When Are SWR & Reflected Power Important

Bill Leonard NØCU

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TechConnect Radio Club

na0tc.org

References

1. Reflections III: Walter Maxwell, W2DU
    - **No longer offered by ARRL**
        - **Used ones are still available on the Internet**
2. ARRL: Transmission Line for Windows (TLW)
    - **No longer offered by ARRL**
        - **Won’t run on Win 10 (or later?)**
    - **Other software options (SimSmith & SimNec)**
3. “Understanding SWR by Example “ Nov 2006 QST
4. “Do You Need an Antenna Tuner?” Jan 1994 QST

SWR Quiz – True or False

1. Lowest SWR ensures best performance
2. High SWR ensures poor performance
3. An antenna needs to be resonant to perform well
4. Reflected power always represents lost power
5. Reflected power flows back into the transmitter causing increased power dissipation
6. It is always best to try to achieve an SWR close to 1.0:1
7. Any transmission line with high SWR produces unwanted radiation
8. Antenna impedance can only be accurately determined at the antenna
9. The SWR at the transmitter can be improved by changing the length of the transmission line
10. The lowest SWR at the input to a transmission line feeding an antenna always occurs at the same frequency as resonance

SWR Quiz – True or False

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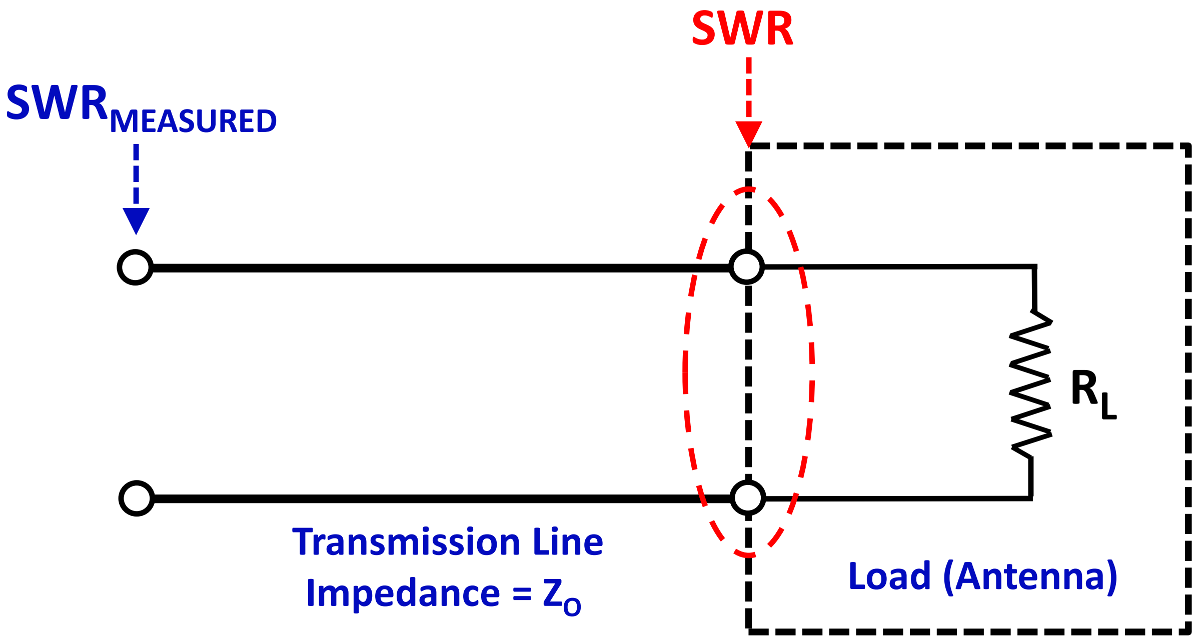
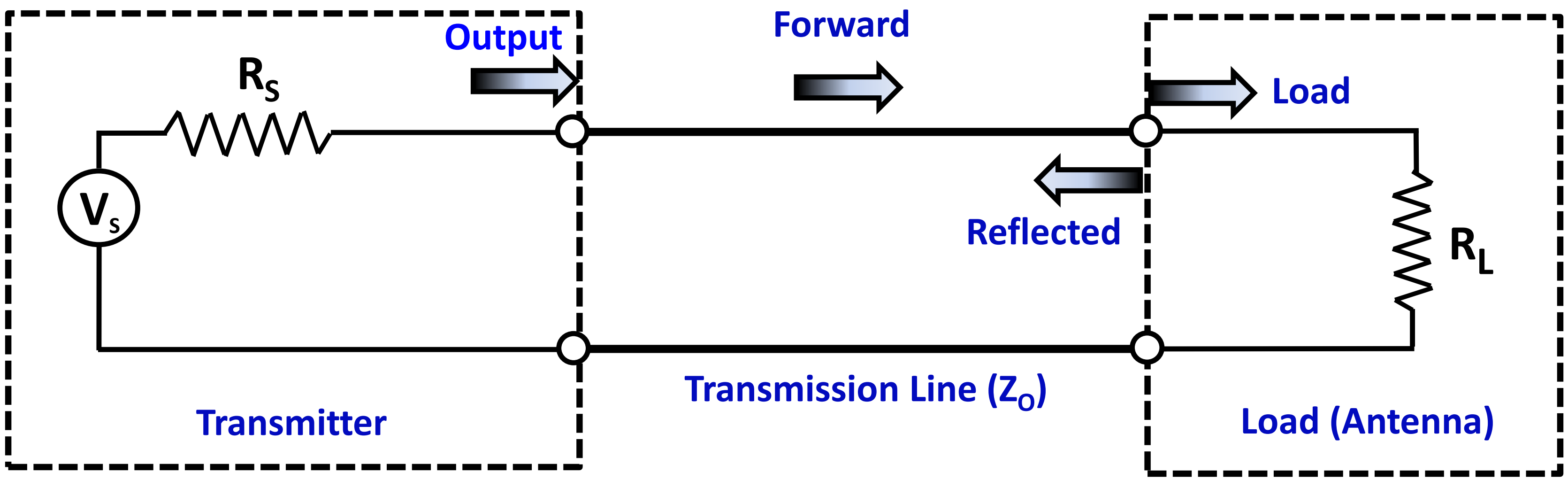
All are False (*with a few caveats)

What Is Standing Wave Ratio (SWR)?



- The Standing Wave Ratio is a measure of the impedance mismatch between a load and a transmission line
- In most cases SWR$_{MEASURED}$ is very close to SWR at the antenna
- An SWR measurement helps in determining:
  - Whether impedance matching is required
  - Whether the antenna system is performing as expected

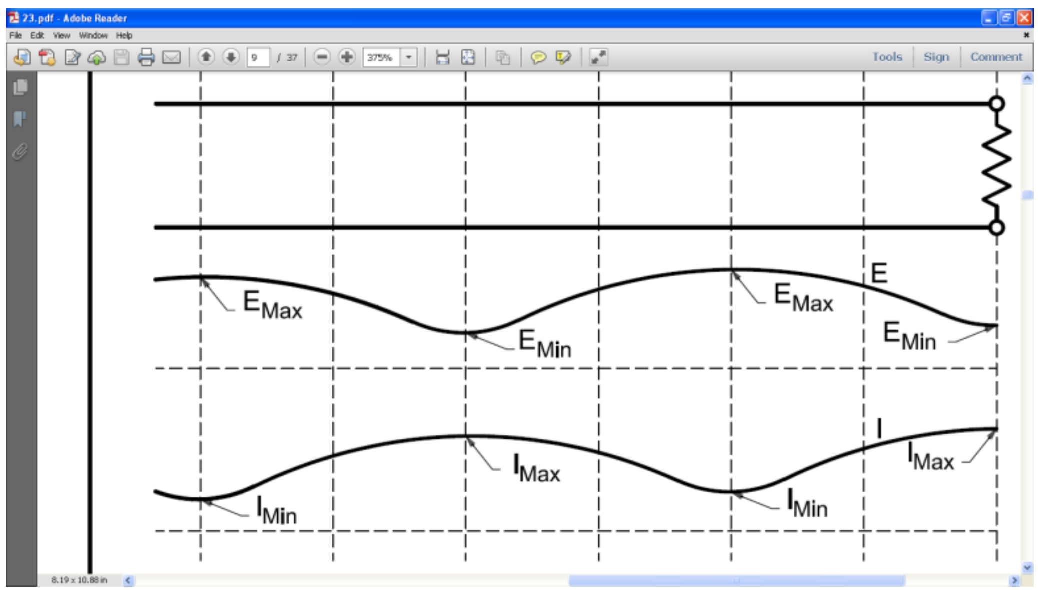
Traveling And Standing Waves



- An RF voltage at the input to the transmission line creates an electromagnetic (traveling) wave in the forward direction
- If the SWR = 1.0:1, $Z_O = R_L$ and all of the energy is dissipated in the load
  - No reflected wave => no standing wave
- If the SWR > 1.0:1, then:
  - A second Traveling Wave is reflected back from the load back toward the transmitter
  - A Standing Wave will be created from the interaction of the forward and reflected traveling waves

Standing Waves

- A Standing Wave:
  - Is created by the interaction of the two traveling waves
  - Is a <u>stationary</u> wave with an amplitude modulation pattern with:
    - Maximums (anti-nodes) and
    - Minimums (nodes)
    - Voltage maximums occur at current minimums, and visa versa
- Standing Wave Ratio (SWR) = $E_{MAX}/E_{MIN} = I_{MAX}/I_{MIN}$



Voltage

Current

How To Determine SWR

1. For resistive loads:

$$SWR = \frac{R_L}{R_O} = \frac{R_O}{R_L}$$

Ex: $SWR\ (3:1) = \frac{50}{16.7} = \frac{150}{50}$

2. SWR meters usually calculate SWR using Forward & Reflected power measurements:

$$SWR = \frac{1 + \rho}{1 - \rho}$$

Reflection coefficient (ρ) $= \sqrt{\frac{P_R}{P_F}} = \frac{Z_L - Z_O}{Z_L + Z_O}$

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

Note: $Z_L = R +/- jX$ (a complex number)

Z_O is the system impedance

Reflected power $= \rho^2 \times P_{FORWARD}$

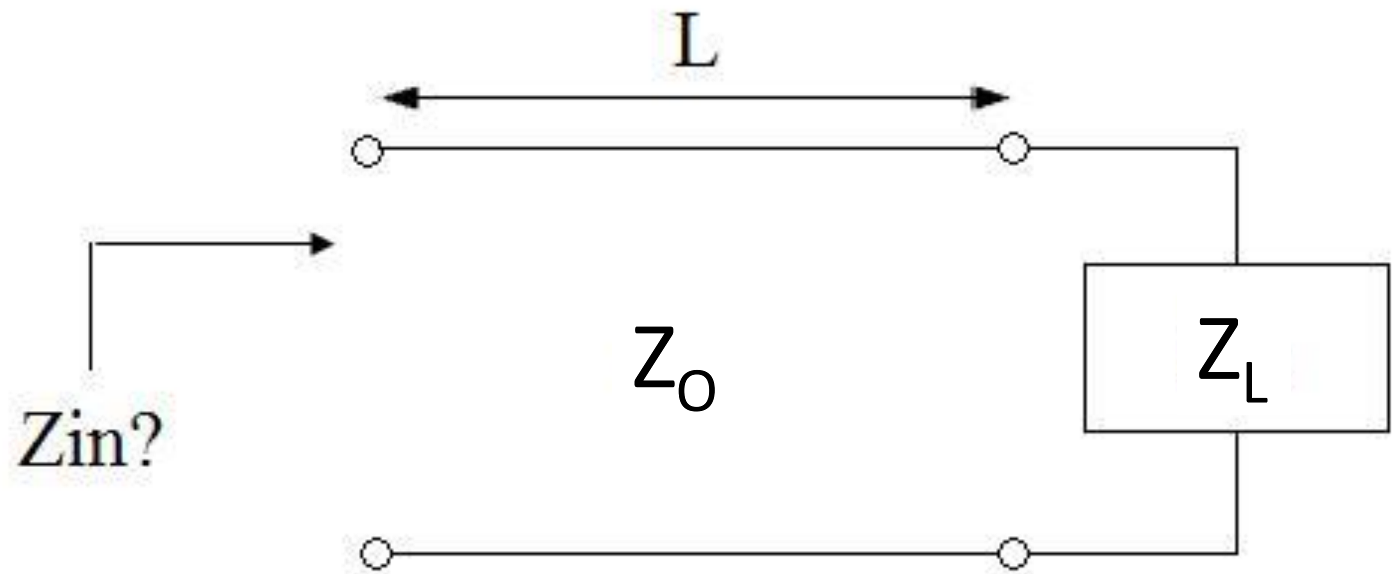
Power transferred to the load $= (1-\rho^2) \times P_{FORWARD}$

3. SWR can also be determined from Return Loss (RL):

$$SWR = \frac{1 + 10^{\frac{-RL}{20}}}{1 - 10^{\frac{-RL}{20}}}$$

Sometimes We Need To Know Impedance

Transmission line with impedance = Z_O



Why Was The Smith Chart Developed?

Frank Lynch, W4FAL

The Formula!

Impedance looking into a Transmission Line

Hyperbolic Tangent

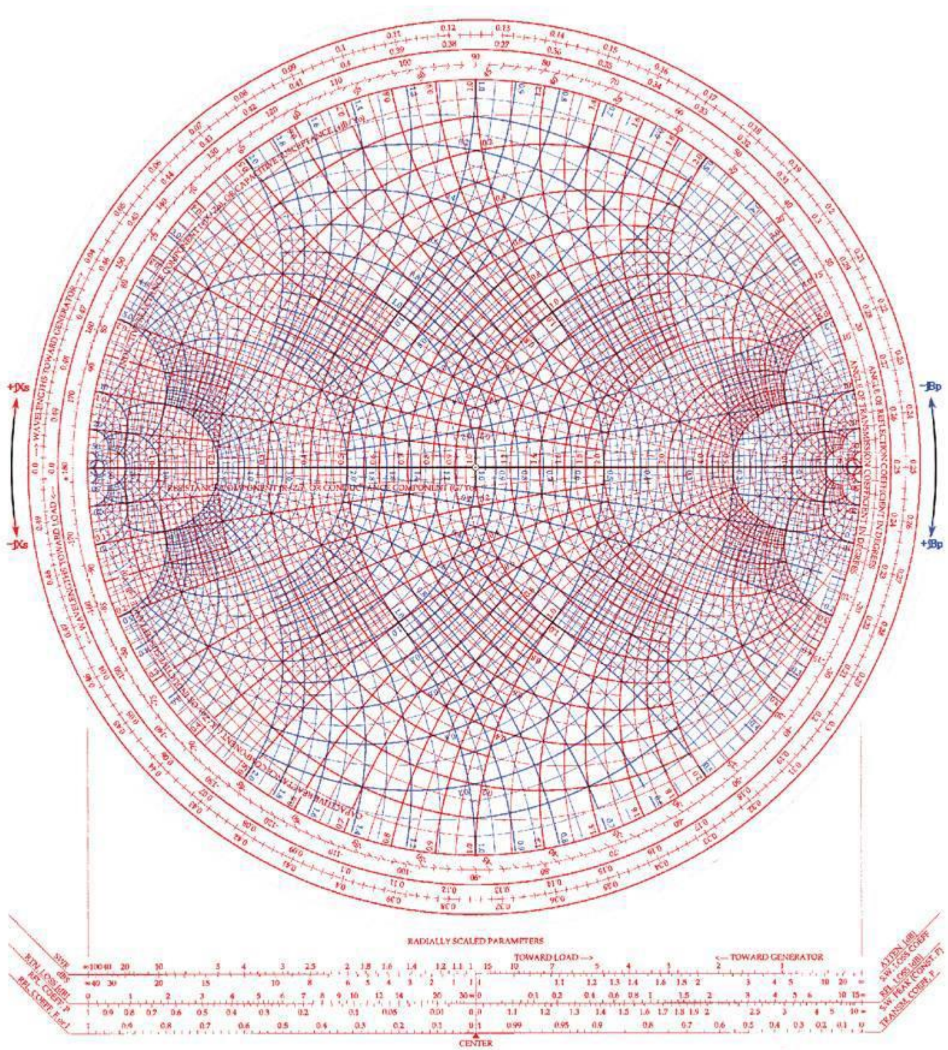
$$Z_{IN} = Z_0 \frac{Z_L + Z_0 \tanh \gamma x}{Z_0 + Z_L \tanh \gamma x}$$

$$\gamma = \alpha + j\beta$$

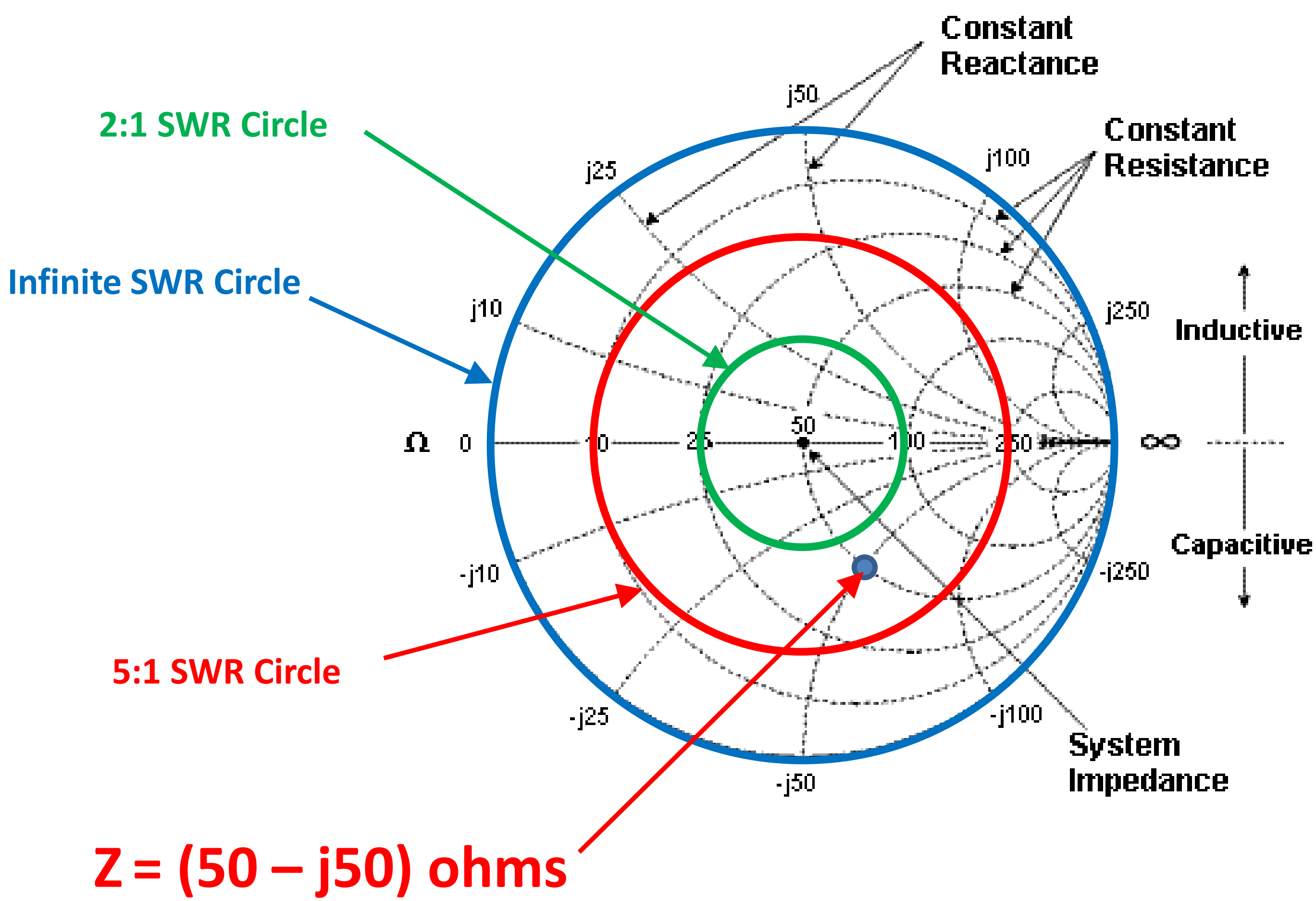
Complex Numbers

The Smith Chart

The Smith Chart is an impedance map developed by Philip Smith in the 1930s



Constant SWR Circles (Lossless Lines)



