Understanding Transmission Lines

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Intended Audience

- Some limited transmission line exposure including concepts of SWR, reflections, dB, and loss
- Grasp basic electrical concepts such as voltage/current phase and Kirchoff's circuit laws.
- Impedance replaces resistance and terms like 50+j20 Ω should be familiar

Presentation Format

- No wave equations or telegrapher's equations (http://en.wikipedia.org/wiki/Transmission_line#Matched_load
- Software simulation is invaluable for better understanding of the concepts
- Inexpensive test equipment allows measurements that only a lab could make 20 years ago
- Transmission lines and impedance matching are closely related

Transmission Lines

- Deliver RF signals to another location efficiently
- Early transmitters did not use transmission lines but transmission lines pre-date radio
- 2/4 wire open wire lines, flexible coax, hard line, twisted pair, stripline, microstrip, wave guide, etc.
- Computer motherboards, Ethernet, USB cables
- Nearly all digital signals are RF these days

Who Can You Believe?

- Too much misinformation and incomplete information exists in the amateur radio community
- Transient and steady state conditions are often incorrectly mixed together
- All concepts presented have been measured in hardware and simulated in software, often in multiple programs, with total agreement
- Please challenge me on any topic

Simulation Programs

(currently available)

- LTSpice IV http://www.linear.com/designtools/software/ (Free)
  Previously called SwitcherCAD, updated extremely often
  WinXP/7 32-64bit, Mac/Linux via Wine
- TLW v3.1 Comes with ARRL Antenna Handbook, WinXP/7 32-64bit
- SWR Calculator v1.2 http://www.vnahelp.com/products.html
  (Free), WinXP/7 32-64bit, Not a simulation program but very useful
- Coax loss & power handling calculator
  http://www.timesmicrowave.com/cgi-bin/calculate.pl (Free)
  Not a simulation program

Current Smith Chart Programs

(currently available)

- SimSmith v6.2 http://www.ae6ty.com/Smith_Charts.html (Free)
  WinXP/7, Mac, Linux needs Java Runtime Environment (Free)
- SuperSmith v2.09 http://www.tonnesoftware.com (Free) WinXP/7
  Temporarily removed, back with new name or get directly at
  http://www.tonnesoftware.com/downloads/SuperSmithInstall209.exe
- Quick Smith v4.2 http://www.nathaniyer.com/qsdw.htm (free)
  Does not run on Win7-64, see Jul/Aug & Sep/Oct 2010 QEX
- fk Smith v1.15 http://pesona.mmu.edu.my/~wlkung (free) Win only
- WinSmith v2.0 Noble Publishing, bought by Agilent (No longer available but download on internet), Does not run on Win7-64

Weaknesses in Software Tools

- LTSpice
  - Transmission line loss vs frequency
  - Q of components vs frequency
  - Can't model transmission line shielding
- TLW
  - Q of components vs frequency
- Smith Chart Programs
  - Trans. line loss and Q vs frequency (ex. SimSmith v6+)
- Weaknesses are minimal

Hardware Tools

(currently available)

- DG8SAQ VNWA http://www.mydarc.de/dg8saq/NWA.html
  http://www.sdr-kits.net/VNWA/VNWA_Description.html
  kits and assembled versions, Jan/Feb & May/Jun 2009 QEX
- AIM 4170C, 4170UHF, & VNA2180 (W5BIG)
  http://www.arraysolutions.com
- RigExpert self contained analyzers AA-30, AA-54, AA-230, AA230PRO, AA-520 http://www.arraysolutions.com
- miniVNA (IW3HEV) http://miniradiosolutions.com/
- N2PK VNA http://n2pk.com/VNA/VNAarch.html (mostly kit)

Hardware Tools

(currently available)

- HP/Agilent, Rhode & Schwarz VNAs

  professional, very high frequency, expensive unless used

- VNA Calibration Standard Kit

  ultimate analyzer accuracy is no better that the cal. kit

- Homebrew TDR (Time Domain Reflectometer)

dB (Decibel)

- **Relative** measurement, ratio of **power or intensity** without units
- Used in acoustics, optics, and electronics
- Convert to voltages or currents, $dB = 10*\log_{10}(Po/Pi)$, $dB = 20*\log_{10}(Vo/Vi)$ if impedance is constant
- 2x = 3dB, 4x = 6dB, 8x = 9dB, 1/2x = -3dB, 10x = 10dB, 5x =7dB, 100x = 20dB, .0001x = -40dB etc.
- Absolute dB terms (dBm, dBrnC0, dBW, dBV, dBuV)
- Impedance issues, double termination = -3.52dB

How Do Transmission Lines Work?

- At every point along the transmission line the currents in each wire are the same magnitude and 180 degrees out of phase
- For coax, these currents are on the outside of the center conductor and the inside of the shield
- Net AC current flow produces a magnetic field that opposes current flow
- Transmission line currents produce the minimum magnetic field which also minimizes radiation

Other Currents on the Line

- A current can flow on both wires equally and is in phase for open wire line or on the outside of the shield for coax
- This is an antenna current that does radiate and is generally unwanted
- Common mode chokes and winding in a loop are techniques used to reduce this current to acceptable levels

Terminology of Currents

- Transmission line currents are also known as differential or metallic currents
- Common mode currents are also known as longitudinal or antenna currents
- Both types of currents can coexist but there is always a small conversion from one type to the other which can be problematic

Properties of coaxial cable

- Characteristic (surge) impedance
- Attenuation (matched loss) vs. frequency
- Power rating (current rating) matched vs. frequency
- Dielectric material (voltage breakdown, temperature rating)
- Center conductor (size and composition)
- Shield(s) material (shielding effectiveness)
- Outside jacket (weather, temperature, abrasion rating)
- Minimum bend radius, flexibility
- Physical size and connector compatibility
- Velocity factor
- Not all properties are important for a particular application

Characteristic (Surge) Impedance

- Load impedance where no wave is reflected back into the transmission line
    - Next 3 demonstration slides
- Notice how the ratio of the voltage divided by the current is the surge impedance of the transmission line independent of the load!

