IMPEDANCE MATCHING AND RELATED CONSIDERATIONS
PARTS 1 & 2

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Amateur Radio Club

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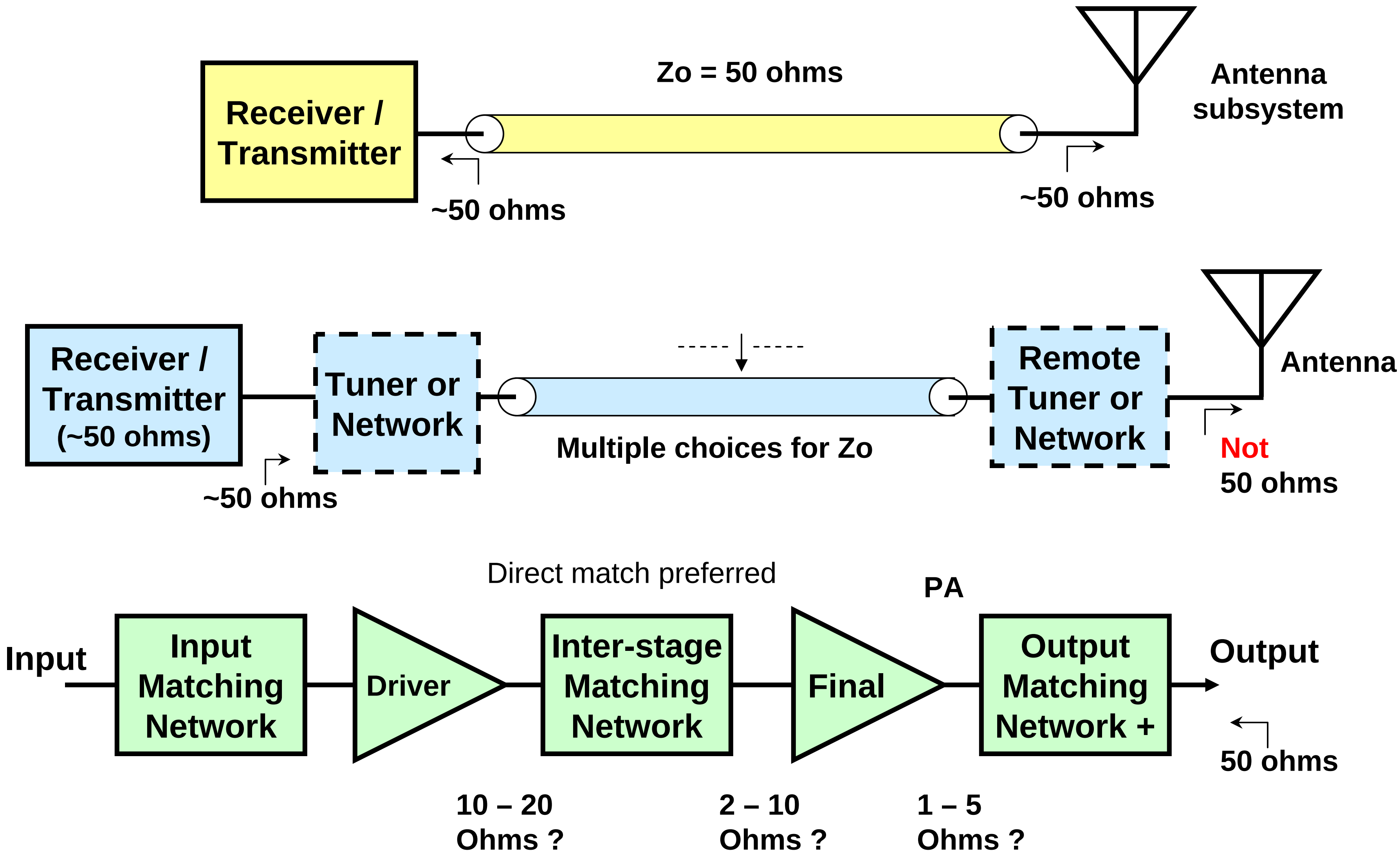
There is no magic in RF: There is a reason for everything
(the reason may not be obvious)

Why Impedance Match

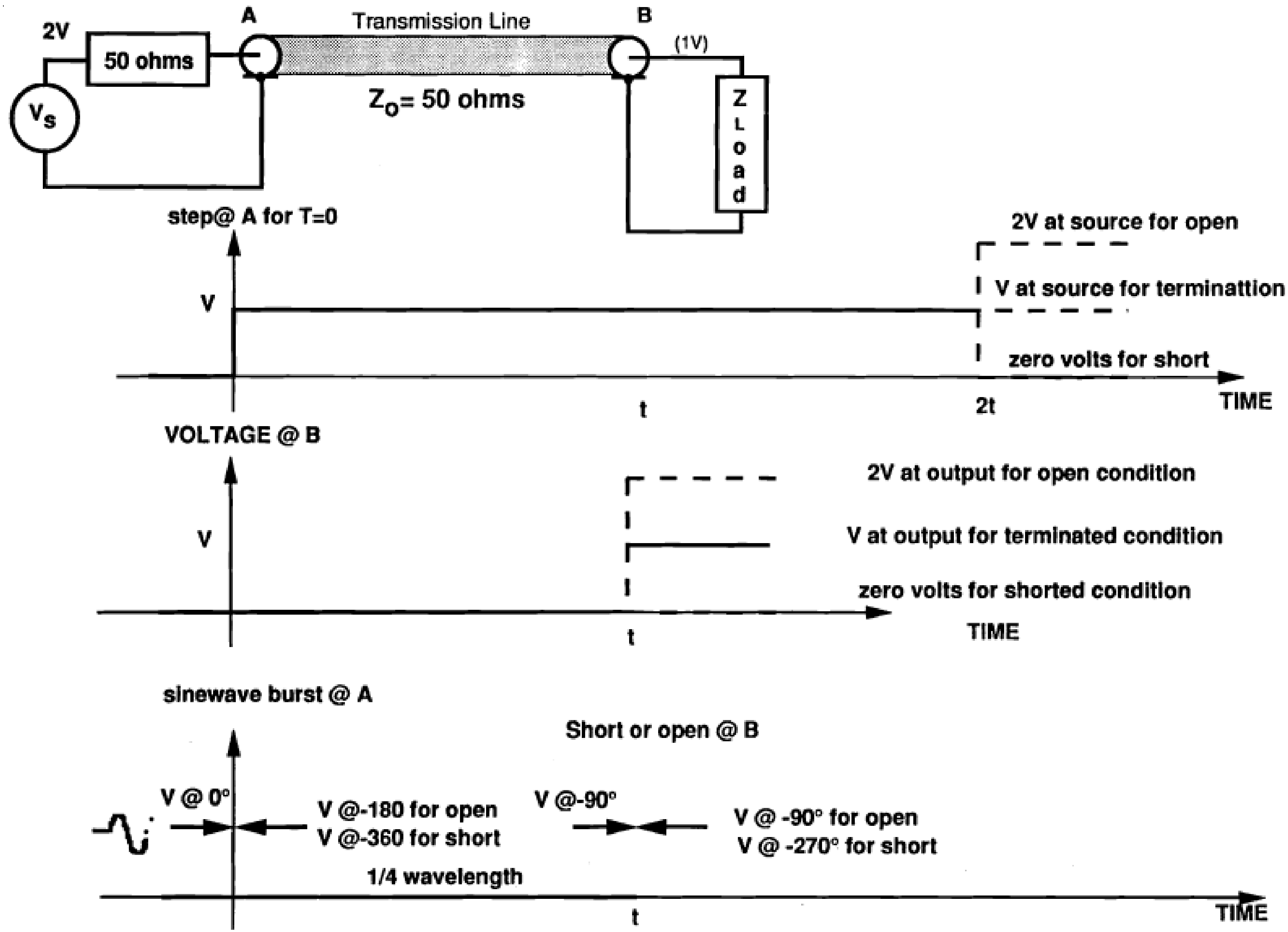
- We use impedance matching circuitry for the following:
  - Transfer power and optimize gain from one RF circuit to another
  - Optimize the transmit power transferred into an antenna
  - Optimize either the signal amplitude or the signal-to-noise level received from an antenna
    - Power match verses Noise match
    - Prefer to achieve simultaneous optimization (ala MRF901)
  - Present a load to a RF device that will cause it to be stable, generate the desired output power, maintain a reasonable spectrum and keep the device in a safe operating condition.
  - Assure oscillators behave as desired (start, freq, amplitude …)
  - Maintain proper filter amplitude, phase and transient response
  - Control the direction of energy flow and efficiency in frequency multiplier circuits
  - Minimize ripple and loss over frequency in transmission lines

Several Tuners and Impedance Measuring Units

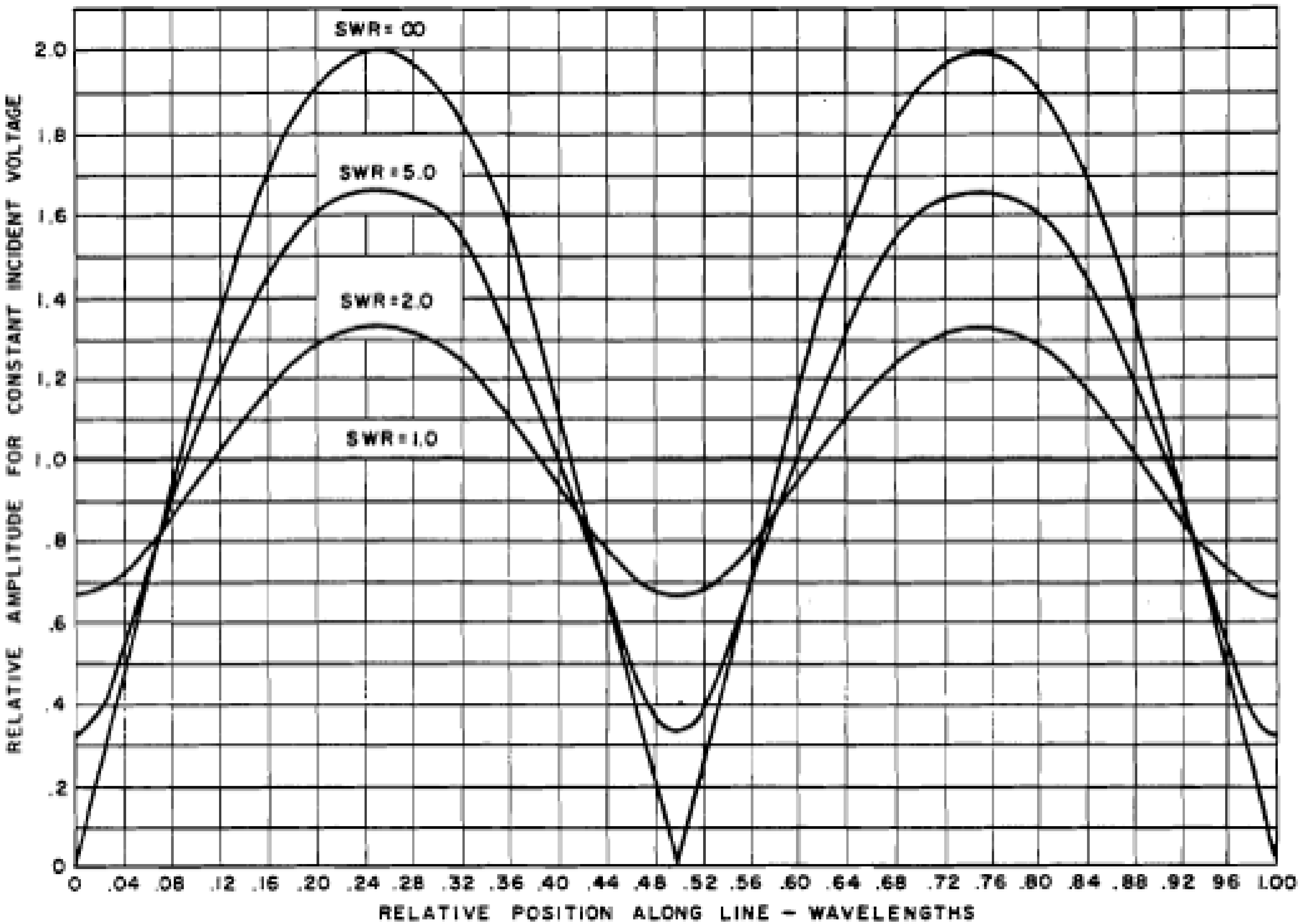
Some Typical Matching Examples



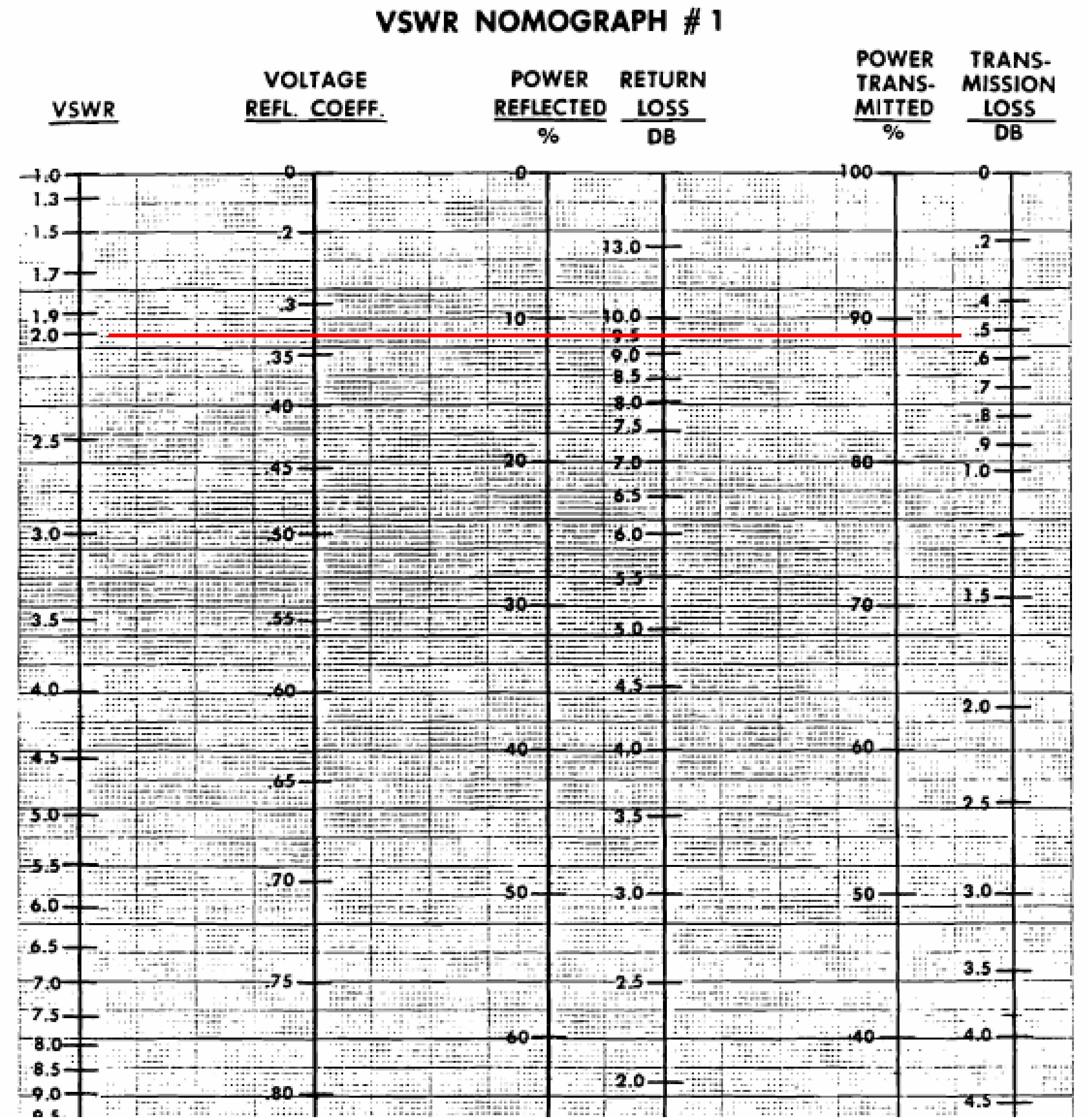
Transmission Line Effects



Example of Standing Wave Ratios



Partial Nomagraph Shows Various Relationships



Draw a horizontal line thru a known condition (2:1 VSWR shown)

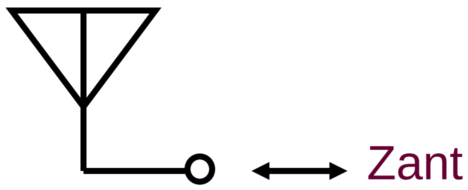
A given mismatch causes an associated reflection which causes an associated set of standing waves.