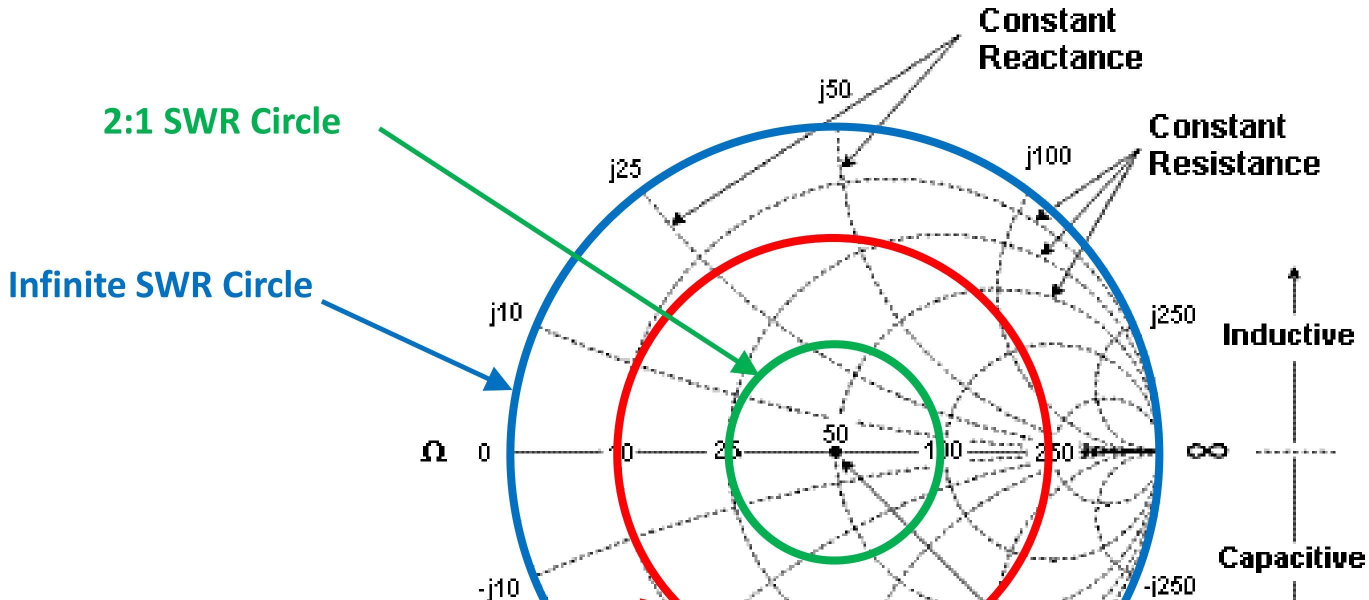
Adding Length to a <u>Lossless</u> Transmission Line causes :

1- Clockwise Rotation Around a Constant SWR Circle

2- Z changes but SWR remains constant

3- One Full Rotation Equals ½ Wavelength

Constant SWR Circles (Lossless Lines)



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1- Clockwise Rotation Around a Constant SWR Circle

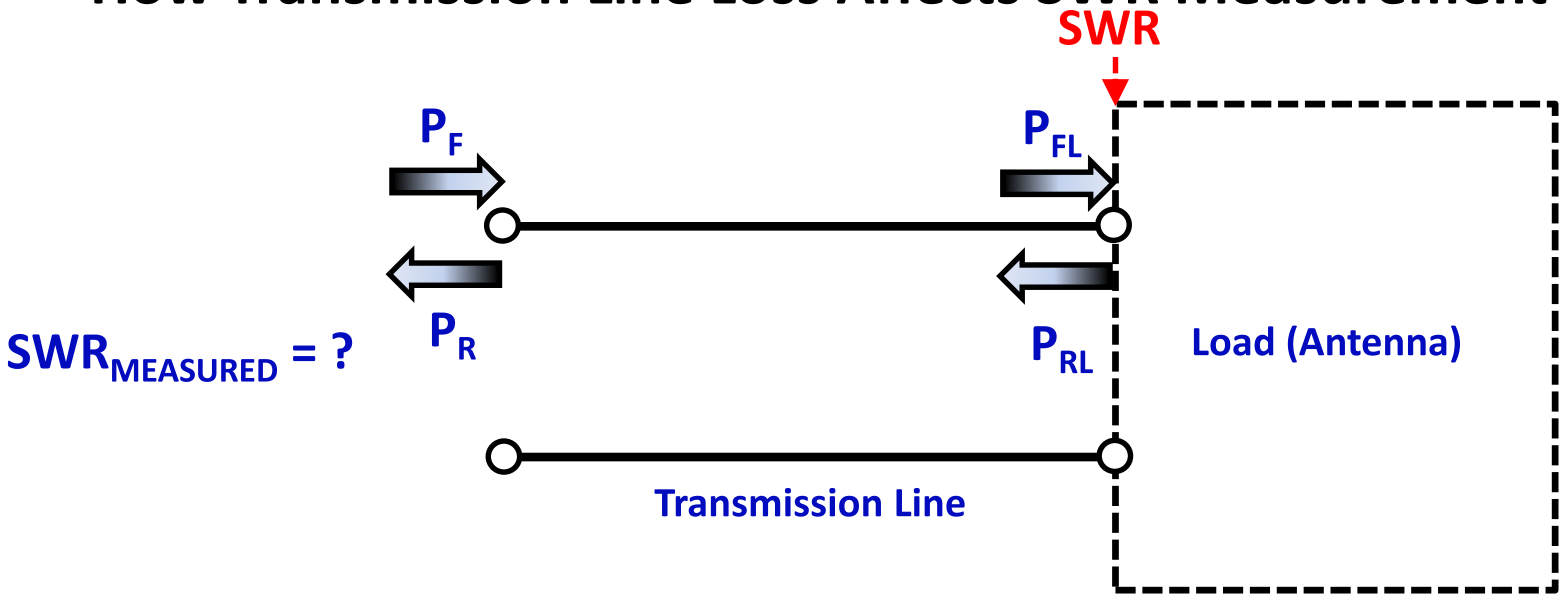
2- Z changes but SWR remains constant

3- One Full Rotation Equals ½ Wavelength

A transmission line is an Impedance Transformer*. Changing the length changes the impedance seen looking into the line, not the SWR

*Ref: "Transmission Lines As Impedance Transformers" 2017 TechFest

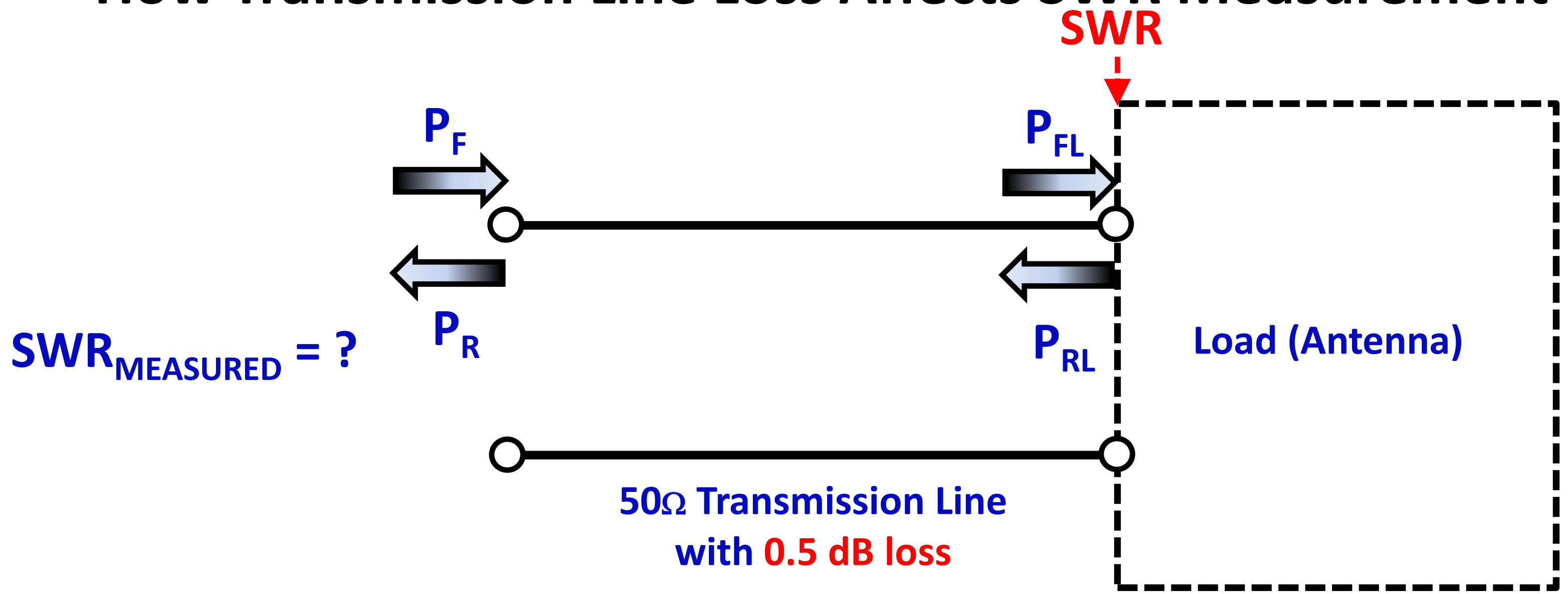
How Transmission Line Loss Affects SWR Measurement



- $SWR_{MEASURED}$ = SWR only when the line loss = 0 dB
- When line loss is > 0 dB:

  $SWR_{MEASURED} < SWR_{AT\ LOAD}$

How Transmission Line Loss Affects SWR Measurement



Load = 150 ohms:

$SWR_{AT\ LOAD}$ = 3:1

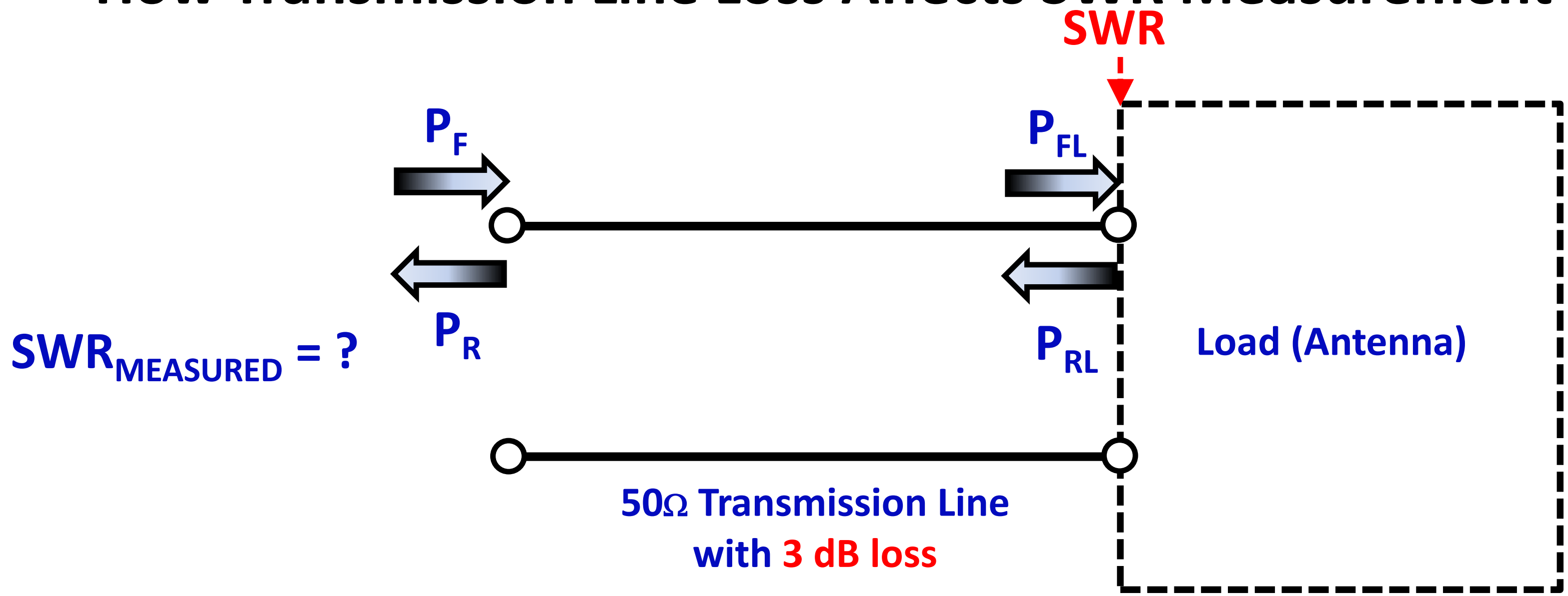
$SWR_{MEASURED}$ = 2.6:1

Load = open/short circuit:

$SWR_{AT\ LOAD}$ = Infinite

$SWR_{MEASURED}$ = 17:1

How Transmission Line Loss Affects SWR Measurement



An auto tuner can mask a problem!
(Remote stations??)

Load = 150 ohms:

$SWR_{AT\ LOAD}$ = 3:1

$SWR_{MEASURED}$ = 1.7:1 (power radiated by antenna <40%)

Load = open/short circuit:

$SWR_{AT\ LOAD}$ = Infinite

$SWR_{MEASURED}$ = 3:1 (power radiated by antenna 0%)

How To Measure Transmission Line Loss

1. Measure power at both ends of a transmission line
2. Using a shorted or open transmission line, either measure SWR or calculate SWR from forward and reflected powers

Measured SWR Open Line	Line Loss dB
1.0	Infinite
1.5	7.0
2.0	4.8
2.5	3.7
3.0	3.0
3.5	2.6
4	2.2
5	1.8
6	1.5
7	1.3
8	1.1
9	1.0
10	0.85
15	0.55
17	0.50

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

SWR meters lose accuracy & resolution

What is the most important part of an SWR measurement?

What is the most important part of an SWR measurement?

Knowing what the number <u>should be</u>!

(There is no one “best” SWR number)

Some Reasons To Reduce SWR?

- **Prevent activation of transmitter high SWR shutdown circuit**
  - **Typical activation SWR ~ 2:1 (some rigs > 3:1)**
- **Increase usable bandwidth**
- **To avoid exceeding voltage or current limits of components**
  - **Peak current and voltage increase as $\sqrt{SWR}$**
- Reduce transmission line loss
  - SWR related line losses are usually < 0.5 dB
  - Improvement only achieved when the match is done <u>at the antenna</u>
- To maximize power output from the transmitter
  - Usually not worth the effort/expense
- To minimize power dissipation in the transmitter
  - May not be worth the effort/expense

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- **Prevent activation of transmitter high SWR shutdown circuit**
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Note: reducing lost power due to reflected power being dissipated in the transmitter is not on the list

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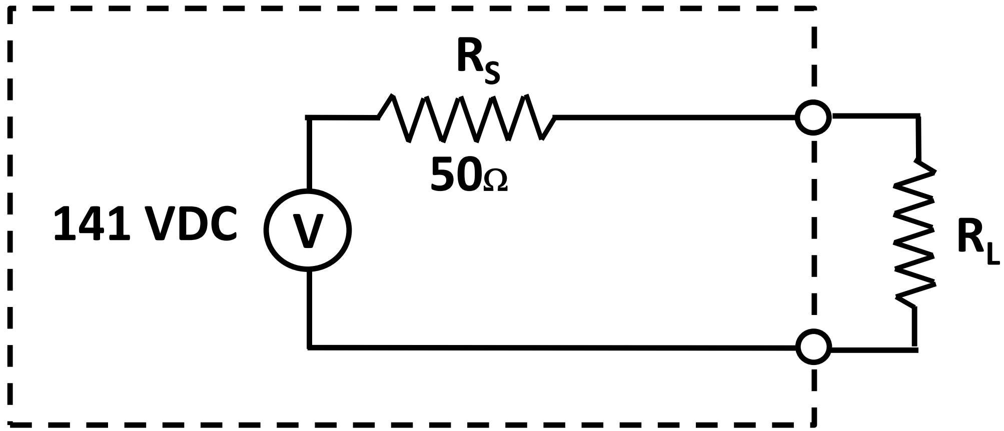
How To Reduce SWR?