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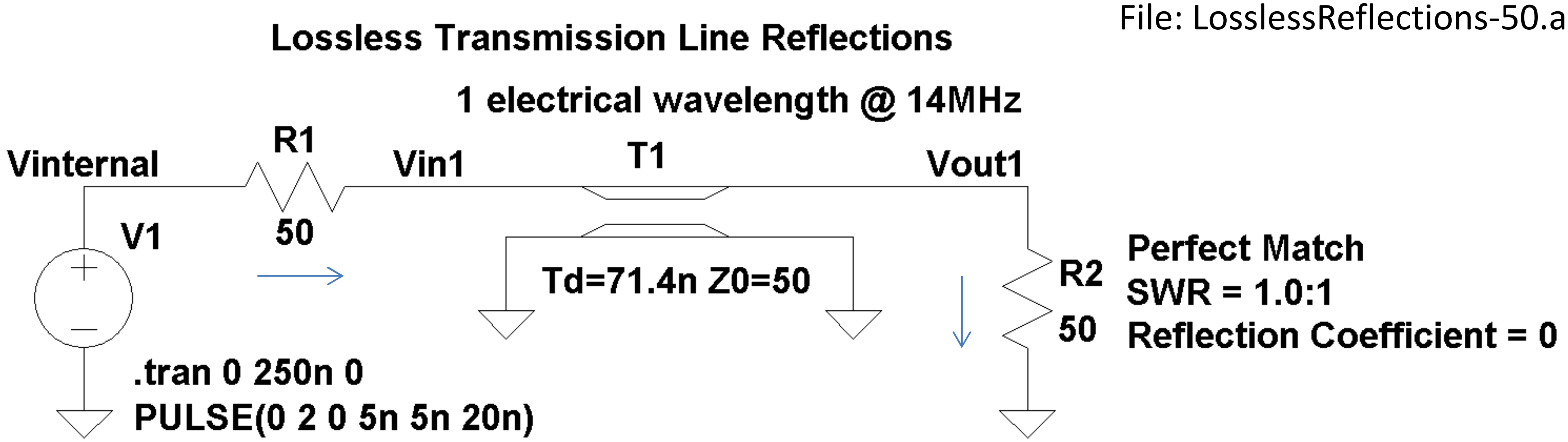

