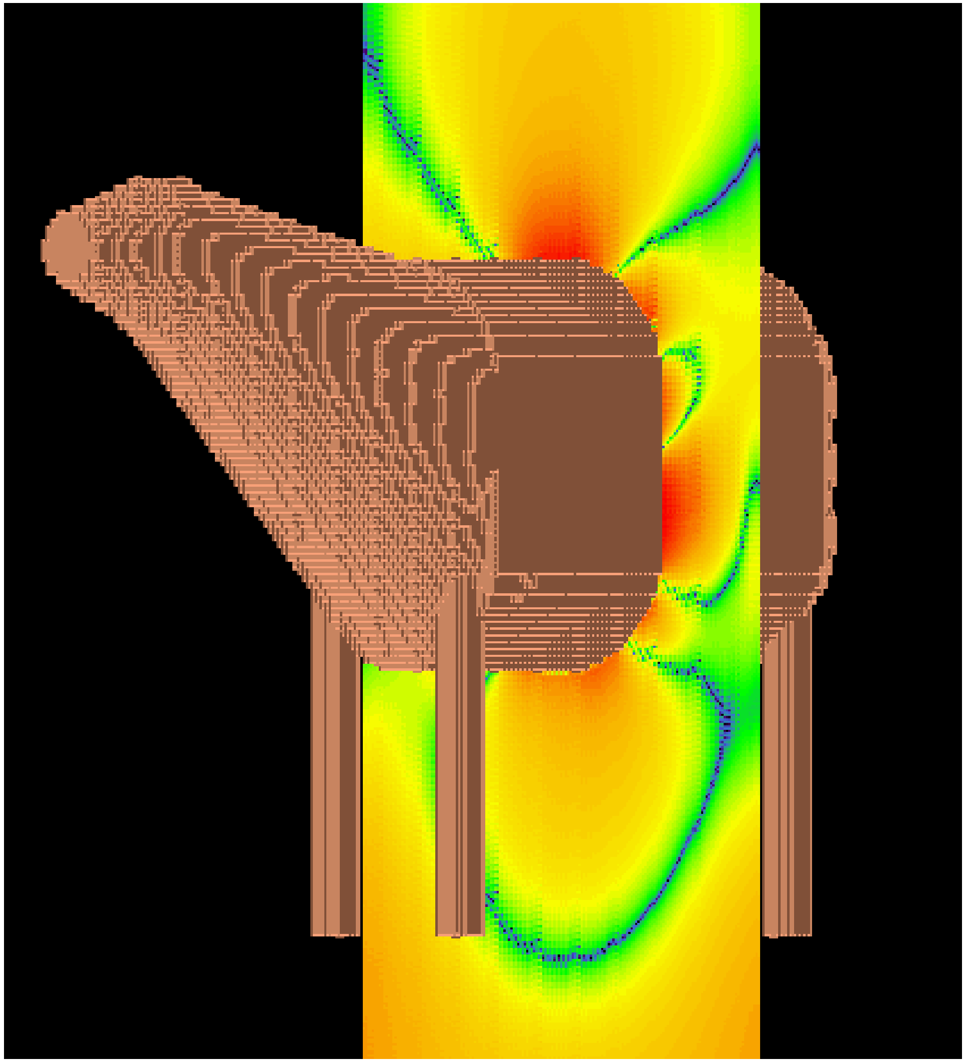
Transmitter Inside Cow



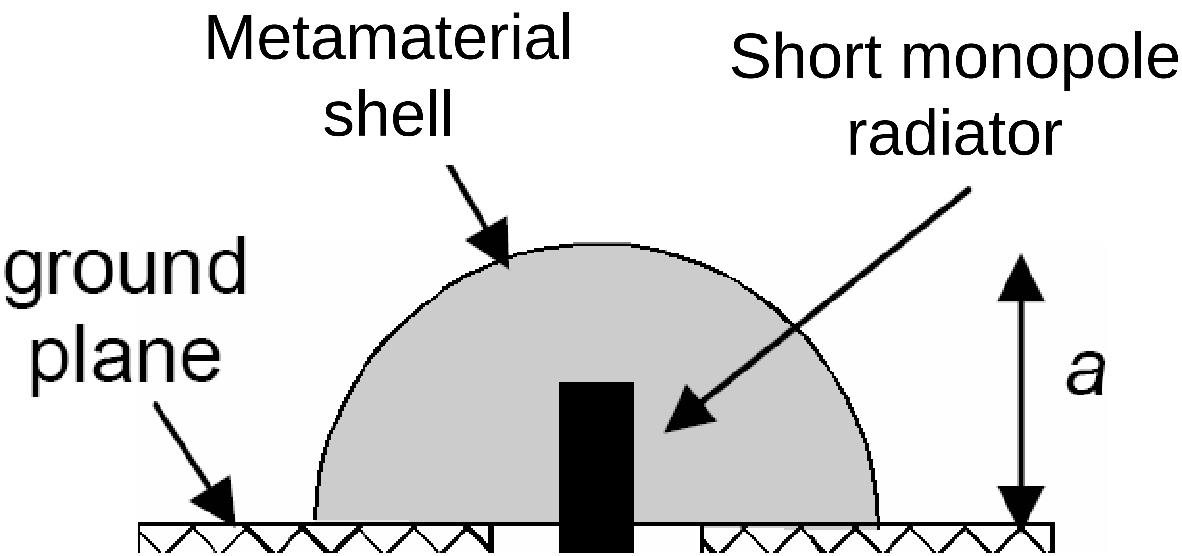
Performance of Cow Radome – Longitudinal Plane