1. **Make adjustments to the antenna**
2. **Use a matching network to achieve a "Match"**
   - **Can be done at the antenna or at the transmitter**
   - **Each approach has advantages and disadvantages**

How To Achieve A Match

1. What value of R_L maximizes power dissipation in R_L?



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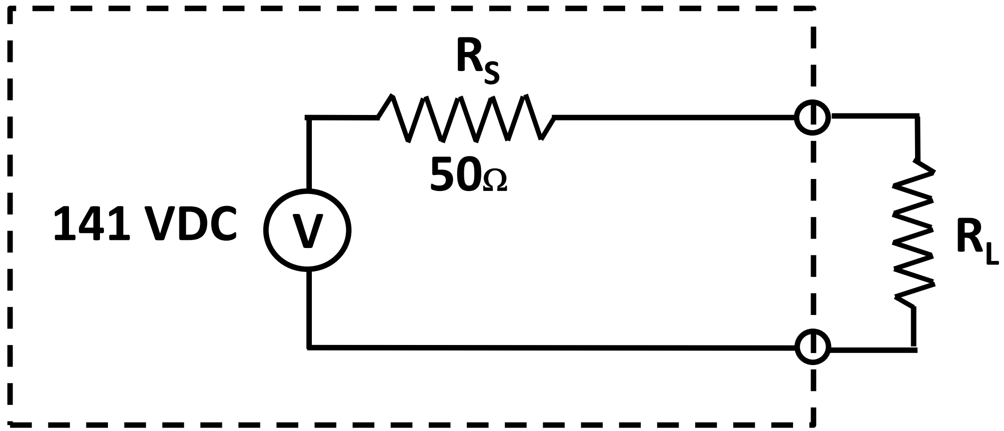
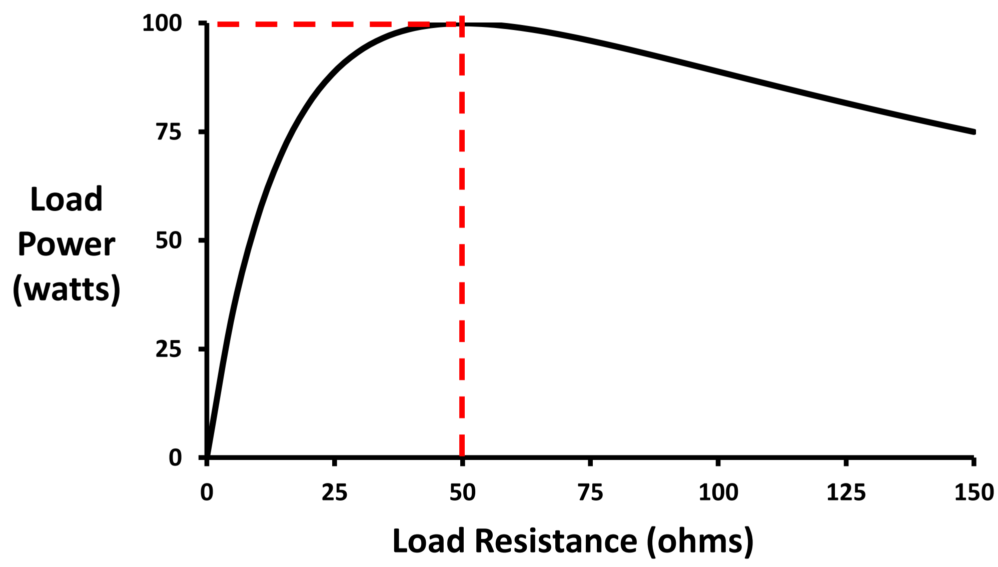


Maximum power is dissipated in the load when $R_L = R_S$

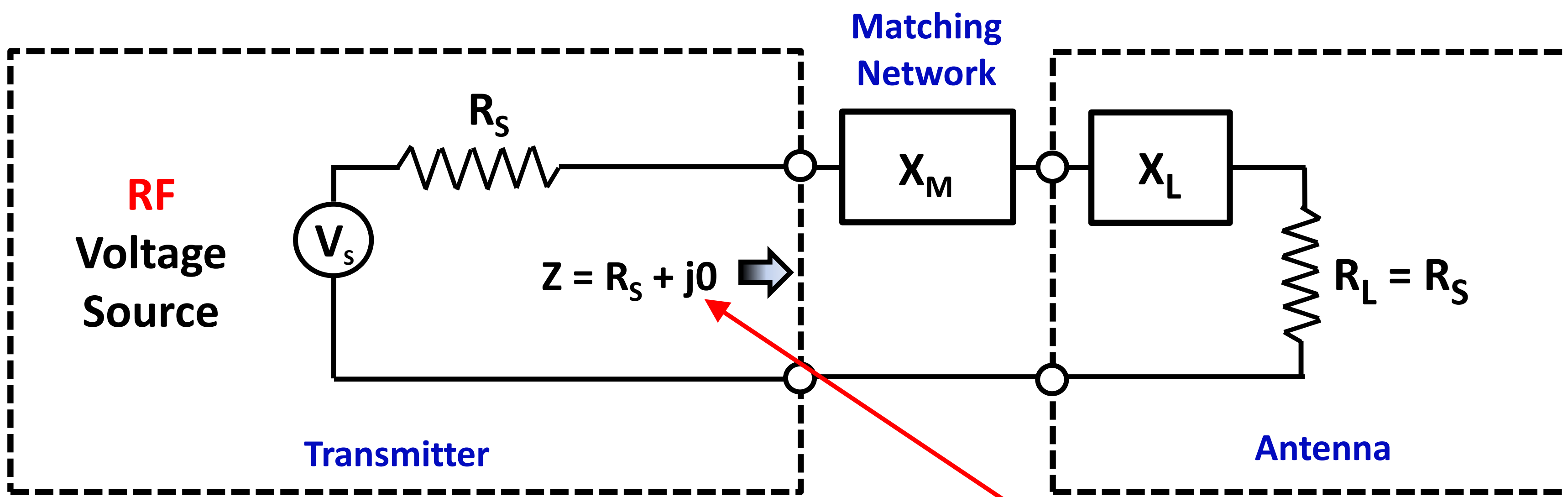


When $R_L = R_S$ => "Perfect" Match

- P_{OUT} = 100 W = P_{SOURCE}
- P_{TOTAL} = 200 W
- Max efficiency is only 50%
- RF amps usually exhibit higher efficiencies (Class AB_2 ~ 65%)

How To Achieve A Match

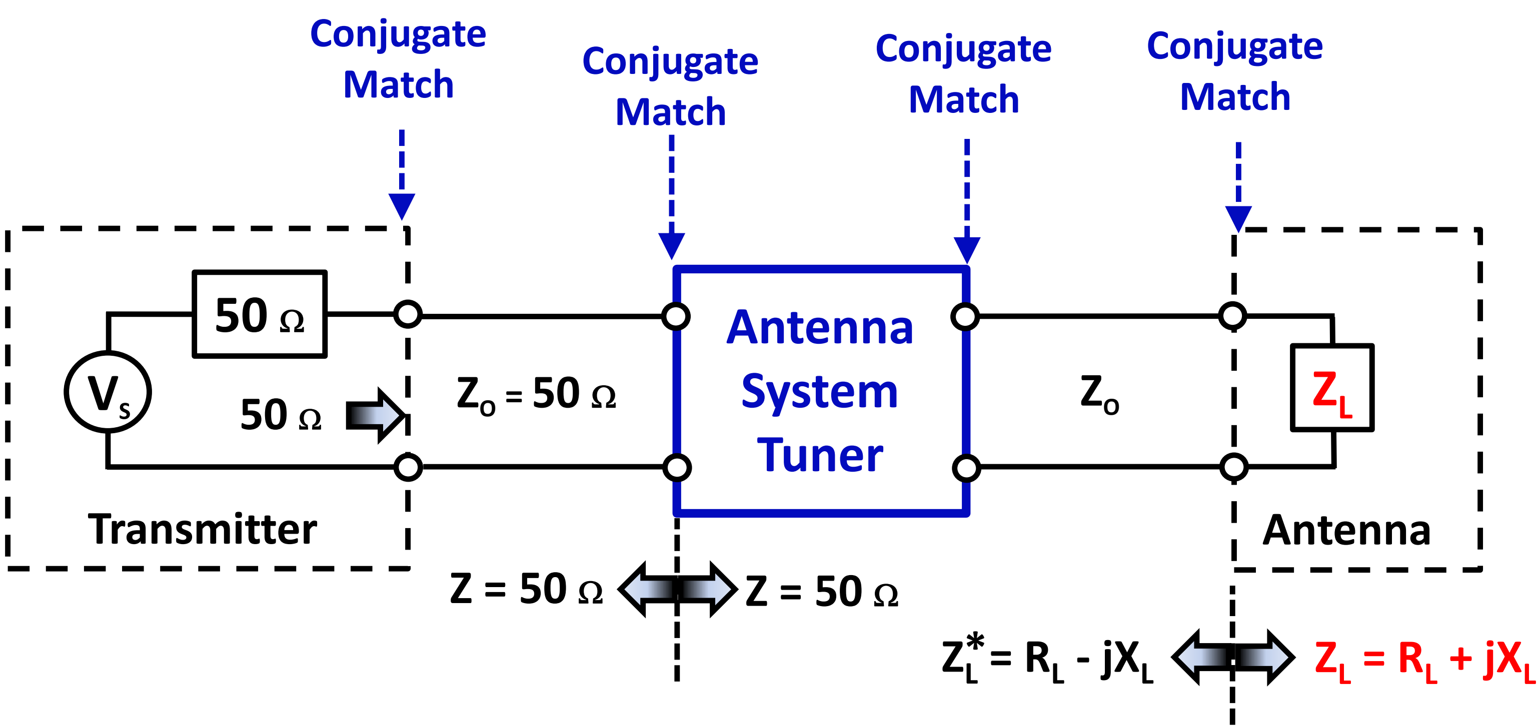
2. When RF is involved, we need a "Conjugate" match



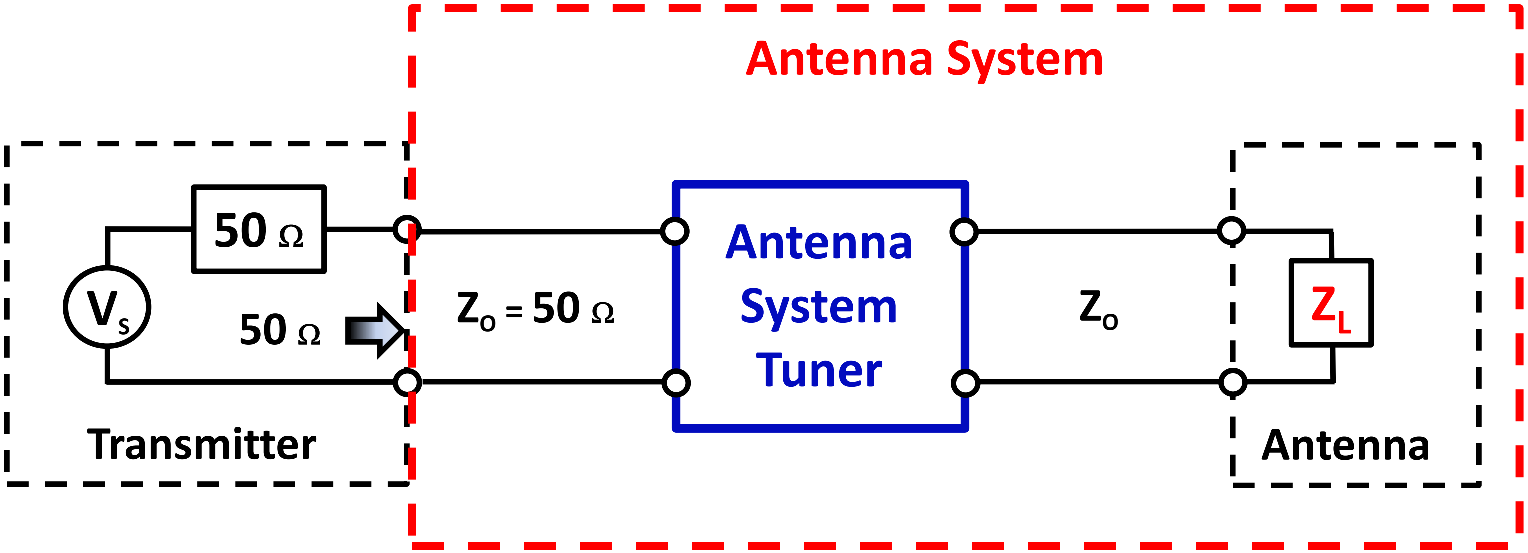
- A Conjugate match requires both:
  - $R_L = R_S$
  - $X_M = - X_L$
    - This equates to the circuit (not the antenna) being resonant
- A Conjugate match exists at only one frequency

How To Achieve A "Conjugate Match"

- Use a Resistance Transformer when there is no reactance
- Use an Antenna System Tuner when there is reactance:
  - Antenna tuners tune the entire Antenna System to resonance
    - Antenna tuners <u>do not</u> tune the antenna to resonance
    - When a conjugate match is achieved, it occurs at all points in the antenna system



Antenna System



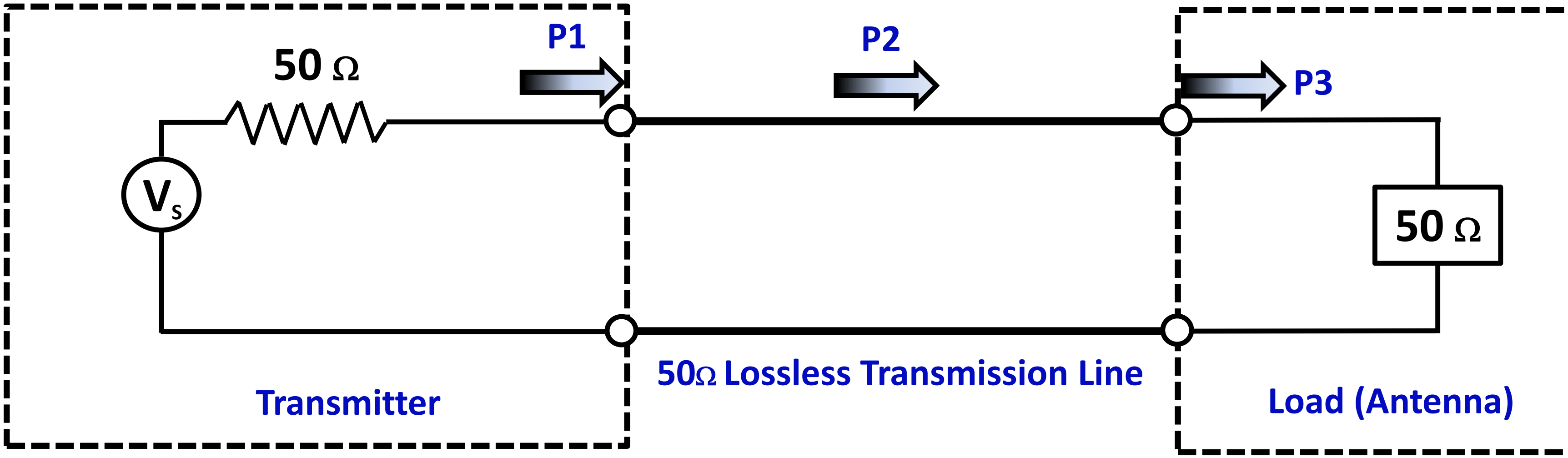
Reflected Power

- **Reflected power is not dissipated in the transmitter**
- **All of the power delivered into a lossless transmission line by a transmitter is radiated by the antenna, regardless of SWR**

Conservation Of Energy

- **“Energy can neither be created nor destroyed”**
  - First Law of Thermodynamics
- **The power flowing into a port must equal the power flowing out of a port**
  - Extension of Kirchhoff's Current Law

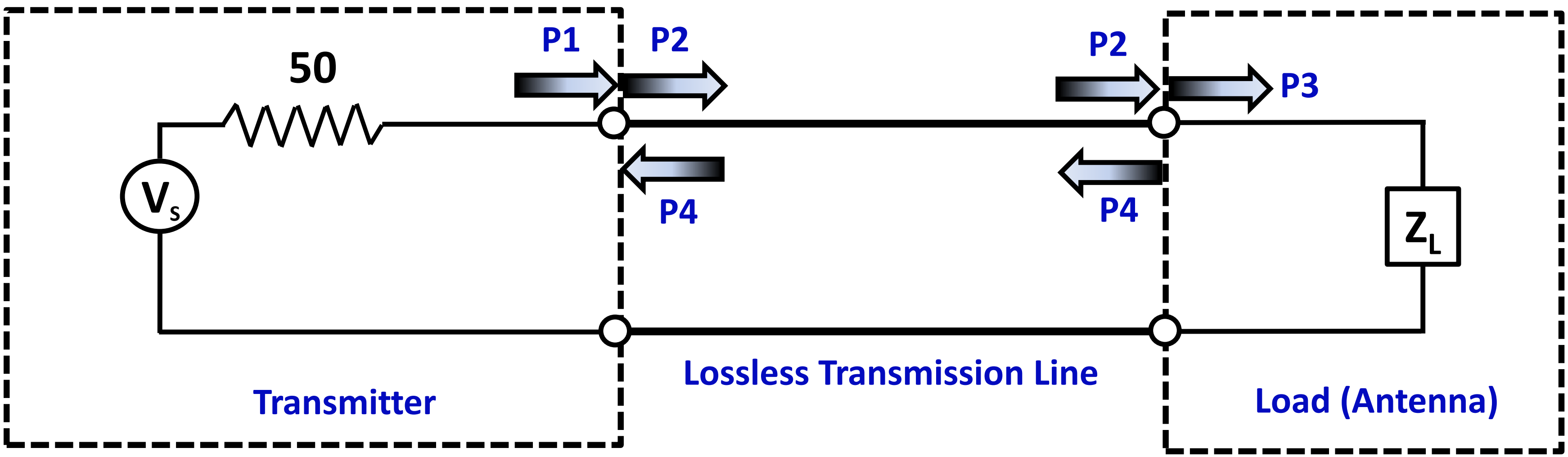
Conservation Of Energy (Matched Load)



- **With a matched load, there is no reflected power**
- **With an ideal lossless line, conservation of energy requires:**

$$P3 = P2 = P1$$

Conservation Of Energy (Mismatched Load)



- With an ideal lossless line, conservation of energy requires that energy leaving a port must equal the energy entering a port:

P1 + P4 = P2

P3 + P4 = P2

P3 + P4 = P1 + P4

P3 = P1 (regardless of SWR)

What Happens To Reflected Power?