So for a given VSWR there is a corresponding reflection coefficient and associated return loss.

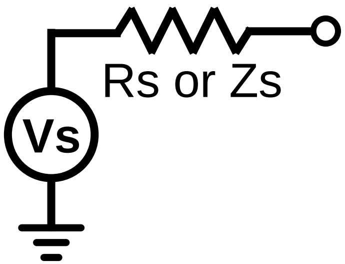
A point is that if you know any one of these you effectively know them all.

The Basics – Source Impedance

Antenna representation



Source representation

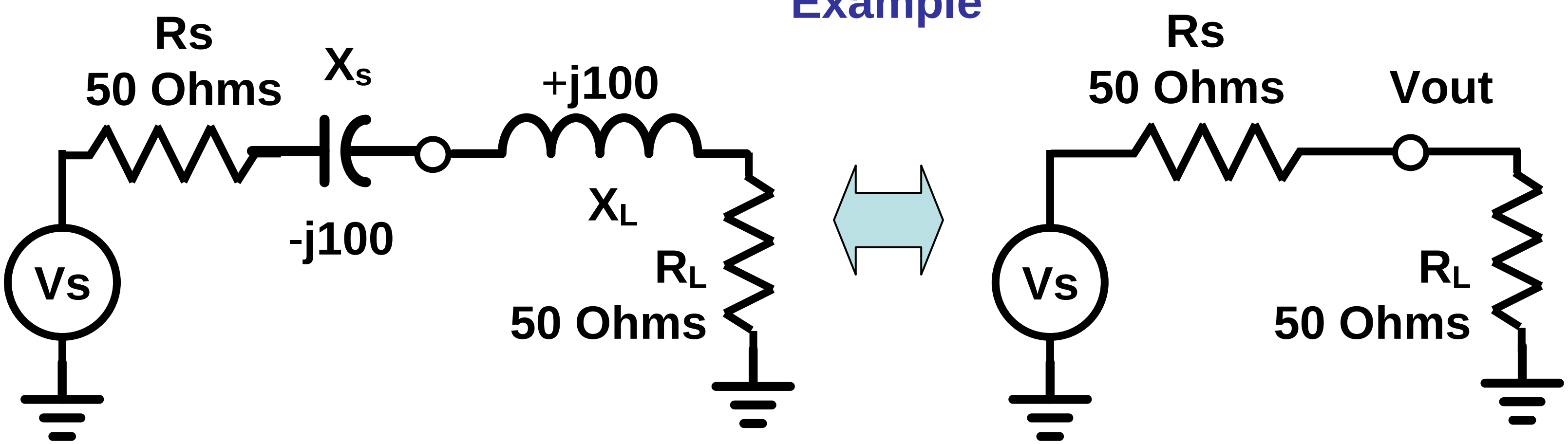


- **Every source of electrical energy has an associated source impedance:**
  - **This included amplifiers, oscillators, multipliers, batteries, generators, wall outlets, and antennas.**
  - **The source impedance may be resistive (R in ohms) or complex (R+-jX)**
  - **Most RF interfaces are designed to be ~50 ohms, or sometimes 75 or 300**
  - **The source impedances of batteries, generators and wall outlets are low, and for safety and voltage reasons the loads are kept relatively high**
  - **The source impedances of power transistors are generally low and require matching up to 50 ohms**
  - **The source impedance of antennas is resistive at resonance but rapidly gets reactive at other frequencies**
    - **The resistive part is a combination of loss resistance and radiation resistance**
- **The maximum amount of energy is extracted from the source when the load is properly matched to the source**

Conjugate Match

- The maximum amount of energy is extracted from the source when the load is a conjugate match to the source (which also means that the source is a conjugate match to the load)
  – The resistive load equals the source resistance.
  – Any reactive load component is equal in magnitude and opposite in sign to the source reactance.
  – So in effect the reactance is canceled out. Note that reactance does not absorb power but it prevents current from getting to the load.

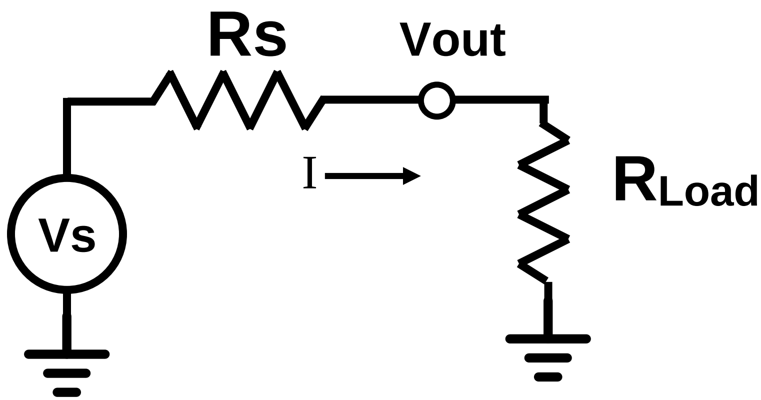
Example



Vout = Vs/2

Miss-match Calculations

Examples:



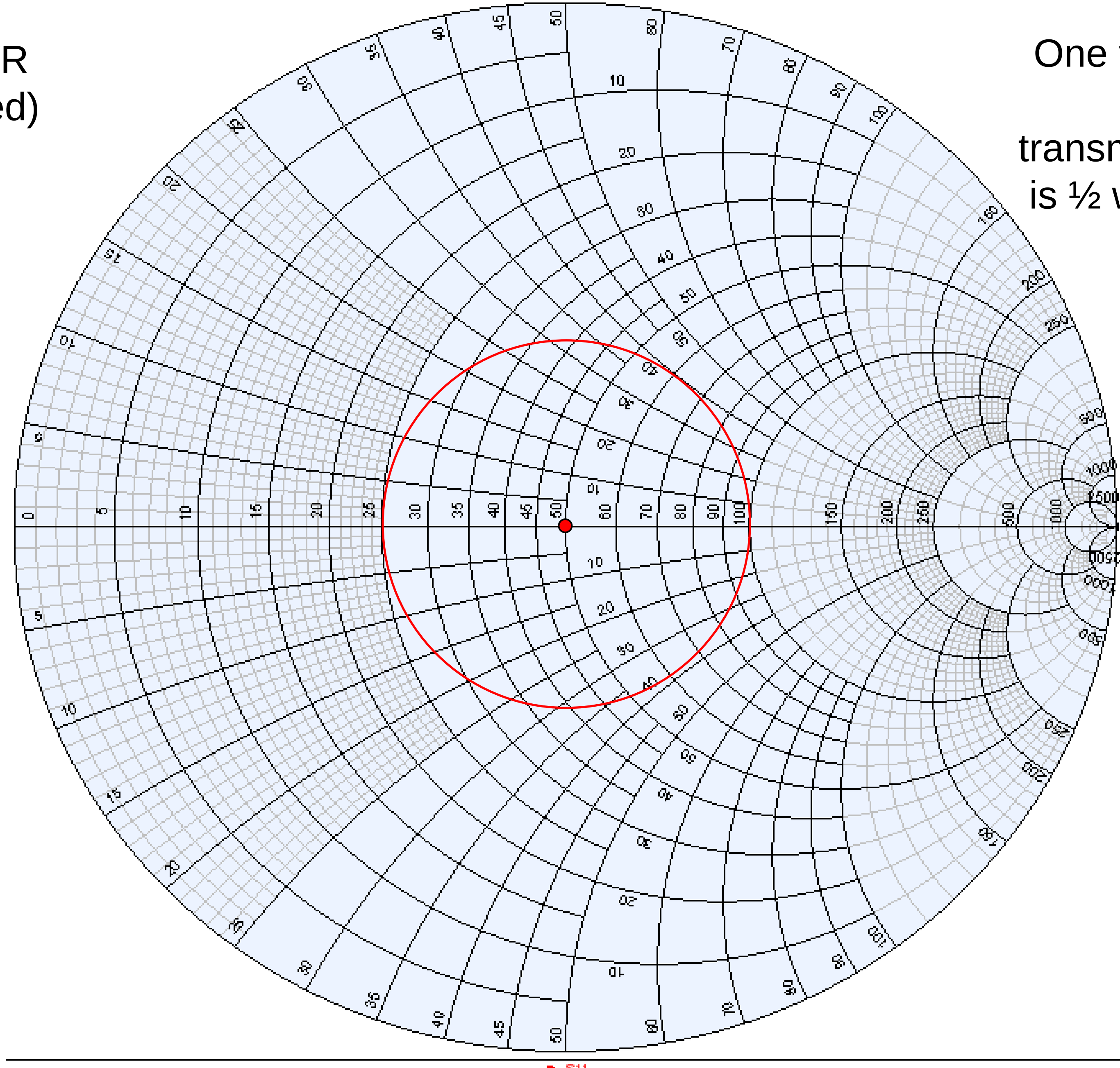
Matched
R_L = Rs

			(1+r)/(1-r)	(Z-Zo)/(Z+Zo)	20 Log r					
				Reflection	**Return**				**10 Log**	
Vs	**Rs**	**Rload**	**VSWR**	**Coefficient**	**Loss**	**Vout**	**Current**	**Pload**	**Pload**	**Change**
(Volts)	(Ohms)	(Ohms)		(ratio r)	(dB)	(Volts)	(Amps)	(Watts)	(dBw)	(Percent)
100	50	50	1.0:1	0.00	-∞	50	1	50	17.0	
14.1	50	50	1.0:1	0.00	-∞	7.07	0.141	1	0.0	
2	1	1	1.0:1	0.00	-∞	1	1	1	0.0	**Ref.**
2	1	**2**	2.0:1	0.33	-9.5	1.33	0.67	0.89	-0.51	-11%
2	1	**0.5**	2.0:1	0.33	-9.5	0.67	1.33	0.89	-0.51	-11%
2	**-0.99**	1	-1.0	199.00	46.0	200	200	40,000	46.0	40000X

Conventional Smith Chart for 50 ohms

2:1 VSWR
Circle (red)

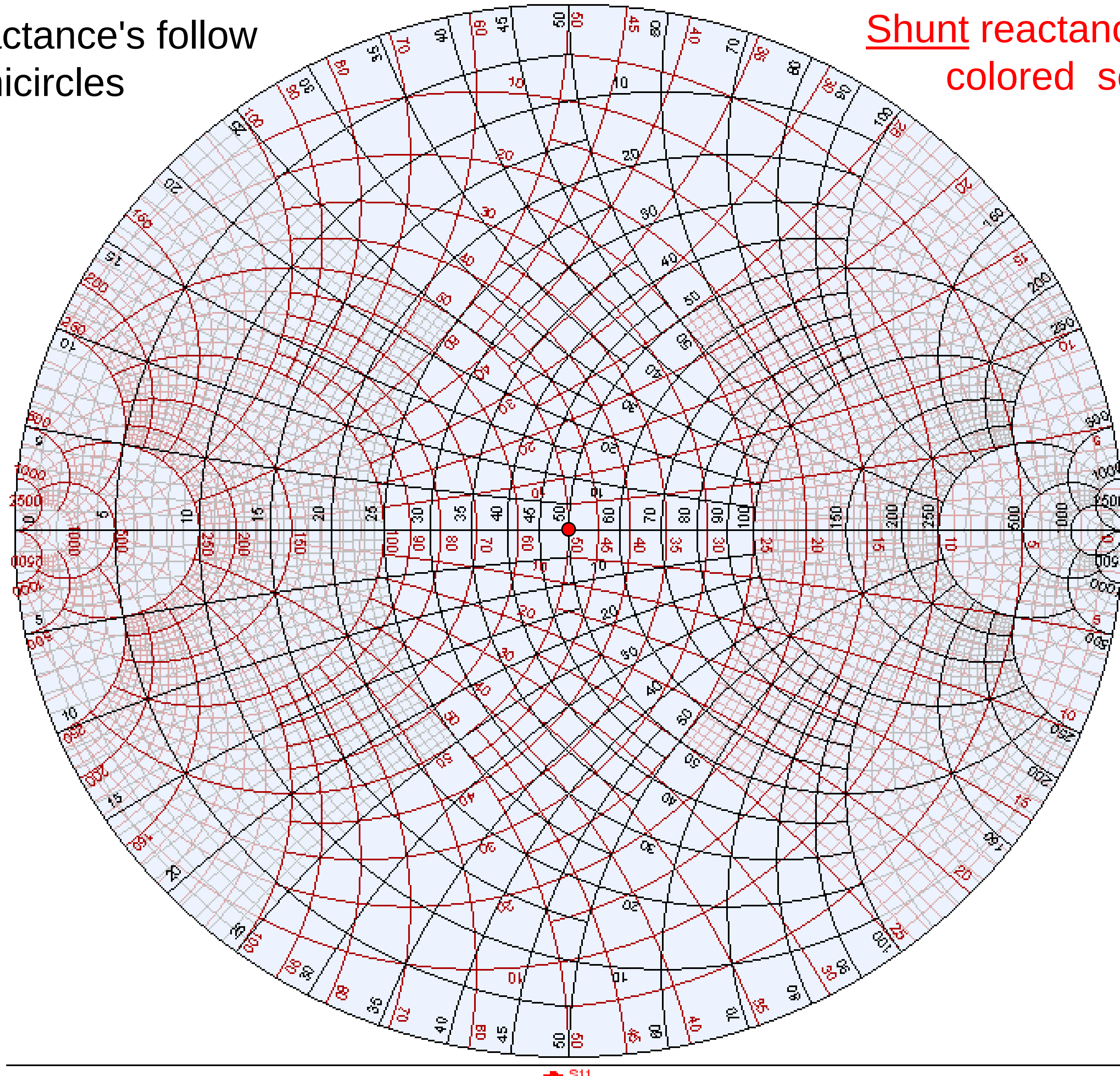
One full rotation
down a
transmission line
is ½ wavelength