Cow Radome – Transverse Plane

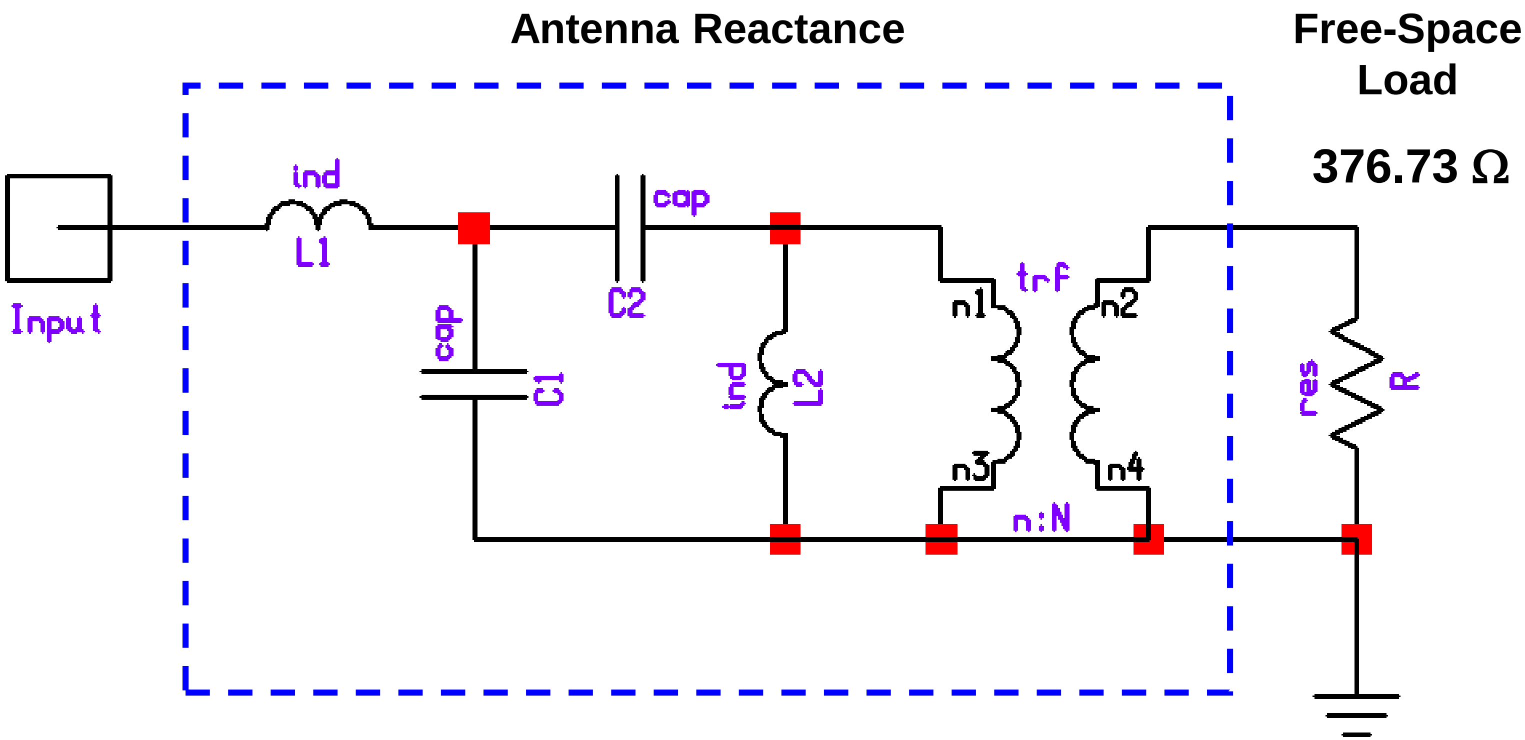


Bell Laboratories Monopole in Metamaterial Shell

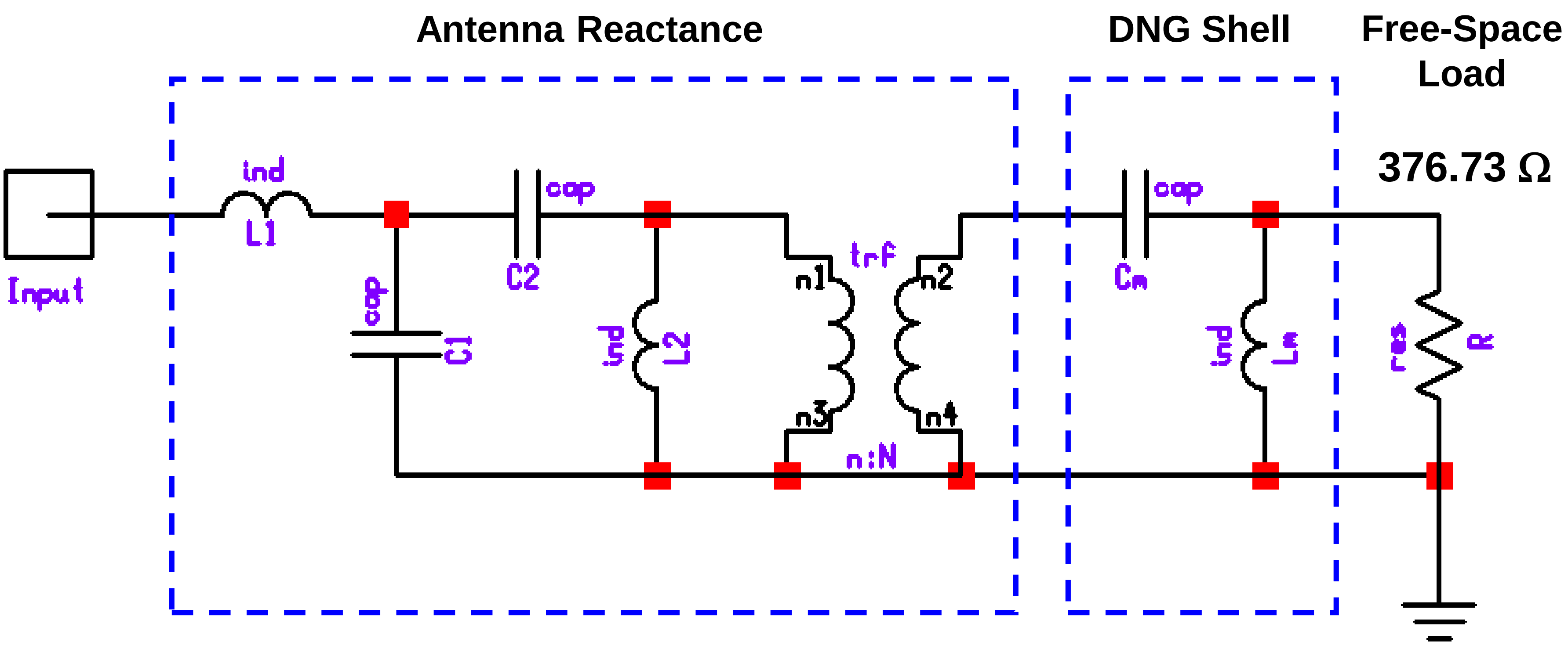


- Shell type: ENG
- Stub length: $\lambda/50$
- Shell radius: $\lambda/18.5$
- Frequency: 2.025 GHz
- *Z*: 50 ohms real
- VSWR: < 1.02
- Bandwidth: 4.76%
- Q_A: 42 (Q_{Chu} = 28.9)
- Polarization: vertical
- Efficiency: > 61%

Two-Port Equivalent Circuit of Monopole



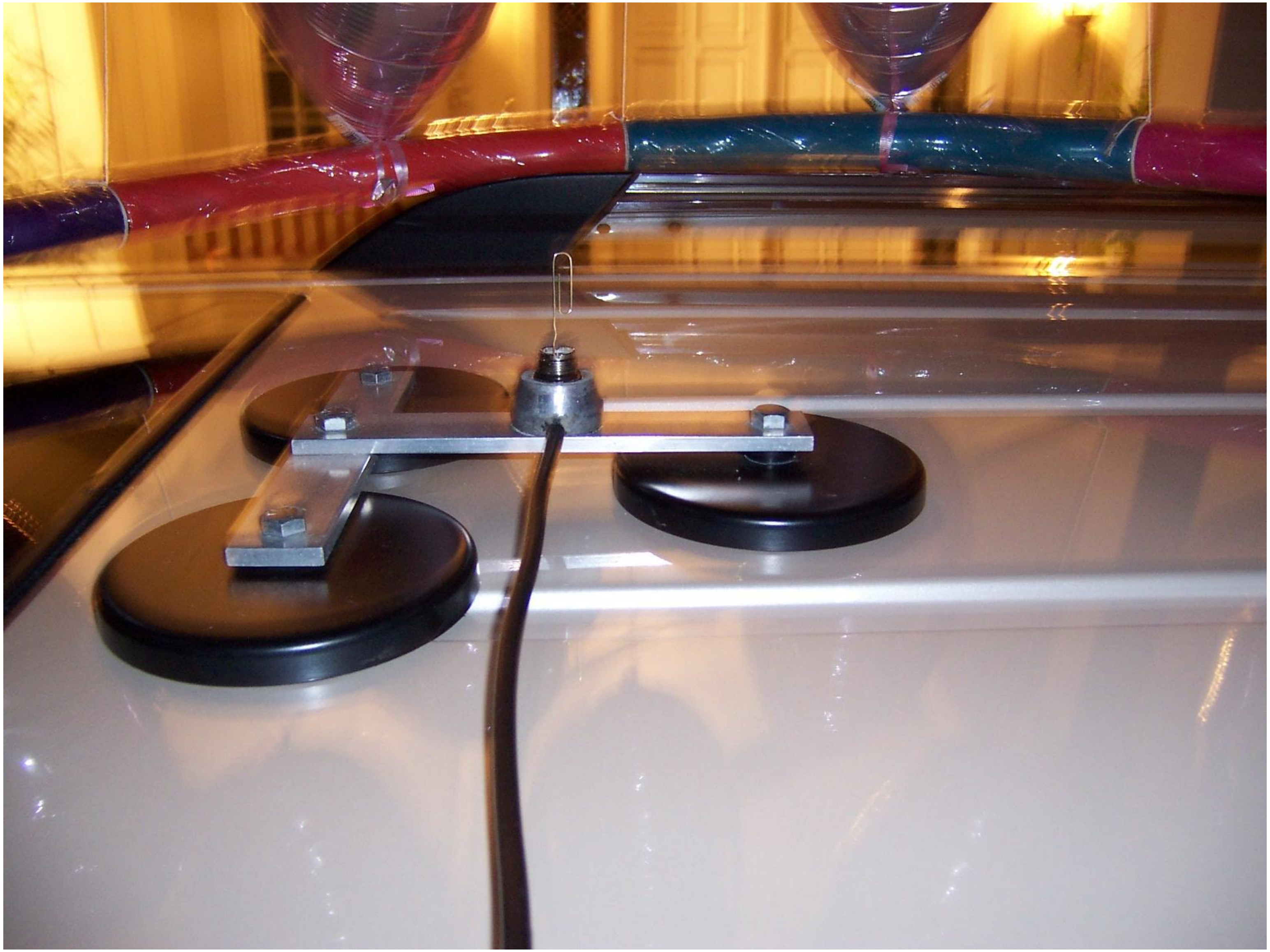
Monopole Space-Matched by Thin DNG Shell