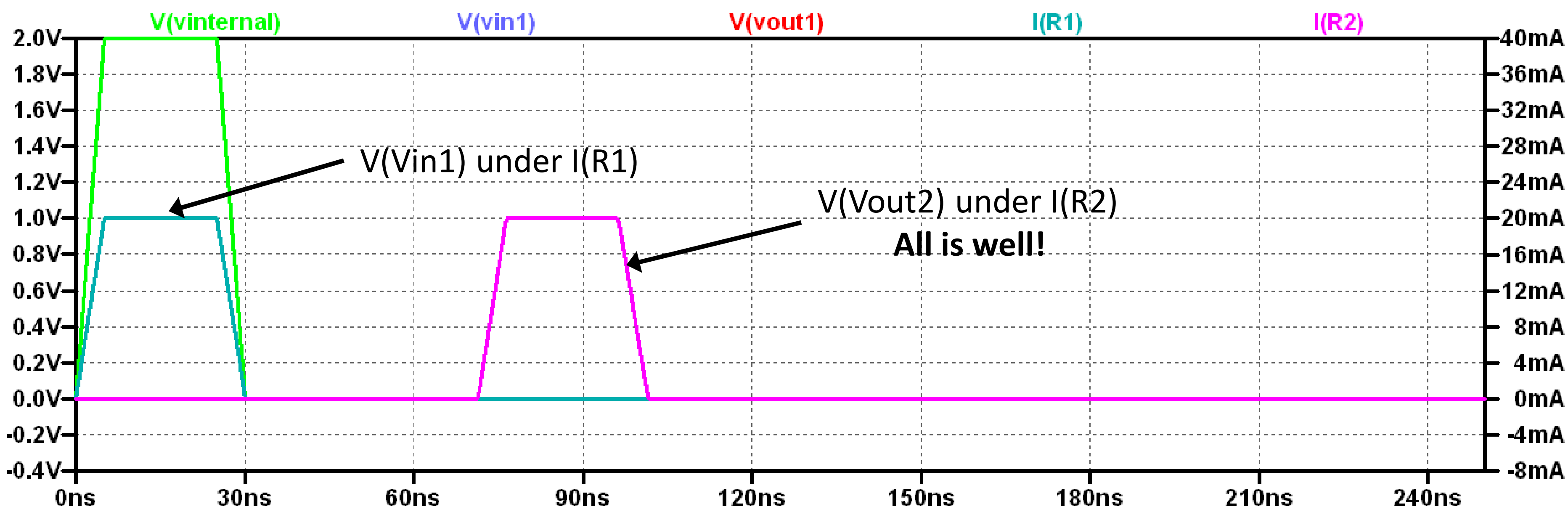

Lossless Transmission Line Reflections

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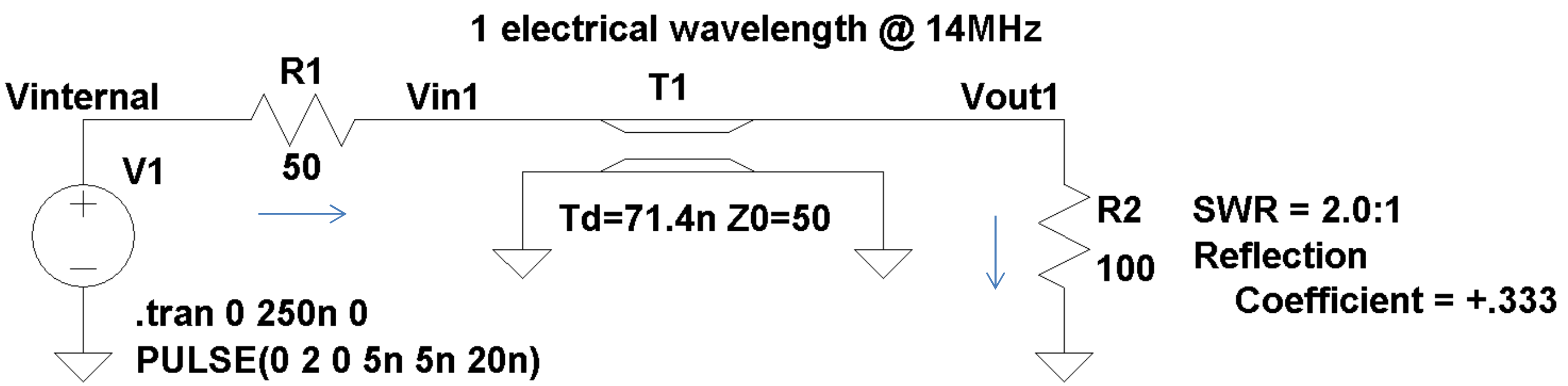