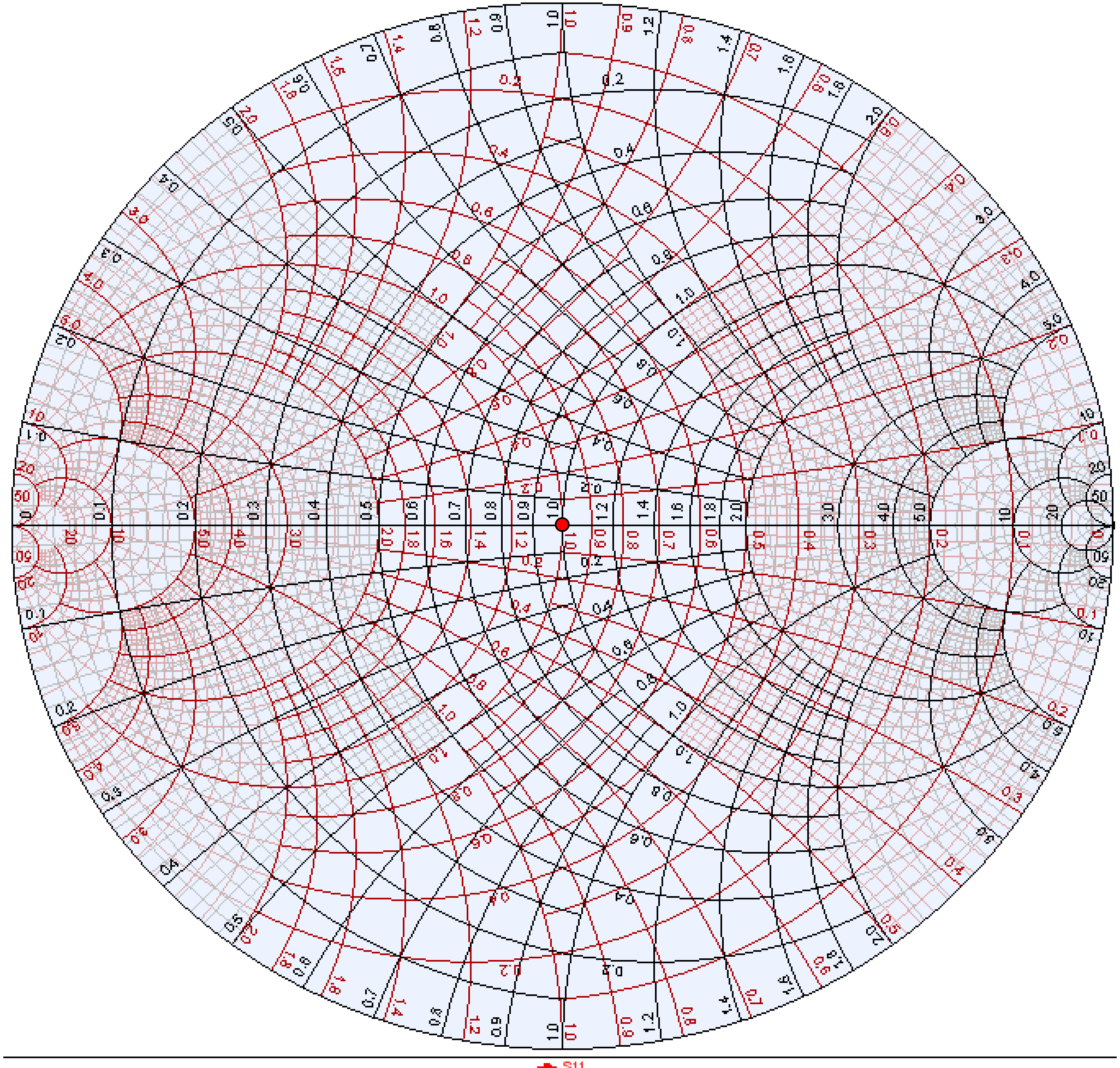
50 Ohm Smith Chart with Admittance Circles

Series reactance's follow
Black semicircles

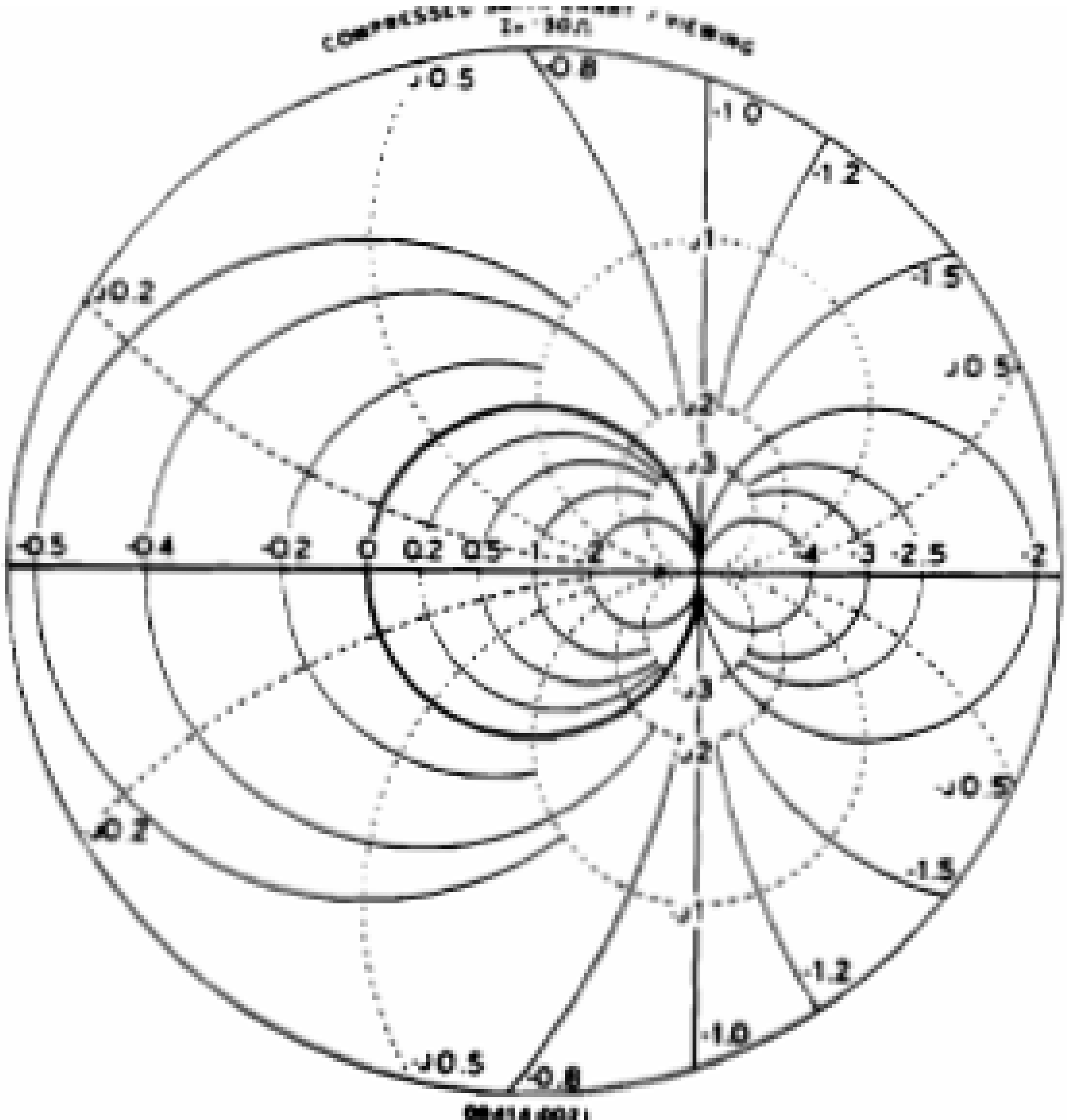
Shunt reactance's follow
colored semicircles



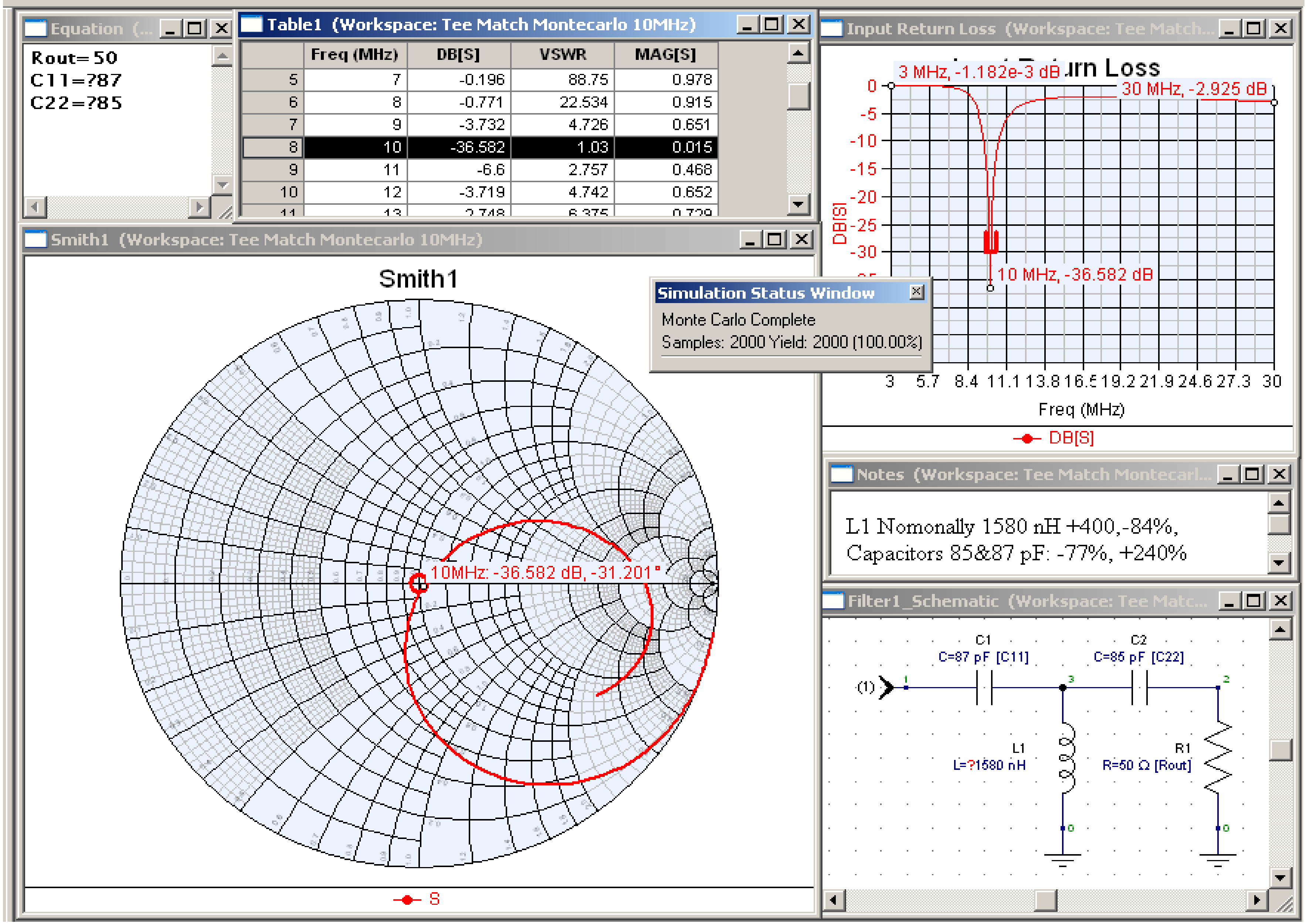
Normalized Smith Chart (1 ohm center)



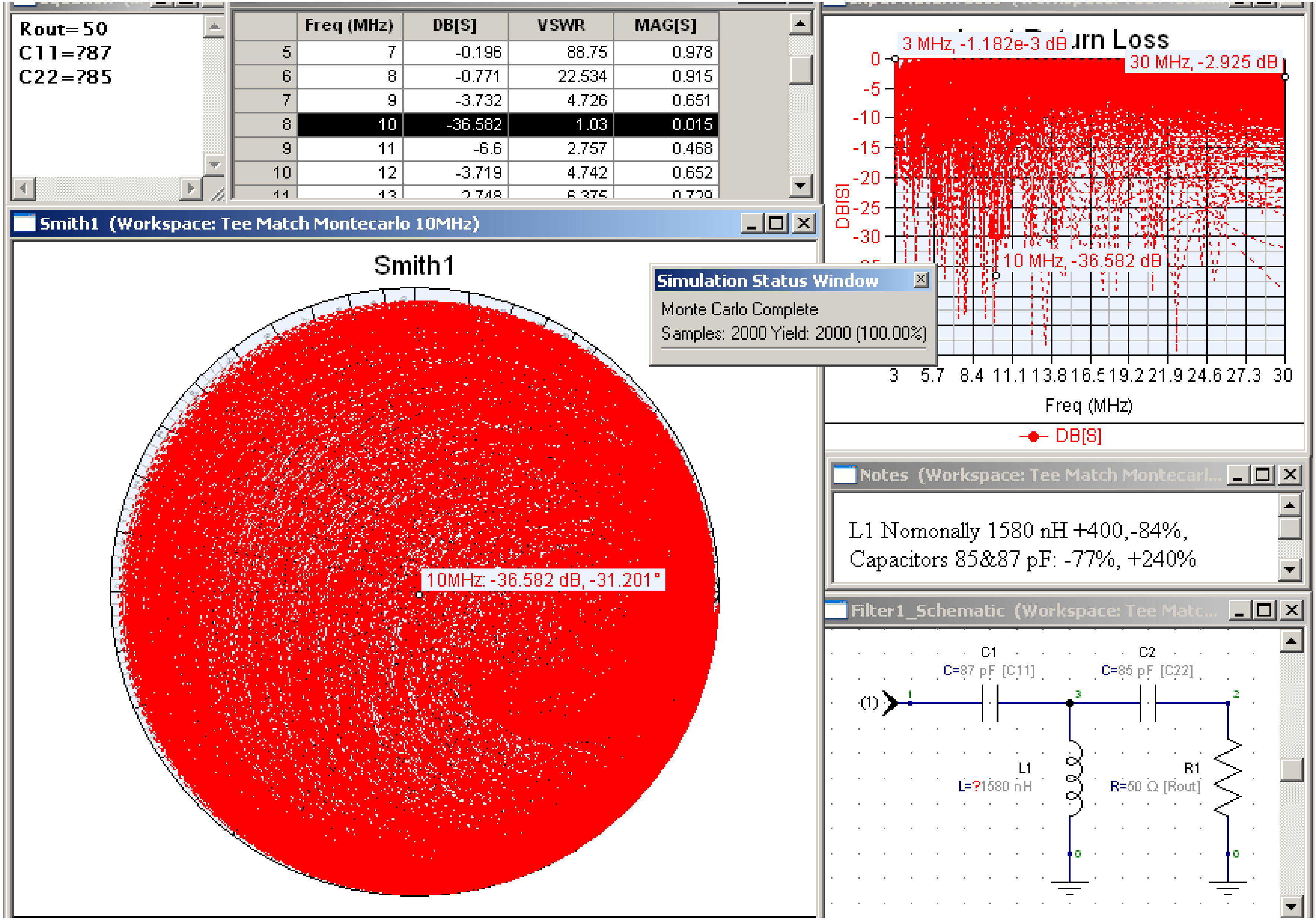
Compressed Smith Chart Shows Negative Impedances