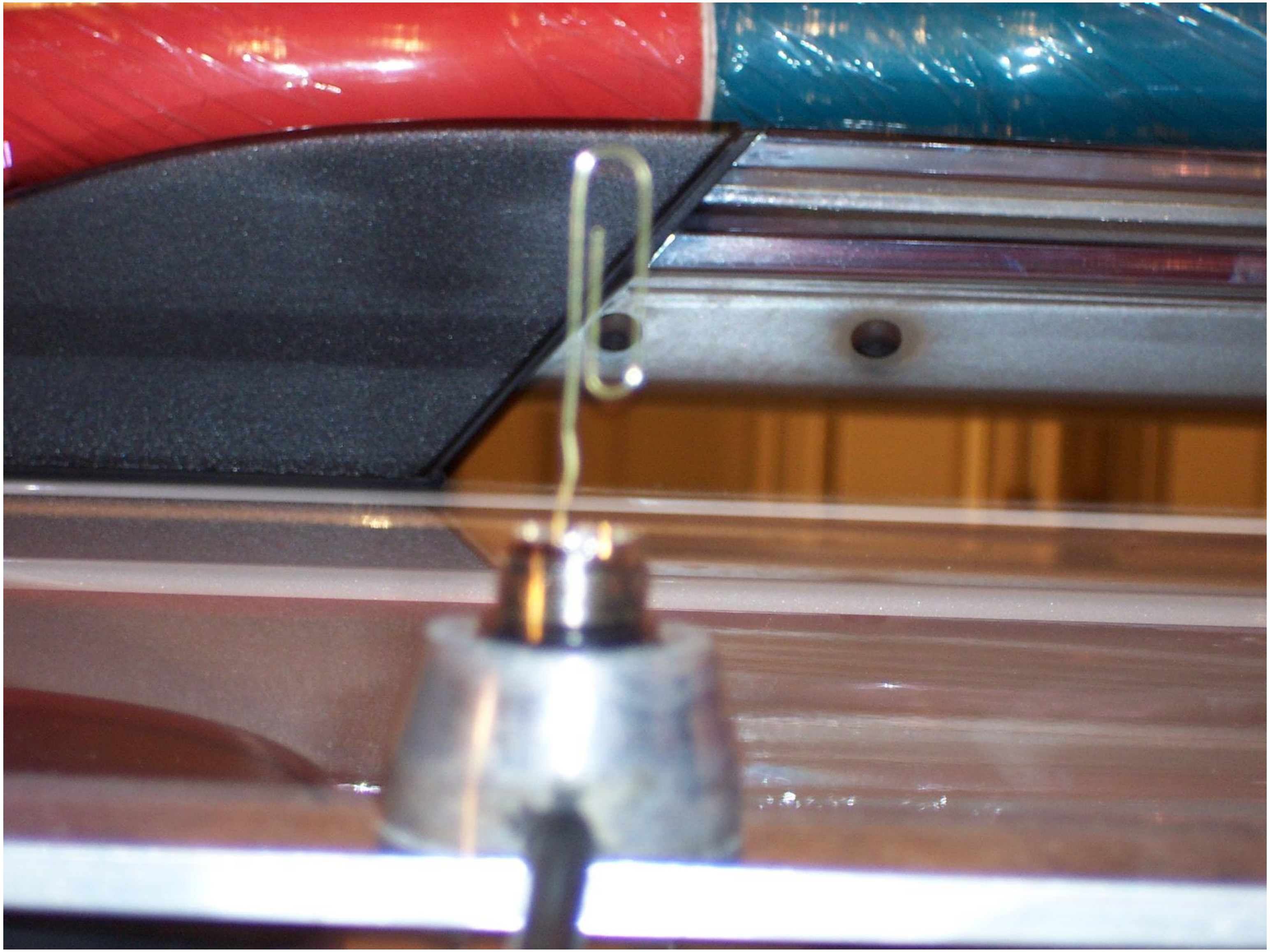
K6OIK's Electrically-Small 2-Meter Antenna

Space-Matched Using Metamaterial Radome

An Electrically-Small Radiator



Close Up View of the Radiator



A Double-Negative Metamaterial Radome

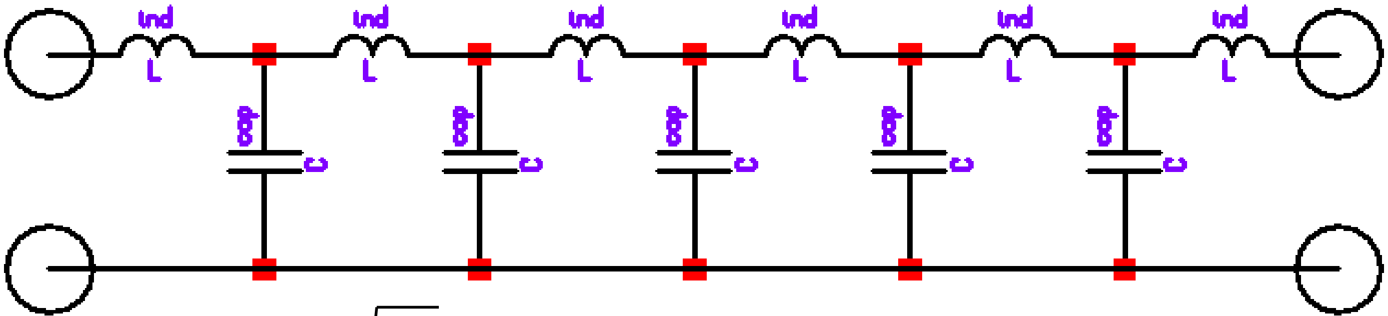
2-Meter Double-Negative Radome

The Strange Story of Backward Waves

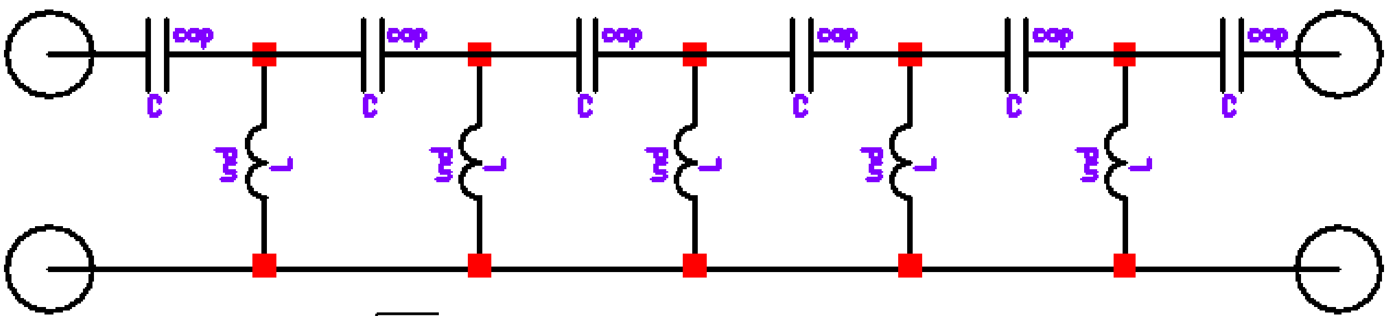
What is a Backward Wave?