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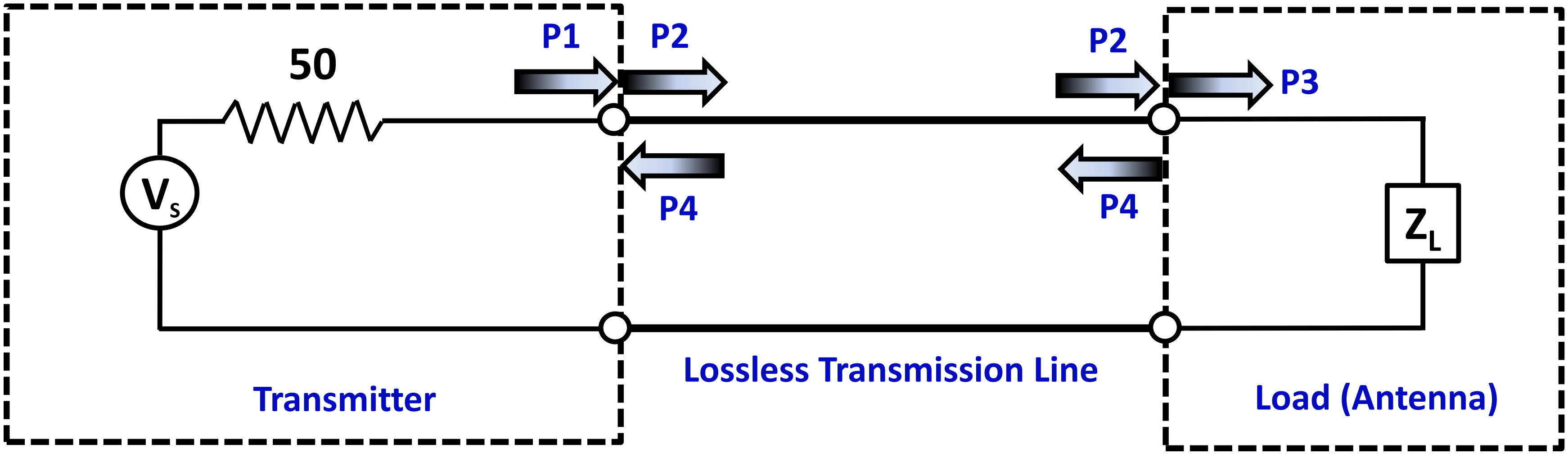


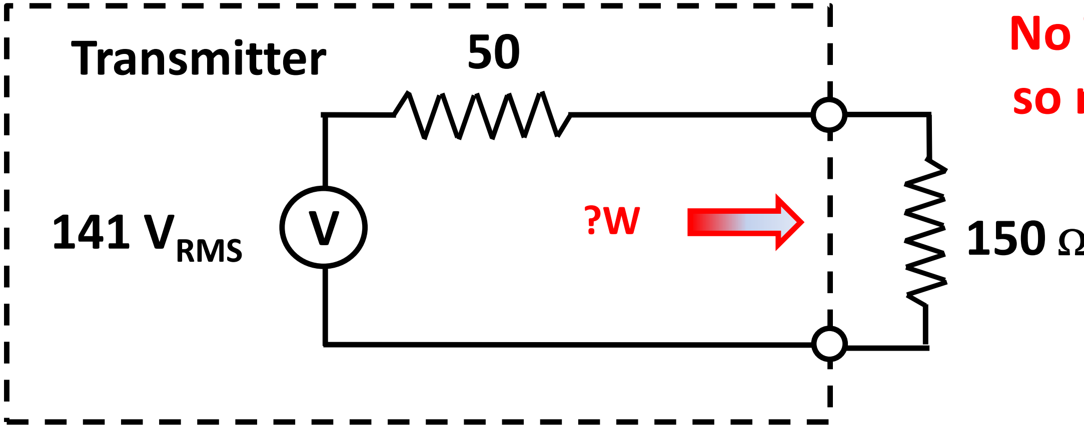
- Reflected power flows back and forth between the transmitter and the load
  - "The reflection loss at the load is offset by the reflection gain at the transmitter"
  - Maxwell uses Wave Mechanics to explain (Reflections)
- When P1 goes to zero, P4 is eventually radiated by the antenna
- P4 is not lost due to dissipation in the transmitter

A Mismatch Does Affect A Transmitter

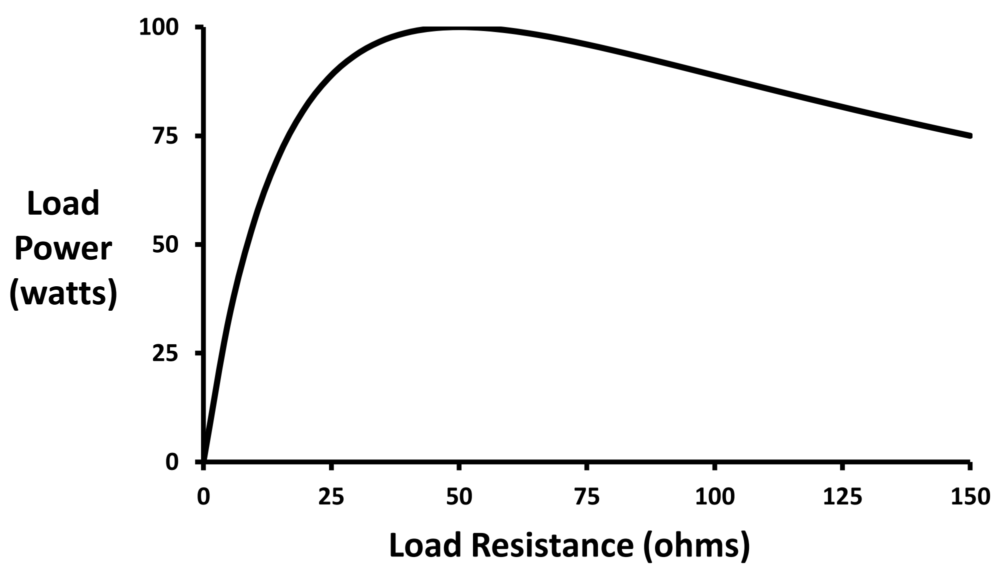
1. Reduced output power
2. Increased power dissipation
   - <u>Not</u> due to reflected power

A Mismatch Reduces Transmitter Output Power

- Assume 100 watt transmitter and R_{LOAD} = 150 Ω



No Transmission Line, so no reflected power



A Mismatch Reduces Transmitter Output Power

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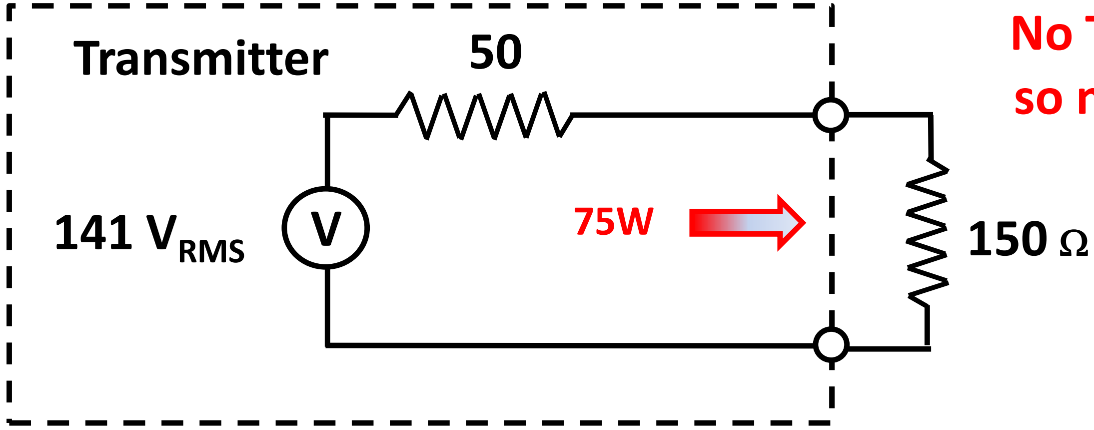

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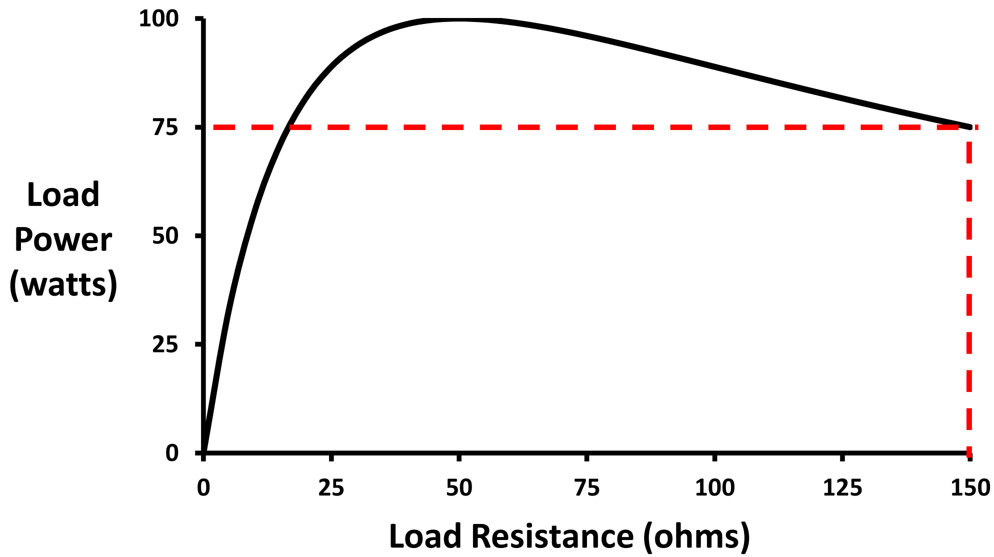


1. The 100 W transmitter can only deliver 75 watts into a 150 ohm load due to the impedance mismatch
2. 25 W is not lost due to dissipation in the transmitter

Transmitter Output Power vs. SWR

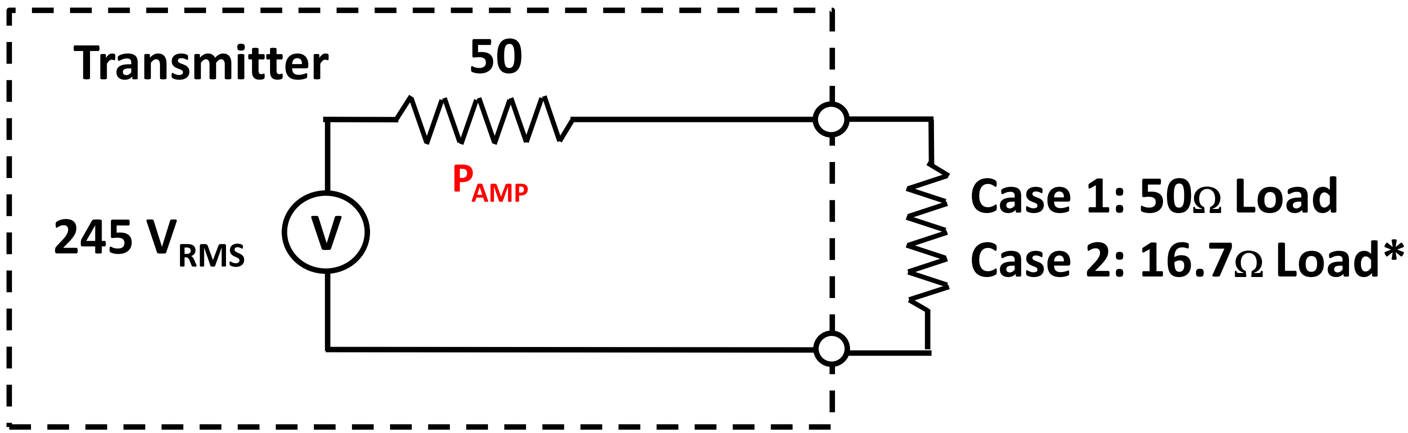
Reducing SWR from 2:1 to 1:1 only increases transmitter output power by 0.5 dB

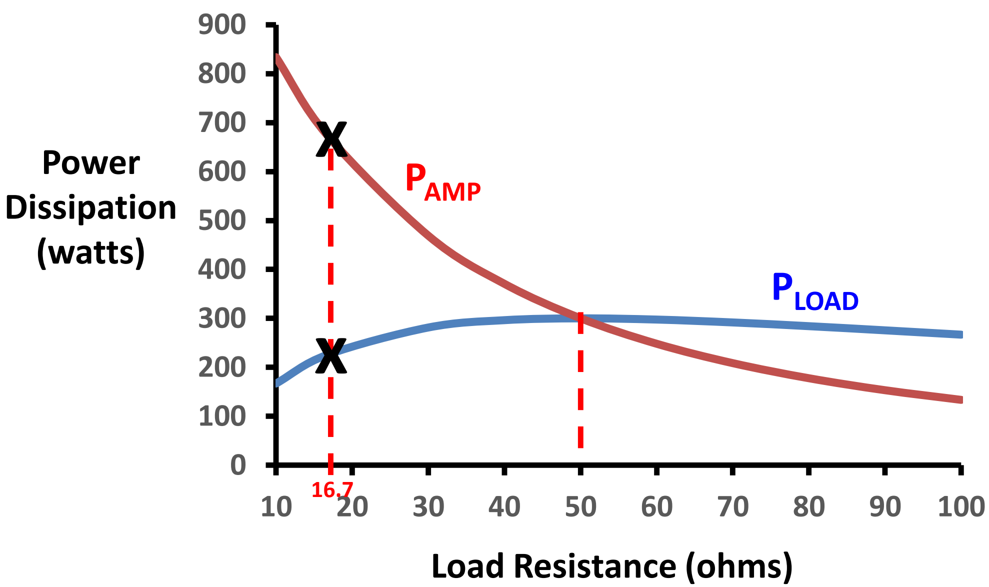
SWR	Power Drop	
	%	dB
1.0:1	0	0
1.5:1	4	-0.2
2.0:1	11	-0.5
3.0:1	25	-1.2
4.0:1	36	-1.9

1/12 of an S unit (1.0:1 to 2.0:1)

A Mismatch Increases Transmitter Dissipation

- Theoretical performance for a 300 watt transmitter:





LOAD OHMS	P_{TOTAL} WATTS	DISSIPATION WATTS		EFFICIENCY %
		P_{AMP}	P_{LOAD}	
50	600	300	300	50
16.7	900	675	225	25

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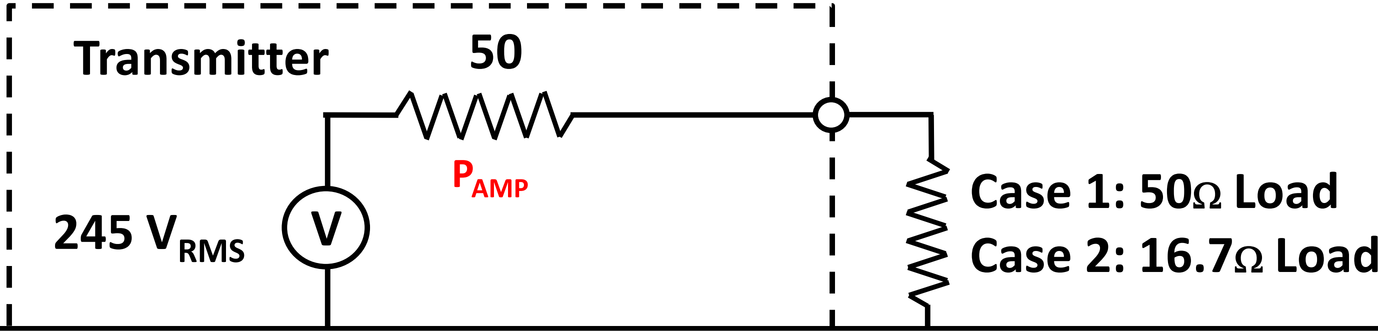
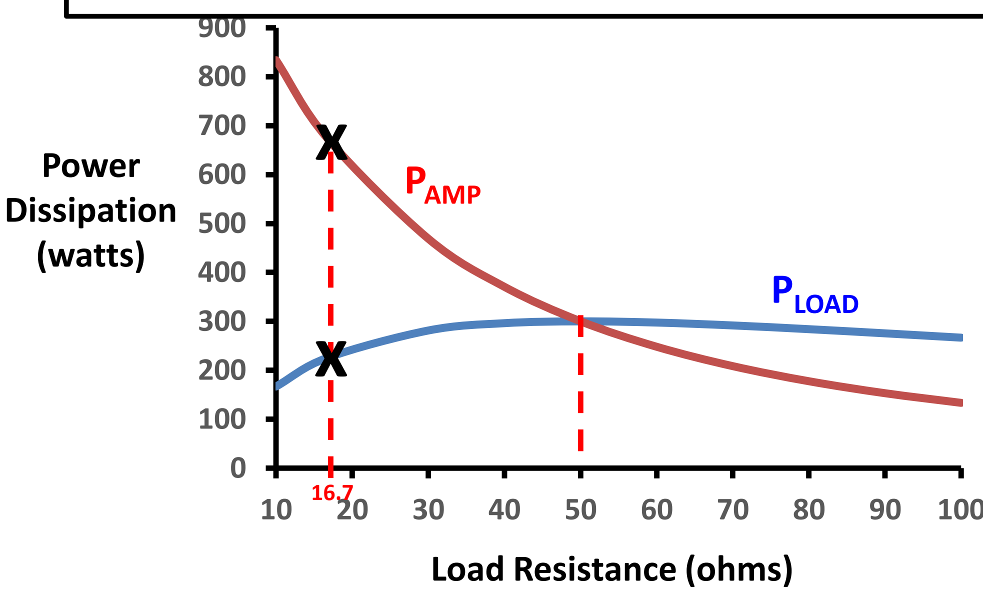