Tuner Analysis (Tee Match) 3 to 30 MHz



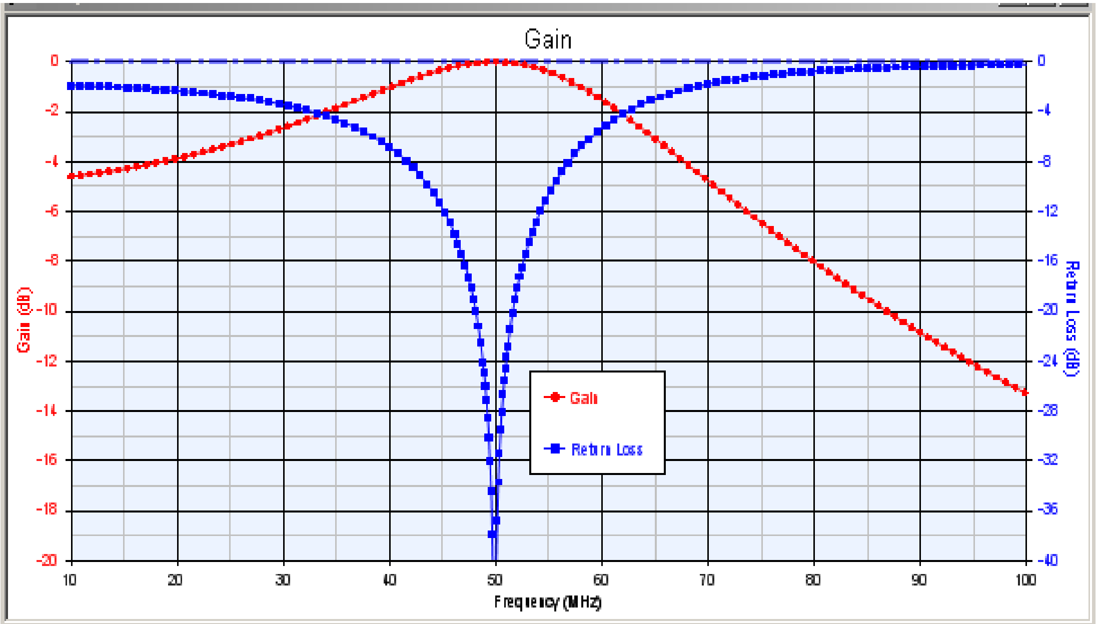
Tee Match: Monte Carlo Run, 3 to 30 MHz

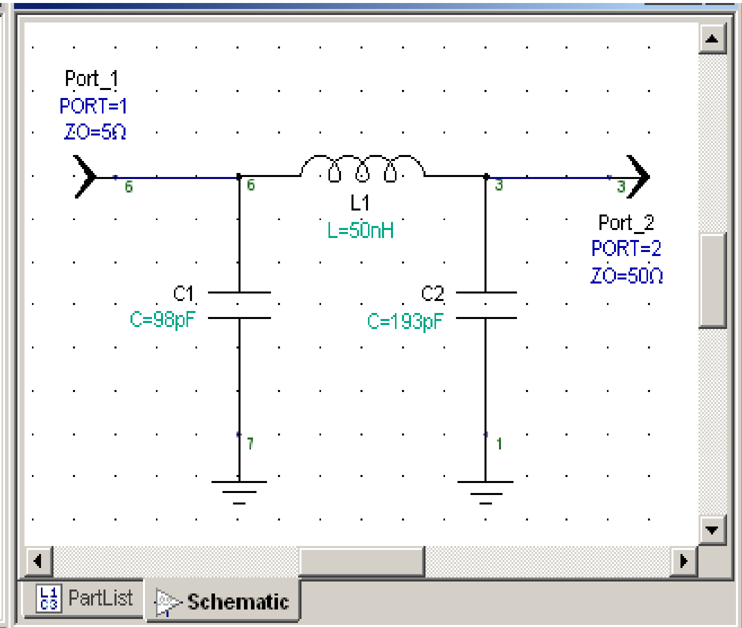


Matching Circuits

- Implementation
  - Hi pass or low pass configurations
  - Lumped or distributed components
  - Transformer implementations (often broadband)
    - Conventional
    - Autotransformers (tapped inductors)
    - Transmission line and toroidal wound
  - Transmission line matching circuits
- Passive matching circuits are reciprocal
  - Meaning that if you are matched in one direction, you are matched in the other
- Active matching circuits take advantage of device characteristics and often negative feedback
  - Example: Emitter followers translate high to low

Pi Match: 5 Ohms to 50 Ohms, Well behaved over 5% Bandwidth





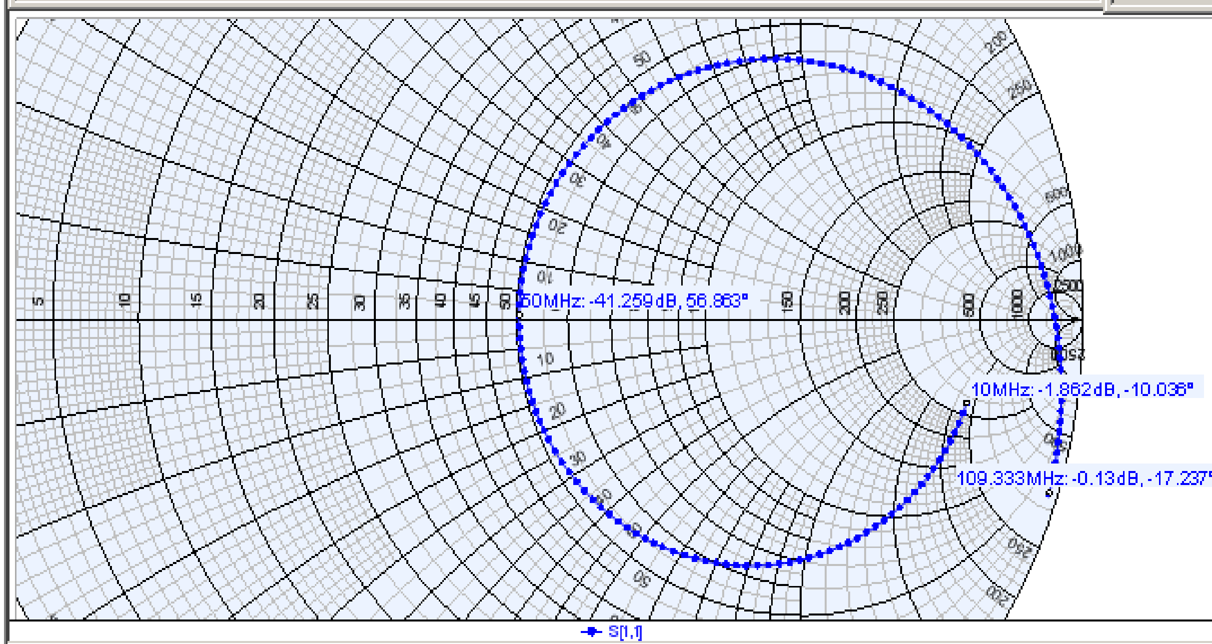
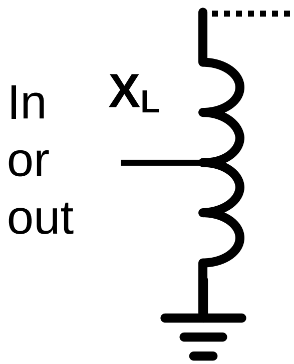


Table1

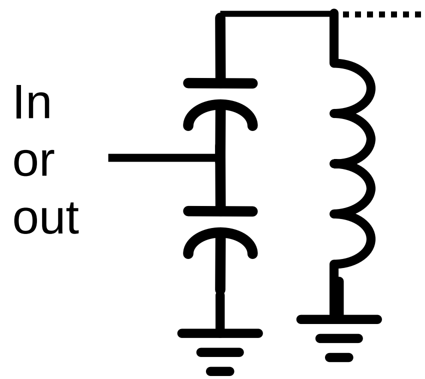
	F	Loss	Return Loss	VSWR1
1	43	-0.554	-9.218	2.058
2	44	-0.42	-10.352	1.872
3	45	-0.3	-11.757	1.697
4	46	-0.196	-13.551	1.532
5	47	-0.111	-15.964	1.379
6	48	-0.049	-19.517	1.236
7	49	-0.011	-25.979	1.106
8	50	-352.7e-6	-41.262	1.017
9	51	-0.019	-23.628	1.141
10	52	-0.068	-18.081	1.285
11	53	-0.149	-14.726	1.45
12	54	-0.261	-12.34	1.637
13	55	-0.404	-10.51	1.85
14	56	-0.577	-9.048	2.09

Various Matching Techniques

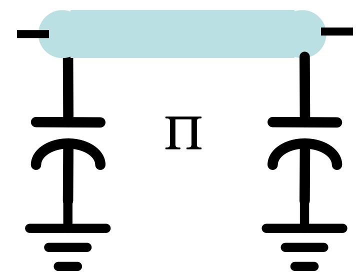
Tapped Inductor (autotransformer)



Split C

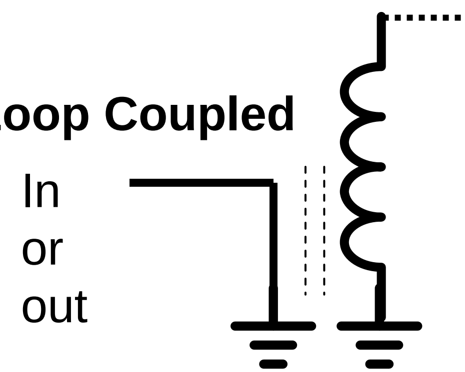


Microstrip L

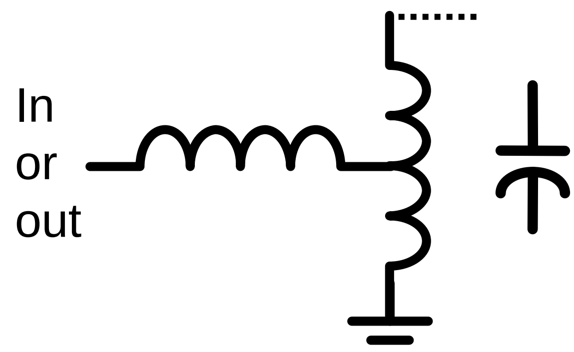


Also many different high and low pass LC ladder networks

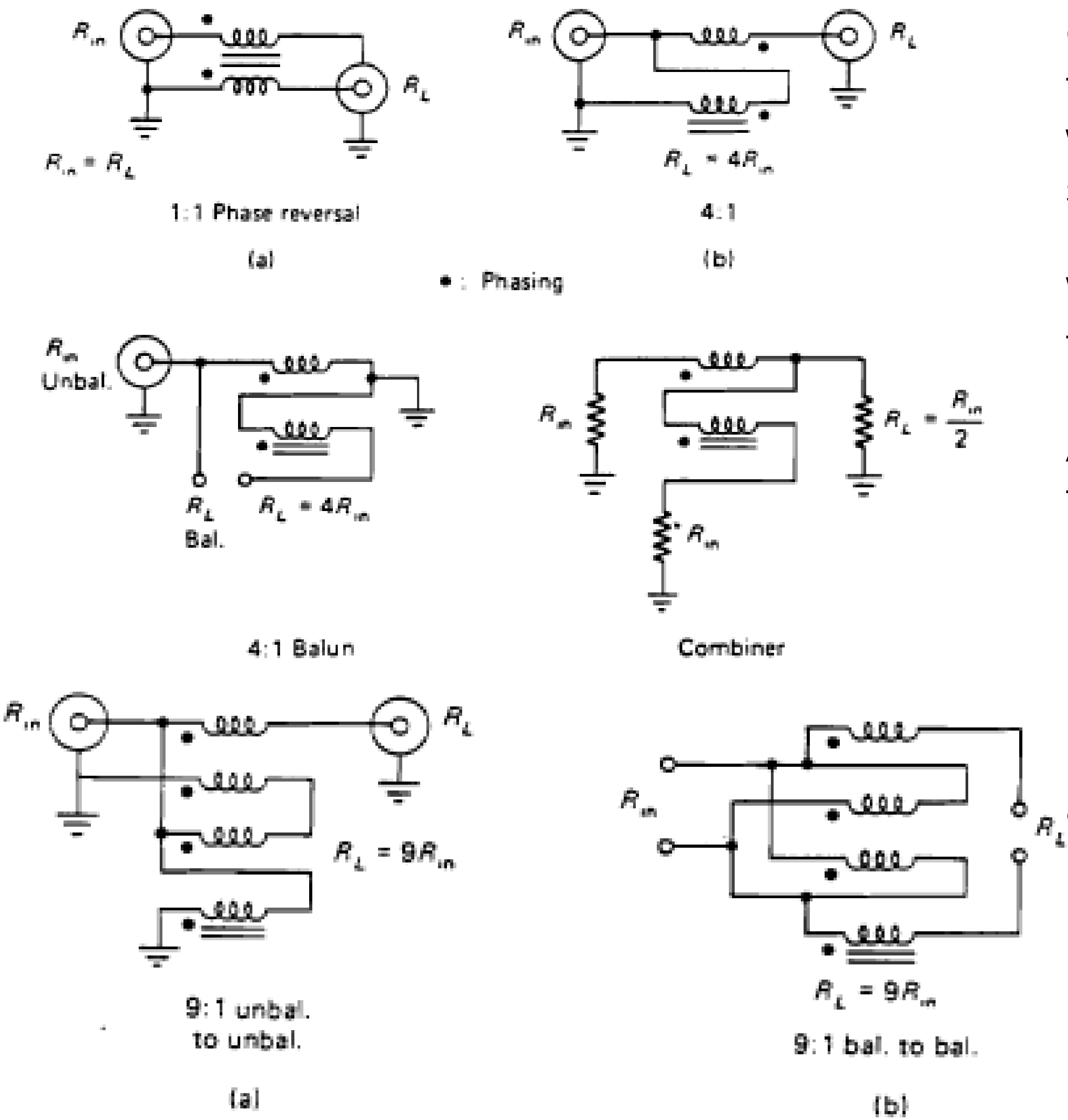
Loop Coupled



For Varactor Tuned Filters



Bifilar and Quadfilar Transformer Configurations



Other configurations such as trifilar and shotgun bead wound transformers not shown, also 16:1(Z)

Wires are twisted together and then wound around cores

Amidoncorp.com is a source for cores, also Partandkits.com

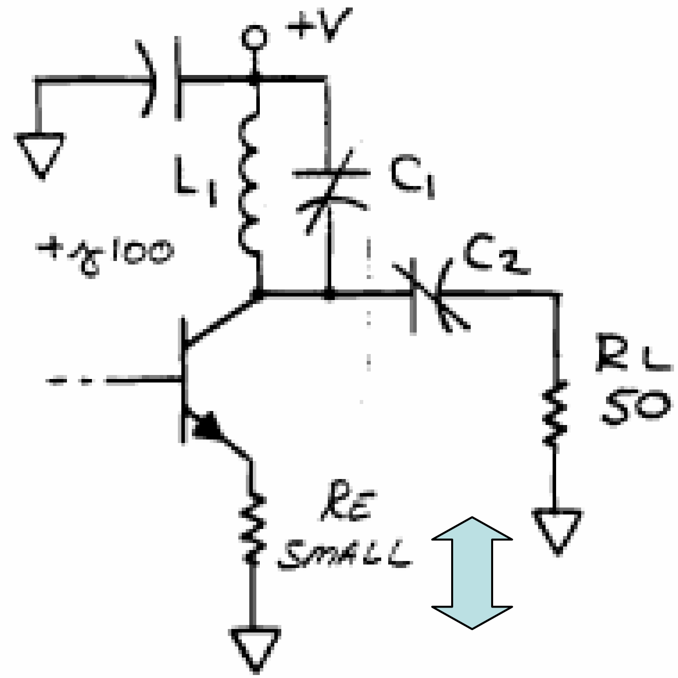
Lower perm cores work at higher frequencies

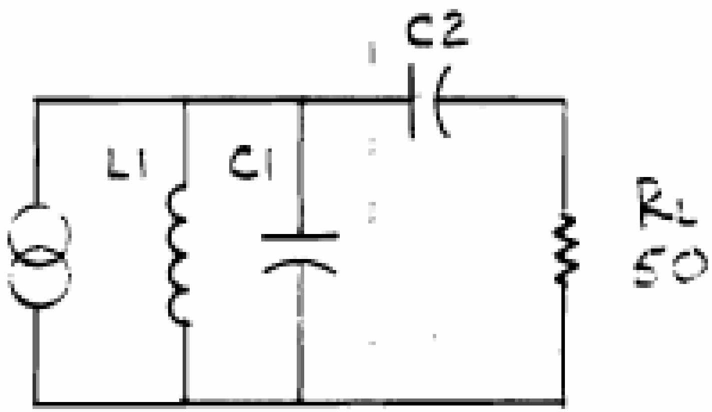
Decade plus bandwidths are achievable – involves art.