- **Is not an ordinary reflected wave**
- **Is a type of wave in which power and phase travel in opposite directions**
- **Exists in certain transmission line ladder networks**
  - Low-pass to high-pass transformation
  - Low-pass to bandpass transformation and stay below f_0
  - Low-pass to band stop transformation and stay above f_0
- **Exists in certain antennas**
  - A Yagi-Uda traveling-wave antenna converts from "slow-wave" to backward wave structure by changing dimensions
  - Backfire antennas launch a backward wave toward a reflector. The wave traverses the boom twice, giving greater gain
- **Exists in double-negative metamaterials**
  - Dielectric constant and permeability are both negative

Positive and Negative Transmission Lines

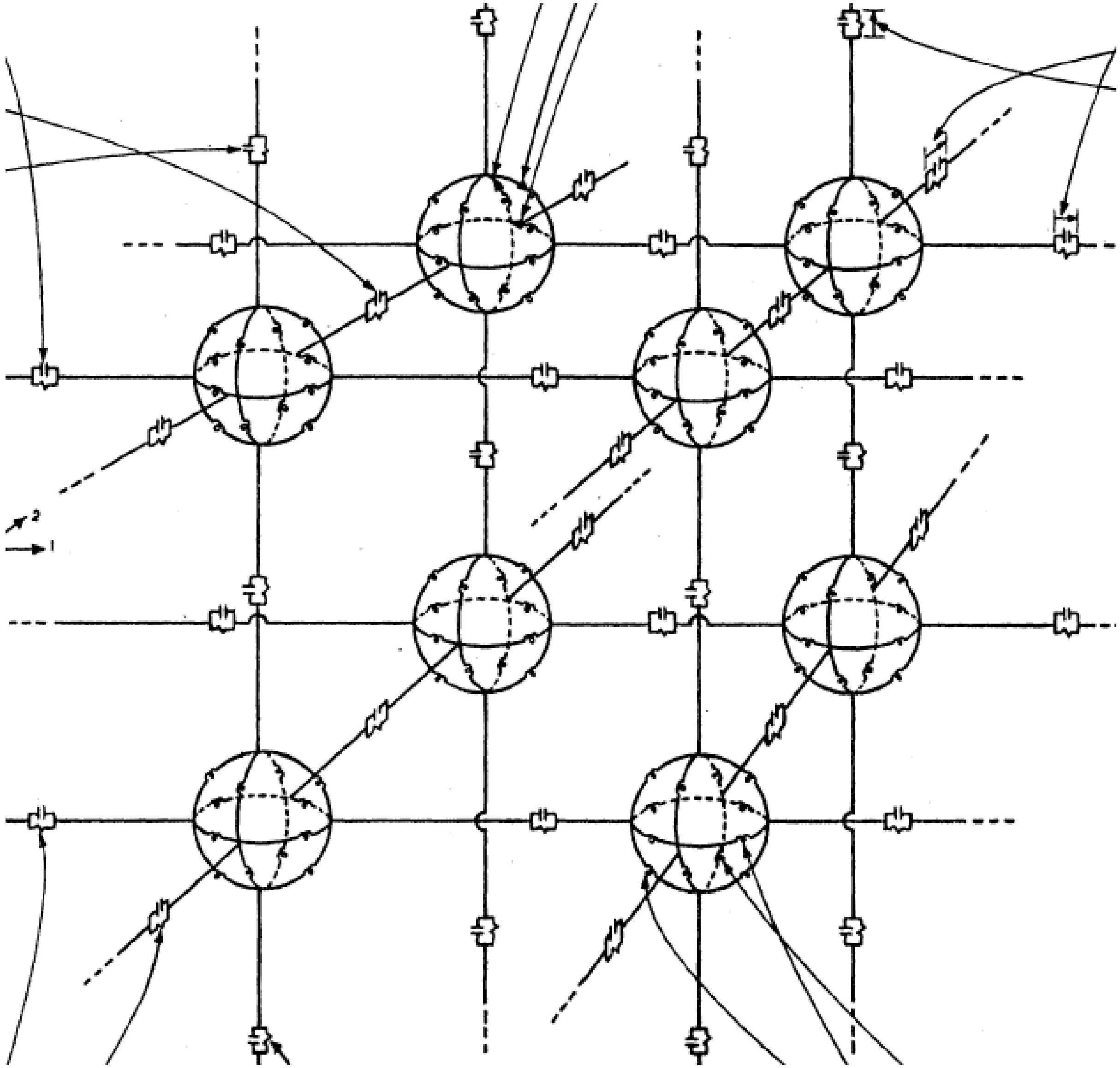


$$Z_0 = \sqrt{\frac{L}{C}}, \quad v_p = \frac{1}{\sqrt{LC}}, \quad v_g = \frac{1}{\sqrt{LC}}$$

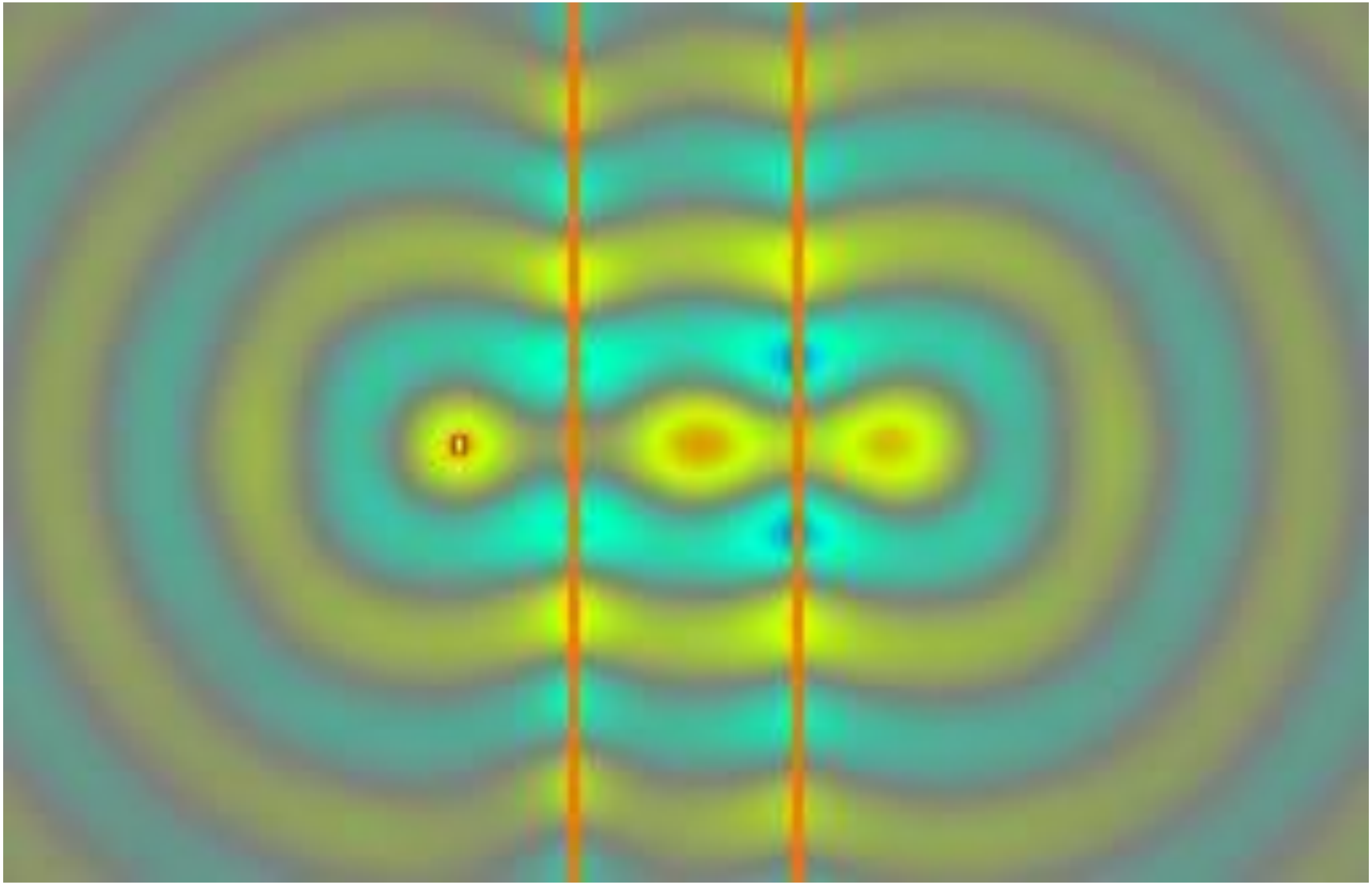


$$Z_0 = \sqrt{\frac{L}{C}}, \quad v_p = \frac{1}{\sqrt{LC}}, \quad v_g = \frac{-1}{\sqrt{LC}}$$

