IMPEDANCE MATCHING 101

VHF SUPER CONFERENCE
APR 26-28, 2019
WASHINGTON-DULLES

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WHY IMPEDANCE MATCH?

- **FOR TRANSMITTING - Impedances are necessarily matched to enable efficient power transfer from one device to another, such as an output amplifier to an antenna or a driver amplifier to an output amplifier.**

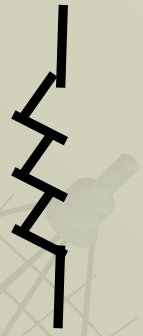
- **FOR RECEIVING – A low noise preamplifier is designed to achieve its minimum noise figure for a particular source or driving impedance. The antenna must be matched to this impedance to achieve the minimum noise performance.**

THE CASE FOR 50 OHMS

- **A common impedance used for Amateur Radio applications is 50 ohms**
- **The feedlines, i.e. the coax, are designed for 50 ohms, a common standard impedance.**
- **The power amplifiers are designed to operate into a 50 ohm load, i.e. the antenna fed with 50 ohm coax.**
- **The receiver preamps are designed to achieve minimum noise figure with a 50 ohm driving source; i.e. the antenna/feedline.**

THE THREE ELEMENTS OF IMPEDANCES

1. **The resistor, R**



2. **The inductor, L**

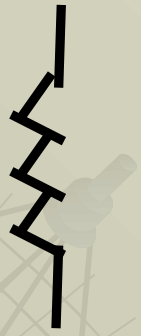


3. **The capacitor, C**



THE BASICS, THE IMPEDANCE OF EACH COMPONENT

$Z = R$



$Z = +jX_L$



$|Z| = |X_L|$

$Z = -jX_C$



$|Z| = |X_C|$

THE IMPEDANCE OF EACH COMPONENT

$$|\mathbf{X_L}| = 2\pi f L,$$

where: f = frequency in Hz

L = inductance in henries

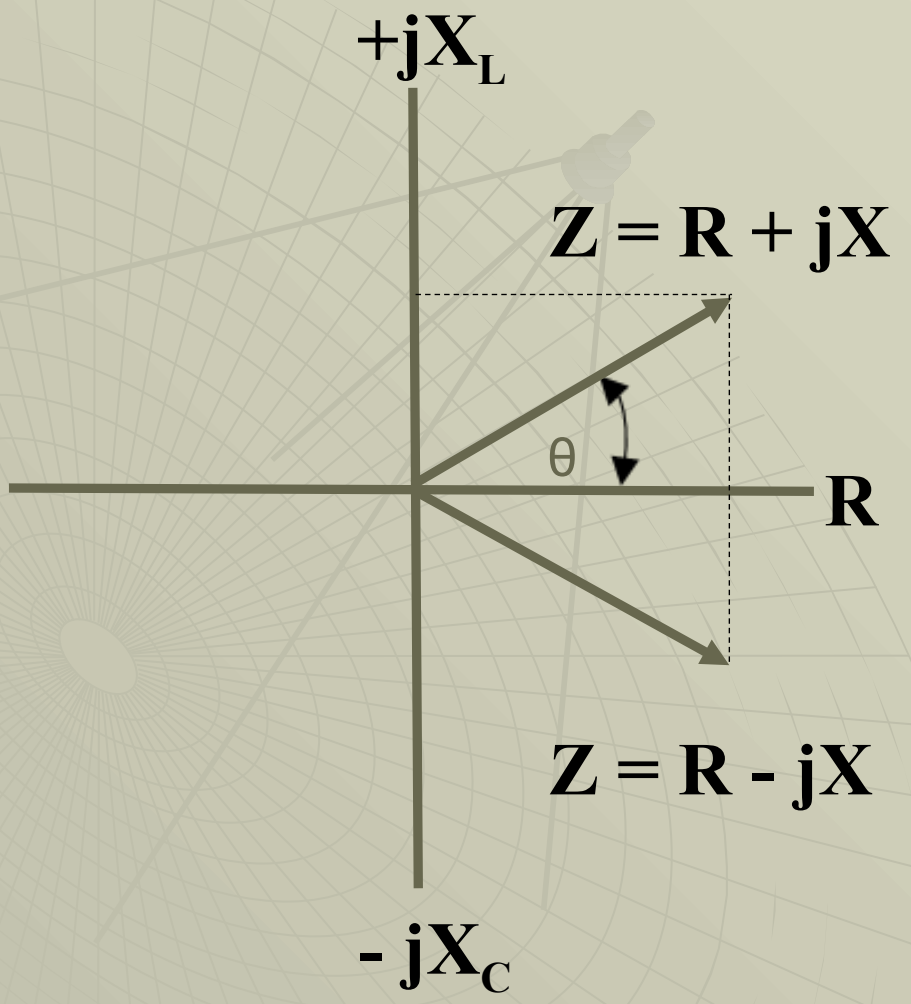
$$|\mathbf{X_C}| = 1/(2\pi f C)$$

where: f = frequency in Hz

C = capacitance in farads

and $\mathbf{Z} = R \pm jX$

THE COMPLEX IMPEDANCE



EXPRESS f, L, AND C USING SCIENTIFIC NOTATION

SHORT CUTS

x 1000 = x 10^{3}

1/1000 = x 10^{-3}

$2\pi = 6.28$

$1/(2\pi) = 0.159 = 159 \times 10^{-3}$

***f in MHz* = x 10^{6}**

(i. e 144 *MHz* = 144 x 10^{6} Hz)