Larger cores for more power

Directional couplers

Basic L Match & Series/Parallel Transformations



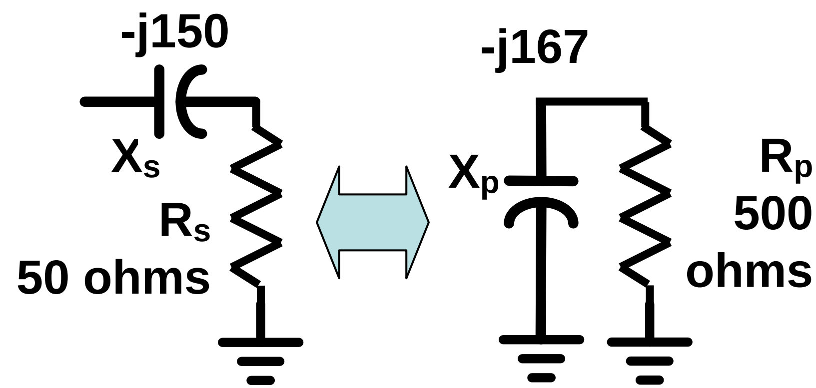


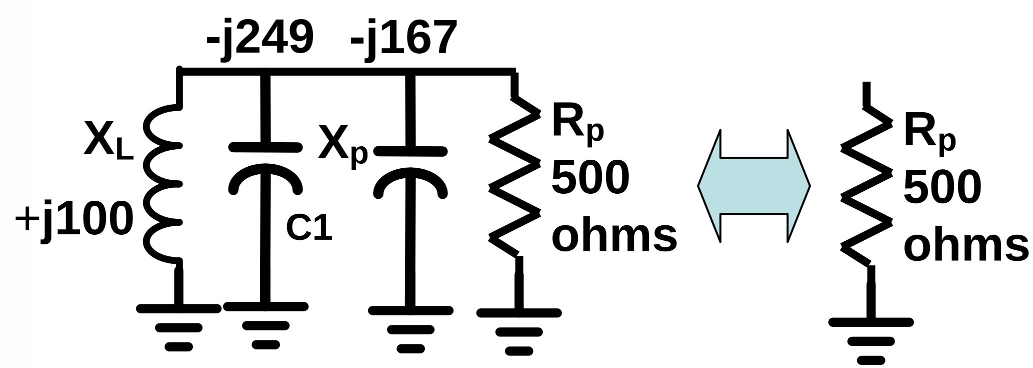
Conversions

$$Q = Xp/Rp = Xs/Rs$$

$$Rp = Rs\ (1+Q^2)$$

$$Xp = Xs(Q^2+1)Q^2$$





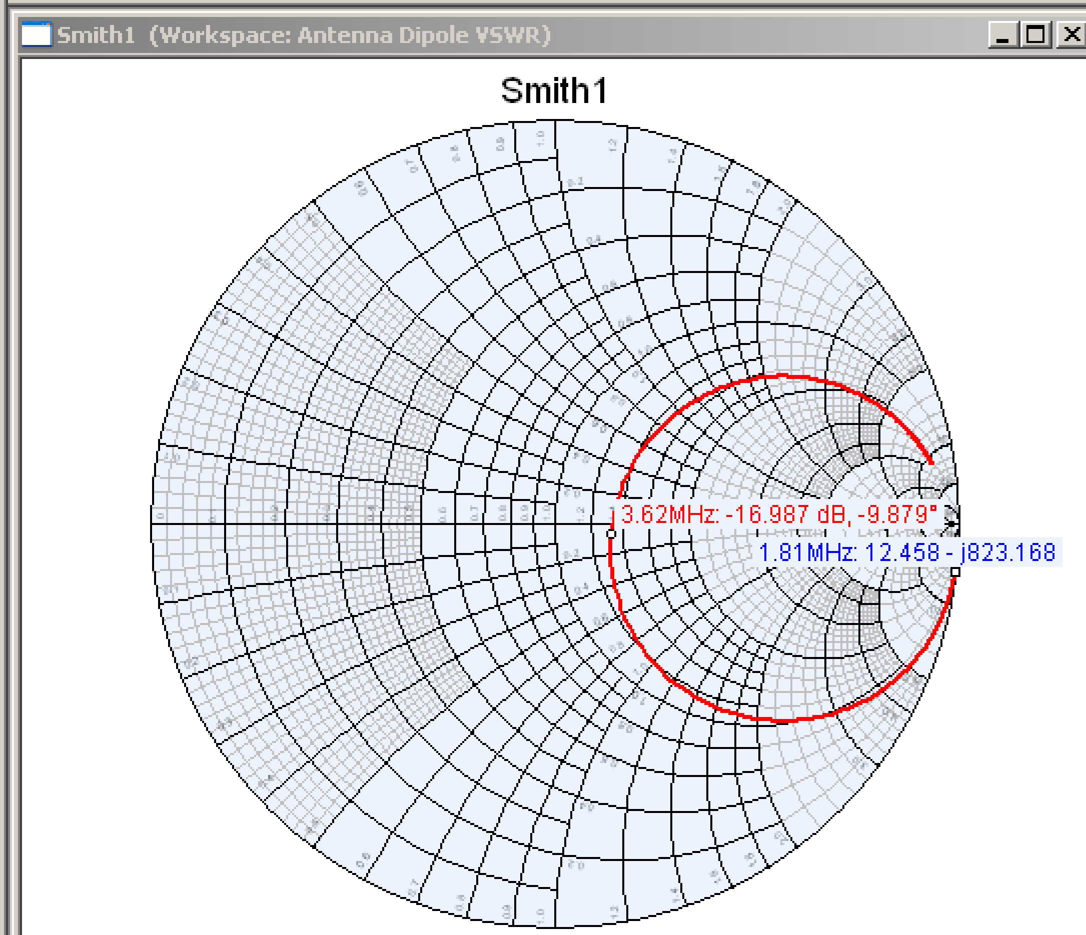
Q_L=5

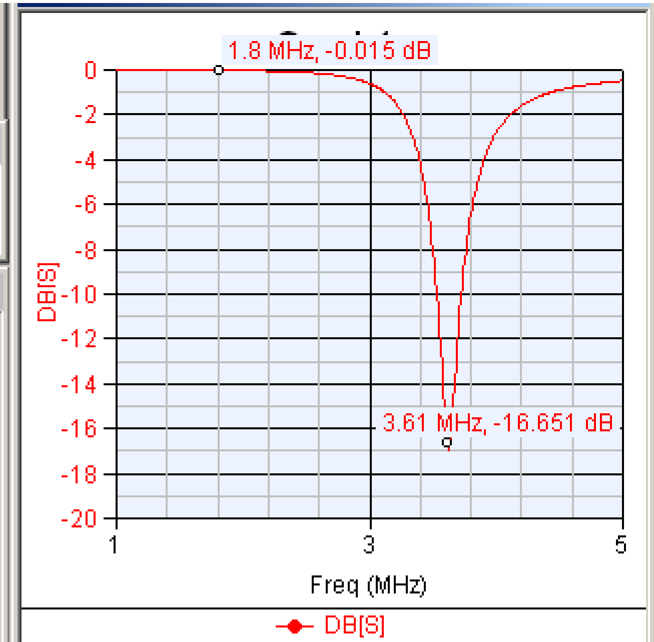
80 Meter Dipole Impedance at 80 &160 Bands

	Freq (MHz)	DB[S]	VSWR	MAG[S]	RE[ZIN]	IM[ZIN]
1	1.81	-0.016	1092.051	0.998	12.458	-823.168
2	3.62	-16.987	1.33	0.141	66.102	-3.274

Notes (Workspace: Antenna Dipole VSWR)

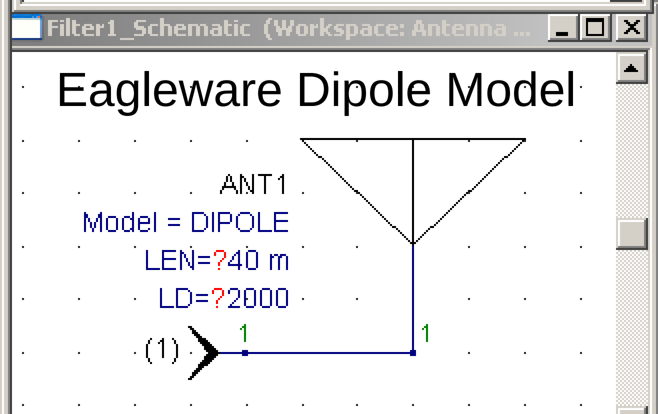
Dipole: total length in meters, note that dipoles are half a wavelength long so a 40 meter physical length goes with 80 meter (3.6 MHz) operation.





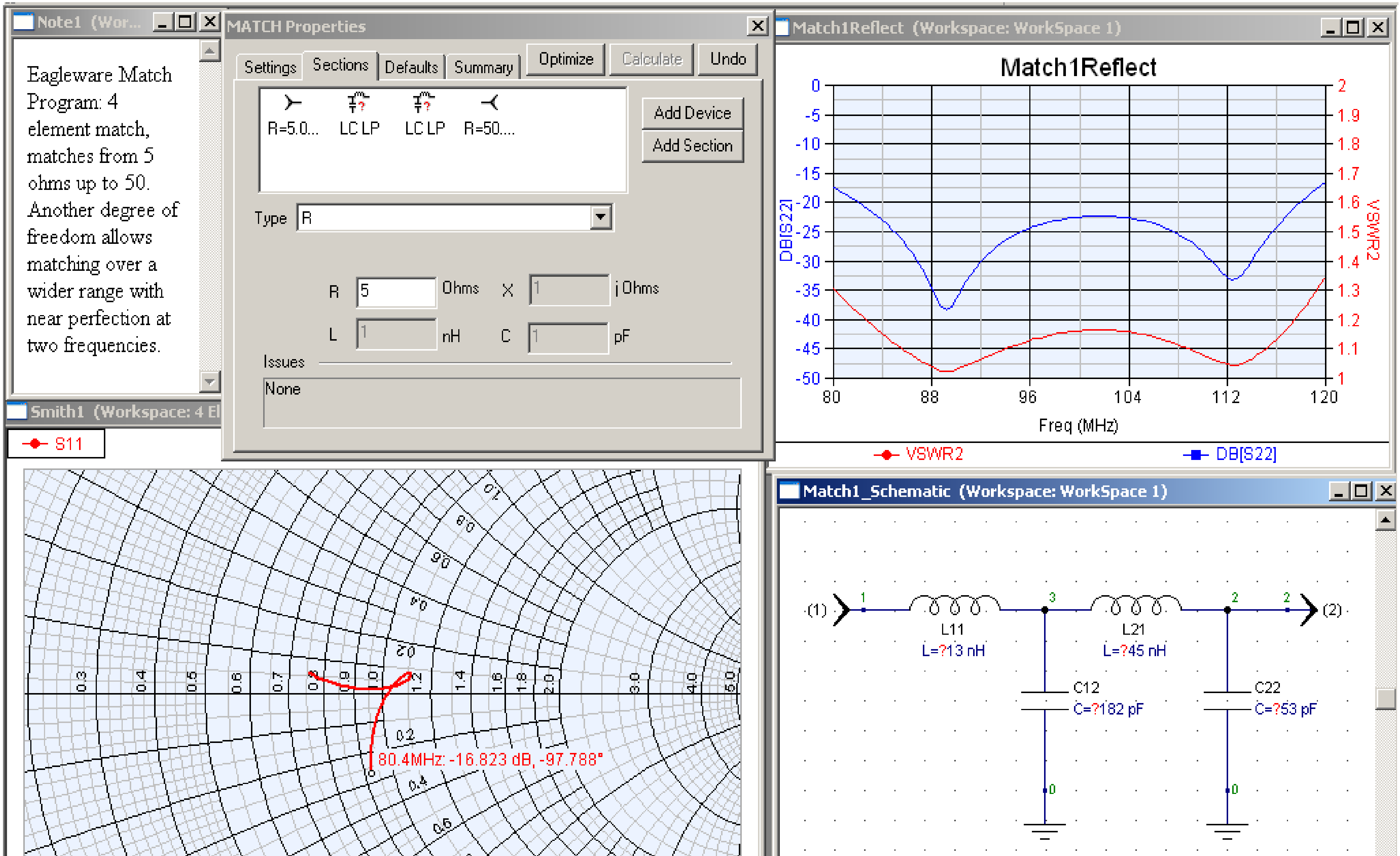
Note2 (Workspace: Antenna Dipole VSW...

1.81 MHz goes with 160 meter operation



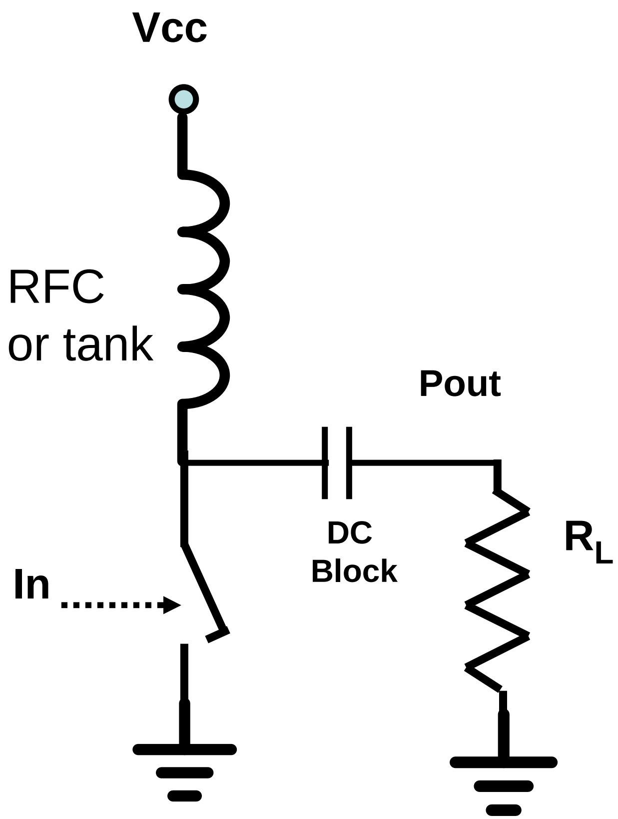
L/D ratio = 12480 so 1/8”, 40 meters

4 Element Match Done on Eagleware Match Program



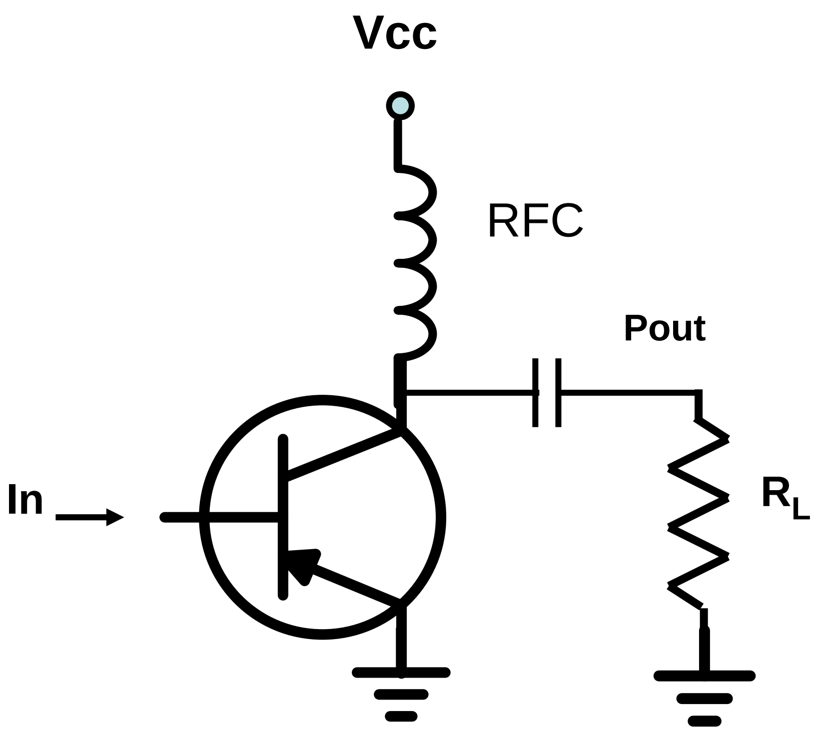
More elements ⇒ wider match

High Frequency Switching Amplifier



- Switch toggles at RF input frequency
- Highly efficient:
  - No voltage when switch is on so no device dissipation
  - No Current when switch is open so no device dissipation
- Question: Output is either open or short so match to what impedance?
- Answer: Make RL what it needs to be to get the output power

Matching to Active Amplification Devices



Base circuit not shown

Probably should have shown a tank circuit instead of an RF Choke.