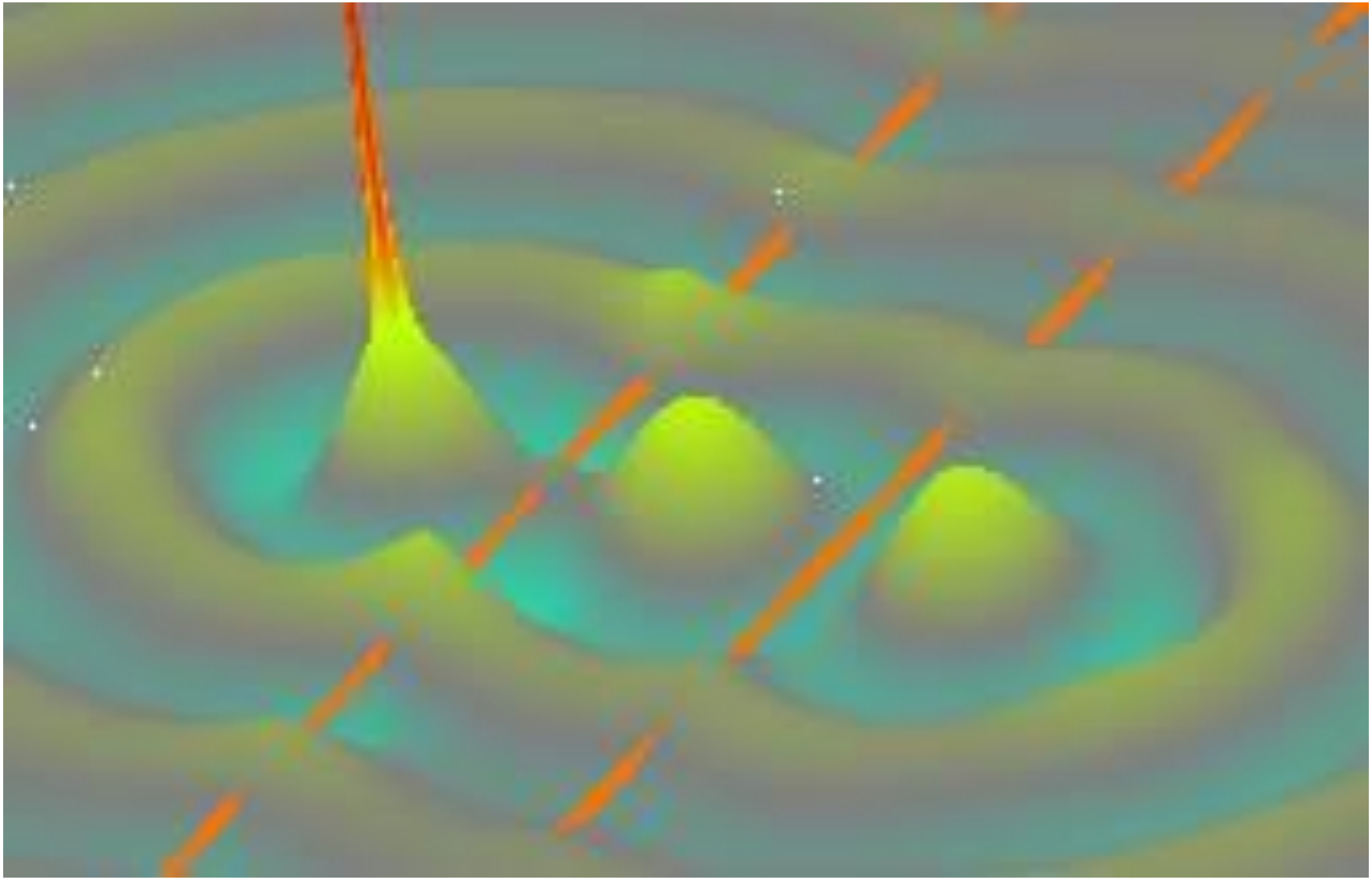
Equivalent Circuit for 3D Wave Propagation (1943)



Backward Waves in Slab of Negative Material



View from an Angle



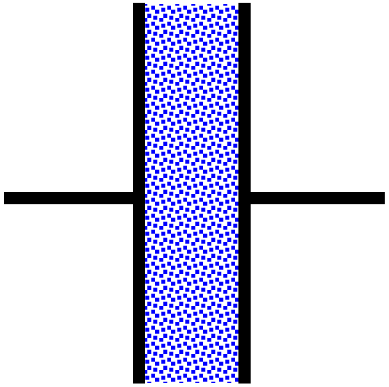
Metamaterials

Negative Capacitors and Inductors

	$\varepsilon_r < 0$	$\varepsilon_r > 0$
$\mu_r < 0$	*DNG*	*MNG*
$\mu_r > 0$	*ENG*	*DPS*