The transmitter puts out 75W less, but dissipates 375W more because it is running at a much less efficient operating point



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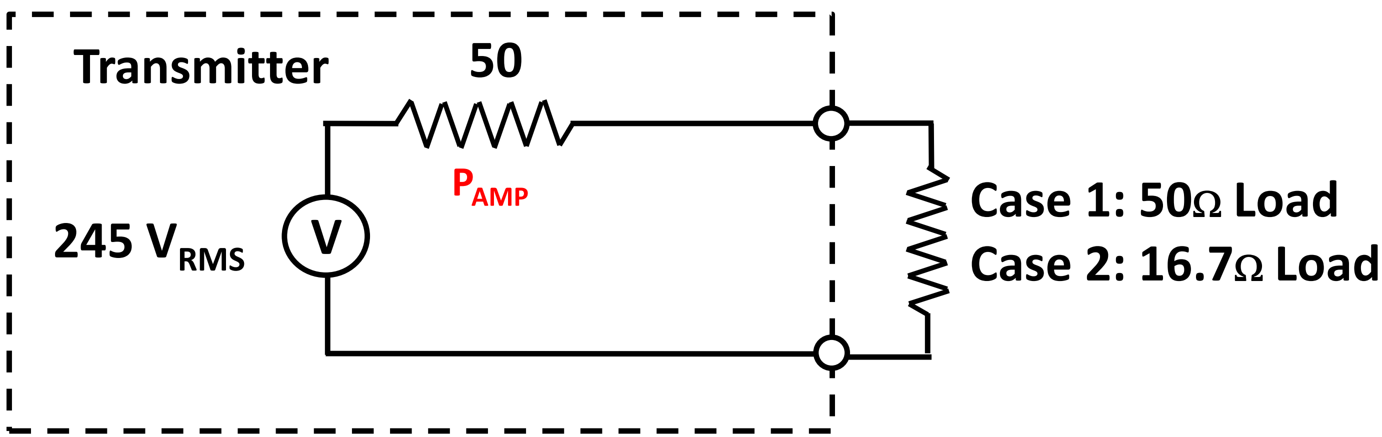
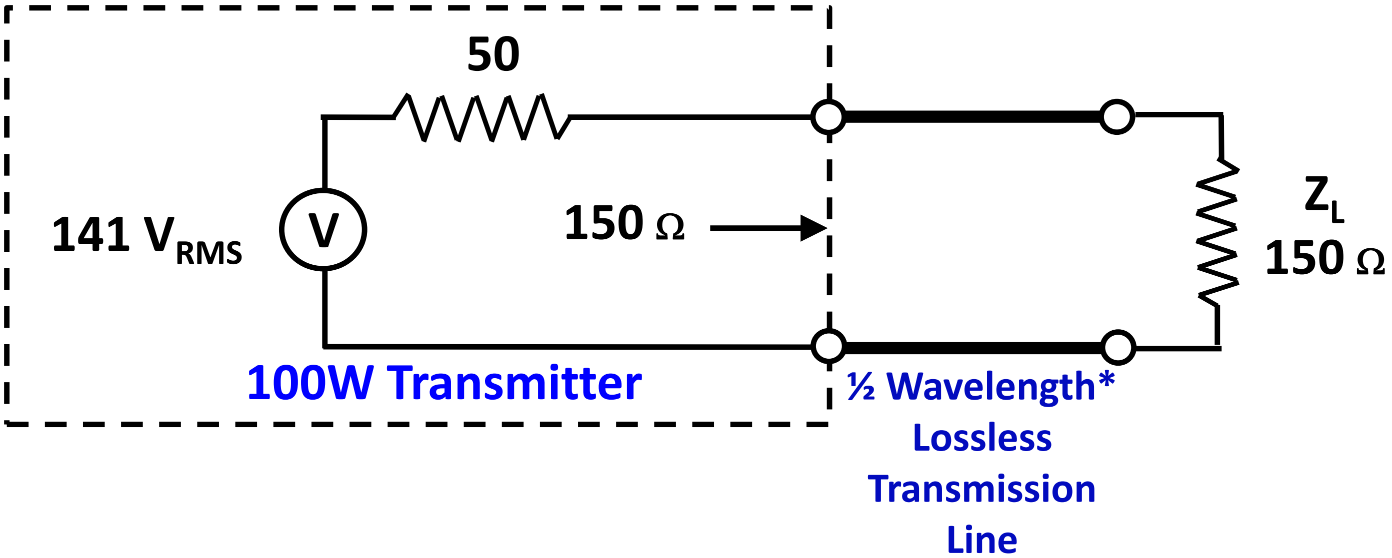


- **Most solid state transmitters and amplifiers have a complex output impedance and are designed to put out maximum power into a 50 ohm load. They are not designed to achieve a conjugate match when terminated in to a 50 ohm load.**
    - **Always tune for minimum SWR, not maximum P_{OUT}**
- **Tube transmitters/amplifiers with a Pi Network for matching should be tuned for maximum P_{OUT}**

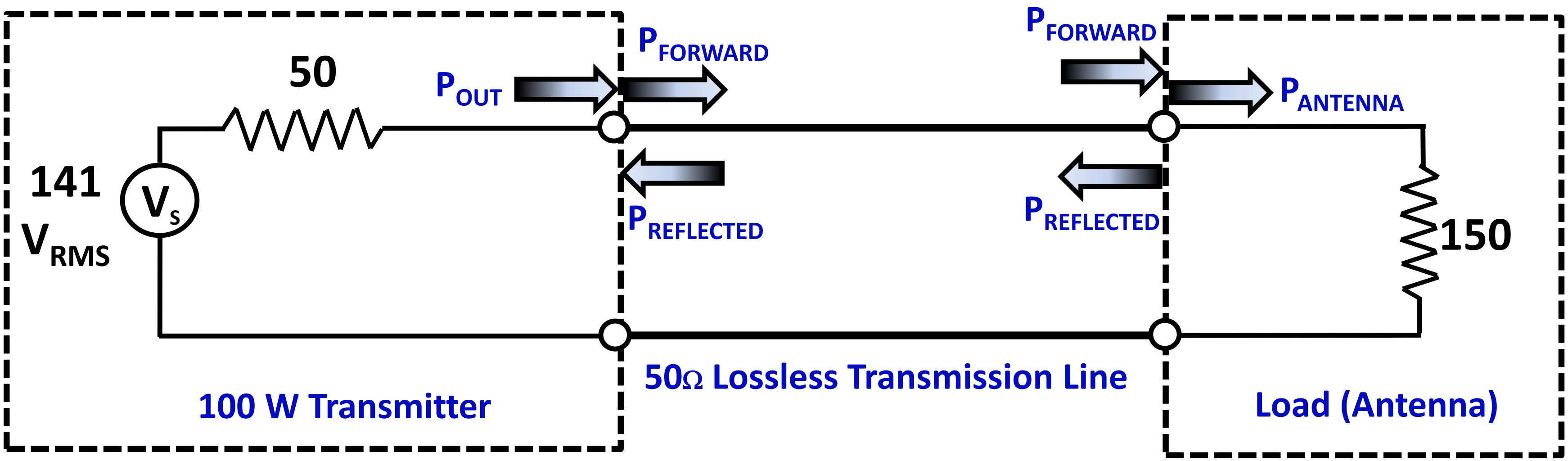
How important is reflected power?

½ Wavelength Lossless Transmission Line



- A ½ wavelength (electrical length) lossless transmission line causes the transmitter to see 150 Ω as a load
  - The final results do not depend on this condition

How To Calculate Forward & Reflected Powers



- With a 150 ohm load at the end of a 50 ohm lossless transmission line:

$$\text{Reflection coefficient} = \rho = \frac{R_L - 50}{R_L + 50} = \frac{150-50}{150+50} = 0.5$$

$$\text{Reflected power} = \rho^2 \times P_{FORWARD} = 0.25 \text{ X } P_{FORWARD}$$

$$\text{Power transferred to the antenna} = (1-\rho^2) \times P_{FORWARD} = 0.75 \text{ X } P_{FORWARD}$$

Forward & Reflected Power vs SWR

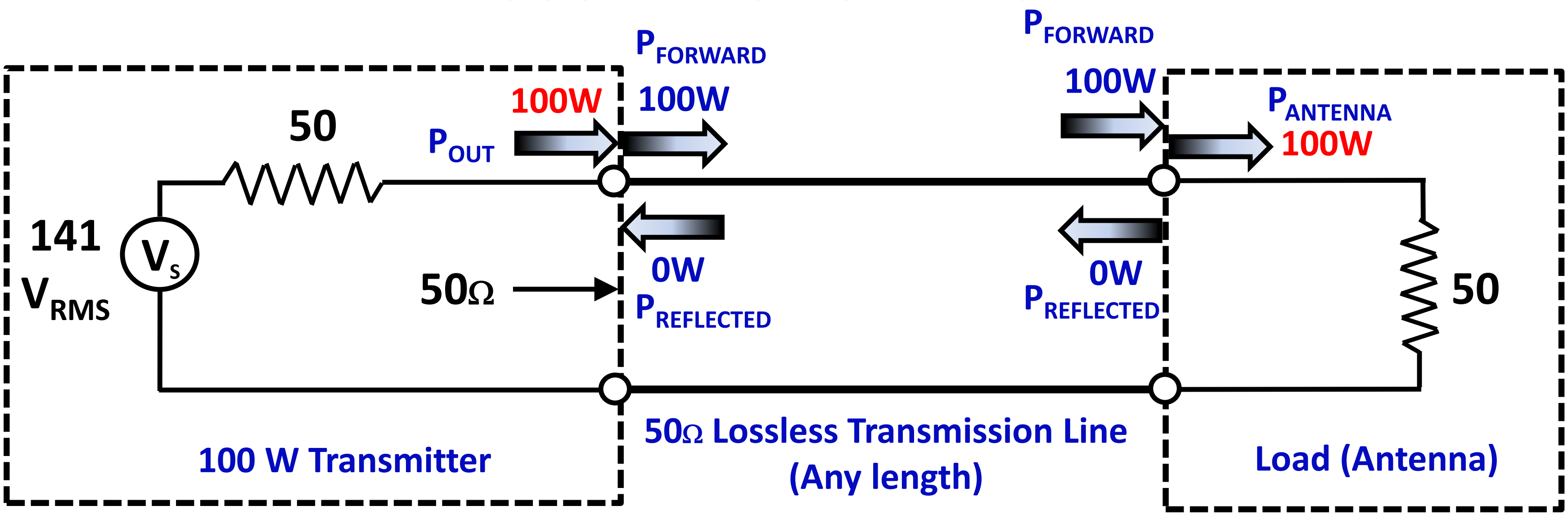
Only 3 cases to consider (Ref: Reflections III – Appendix 6):

1. **A perfect match**

2. **A Mismatch**

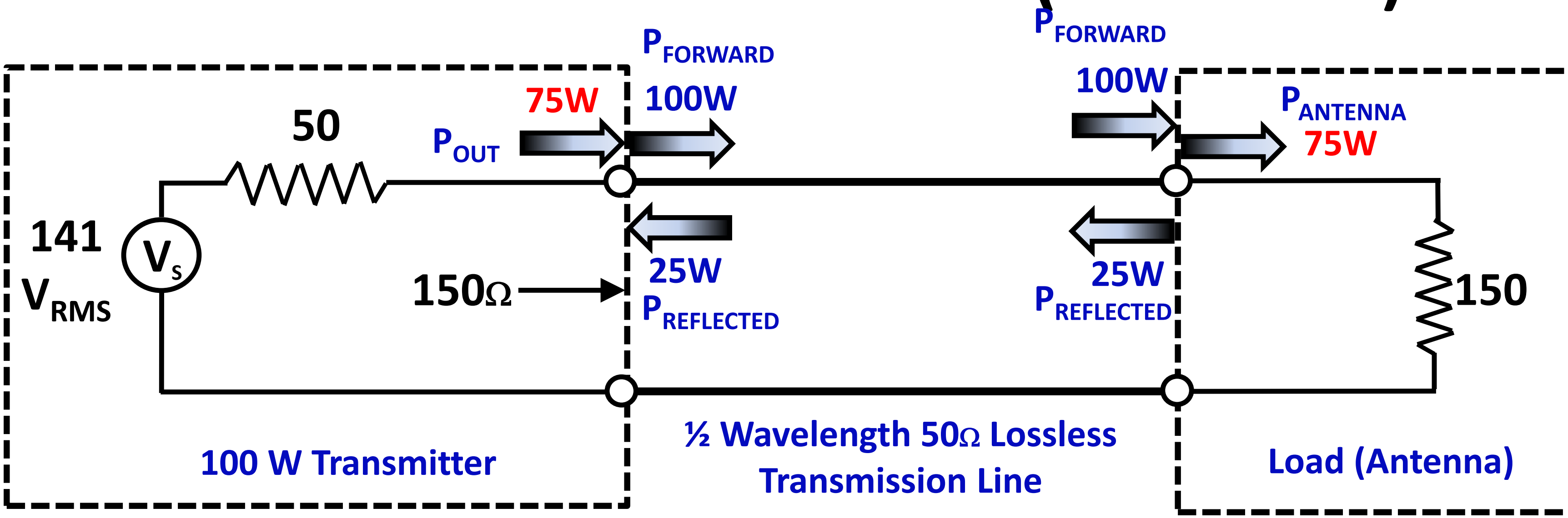
3. **A Mismatch tuned to a Conjugate Match**

Case 1: Perfect Match



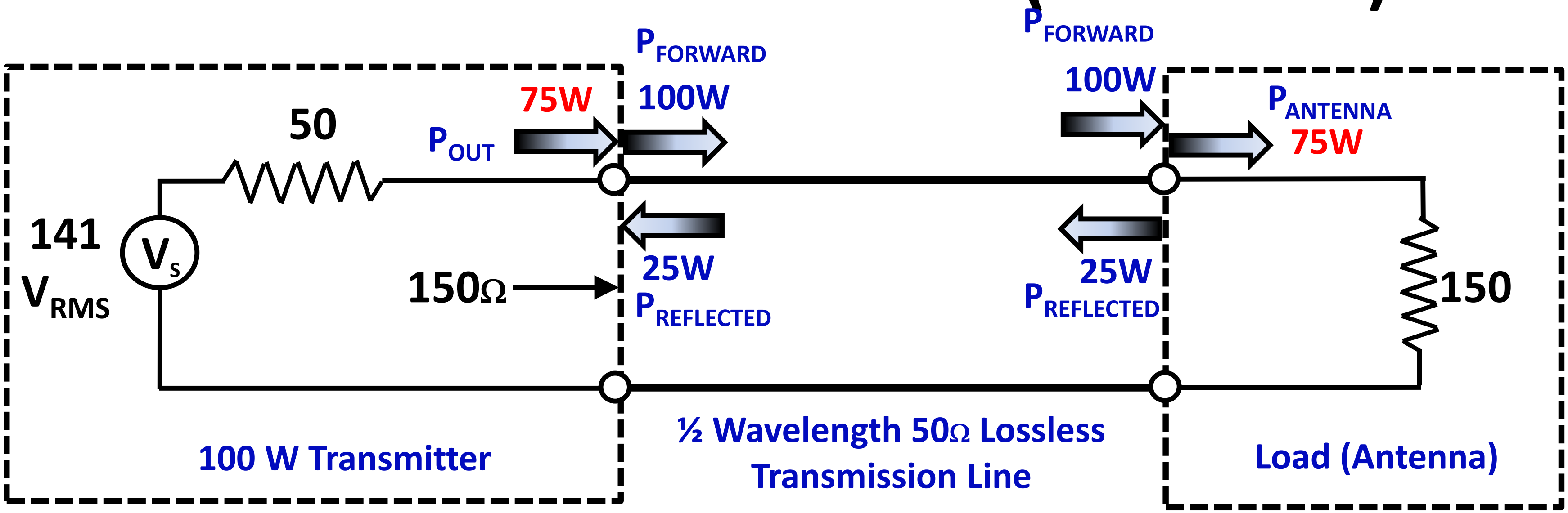
- The transmitter sees a perfect match (50Ω load) and generates it's max available power => P_{OUT} = 100W = P_{OUT} (MAX)
- With perfect match ρ = 0 => $P_{REFLECTED}$ = 0W
- All 100W generated by the transmitter is dissipated in the load
  - $P_{ANTENNA}$ = P_{OUT} = $P_{FORWARD}$ = 100W

Case 2: Mismatched load (SWR = 3:1)