- **Pout = Vcc ^{2} / 2R_L**

$$P_{out} = \frac{V_{cc}^2}{2R_L}$$

- Useful approximation
- Note that 2X on R_L like in 2:1 VSWR is half power, 3 dB down, not half a dB
- Also not that ½ RL like in 2:1 VSWR is twice power if the transistor doesn't self destruct
- Overall transmitters are sensitive to load and usually have VSWR sensors

P/O Matching Application Note AN267

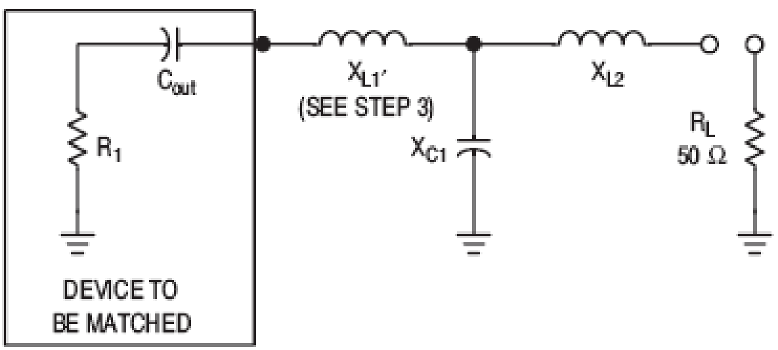
Google AN-267

Freescale Semiconductor, Inc.

AN267

NETWORK D

The following is a computer solution for an RF “Tee” matching network.
Tuning is accomplished by using a variable capacitor for C_1.
Variable matching may also be accomplished by increasing X_{L2} and adding an equal amount of X_C in series in the form of a variable capacitor.



TO DESIGN A NETWORK USING THE TABLES

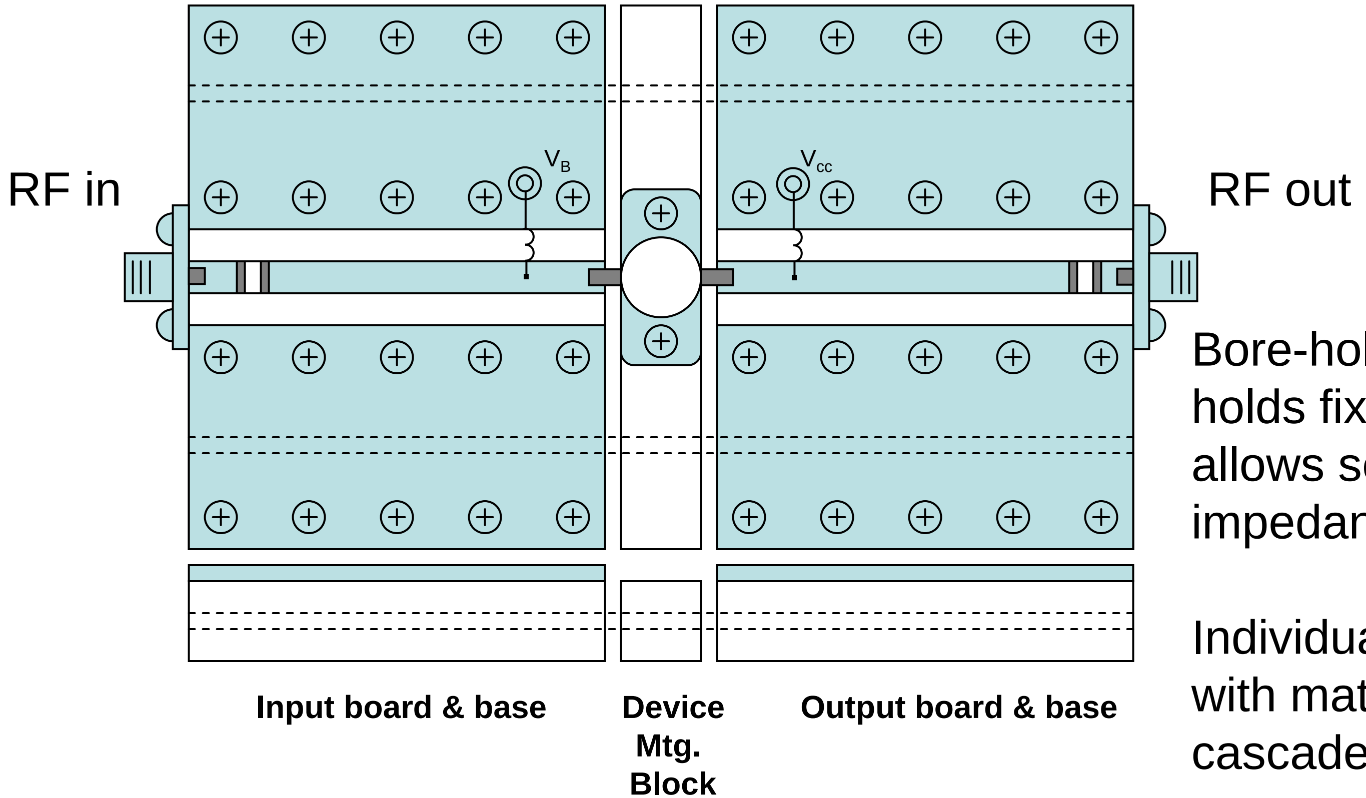
1. Define Q, in column one, as X_{L1}/R_1.
2. For an R_1 to be matched and a desired Q, read the reactances of the network components from the charts.
3. $X_{L1'}$ is equal to the quantity X_{L1} obtained from the tables plus $|X_{Cout}|$.
4. This completes the network.

Q	X_{L1}	X_{L2}	X_{C1}	R_1
1	26	10	43.33	26
1	27	14.14	42.09	27
1	28	17.32	41.59	28
1	29	20	41.43	29
1	30	22.36	41.46	30
1	32	26.46	41.85	32
1	34	30	42.5	34
1	36	33.17	43.29	36
1	38	36.06	44.16	38

Q	X_{L1}	X_{L2}	X_{C1}	R_1
2	50	61.24	38.76	25
2	52	63.25	39.82	26
2	54	65.19	40.86	27
2	56	67.08	41.9	28
2	58	68.92	42.92	29
2	60	70.71	43.93	30
2	64	74.16	45.93	32
2	68	77.46	47.9	34
2	72	80.62	49.83	36

Q	X_{L1}	X_{L2}	X_{C1}	R_1
3	57	83.67	40.66	19
3	60	86.6	42.26	20
3	63	89.44	43.85	21
3	66	92.2	45.42	22
3	69	94.87	46.96	23
3	72	97.47	48.49	24
3	75	100	50	25
3	78	102.47	51.49	26
3	81	104.88	52.97	27

Measurement and Optimization Fixture

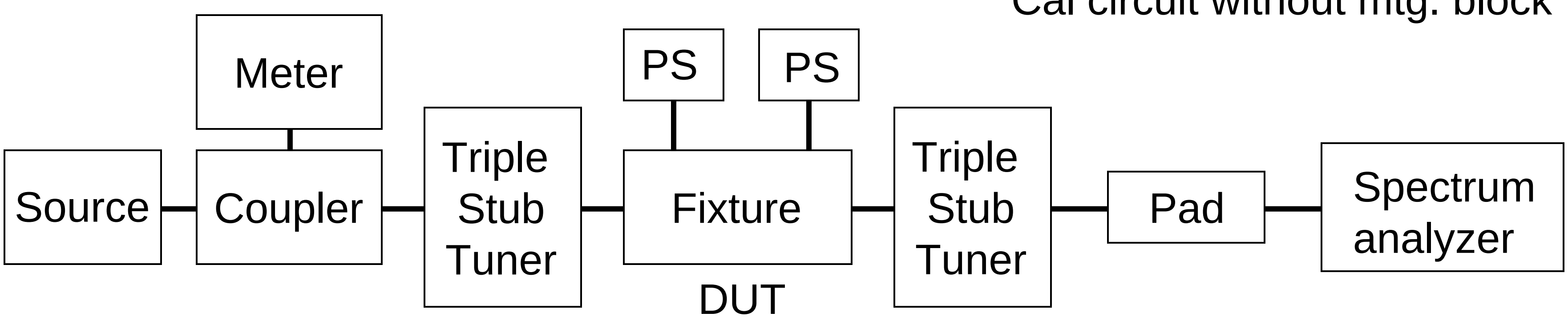


Network Analyzer

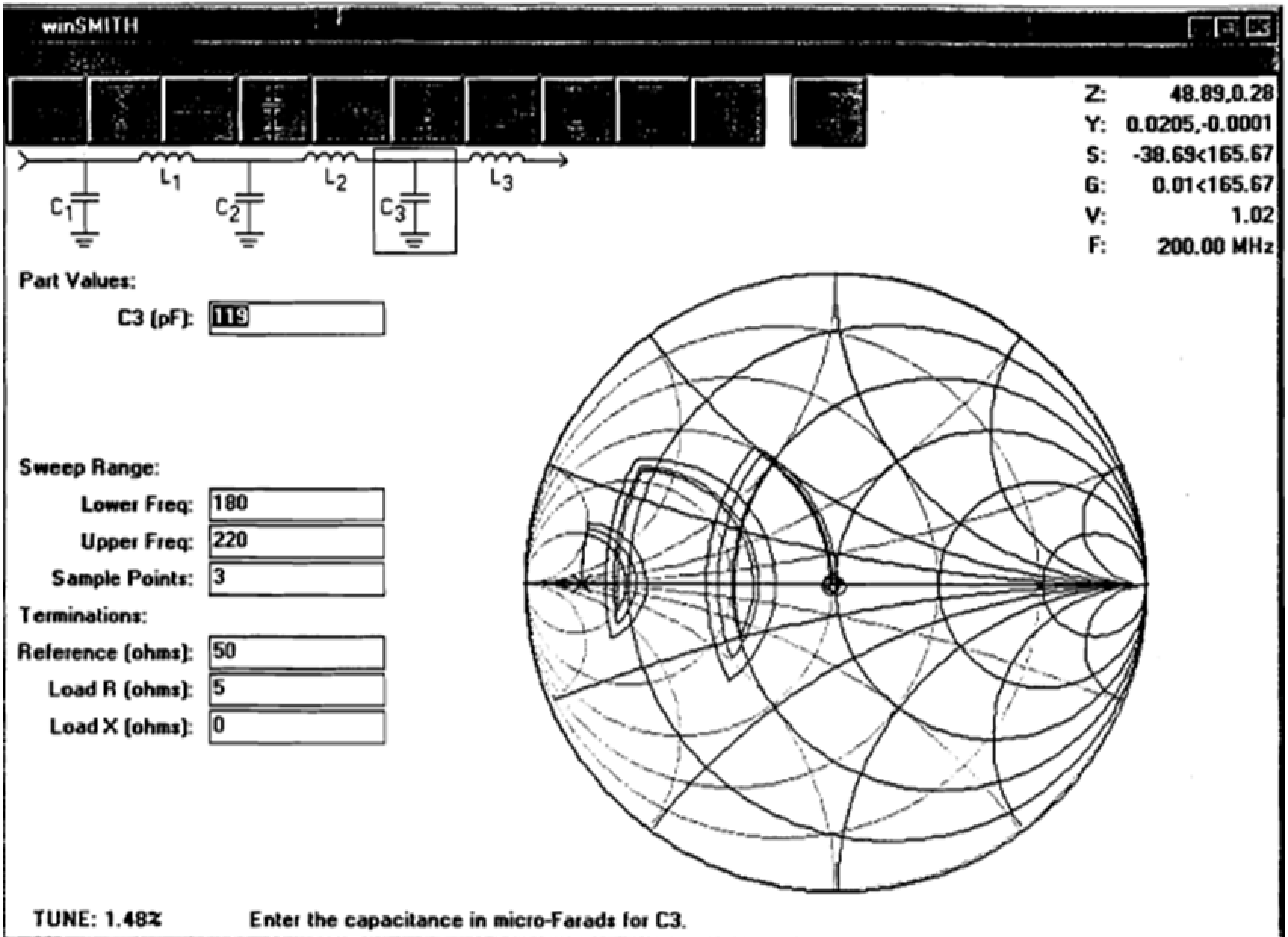
Bore-holes for threaded rods holds fixture together but allows separation for impedance measurement