ENG metamaterial

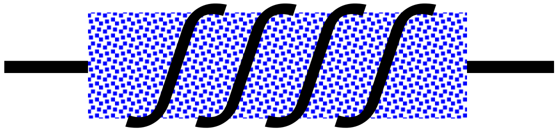
$\varepsilon_r < 0$



$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} < 0$$

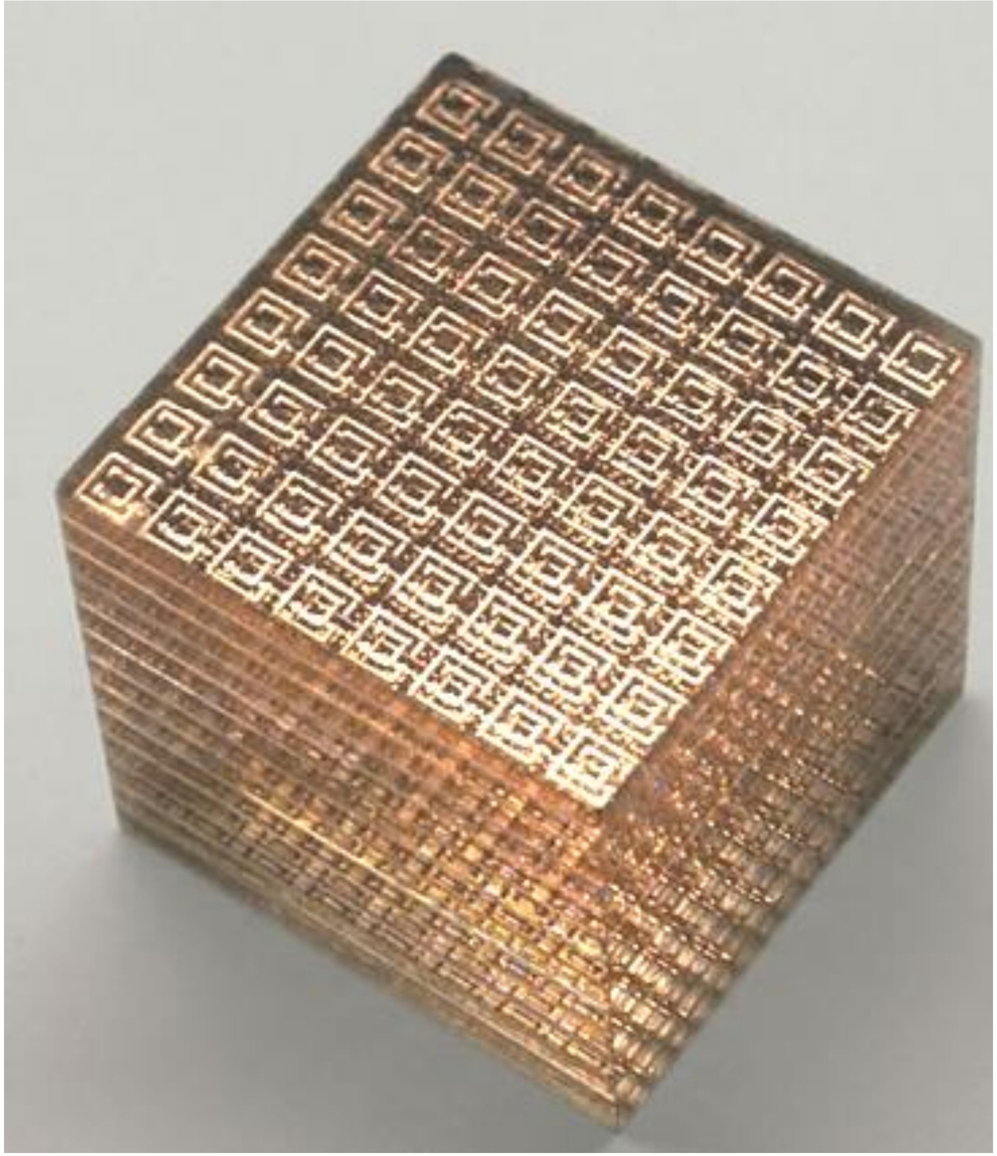
MNG metamaterial

$\mu_r < 0$

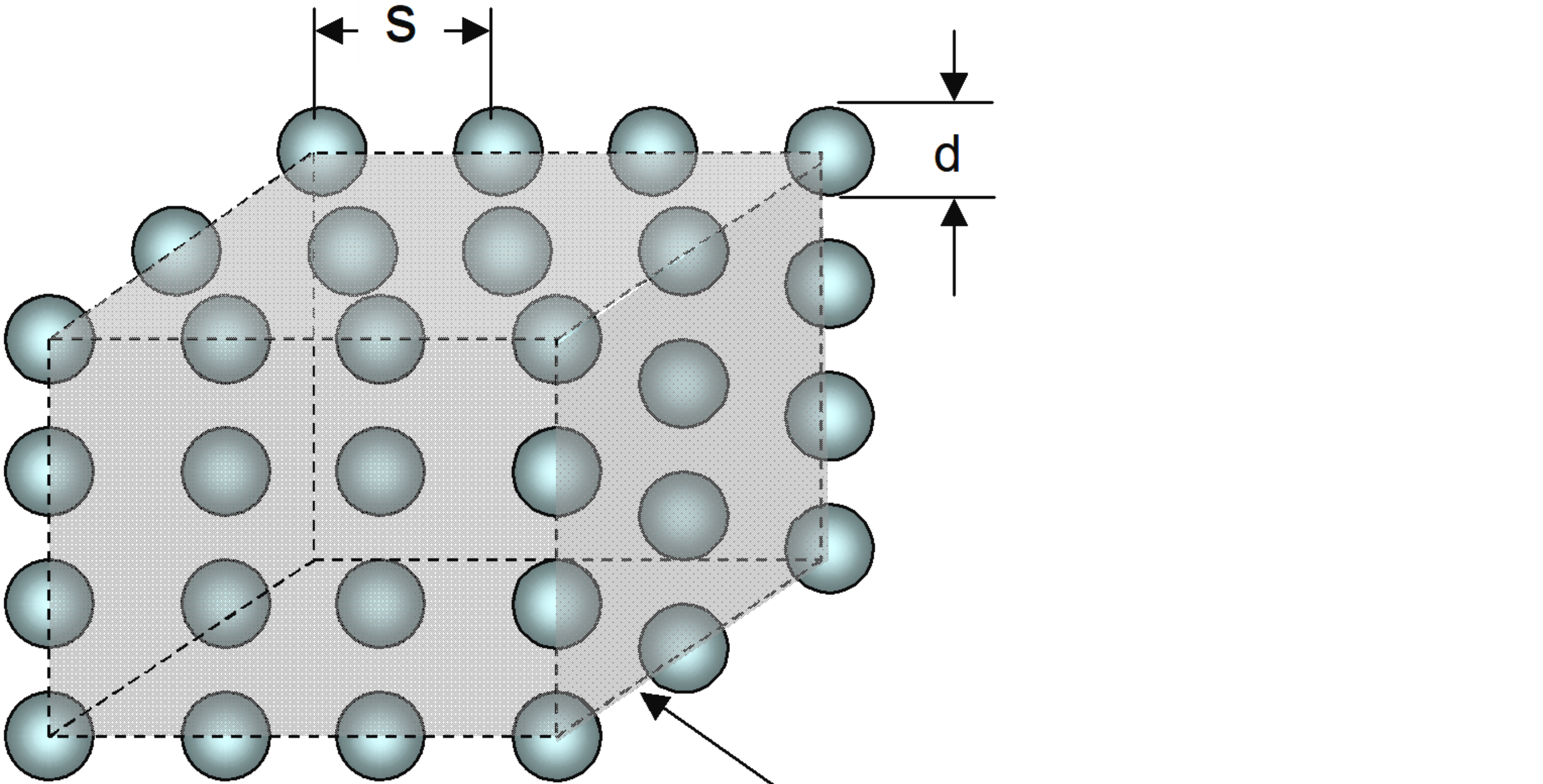


$$L = \mu_r \mu_0 \frac{N^2 A}{d} < 0$$

Professional Metamaterial - The Boeing Cube



Amateur Metamaterial

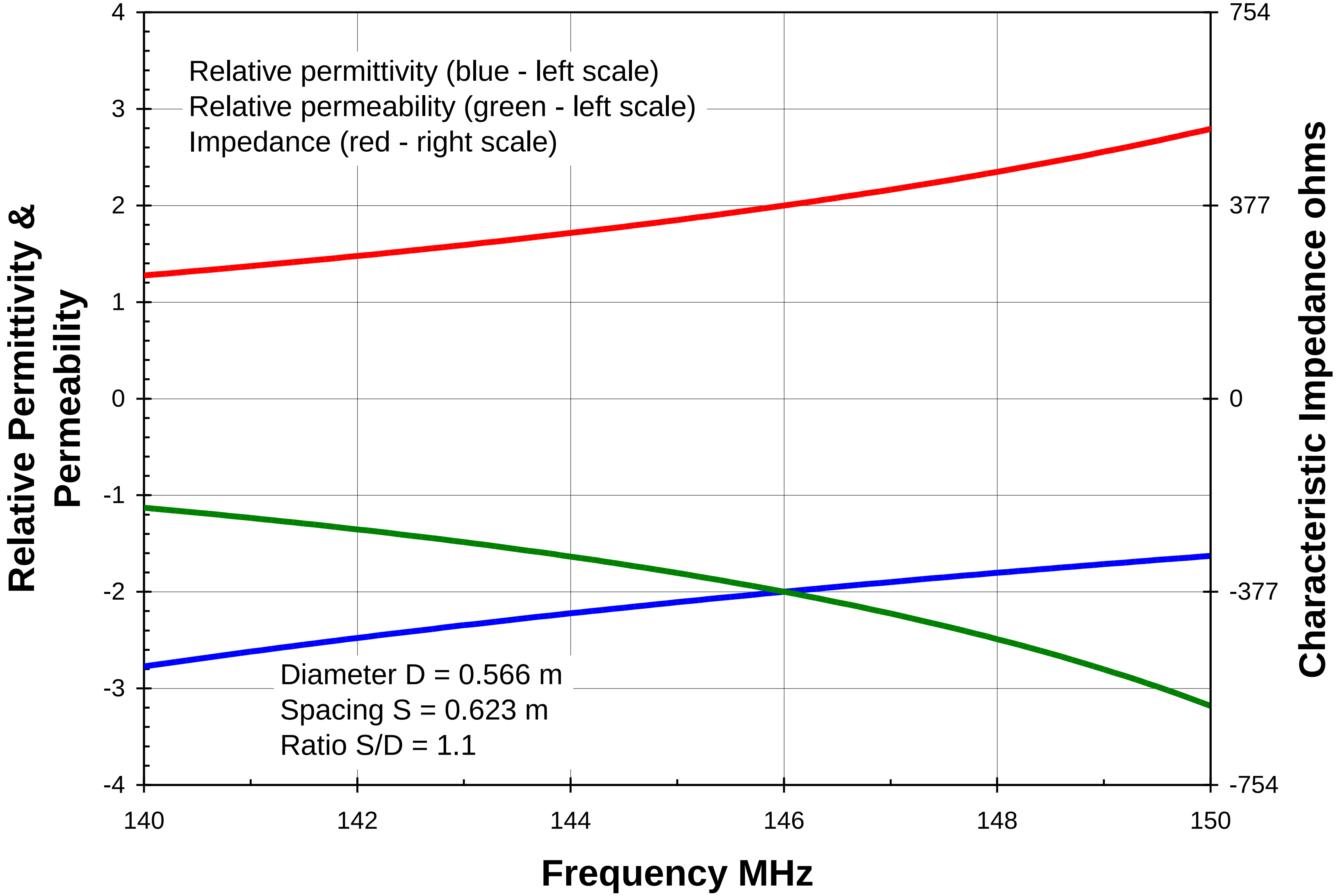


Music of the Spheres – TM_{10} Mode

$$f_{MHz} = \frac{82.642}{D_{meters}} = \frac{3,254}{D_{in}}$$

Frequency MHz	52	146	223	445	915	1270	2375	5790	10,000	24,000
Diameter inches	62.6	22.3	14.6	7.31	3.56	2.56	1.37	0.562	0.325	0.136

Metamaterial for 2-Meters
Using Conducting Spheres in Air



Spheres for Microwave Frequencies

$$D = 4.5\,\text{mm}$$
$$= 0.177\,\text{in.}$$
$$f_{TM_{10}} = 18.4\,\text{GHz}$$

$$D = 15.9\,\text{mm}$$
$$= 0.625\,\text{in.}$$
$$f_{TM_{10}} = 5.21\,\text{GHz}$$

Spheres for UHF Frequencies

Paint with
GC Electronics *Silver Print*

$$D = 40\,\text{mm}$$
$$f_{TM_{10}} = 2.07\,\text{GHz}$$

$$D = 42.7\,\text{mm}$$
$$f_{TM_{10}} = 1.94\,\text{GHz}$$

Inspired by Rob Hill

Spheres for VHF & UHF Frequencies

$D_{rated} = 4\ \text{in.}$	$D_{rated} = 9\ \text{in.}$	$D_{rated} = 11\ \text{in.}$	$D_{rated} = 36\ \text{in.}$