- Because of the ½ wavelength line the transmitter sees a 150 ohm load
  - The transmitter puts out => P_{OUT} = 75W
- At the Antenna:
  - Assume that $P_{ANTENNA} = P_{OUT}$ = 75W
  - $P_{ANTENNA} = P_{FORWARD} – 0.25 \times P_{FORWARD}$
  - $P_{FORWARD} = P_{ANTENNA} /0.75 = 75/0.75 =$ 100W
  - $P_{REFLECTED} = 0.25 \times P_{FORWARD} = 0.25 \times 100 =$ 25W
  - $P_{ANTENNA} = P_{FORWARD} – P_{REFLECTED} = 75W = P_{OUT}$
- Power meter at the transmitter measures $P_{FORWARD}$ and $P_{REFLECTED}$
  - $P_{ANTENNA} = P_{FORWARD}$ only when SWR=1:1

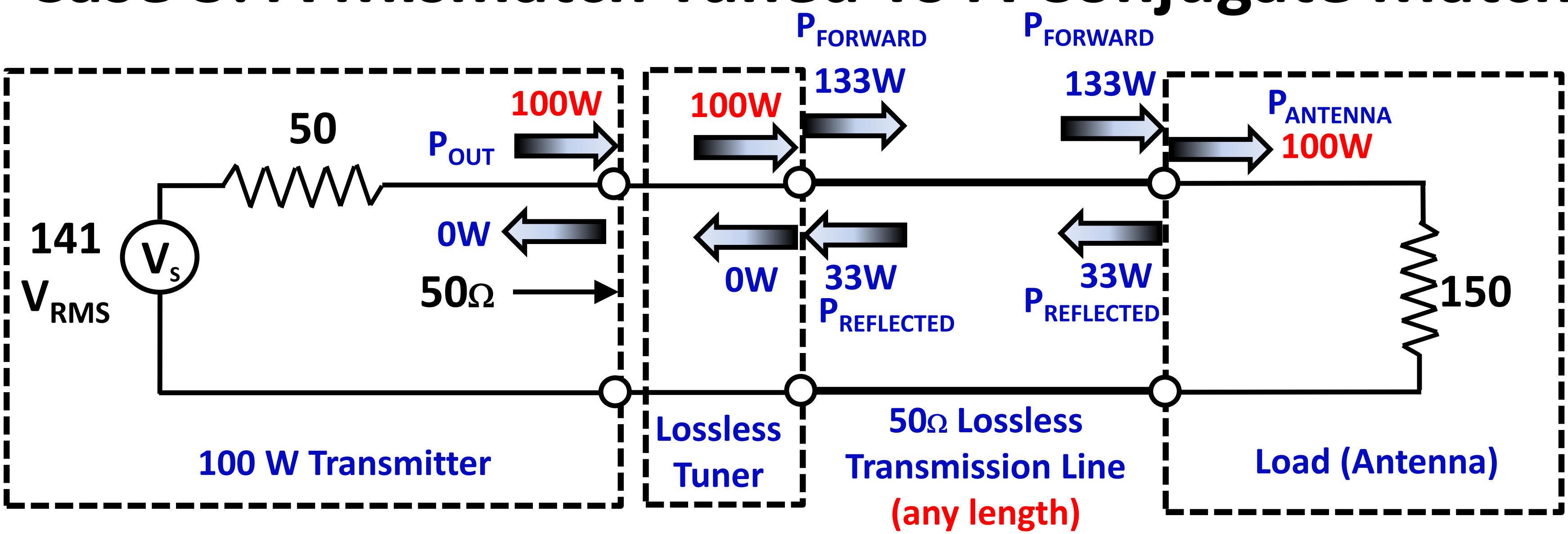
Case 2: Mismatched load (SWR = 3:1)



Reflected Power: “lost” vs “not generated”

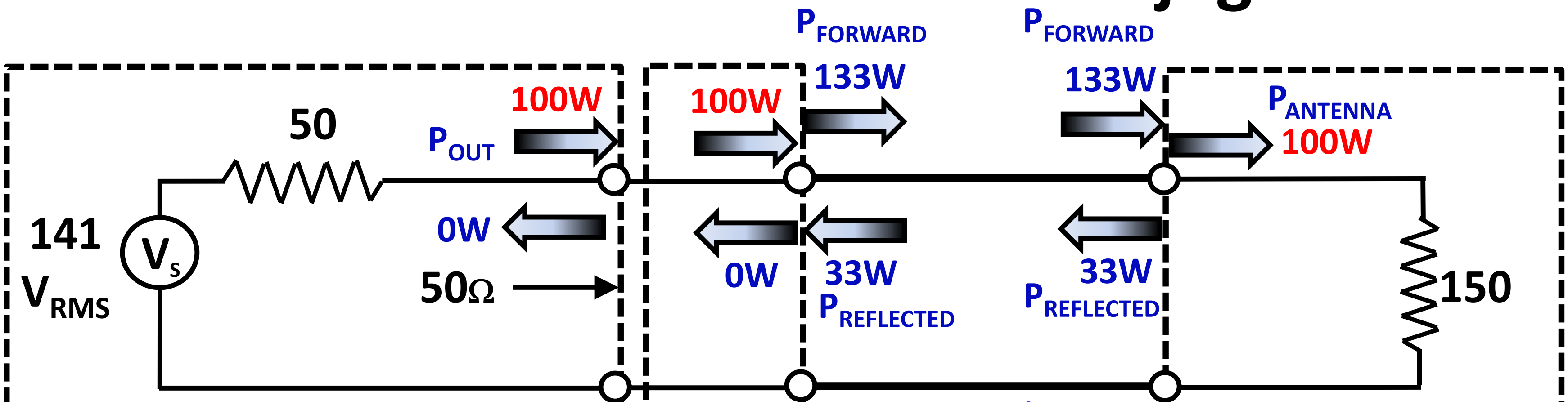
- “Lost power” = power dissipated as heat = 0 W
- “Power not generated” = the difference between what the transmitter is putting out and what it would put out with a perfect match = 25 W
- For this case, Reflected power = power not generated

Case 3: A Mismatch Tuned To A Conjugate Match



- The transmitter sees a perfect match => P_{OUT} = 100W = P_{OUT} (MAX)
- At the Antenna:
  - Assume that $P_{ANTENNA} = P_{OUT} = P_{FORWARD} - 0.25 \times P_{FORWARD} = 100W$
  - $P_{FORWARD} = P_{ANTENNA} /0.75 = 100/0.75 = 133W$
  - $P_{REFLECTED} = 0.25 \times P_{FORWARD} = 33W$
  - $P_{ANTENNA} = P_{FORWARD} - P_{REFLECTED} = 100W = P_{OUT}$

Case 3: A Mismatch Tuned To A Conjugate Match



- Some hams see 133 W/33W on their power meter and conclude:
  1) The transmitter is putting out 133 watts!
     - The transmitter is only putting out 100 watts
  2) The antenna is radiating 133 W
     - The antenna is radiating $P_{FORWARD} - P_{REFLECTED}$ = 100 W
  3) $P_{REFLECTED}$ (33 W) is being dissipated in the transmitter
     - At the transmitter output $P_{REFLECTED}$ = 0 W
- When there is a conjugate match, the “power not generated” is zero, so Reflected power is simply an indication that there is a mismatch somewhere in the antenna system

Question 1: Lowest SWR ensures best performance

- **Ground mounted resonant ¼ wave monopole (vertical)**
  1. With **100+ radials** over good ground:
     - Radiation resistance = 36 ohms
     - Ground loss = 1 ohm
     - Antenna input resistance = 37 ohms
     - Input **SWR = 1.35:1**
     - **Efficiency = 97%**
  2. With **4 radials** over poor ground:
     - Radiation resistance = 36 ohms
     - Ground loss = 14 ohms
     - Antenna input resistance = 50 ohms
     - Input **SWR = 1.0:1**
     - **Efficiency = 72%**
       - The lost power is being dissipated in the ground as heat
- **Lowest SWR does not ensure best performance**

Question 2: High SWR ensures poor performance

- **Feed options for a 14 MHz resonant dipole with Z_{IN} = 50 ohm:**
  1. 100 feet RG-58 with balun at antenna:
     - **SWR** on line **= 1.0:1**
     - Transmission Line Matched loss = 1.9 dB
     - Transmission Line Mismatched loss = 0 dB
     - Balun loss = 0.5 dB
     - **Overall Efficiency** = **57%**
  2. 97 feet 450 ohm ladder line* with balun at transmitter:
     - **SWR** on line **= 9:1**
     - Transmission Line Matched loss = 0.1 dB
     - Transmission Line Mismatched loss = 0.3 dB
     - Balun loss = 0.5 dB
     - **Overall Efficiency** = **81%**
- **High SWR does not ensure poor performance**

***97 ft (1.5 wavelengths) yields 50 + j0 ohm load impedance at transmitter**

Question 6: It is always best to achieve an SWR close to 1.0:1

If starting with a 2:1 SWR and a 1 dB line loss, adding an antenna tuner:

SWR	Power Drop	
	%	dB
1.0:1	0	0
1.5:1	4	-0.2
2.0:1	11	-0.5
3.0:1	25	-1.2
4.0:1	36	-1.9

At the transmitter:

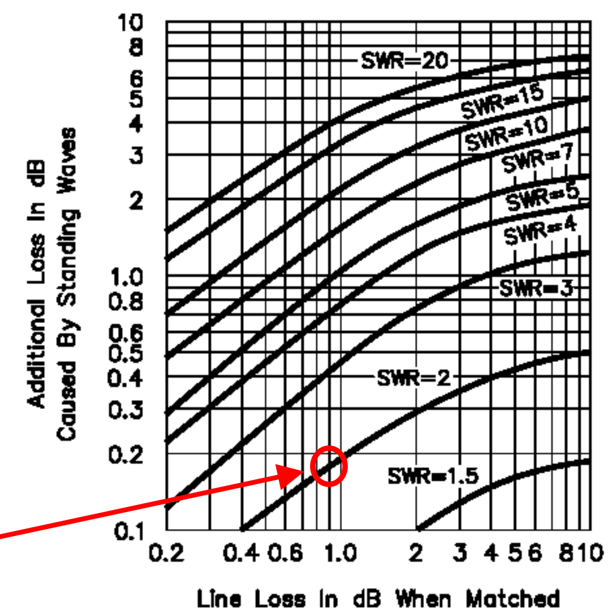
1) Reduced loss on transmission line* = 0.0 dB
2) Increased power out of transmitter = 0.5 dB
3) Additional loss from tuner = 0.5 dB

Net improvement < 0 dB

At the antenna:

1) Reduced loss on transmission line* = 0.2 dB
2) Increased power out of transmitter = 0.5 dB
3) Additional loss from tuner = 0.5 dB

Net improvement < 0.2 dB



***This improvement (~0.2 dB) only occurs when the tuner is located at the antenna**

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At the transmitter:

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Net improvement < 0 dB

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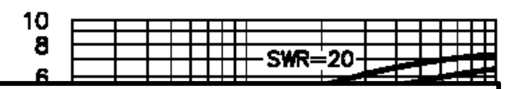
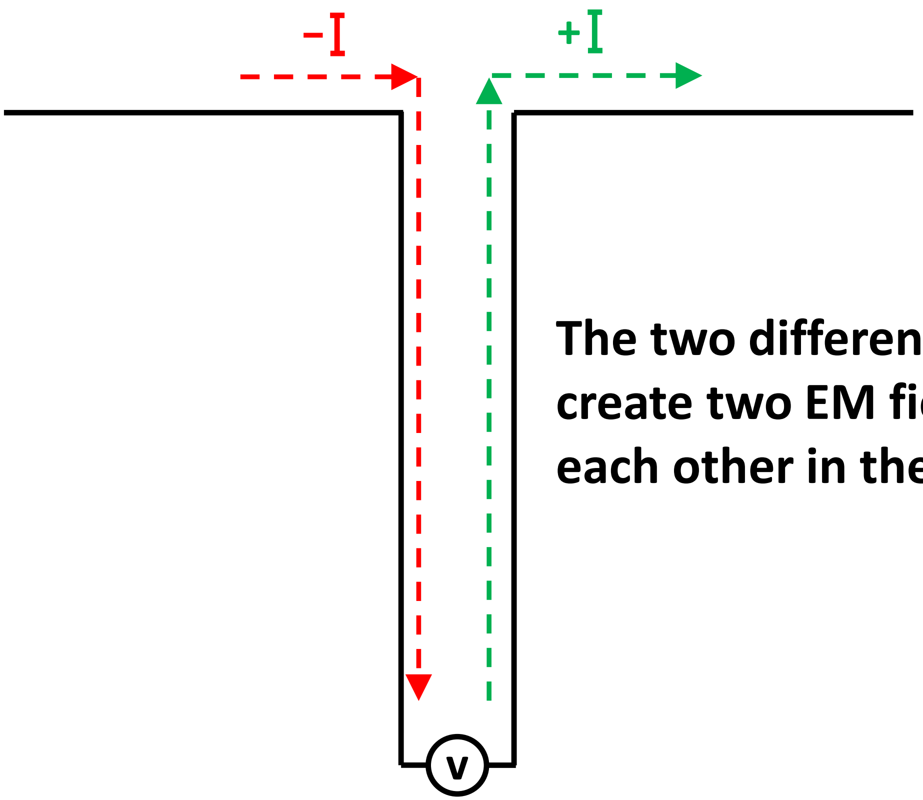


- **If a solid state transmitter is not shutting down on any of your normal operating frequencies, there may not be a need to reduce SWR**
- **The 2015 ARRL Handbook claims that up to 6:1 SWR is ok in some situations => ???**
  - **High SWR can cause component failures at high power**

Question 7: Transmission line radiation with high SWR

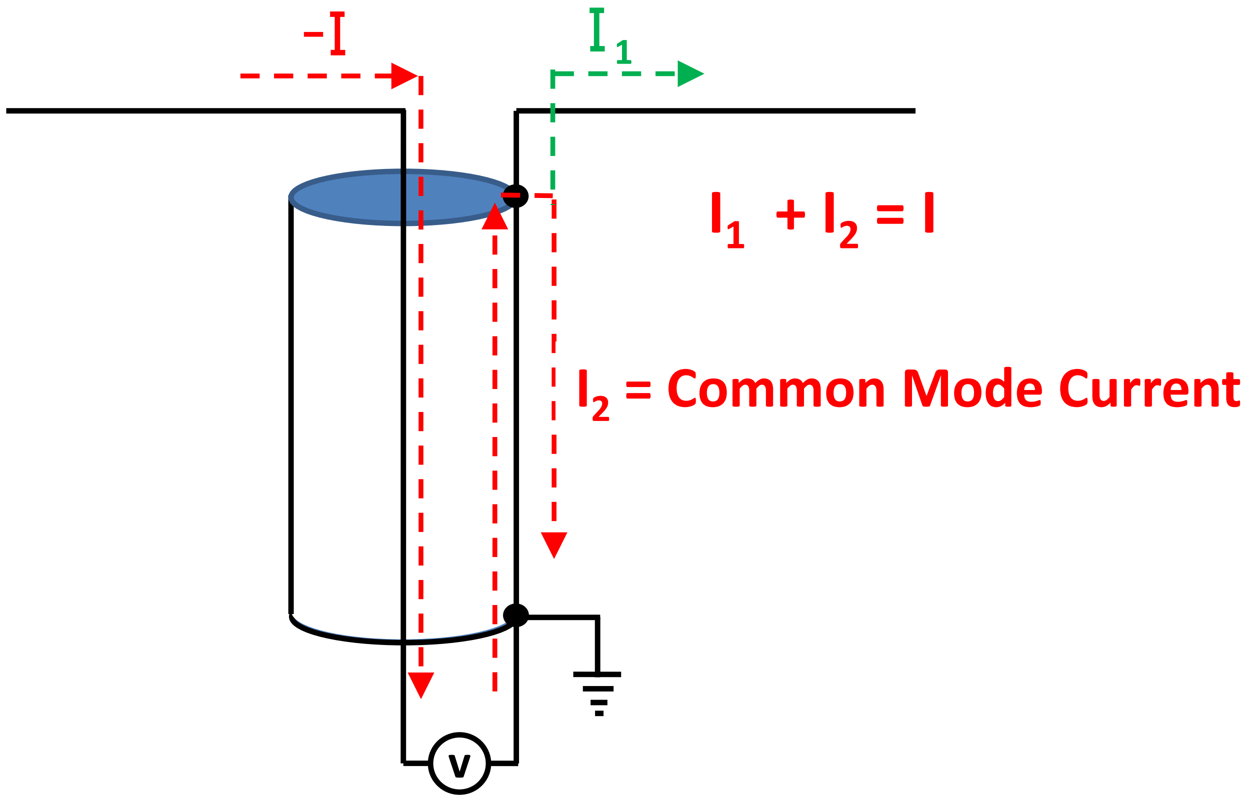
- **Properly installed transmission lines do not radiate, regardless of SWR**



The two differential currents create two EM fields that cancel each other in the far field

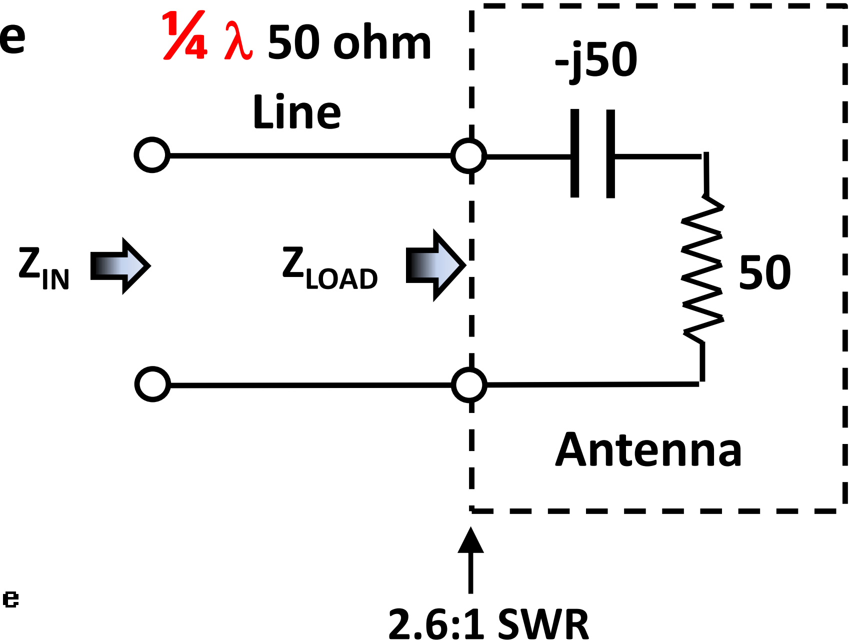
Question 7: Transmission line radiation with high SWR