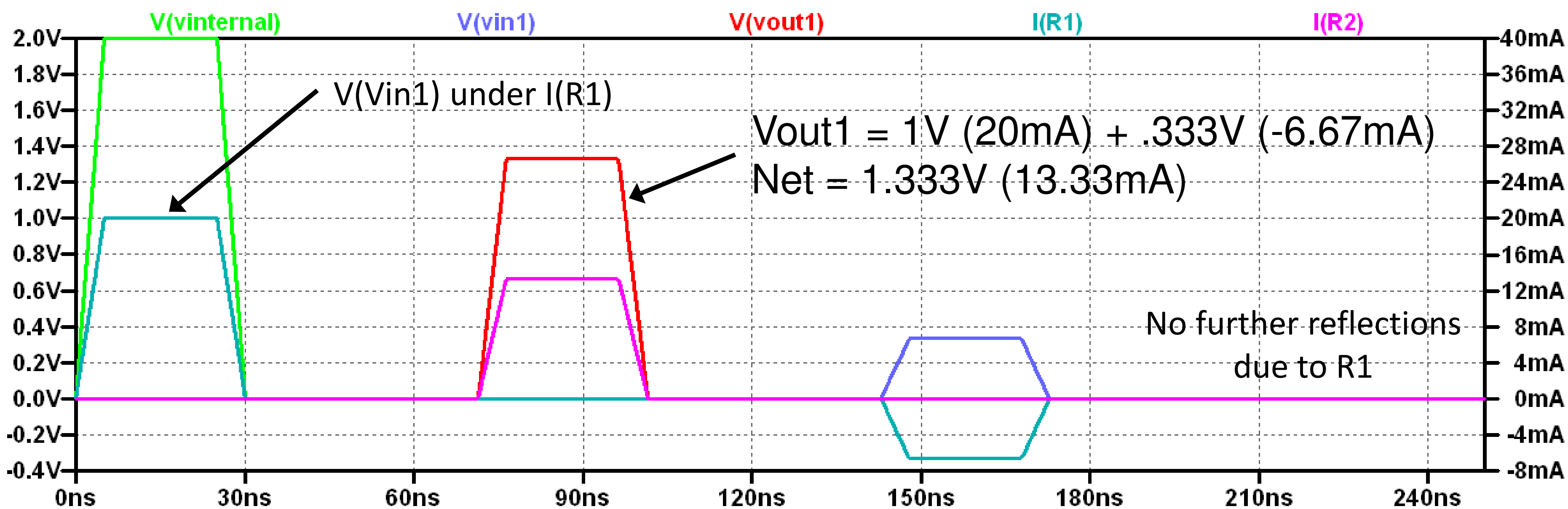

Lossless Transmission Line Reflections

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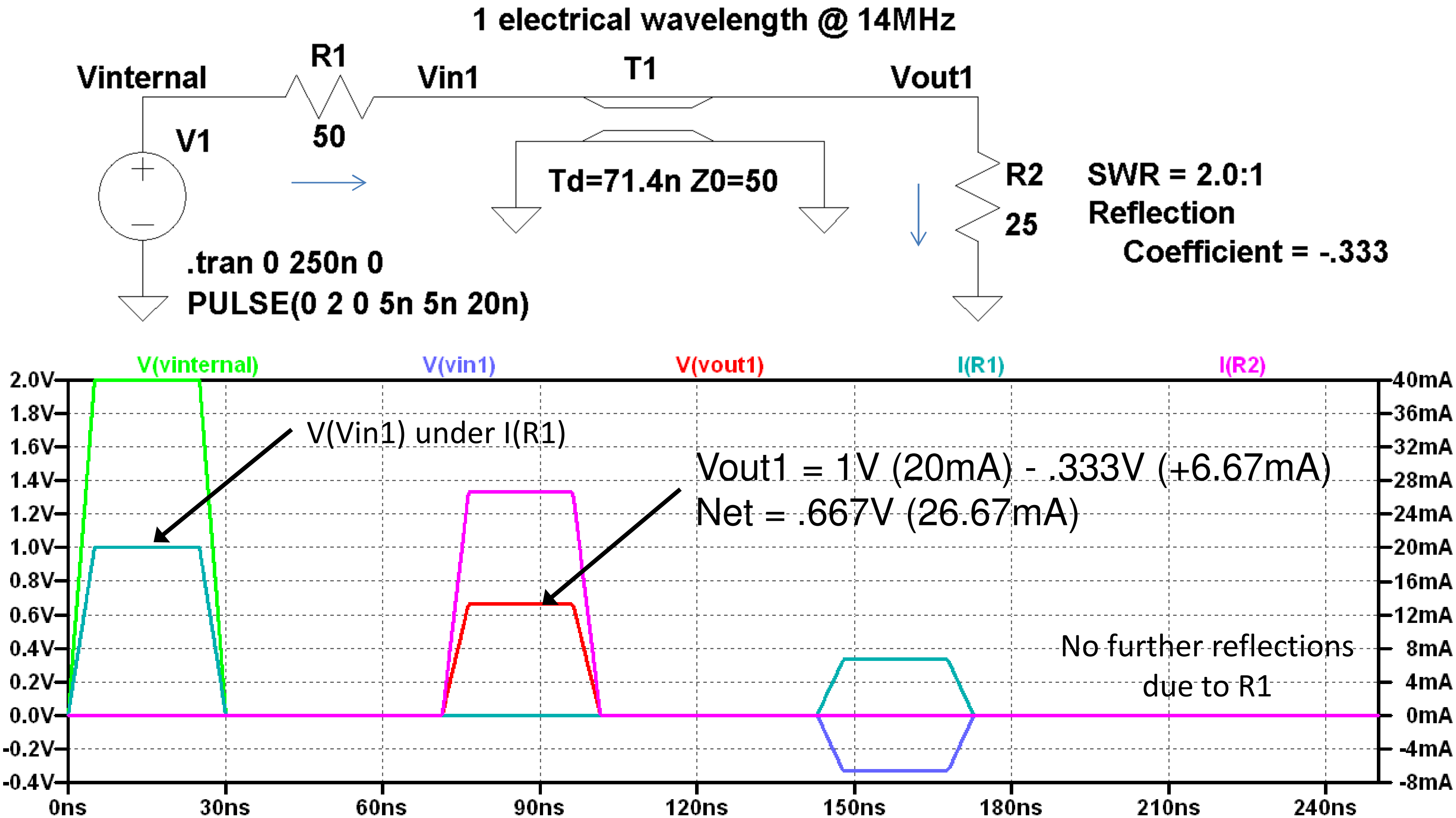


Surge Impedance Continued

- All forward & reflected waves have a V/I ratio that equals the surge impedance of the line!
- Maximum power is delivered into the load when the load impedance matches the surge impedance of the transmission line
- Maximum power is delivered into a <u>matched</u> transmission line if the transmitter output impedance matches the surge impedance

Surge Impedance Again

- $Zo = \sqrt{L/C}$ per unit length, equivalent circuit no loss
- Why a particular impedance?
  - Maximum power 30Ω, minimum loss 77Ω, max. voltage breakdown 60Ω (1929 Bell Laboratories) “modern coax”
  - Maximum power per pound of copper 52Ω (F. Terman?)
  - Today 75Ω, 50Ω, 52Ω, 53.5Ω, 25Ω, 80Ω, 93Ω, etc.

SWR by other names

- SWR (standing wave ratio)
  - Maximum voltage in the line = forward + reflected voltage
  - Minimum voltage in the line = forward - reflected voltage
  - SWR is the maximum divided by the minimum voltage
- Reflection coefficient, return loss, and SWR
  - Different ways to tell the exact same story
  - ρ (reflection coefficient) = Vr/Vf or Ir/If
  - SWR = $(1 + \rho)/(1 - \rho)$
  - RL (return loss) = $-20 \log_{10}(\rho)$
- SWR decreases from load to source if line has loss

Equating SWR, ρ, & Return Loss

SWR	Reflection Coefficient (ρ)	Return Loss (RL)
1	0.000	infinity
1.01	0.005	46.06
1.02	0.010	40.09
1.05	0.024	32.26
1.1	0.048	26.44
1.25	0.111	19.08
1.5	0.200	13.98
2	0.333	9.54
3	0.500	6.02
4	0.600	4.44
5	0.667	3.52
10	0.818	1.74
20	0.905	0.87
50	0.961	0.35

100W 50Ω output transmitter driving lossless coax with various load impedances and no impedance matching