$D_{eff} = 2.55\ \text{in.}$	$D_{eff} = 5.73\ \text{in.}$	$D_{eff} = 7.00\ \text{in.}$	$D_{eff} = 22.9\ \text{in.}$
$f_{TM_{10}} = 1.28\ \text{GHz}$	$f_{TM_{10}} = 568\ \text{MHz}$	$f_{TM_{10}} = 465\ \text{MHz}$	$f_{TM_{10}} = 142\ \text{MHz}$

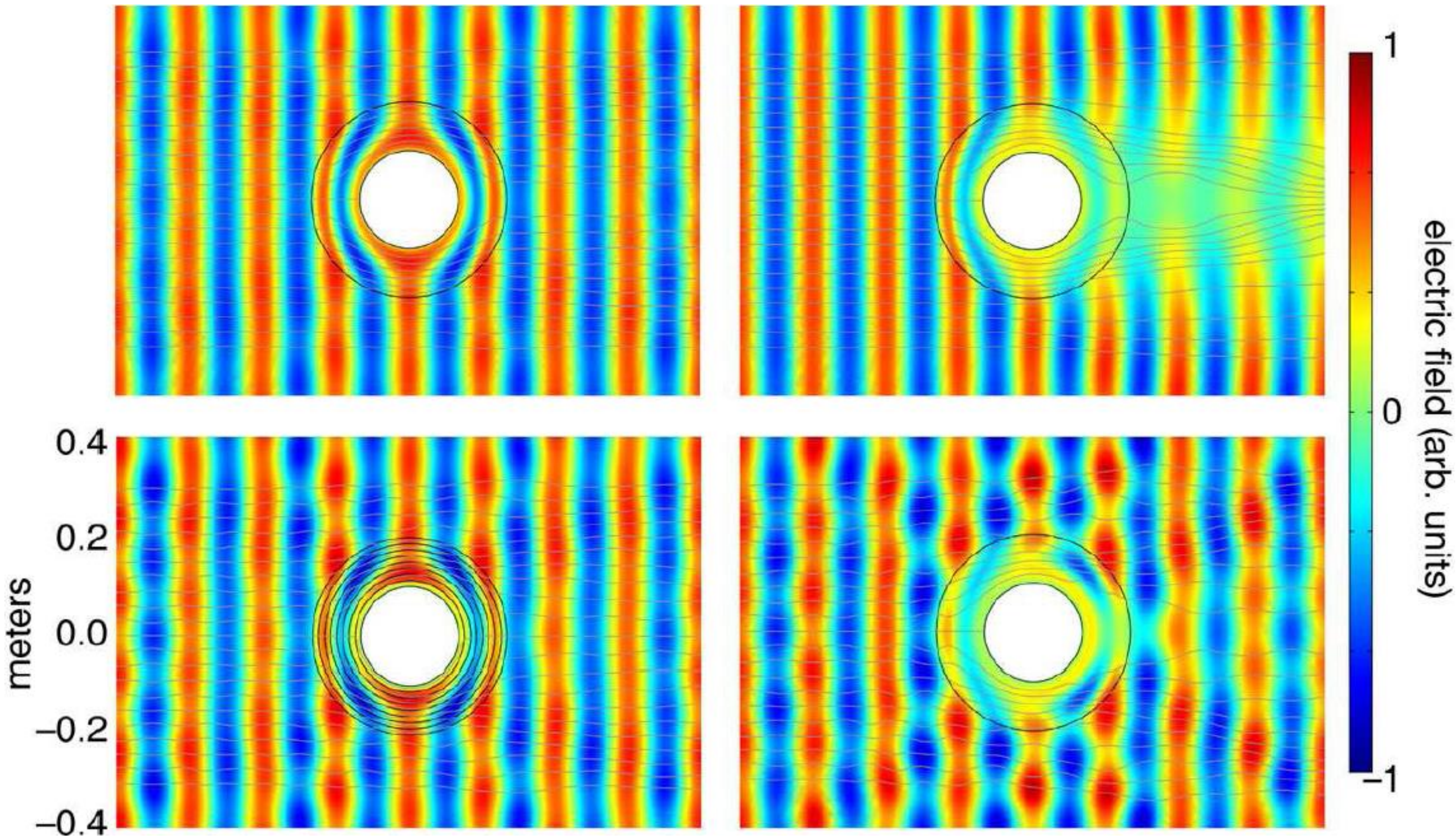
The Final Frontier

Electromagnetic Cloaking

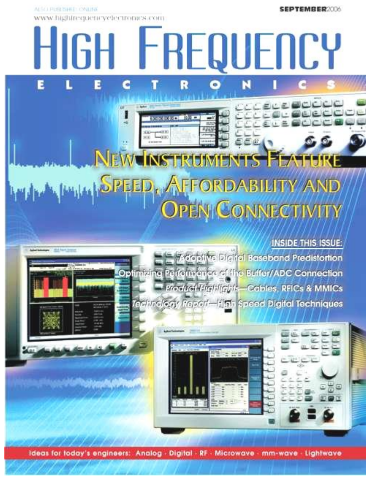
Electromagnetic Cloaking

- **Idea introduced in the *Star Trek* television series, episode 9, on December 15, 1966, which featured a Romulan Bird Of Prey**
- **Neither surface impedance matching nor object transparency are sufficient for invisibility**
- **Scattered and reaction fields must be controlled**
- **Physics of cloaking published in May and July 2006**
- **Two methods are possible using metamaterials**
  - Reflection cloaking
  - Surround or conformal cloaking
- **The latter appears to be feasible and practical**
- **Cloak bandwidth set by metamaterial properties**
- **Objects inside the cloak cannot see or communicate out at the cloaked wavelengths but can communicate out at other wavelengths**
- **Applications: radar invisibility (avoid traffic tickets), stealth antennas...?**