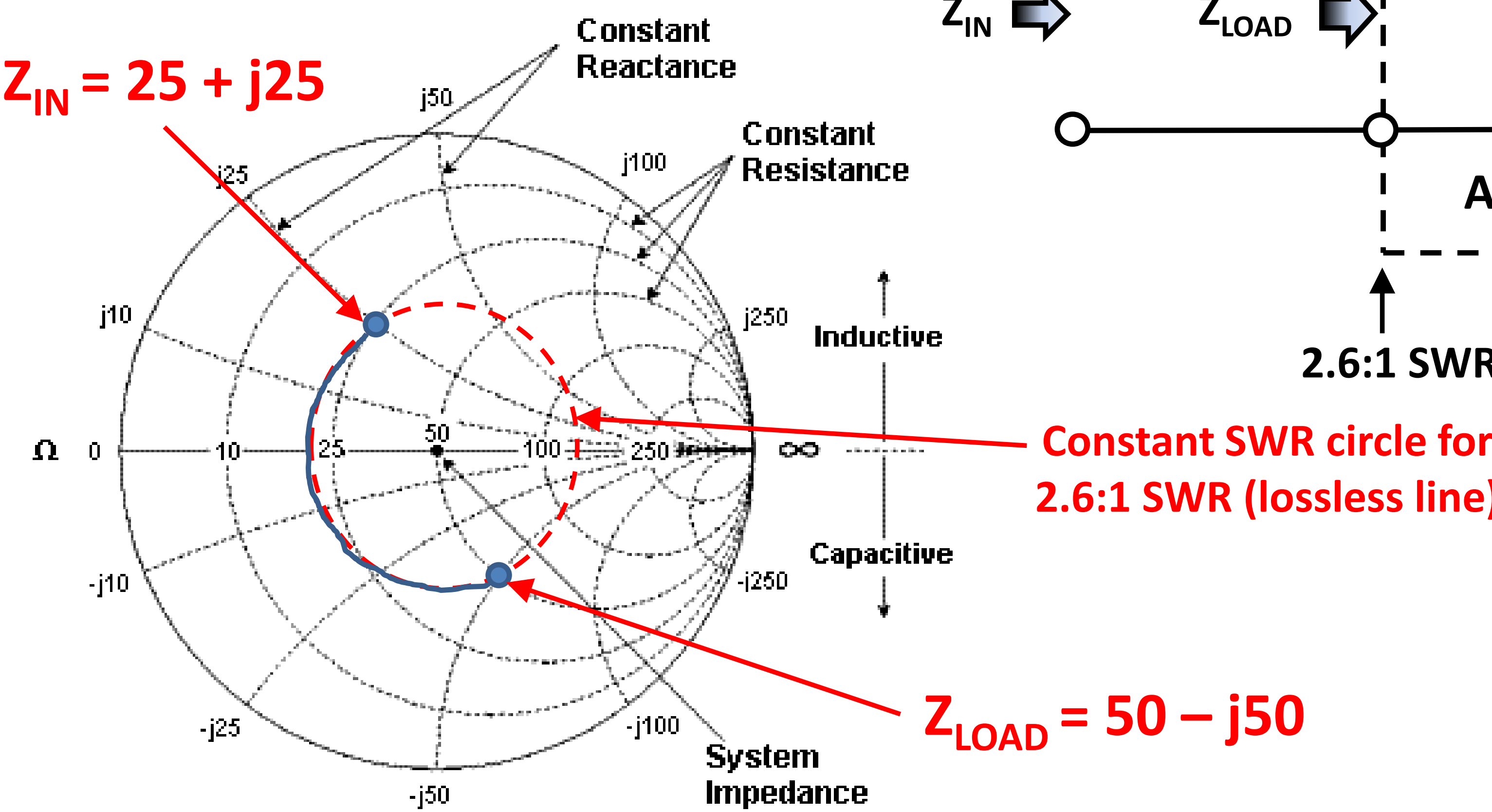
- **Balanced to unbalanced mismatches can cause lines to radiate due to Common Mode Current**
  - **Example: Dipole fed with coax (Tri-pole)**
    - **Amount of radiation is related to I_2**



Question 8: Antenna Impedance Can Only Be Accurately Determined At The Antenna

- Software is available that can calculate Z_{LOAD} from Z_{IN}





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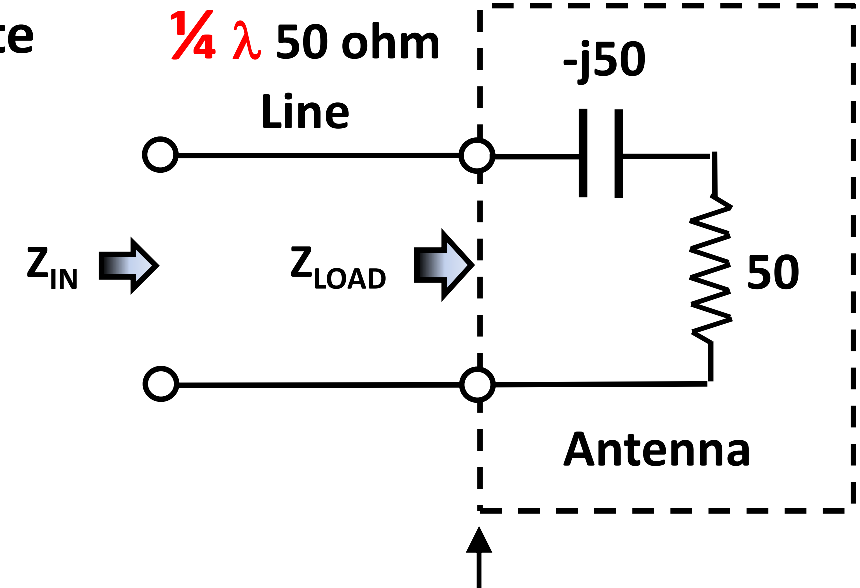
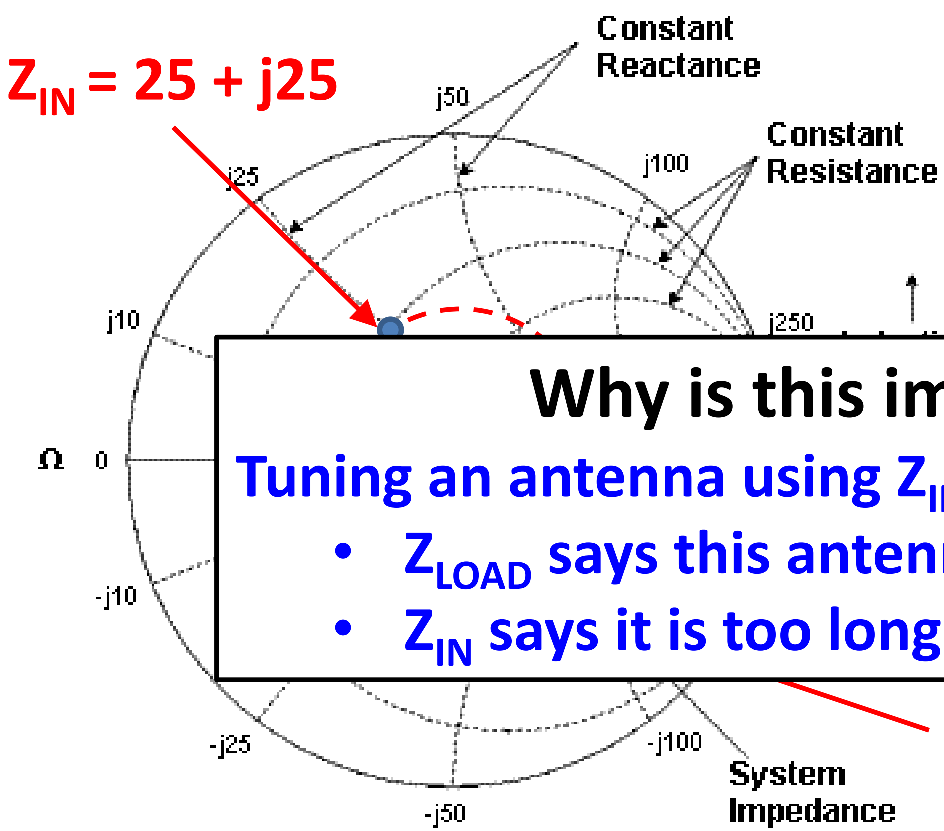




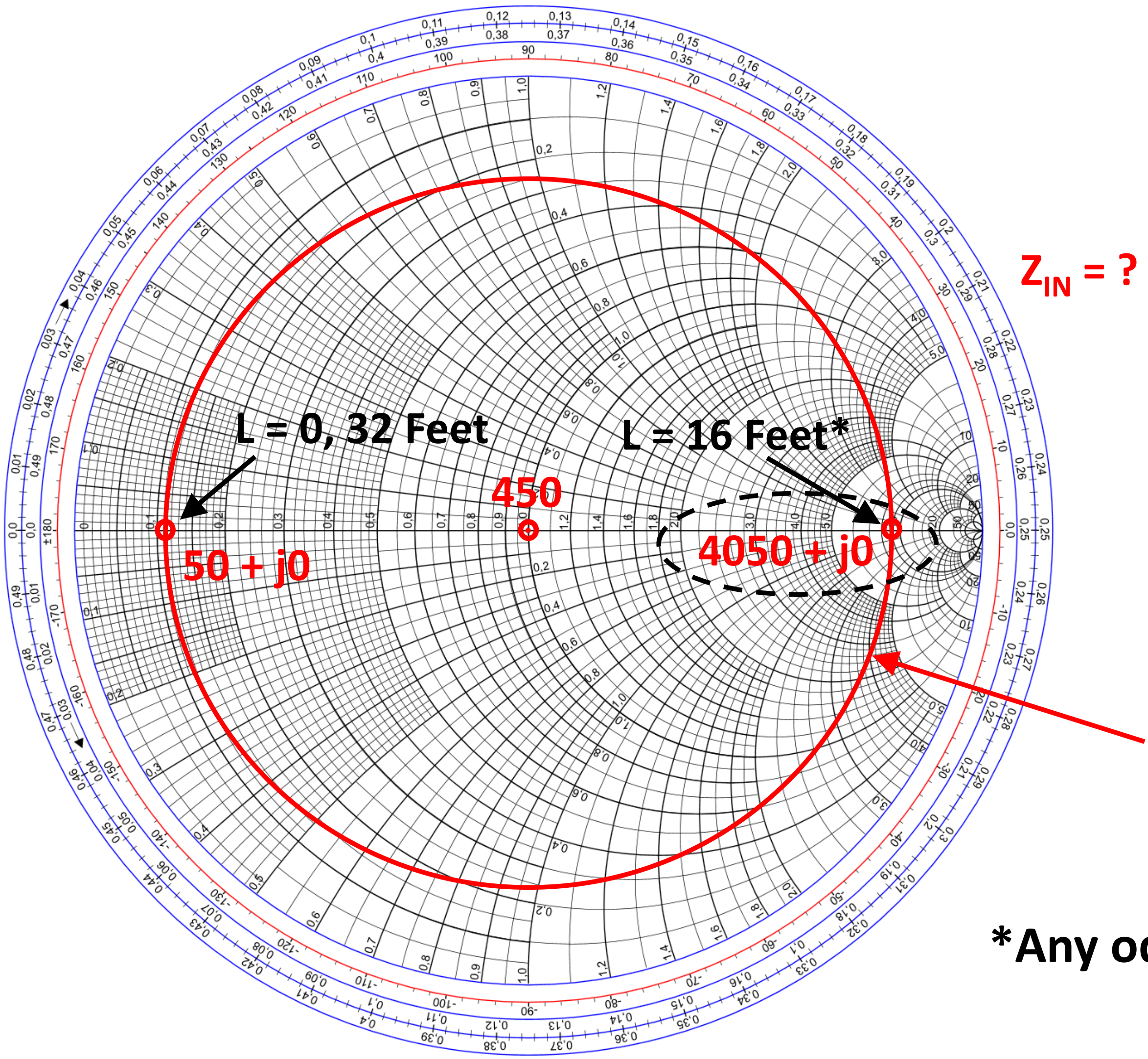
Why is this important?

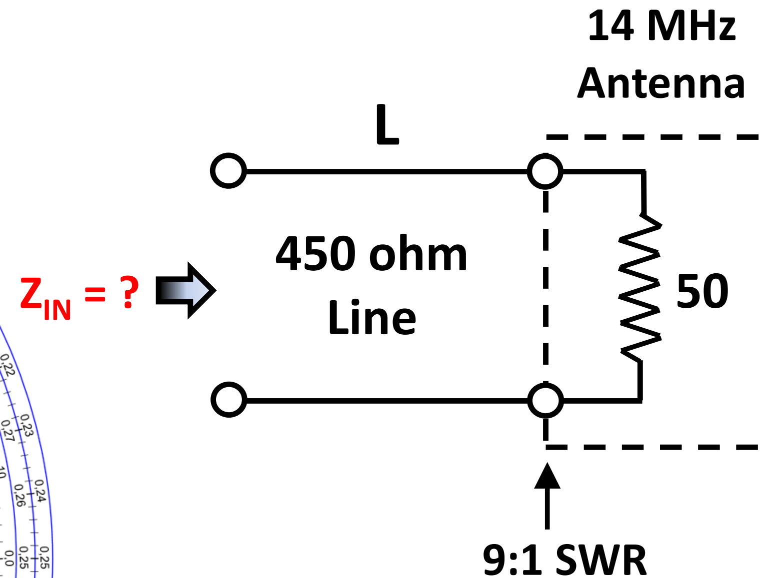
Tuning an antenna using Z_{IN} can be problematic:

- Z_{LOAD} says this antenna is too short, but
- Z_{IN} says it is too long

Question 9: The SWR at the transmitter can be improved by changing the length of the transmission line

- Changing line length changes Z_{IN} , not the SWR

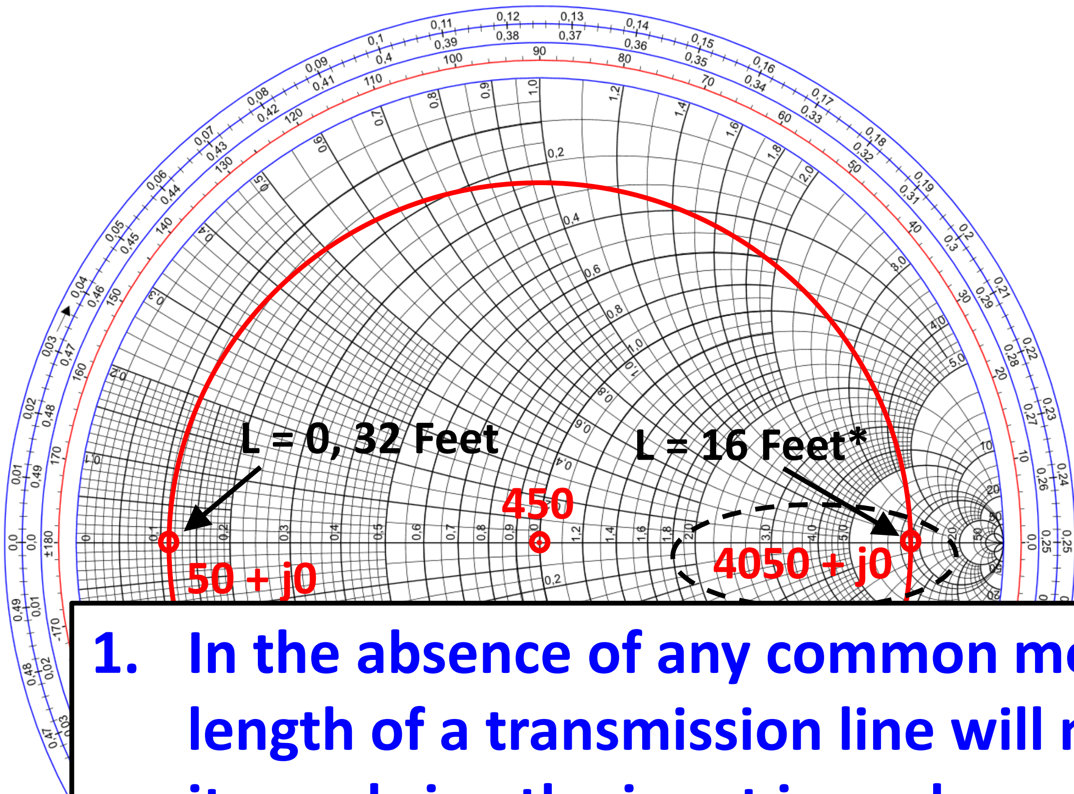


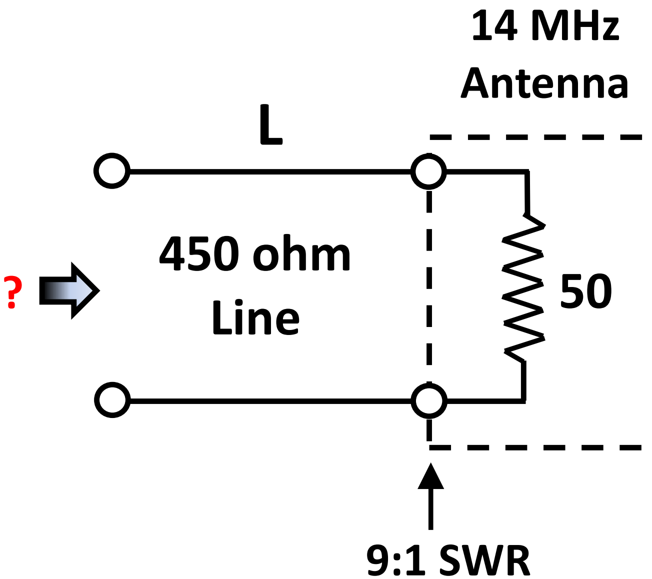


*Any odd multiple of ¼ λ (16 ft)