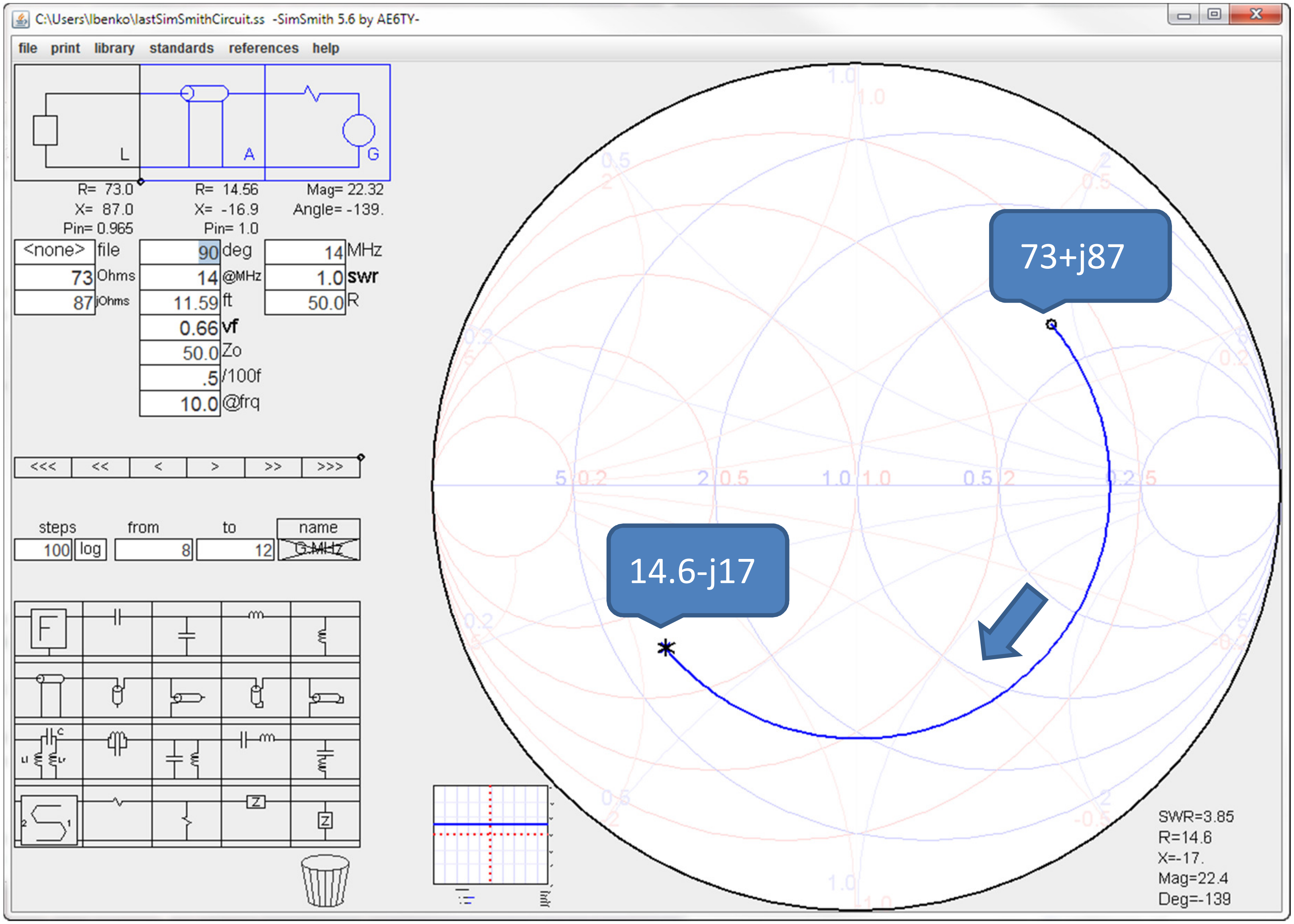
SWR	Example Load Impedance(s)	Power into Load	dB relative to 100W
1	50 + j0	100.0	0
1.25	40 + j0, 62.5 + j0	98.8	-0.05
1.5	33.3 + j0, 75 + j0	96.0	-0.18
1.7	85 + j0	93.3	-0.30
2	25 + j0, 100 + j0, 40 +/- j30	88.9	-0.51
3	150 + j0	75.0	-1.25
4	200 + j0	64.0	-1.94
5	10 + j0	55.6	-2.55
10	5.0 + j0	33.1	-4.81
20	400 + j0	18.1	-7.41
50	1.0 + j0	7.7	-11.14

Effect of Reflections

- For continuous transmissions the signals reflected back into the transmission line can arrive at the transmitter with an amplitude from zero to the original transmitter amplitude and at any phase angle
- The impedance seen by the transmitter varies and for high SWRs can be either very low, very high, or highly reactive causing driving problems for the transmitter

Reflection Examples

- Frequency = 14.0MHz, load = 73 + j87Ω, load SWR = 4.0:1, & various lengths of RG-213
- 11.6’ (.25 λ) = 14.5 - j17.0 (Tx SWR = 3.85:1)
- 14’ = 13.1 – j1.2 (Tx SWR = 3.82:1)
- 25.8’ = 184.2 – j4.1 (Tx SWR = 3.68)
- 23.18’ (.5 λ) = 74.8 + j81.8 (Tx SWR = 3.71:1)
- 46.37’ (1 λ) = 76.1 + j76.8 (Tx SWR = 3.47:1)
- 200’ = 20.5 + j1.9 (Tx SWR = 2.44:1)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X= 87.0
Pin= 0.965
R= 14.56
X= -16.9
Pin= 1.0
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Angle= -139.
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73 Ohms
87 jOhms
90 deg
14 @MHz
11.59 ft
0.66 vf
50.0 Zo
.5 /100f
10.0 @frq
14 MHz
1.0 swr
50.0 R
steps from to name
100 log 8 12
73+j87
14.6-j17
SWR=3.85
R=14.6
X=-17.
Mag=22.4
Deg=-139

Loss

- At HF loss is predominantly due to the RF resistance of the conductors and is incrementally proportional to current squared
- Matched loss at HF is frequency dependent and increases ~ as the square root of frequency Loss(f2) ~= Loss(f1)*sqrt(f2/f1) dB.
- Following example shows losses with and without matching for a 100W transmitter

Reconciling the Loss

Method	Loss Matched	Loss 12.5 ohm Load	Impedance seen by Tx
HP8753B VNA	.59dB	2.70dB	Z = 110 - j80
TLW v.3.01	.59dB	2.66dB = 1.16 + 1.50dB	Z = 108 - j74
LTSpice IV	.62dB	2.69dB	Z = 107 - j69

- Cable was 36’1” of RG-58 type & the tests were done/simulated at 14.0MHz with no matching
- Amazing agreement between hardware & software