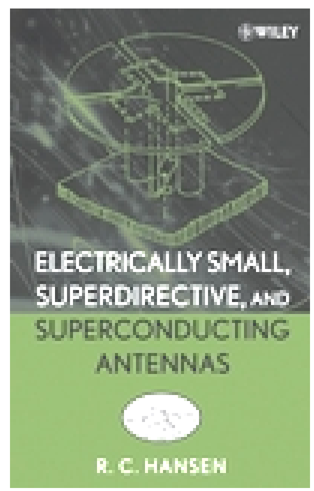
Computer Simulations of Cloaking at 3 GHz



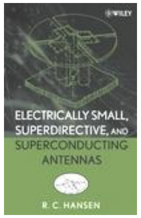
Good Reading

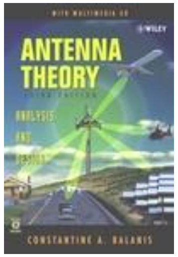


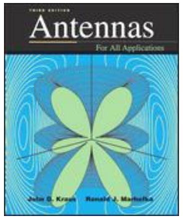
- *High Frequency Electronics*
  http://www.highfrequencyelectronics.com
- *QEX*
  http://www.arrl.org/qex
- R.C. Hansen, *Electrically Small, Superdirective, and Superconducting Antennas*, Wiley, 2006, ISBN 0471782556



Favorite Antenna Books

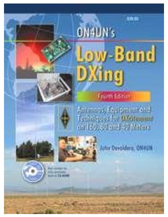


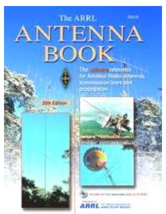


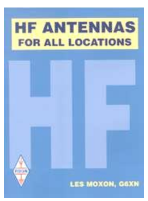


- **Books for antenna engineers and students**
  - R.C. Hansen, *Electrically Small, Superdirective, and Superconducting Antennas*, Wiley, 2006, ISBN 0471782556.
  - C.A. Balanis, *Antenna Theory*, 3rd ed., Wiley, 2005, ISBN 047166782X. First published in 1982 by Harper & Row.
  - J.D. Kraus and R.J. Marhefka, *Antennas*, 3rd ed., McGraw-Hill, 2001, ISBN 0072321032. First published in 1950; 2nd ed. 1988.
  - *Antenna Engineering Handbook*, 3rd ed., R.C. Johnson editor, McGraw-Hill, 1993, ISBN 007032381X. First edition published in 1961, Henry Jasik editor.
  - 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. Download from 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.

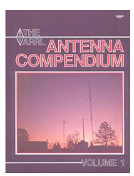
Favorite Antenna Books continued

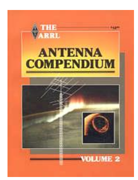




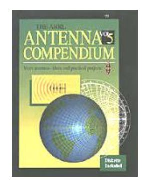


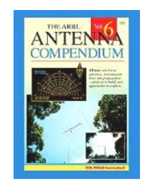
- **Books for radio amateurs**
  - J. Devoldere (ON4UN), *ON4UN's Low-Band Dxing*, 4th ed., American Radio Relay League, 2005, ISBN 0872599140.
  - *ARRL Antenna Book*, 20th ed., Dean Straw (N6BV) editor, American Radio Relay League, 2003, ISBN 0872599043.
  - J. Sevick (W2FMI), *The Short Vertical Antenna and Ground Radial*, CQ Communications, 2003, ISBN 0943016223.
  - J.D. Heys (G3BDQ), *Practical Wire Antennas*, Radio Society of Great Britain, 1989, ISBN 0900612878.
  - 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**

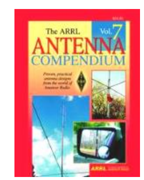




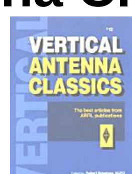
OOP

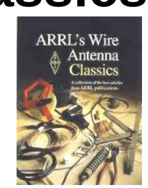


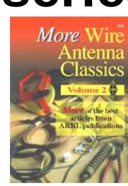


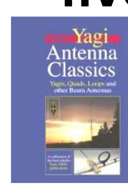


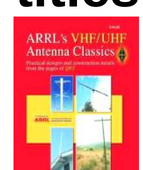
- **ARRL Antenna Classics series – five titles**











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- **Fundamental limits**
  - R.M. Fano, *Theoretical Limitations On the Broadband Matching of Arbitrary Impedances*, doctoral dissertation, Massachusetts Institute of Technology, May 1947. Published in condensed form as a two-part paper in *Journal of the Franklin Institute*, vol. 249, pp 57-83, Jan. 1950, and pp. 139-154, Feb. 1950.
  - L.J. Chu, “Physical Limitations of Omni-Directional Antennas,” J. *Appl. Physics*, vol. 19, pp. 1163-1175, Dec. 1948.
  - D.M. Grimes and C.A. Grimes, “Minimum Q of Electrically Small Antennas: A Critical Review,” *Microwave and Optical Technology Letters*, vol. 28, no. 3, pp. 172-177, Feb. 5, 2001. Gives the exact expression for the Chu bound.
  - H.J. Carlin and R. LaRosa, “Broadband Reflectionless Matching with Minimum Insertion Loss,” *Modern Network Synthesis*, vol. 1, pp. 161-178, Polytechnic Institute of Brooklyn, New York, 1952.

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- **Interesting antennas**
  - F.M. Landstorfer, “A New Type of Directional Antenna,” *Proc. IEEE Ant. Prop. Soc. Int’l Symp*., session 6, pp. 169-172, Oct. 1976.
  - S.R. Best, “The Radiation Properties of Electrically Small Folded Spherical Helix Antennas,” *IEEE Trans. Antennas Propagat*., vol. 52, no. 4, pp. 953-960, April 2004.
  - G.E. Mueller and W.A. Tyrell, “Polyrod Antennas,” *Bell Sys. Tech. J*., vol. 26, pp. 837-851, Oct. 1947.
  - L.R. Lewis, M. Fasset, and M. Hunt, “A Broadband Stripline Array Element,” *Proc. IEEE Ant. Prop. Soc. Int’l Symp*., pp. 35-37, June 1974. (the Vivaldi antenna)

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  - S.B. Cohn, "Artificial Delay Lenses," sec. 14.6 in *Antenna Engineering Handbook*, 1st ed., Henry Jasik editor, McGraw-Hill, 1961.
  - E.F. Kuester and C.L. Holloway, "Comparison of Approximations for Effective Parameters of Artificial Dielectrics," *IEEE Trans. Microwave Theory Tech*., vol. MTT-58, no. 11, pp. 1752-1755, Nov. 1990.

- **Electromagnetic cloaking**

  - S.A. Cummer, B-I. Poppa, D. Schurig, D.R. Smith, and J. Pendry, "Full-Wave Simulations of Electromagnetic Cloaking Structures," July 2006.
  - U. Leonhard, "Notes on Conformal Invisibility Devices," *New J. Physics*, July 2006.

The End

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