Individually replace PWBs with matching circuits; can cascade stages

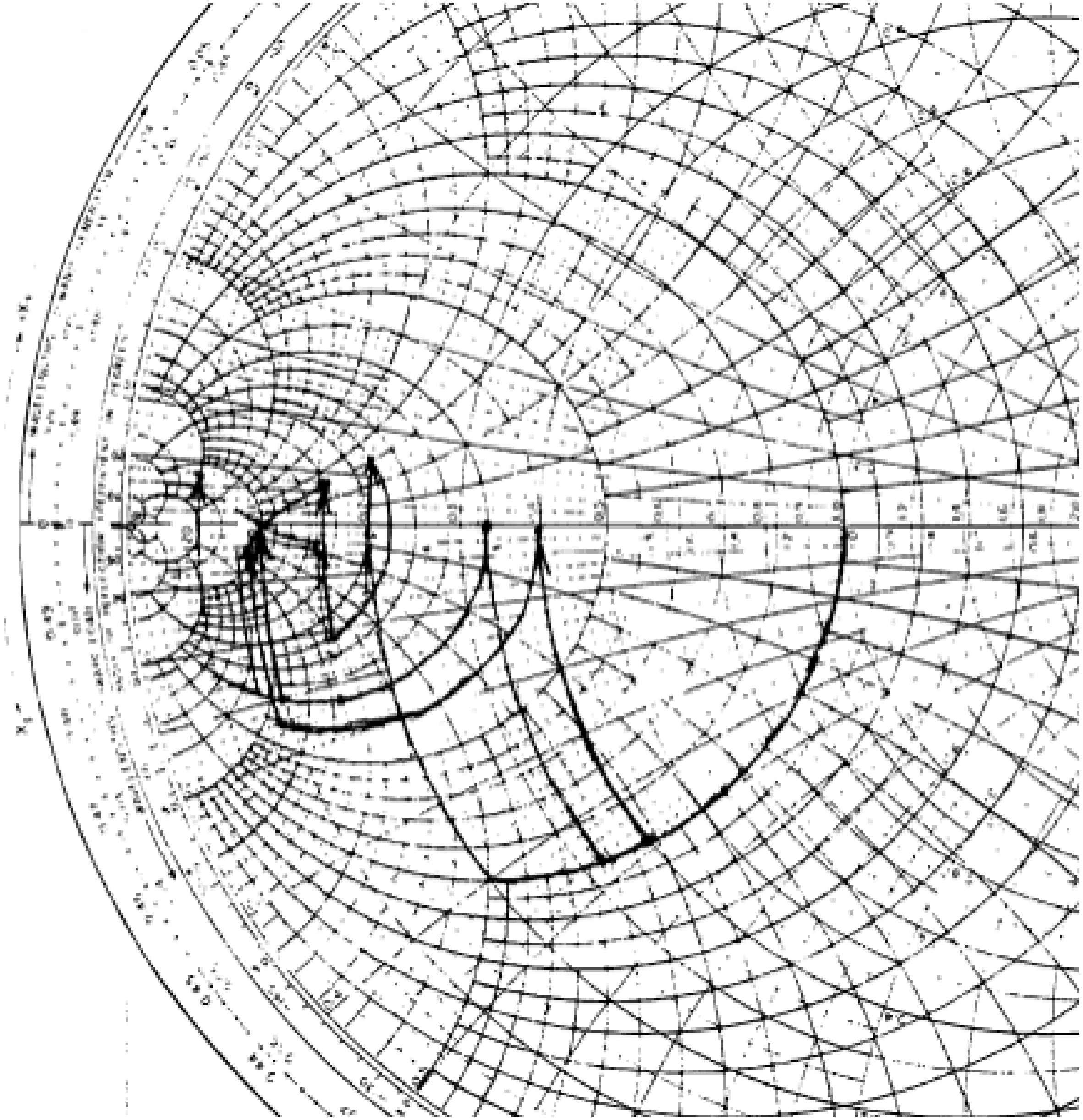
Cal circuit without mtg. block



WinSmith Program for Matching



Match Design Shows Good Orthogonality



4 Element match with two shunt variable capacitors and two series inductors

Traces show nominal and variation associated with two conditions of tuning

Hard to see but note orthogonality of tuning

Orthogonality is desirable to cover possible device variations, ie a good design.

Observations

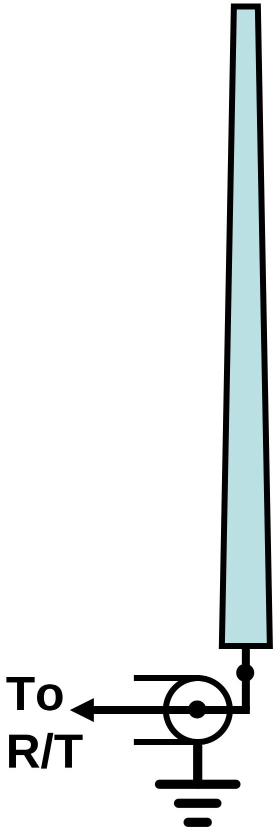
- A direct inter-stage match is preferable to matching to an interim 50 ohm location in an amplifier chain (cost, bandwidth, stability).
- It is preferable although not necessarily convenient to correct mismatch at the location where it occurs as opposed to at some other location like the operational room (otherwise potentially more loss, and the complexity of any cable impedance spin over frequency for the matching network)
  - So at least a partial match (like at the antenna) is helpful
- Inter-stage matching often includes some tilt or peaking at the high frequency end to achieve flatness in an RF chain.
- Input matching networks, especially for older bipolar transistor PA stages often include a stabilization resistor to prevent parasitic oscillations at the expense of some gain.
- Attenuators (pads) correct return loss 2 dB per dB of attenuation and are often used to improve VSWR
- More

IMPEDANCE MATCHING AND RELATED CONSIDERATIONS
Part 2

Balanced and Unbalanced configurations, inductors and transformers, measuring devices, manual and automatic tuners

Examples of Unbalanced and Balanced Loads

Monopole

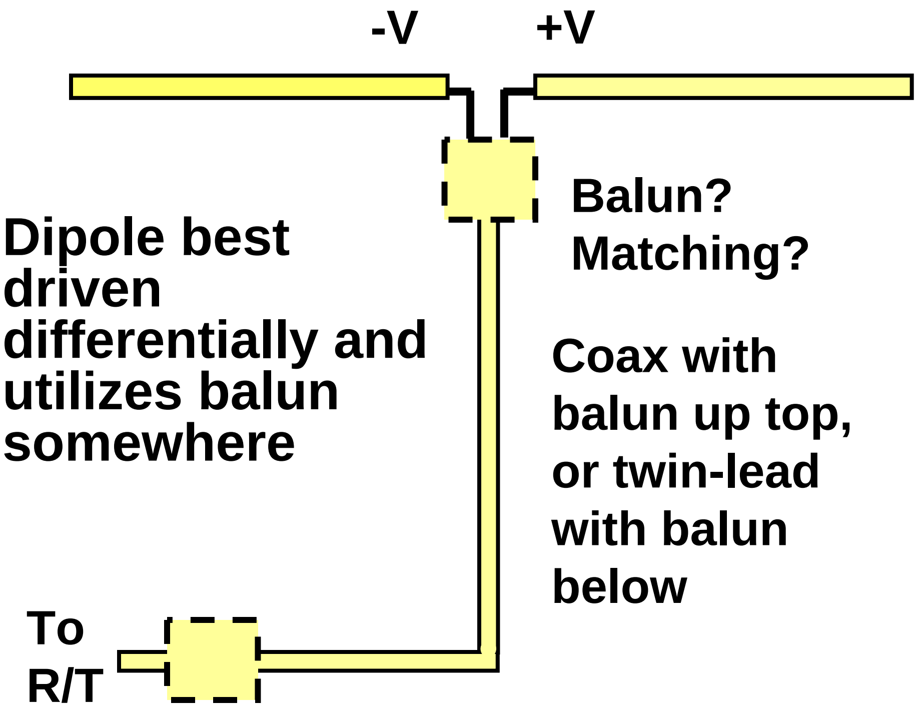


Quarter Wave length?

Radial ground?

- **Monopole presents an unbalanced load and is driven from coax**
- **Utilizes earth ground and may want matching**

Dipole or Beam feed elements



Balun? Matching?

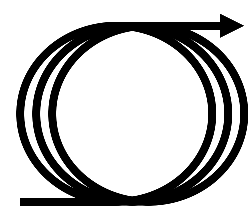
- **Dipole best driven differentially and utilizes balun somewhere**

Coax with balun up top, or twin-lead with balun below

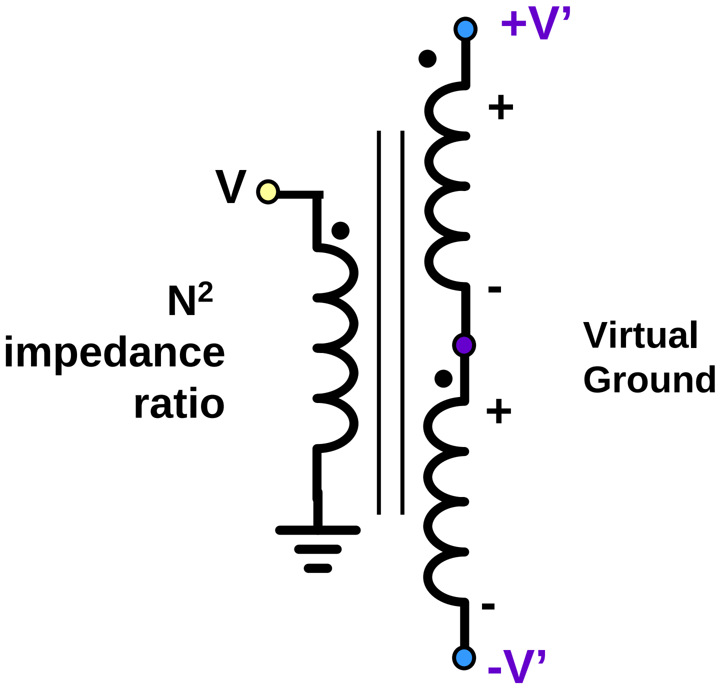
Ladder line, PCArS, Jan Heise

- **Coiled coax increases shield inductance for XFMR action, see next slide**

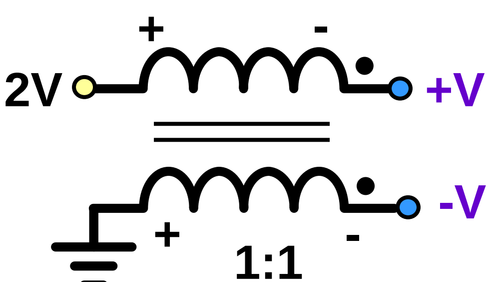
Coiled coax balun



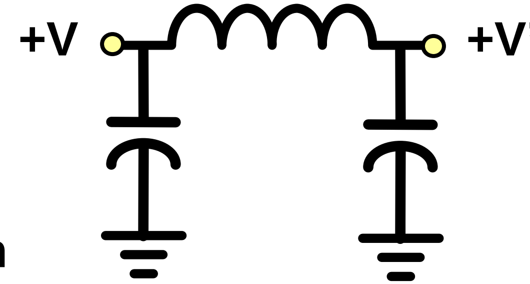
Balun and Balanced Pi Match Examples

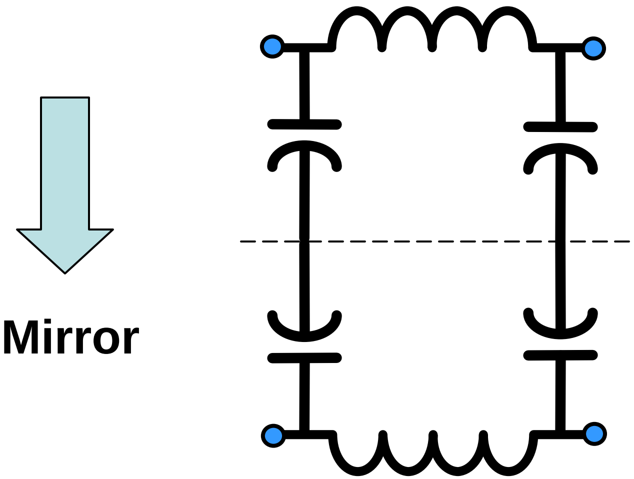


Unbalanced : Balanced



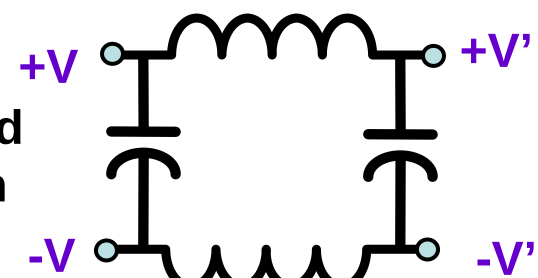
Single
Ended
PI Match



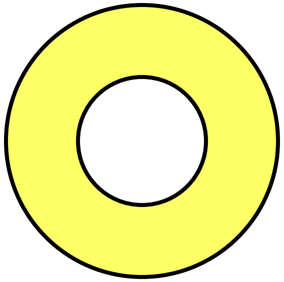


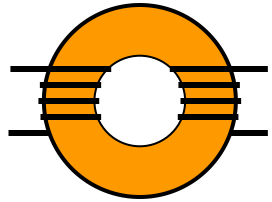
Mirror

Balanced
PI Match



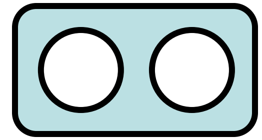
Toriod and Binocular Core Inductors and Transformers

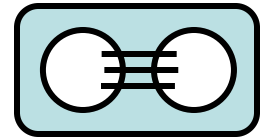




NG

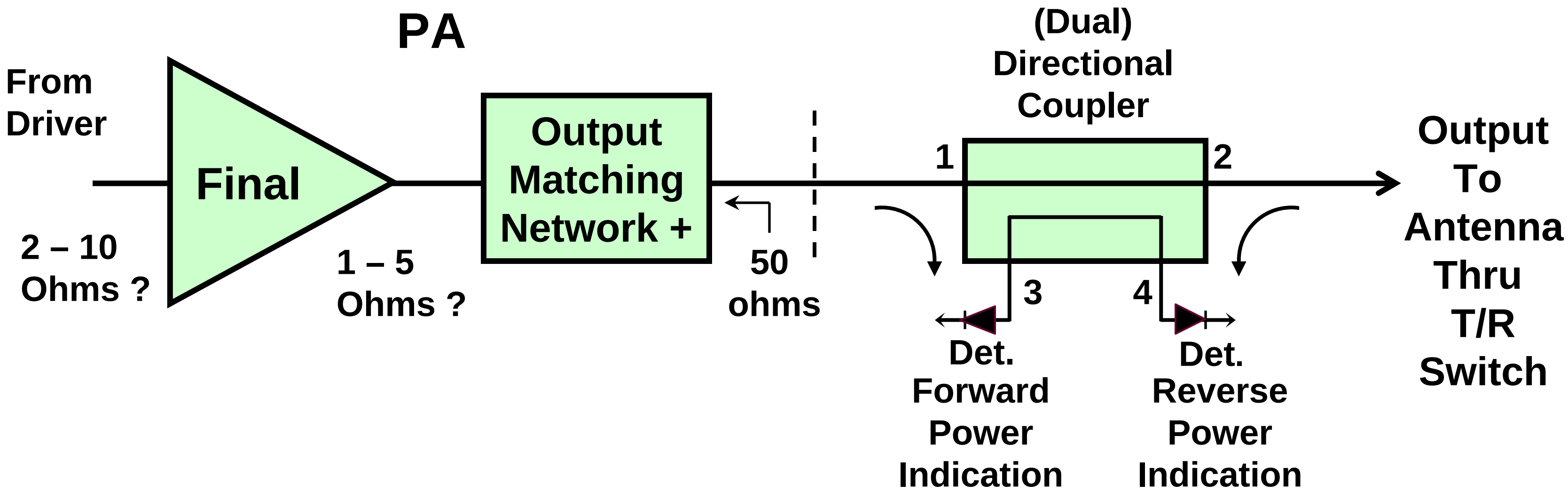
- Toroid (donut) structure for self shielding inductors
- Wind multi-filar for wideband transformers
- Perms 40 to 4, lower for higher frequency operation, also zero perm
- Inductance proportional to N^2
- Can tap inductor for auto-transformer operation
- Larger cores for more RF power
- For cores: Amidoncorp.com, Micrometals.com, Partandkits.com, other





- Binocular cores utilized for RF transformers and couplers plus….
- Wind with multicolored solid enameled (magnet) wire or ..
- Physically convenient structure for winding and mounting
- Excellent performance with multi-decade bandwidth
- Really small ones used in pairs in TO-5 amplifiers
- Stacked versions
- Ceramic Magnetics, Ferronics cores,+, multi-thousand perm

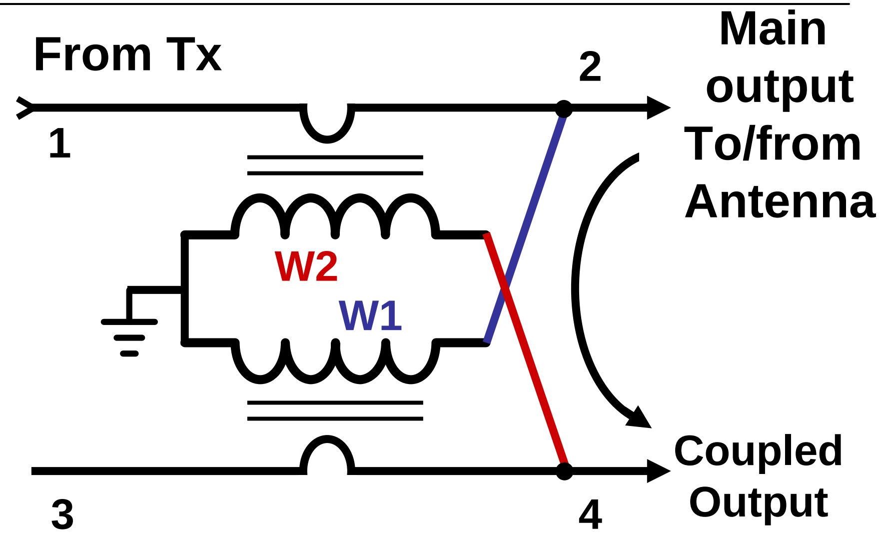
Transmitter Output Topology (Mis-match sensing)



- Typical block diagram of conventional transmitter output
  - Harmonic filter & T/R switch not shown
- Dual directional coupler samples forward & reverse power
- Detected samples are conveyed to processor via A/D converter for VSWR determination and control
- Transmitter drive is reduced with increasing VSWR
- Results in less output power to protect the final
- ALC loop not fast enough to protect for transient conditions?