Loss with No Matching

- 50Ω load
  - Power output = 87.2W
  - Dissipative (heat) loss in transmission line = 12.8W
  - Mismatched non-dissipative circuit loss ~ 0W
- 12.5 Ω load (4:1 load SWR)
  - Power output = 56.0W
  - Dissipative (heat) loss in transmission line = 15.7W
  - Mismatched non-dissipative circuit loss = 28.3W

Loss with Matching

- Matching at transmitter end of transmission line
  - 12.5 Ω load = 78.1W
  - Dissipative loss in line = 21.9W
- Matching at load end of transmission line
  - 12.5 Ω load = 87.2W
  - Dissipative loss in line = 12.8W
- Power output difference is 0.5dB between load & source matching
- Higher SWRs and line loss increase deltas

Overall Circuit Loss

- Dissipative loss in the transmission line
  - Increases with SWR and driving power
  - Transmission line loss is primarily a function of the square of the currents summed over length at HF
- Non-dissipative loss at source end due to mismatch
  - Drive with impedance which is the conjugate match to mismatched line to deliver max. power (antenna tuner)
  - Reducing the mismatch loss via impedance matching increases dissipative loss in line

10:1 SWR Example

- 1λ RG-58A (Belden 8259) 46.368' long @ 14.0MHz connected to a 5 + j0 Ω load with an optional tuner at the antenna, in the shack, or no tuner at all
- Do calculation in both TLW & LTSpice showing consistency in methods
- 0.87dB vs 3.10dB vs 5.68dB (82W vs 49W vs 27W) for a 100W equivalent transmitter not including any SWR power foldback

Options to the Previous Example

- RG-58A :0.87dB vs 3.10dB vs 5.68dB
- RG-213: 0.36dB vs 1.54dB vs 5.17dB
- LMR-500: 0.16dB vs 0.74dB vs 4.95dB
- 4:1 xfmr (.2dB loss) @ antenna (SWR=2.5:1):
  N/A vs 1.38dB vs 1.95dB
- RG-213 + 4:1 xfmr (.2dB) @ antenna:
  N/A vs 0.71dB vs 1.44dB
- Many other choices

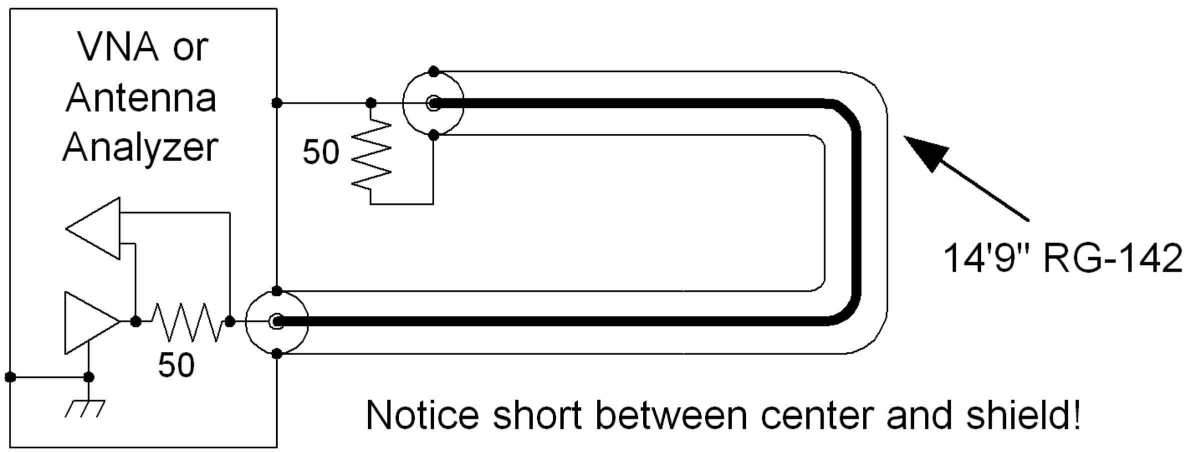
Measuring Line Zo and Loss

- Measuring surge impedance (Zo)
  - Open far end of line, measure Z1 @ phase angle A1
  - Short far end of line, measure Z2 @ phase angle A2
  - Zo = square root (Z1 * Z2) @ phase angle (A1 + A2)/2
  - Usually resultant phase is close to zero
- Measuring Loss
  - Open far end of line, measure return loss RL1
  - Short far end of line, measure return loss RL2
  - Loss ~= (RL1 + RL2)/4