Question 9: The SWR at the transmitter can be improved by changing the length of the transmission line

- Changing line length changes Z_{IN} , not the SWR

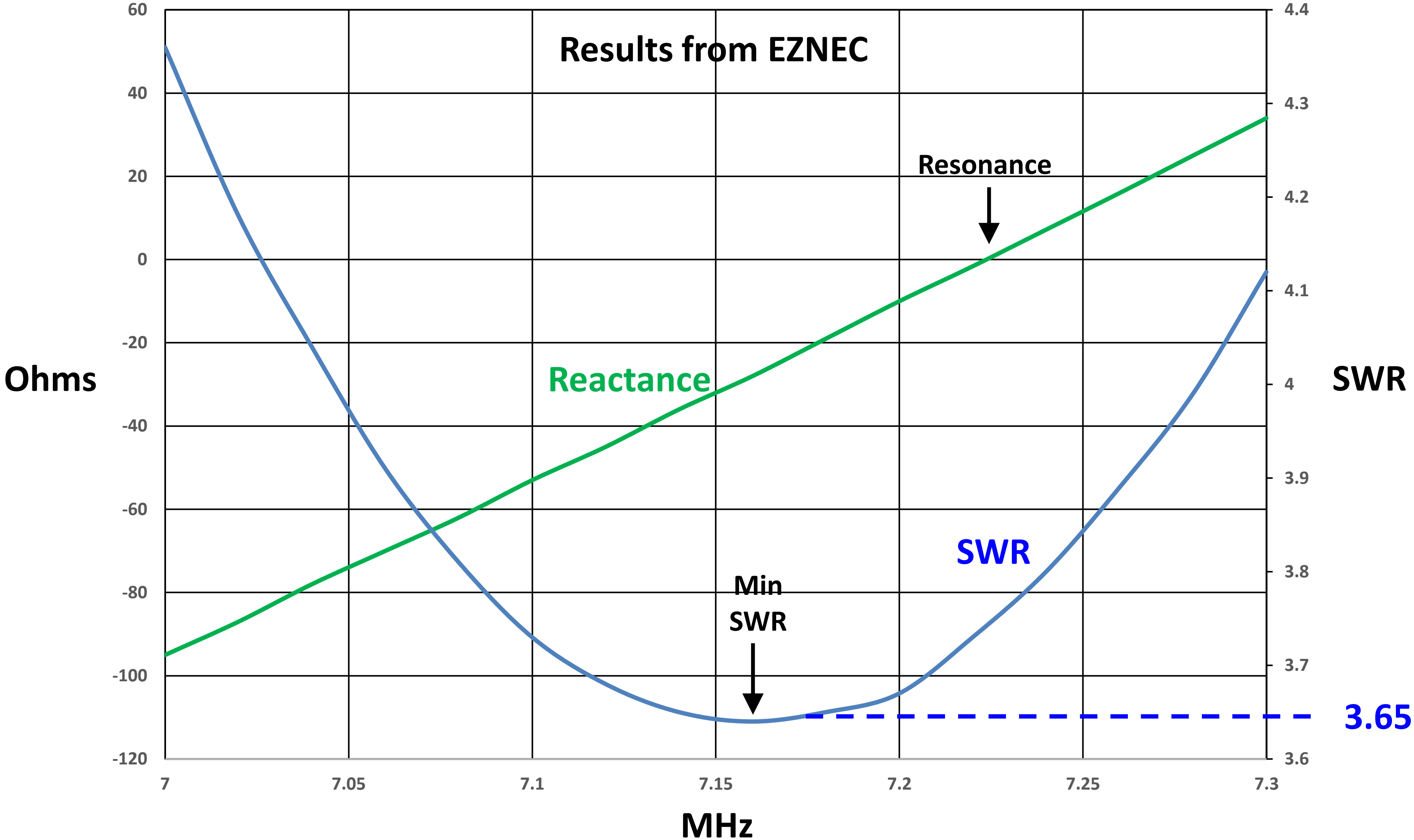




1. In the absence of any common mode current, changing the length of a transmission line will not change the SWR, but it may bring the input impedance seen by the tuner into a range that it can match
2. Common Mode Current can cause SWR to vary with transmission line length

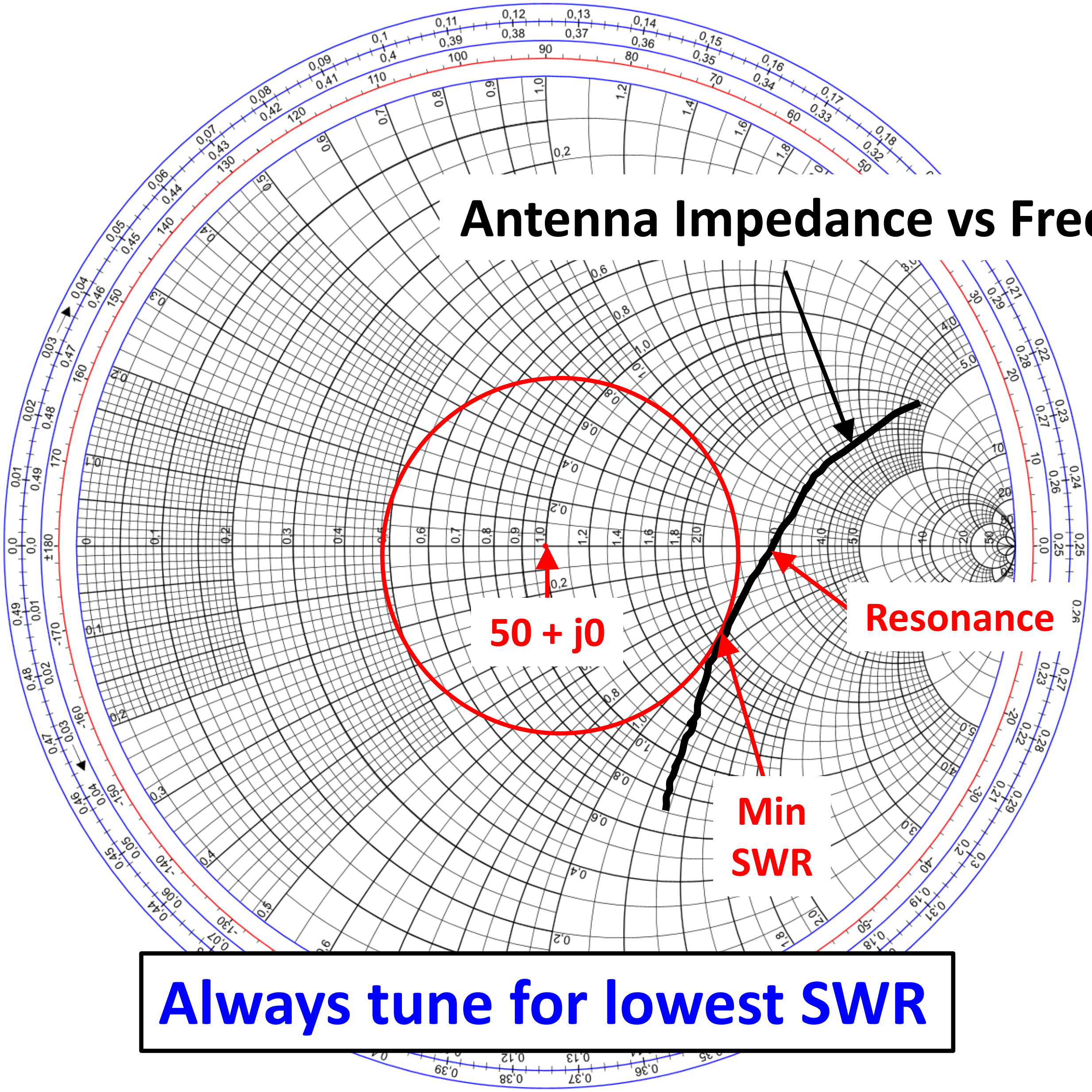
Question 10: Frequency Of Lowest SWR vs Resonance

40M Off Center Fed Dipole

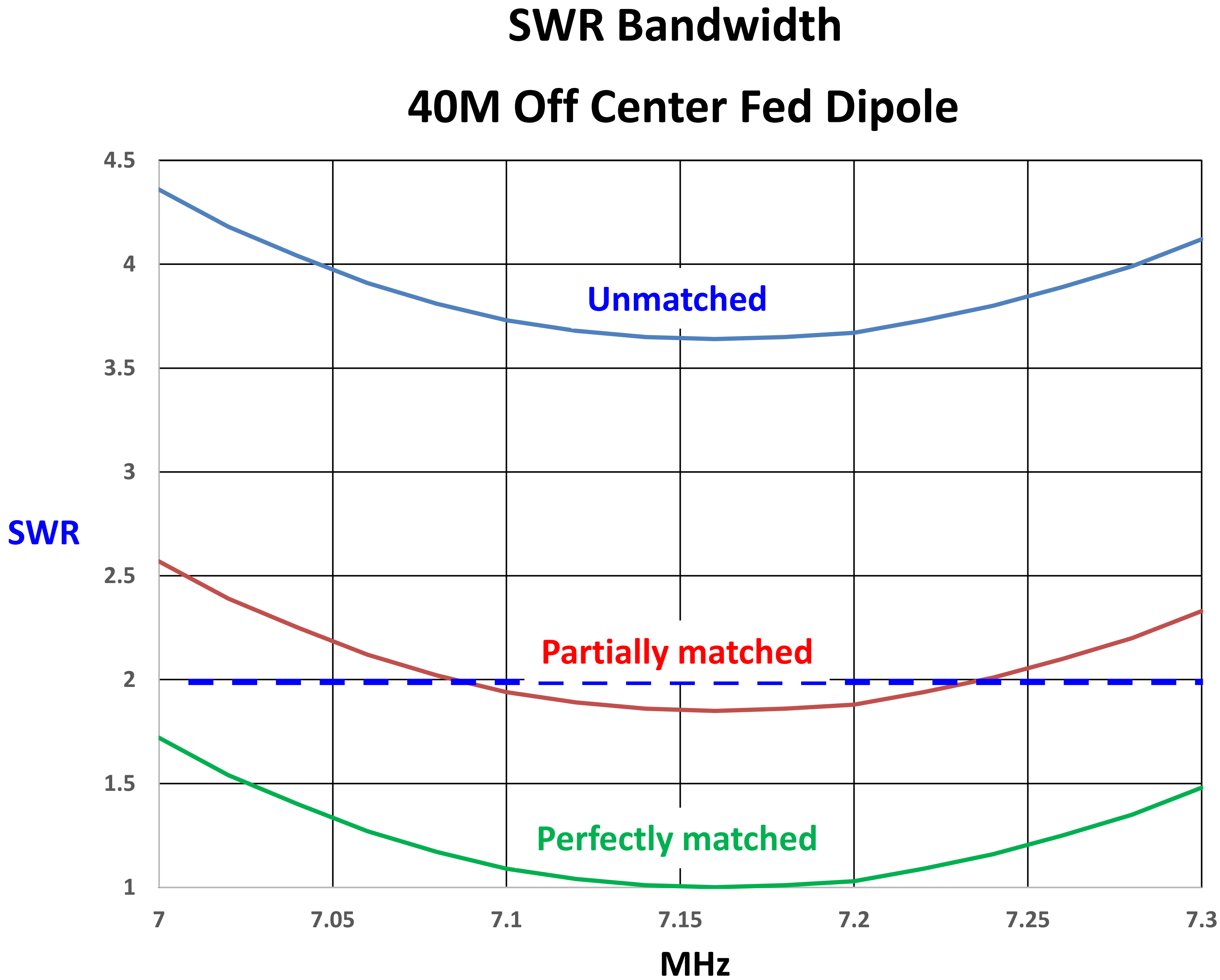


Resonance and lowest SWR do not always occur at the same frequency!

Question 10: Frequency Of Lowest SWR vs Resonance



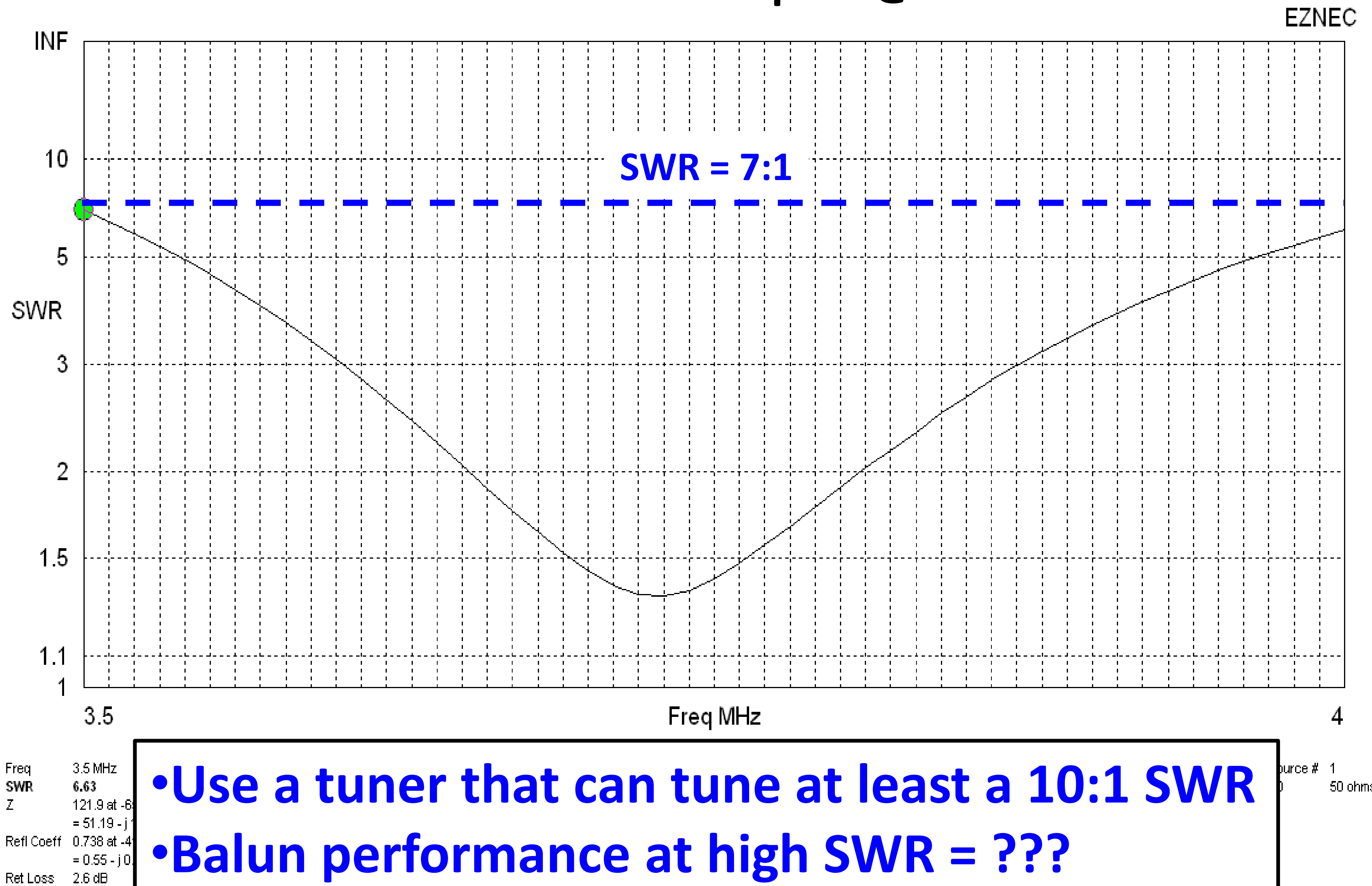
Always tune for lowest SWR



SWR Bandwidth
40M Off Center Fed Dipole
4.5
4
3.5
3
2.5
2
1.5
1
SWR
Unmatched
Partially matched
Perfectly matched
7
7.05
7.1
7.15
7.2
7.25
7.3
MHz

SWR Bandwidth

80M Center Fed Dipole @ 50 ft



- **Use a tuner that can tune at least a 10:1 SWR**
- **Balun performance at high SWR = ???**

The Real World vs The Ideal World

Some "experts" claim that the concept of a "Conjugate Match" is a myth and that Maxwell didn't know what he was talking about.

- **These criticisms are usually based upon the quantitative differences between a lossy system and a lossless system.**
- **Are Newton's Laws invalid because (as Einstein showed) their accuracy degrades under extreme conditions?**

Summary

Reflected power is not dissipated in the transmitter

- Must distinguish between power "lost" and power "not generated"

All of the power going into a transmission line is radiated by the antenna (ignoring losses)

- The power radiated by the antenna = $P_{FORWARD} - P_{REFLECTED}$

Changing transmission line length changes the impedance seen looking into the line, not the SWR (assuming no common mode current)

Reducing SWR below 2:1 yields negligible increase in power radiated from an antenna

Low SWR does NOT ensure best performance

High SWR does NOT ensure poor performance

An antenna does NOT need to be resonant to perform well

A tuner resonates the antenna system, not the antenna

Peak current and voltage increase as $\sqrt{SWR}$

Summary - Continued

High SWR does not cause a transmission line to radiate

Resonance and minimum SWR don't always occur at the same frequency

Antenna SWR & impedance can be calculated from measurements made at the input to a transmission line

Transmission line loss makes SWR look better than it really is

Reflected power does not always represent a reduction in power to the antenna

With solid state rigs, adjust a tuner for SWR_{MIN}, not maximum P_{OUT}