Transformer Implementation for Directional Coupler

- Can be implemented with two separate beads or one shotgun bead (core)
- Port 3 terminated (not shown)
- Coupled port 4 is monitoring the reflected energy from the antenna, maybe 20-30 dB down

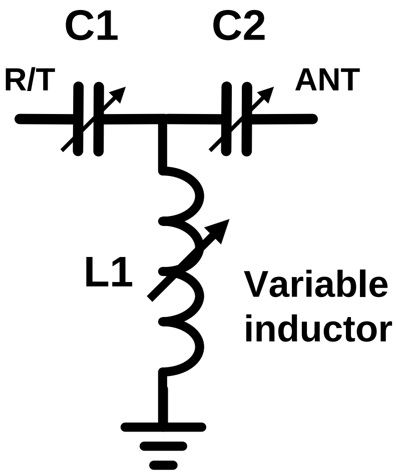


- Winding W1 is sampling the voltage (vector) at port 2
- Winding W2 is sampling the current (vector) at 2
- The windings are such that for a matched load the voltage and current signals (vectors) are equal in amplitude and summed out of phase at the coupled port (4), so they cancel and produce a null
- For mismatched conditions either the current or voltage portion is higher and the coupled port indicates the reflection (vector)
- A good one can exceed 2 decades of bandwidth with >20 dB directivity, 0.5 dB loss, 1.2 VSWR (and the price is right)

Tune-up with a Manual Antenna Tuner

- Tee HF configuration is common in manual (and some auto) tuners, also other features
- Both switched and “roller” inductors
- Larger values of L and C generally used at lower frequencies
- Lack of standardization on range settings so...
- Works for both receive and transmit
- Predetermined band settings for L seem to work reasonably well,   peak for noise, or ……
- Larger values of C suggested as starting points within reason
- Go back and forth from C1 to C2 to null VSWR **@ low power**
- Bandwidth limited for high VSWR
- Balanced configurations for balanced feeds and/or antennas
- Do not band switch inductor while transmitting !!

Tee Configuration



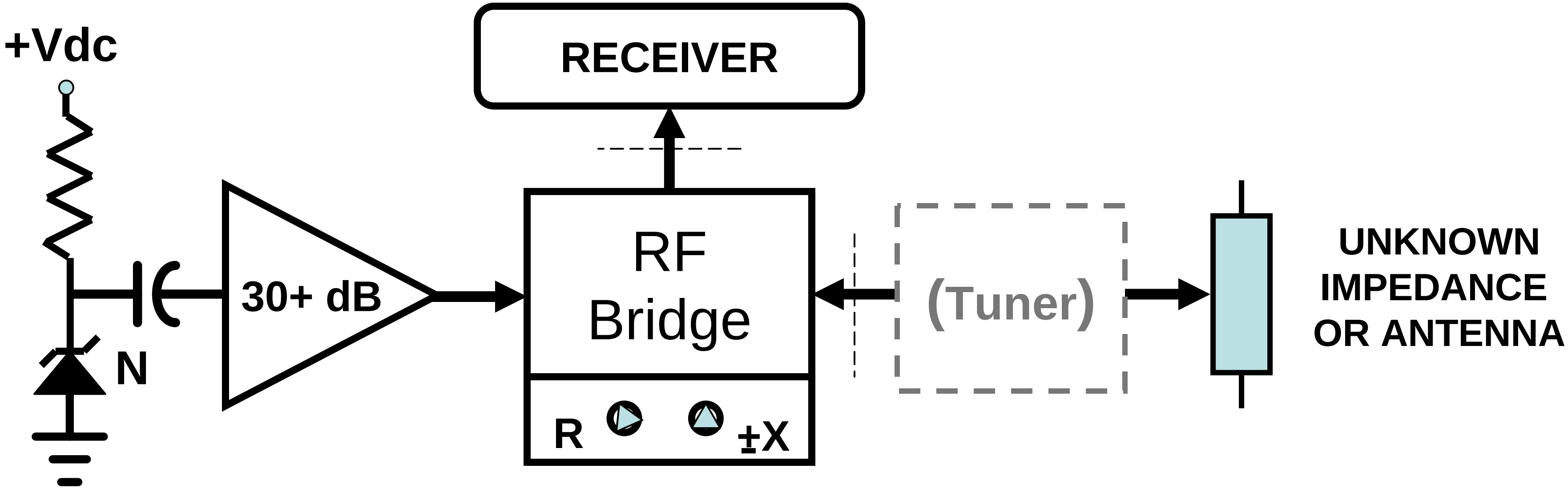
MFJ or…

Automatic Antenna Tuners

- Somewhat expensive but they work for most conditions
- Reasonably fast (several seconds or less)
- Co-located with antenna can have advantages
- Memory settings
- RF Power limitations
- Motor driven Tee configurations
- Relay switched L-C networks
- Tune up with R/T at lower power
- Outboard or inboard in radio
  - Kenwood TS-440 popular (compact R/T, internal tuner)
- ICOM outboard tuners work pretty well with ICOM radios
- MFJ 929, 925 used with Yaesu 857D, talk to Steve Hughey
- Users happy with xx
- Audience comments

751 w AT-500
7000 w AH-4

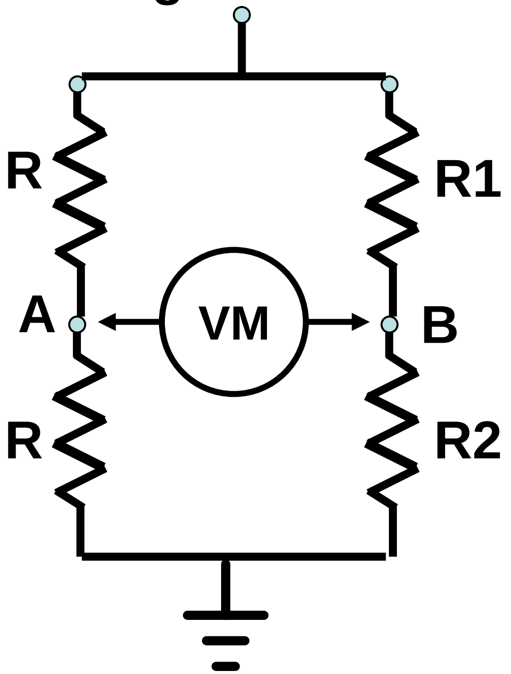
Noise Bridge for Measuring Impedance or VSWR



- Diode is “tickled” into breakdown with low current to produce broadband noise (10’s of uA DC current)
- Amplification brings noise up to low but usable levels
- Receiver monitors noise at frequency of interest for null
- “Calibrated” knobs on bridge are adjusted to achieve null
- Resistance and “reactance” are read off knob pointers
- Single frequency at a time, need clear channel
- Adjust antenna tuner for null after setting to 50-J0

Noise Bridge for Measuring Impedance or VSWR

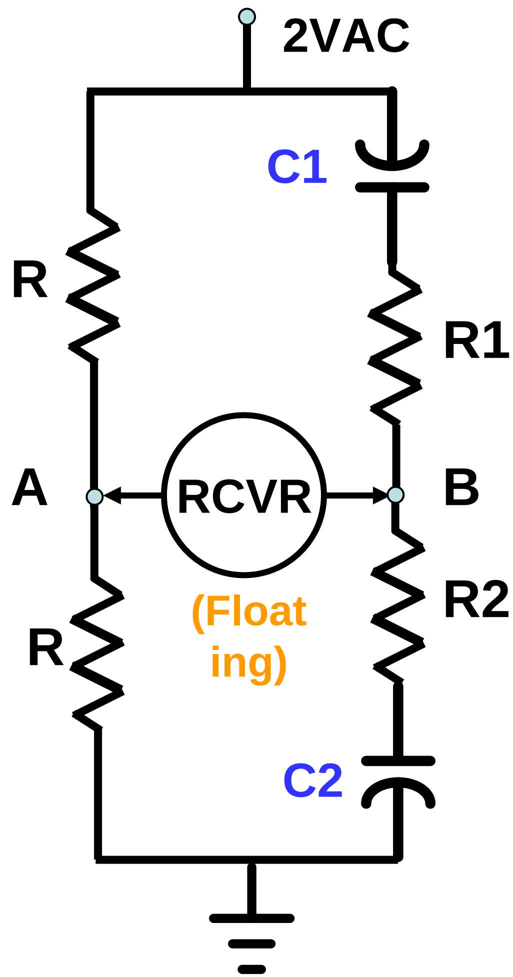
Voltage Source 2V



Basic bridge circuit nulls for R1=R2 (Get V voltage At nodes A & B)

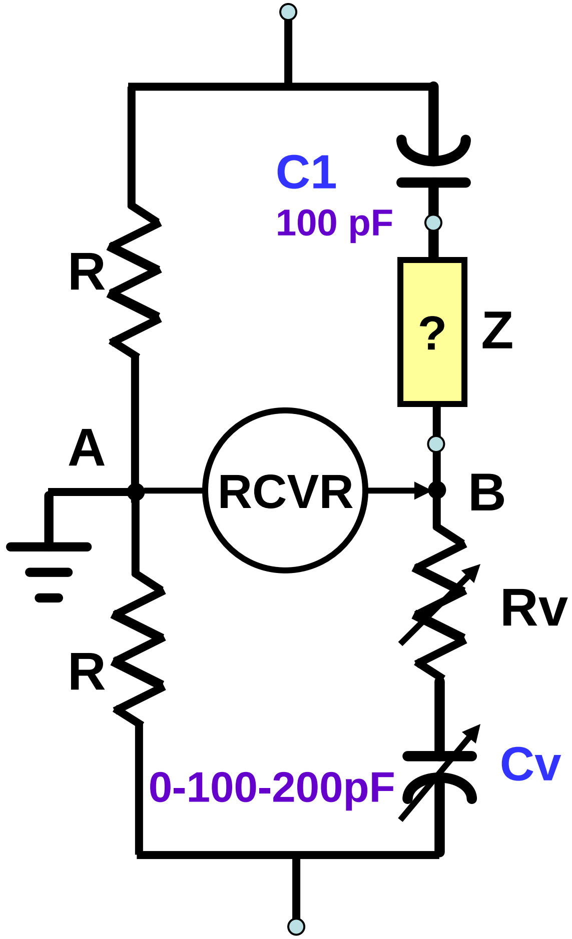
Can therefore measure R1 if R2 is a calibrated variable resistance.

RF or Noise Source



Still get null if R1=R2 & C1=C2

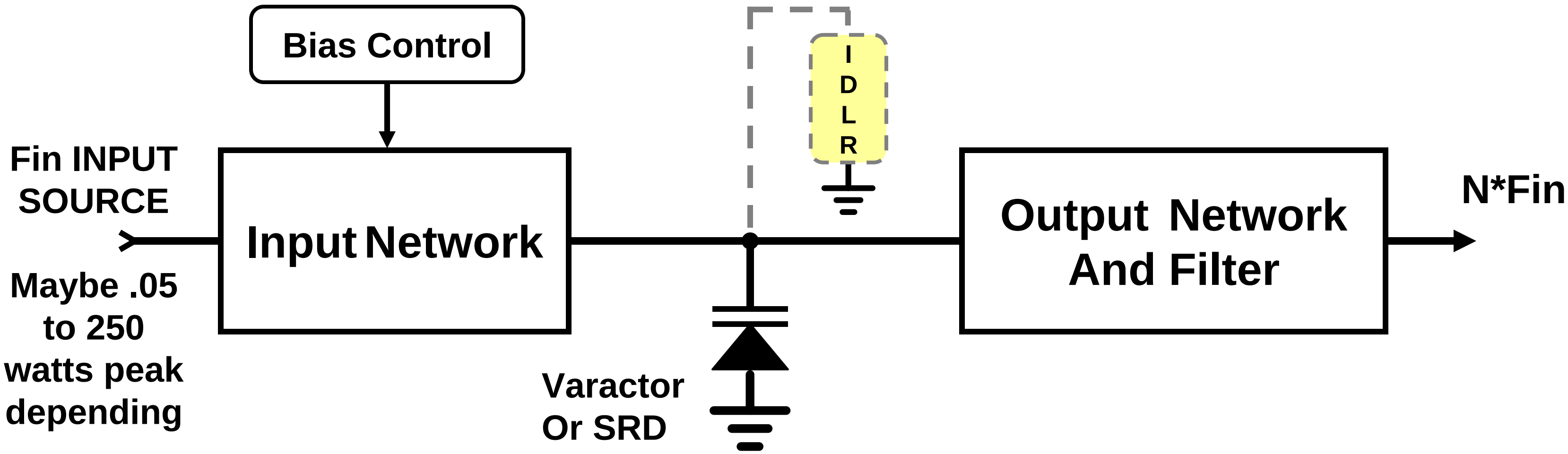
RF Source +V



RF Source -V

C1/Cv also allows inductive measurement

Varactor Multiplier Matching More Constrained



Non-linear device generates harmonics, shunt configuration
Diode looks capacitive so it wants to see inductance for conjugate match

Input Side

- Provide a low loss impedance match at the input frequency
- Provide an open circuit at the output frequency
- Typically blocks DC and provides for bias
- Prevent parasitic oscillations

Output Side

- Provide impedance match at the output frequency
- Provide an open circuit at the input frequency & DC
- Reject the input frequency and undesirable harmonics
- Prevent parasitic oscillations

Candidates for Presentation Additions

- Bandwidth and flatness considerations
- Multiplier example
- Oscillator example
- Noise match example
- Physical examples of RF transformers
- Printed matching examples
- Actual schematics of some couplers and noise bridges
- Other?

New Addition Nov. 09: Fano's Limit

- For a given mismatch load over a finite bandwidth the achievable match, even for an arbitrary number of lossless matching elements can be no better than Fano's Limit (?).
- See http://www.microwavesoftware.com/articles/jl3pg3.html
- R. M. Fano: "The Theoretical limitations on the broadband matching of arbitrary impedances". J. Franklin Inst., 249 Jan./Feb/1950 pp. 57-83 139-154