Shielding in Transmission Lines

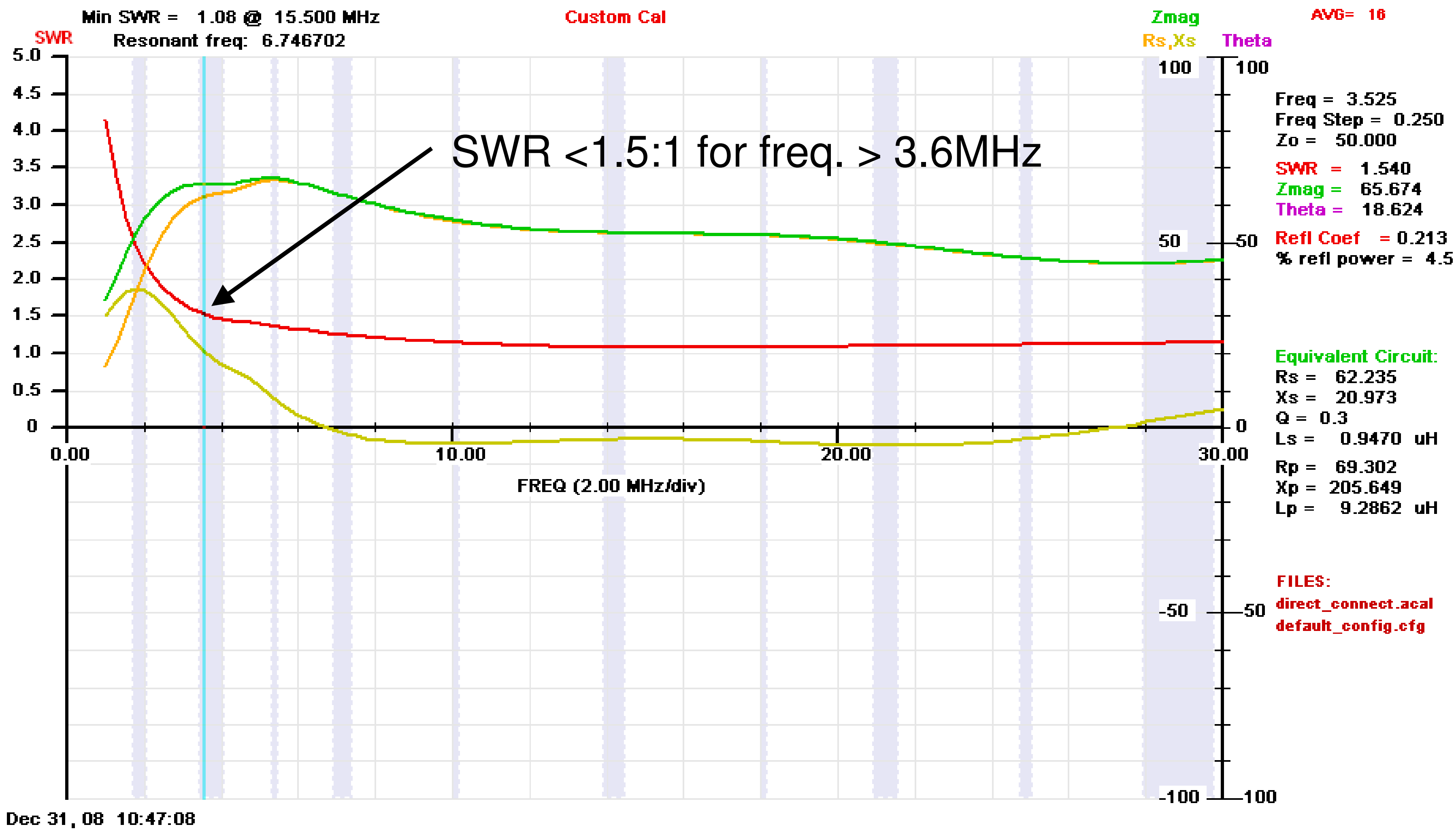
- At every point currents are equal and out of phase resulting in very little radiation and pickup
- Coaxial transmission line currents are on the outside of the center conductor and inside of shield
- Current on the outside of the coax does affect the currents on the inside very minimally & vice versa
- Currents on the outside of the shield do radiate

Strength of Transmission Line Currents

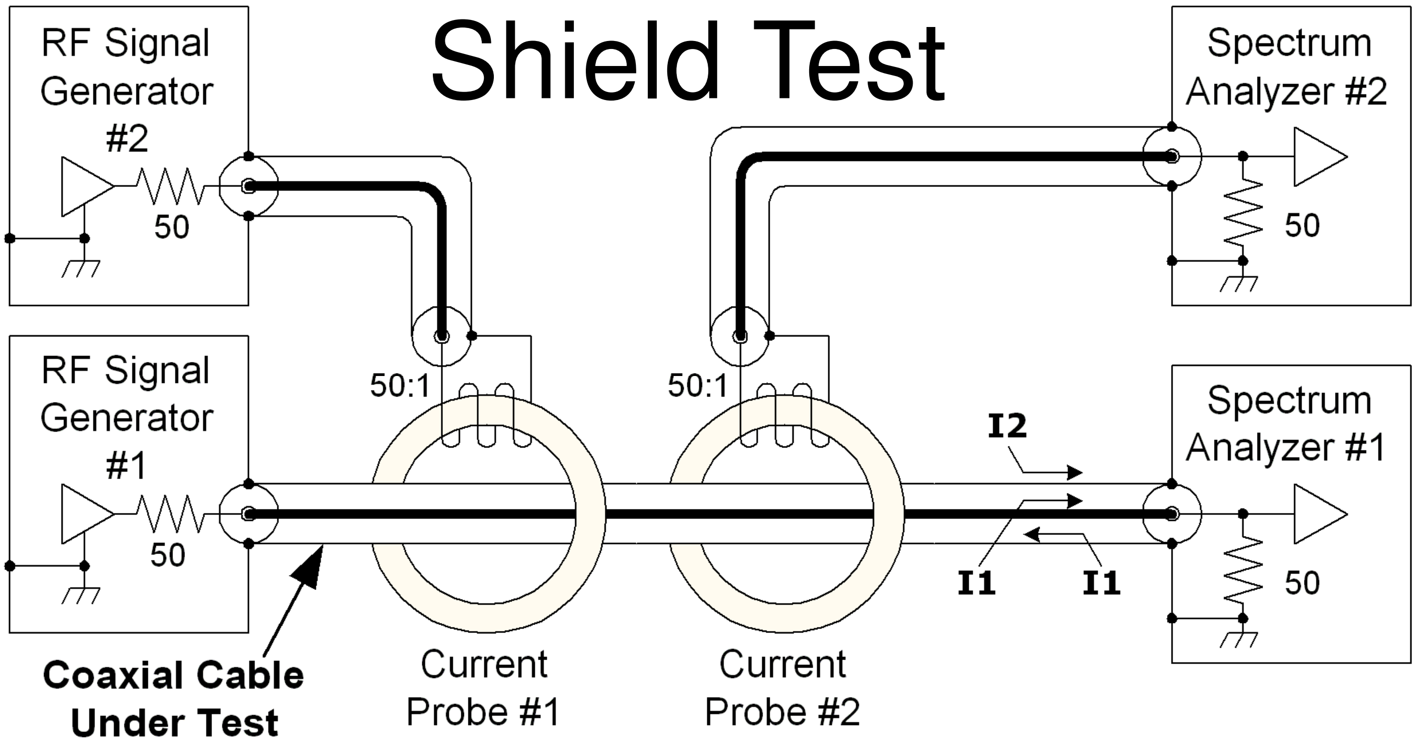


- Coax is electrically λ/4 @ 11.5MHz
- Currents flow where impedance is minimum

Impedance measured by AIM4170

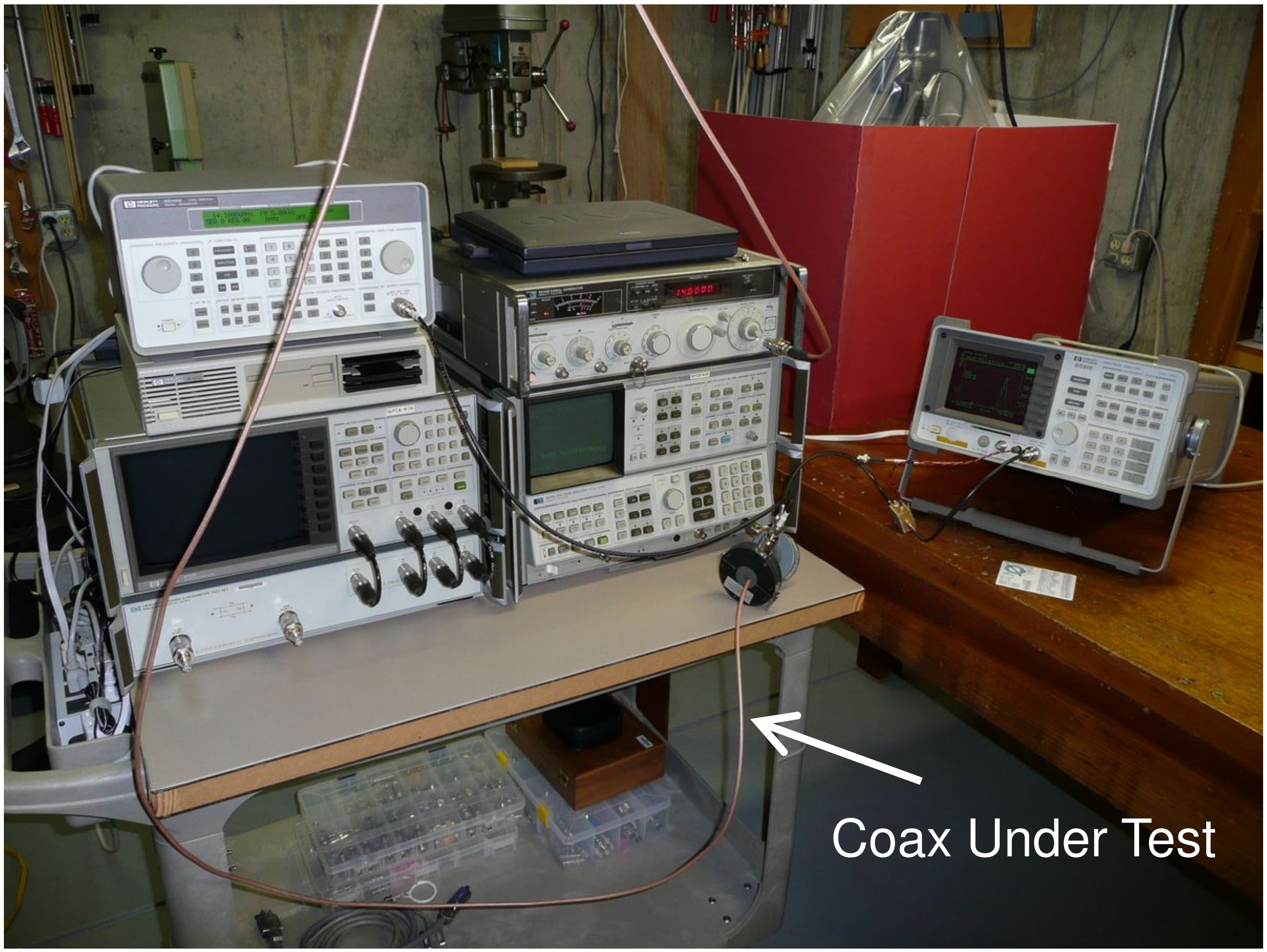


Shield Test



- Sig. Gen. #1 = 14.0MHz @ -20dBm
  - transmission line currents = 447uA
- Sig. Gen. #2 = 14.1MHz @ +21dBm (adjusted)
  - to produce common mode current of 447uA via Probe #1

Shield Test Setup



Shield Test Results

Test	Spectrum Analyzer #1	Spectrum Analyzer #2
12’2” Belden RG-58A/U	-20dBm @ 14.0MHz -67dBm @ 14.1MHz	-103dBm @ 14.0MHz -54dBm @ 14.1MHz
14’9” double shield silver RG-142	-20dBm @ 14.0MHz -103dBm @ 14.1MHz	nil @ 14.0MHz -54dBm @ 14.1MHz

Both tests had 447uA of transmission line current @ 14.0MHz & 447uA of common mode current @ 14.1MHz

Transmission Line Conclusion

- Was level of material appropriate?
- Follow up with impedance matching
- Other topics such as troubleshooting, phasing, and transmission line transformers