10^{-9} henries = nanohenries, nH

10^{-12} farads = picofarads, pf

MORE BASICS

The loaded Q = Xs/Rs = Rp/Xp

A series R & X circuit has an equivalent parallel R & X circuit.

Xs is the series reactance,
Rs is the series resistance,
Rp is the parallel resistance,
Xp is the parallel reactance.

HELPFUL HINTS

Do not try to match more that a 4:1 impedance transformation. If you have to match over a larger impedance ratio, use two or more matching sections.

Before using a series L or series C, look at your design. If you need a d.c. blocking capacitor, use your matching C for this d.c. block. If you need to feed d.c. to a circuit component, use an L for this as part of the matching circuit.

HELPFUL HINTS (con't)

Use complimentary L sections for broader bandwidth and higher impedance transformations; i.e. a two stage match.

Always match low to high impedances to simplify calculations. If you need to match a high impedance to a low impedance, do the calculations for low to high. Then remove the low impedance and connect the high impedance. The matching circuit is reciprocal and works both ways.

COMPONENT CALCULATIONS



A series impedance has an equivalent parallel impedance. Both the series and parallel circuits have the same Q, and:

$\underline{R_p = R_s (Q^2 + 1)}$ (Remember this!!!)

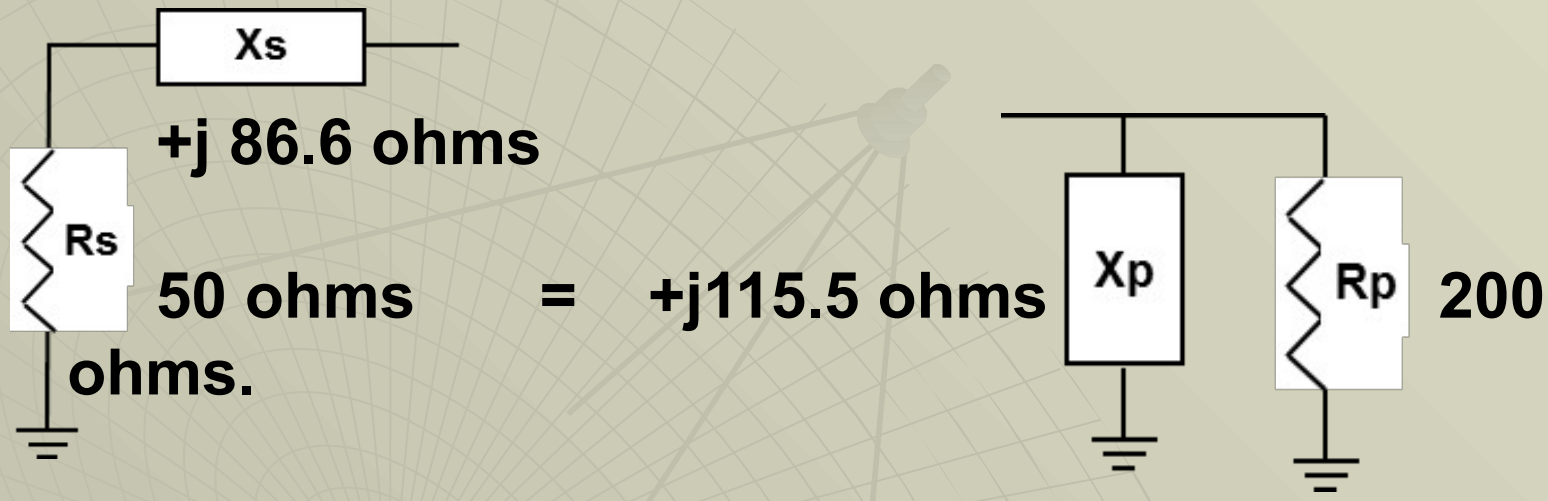
EXAMPLE 1 – COMBINING FOUR ANTENNAS

Match 50 ohms, such as an antenna, to 200 ohms. Rs = 50 ohms, Rp = 200 ohms.

Calculate Q from $Rp = Rs (Q^2 + 1)$.
$Q^2 + 1 = (200/50) = 4$,
$Q^2 = 3$, $Q = 1.732$
Since $Q = Xs/Rs$,
$Xs = Q * Rs = (1.732 * 50) = |86.6|$ ohms.

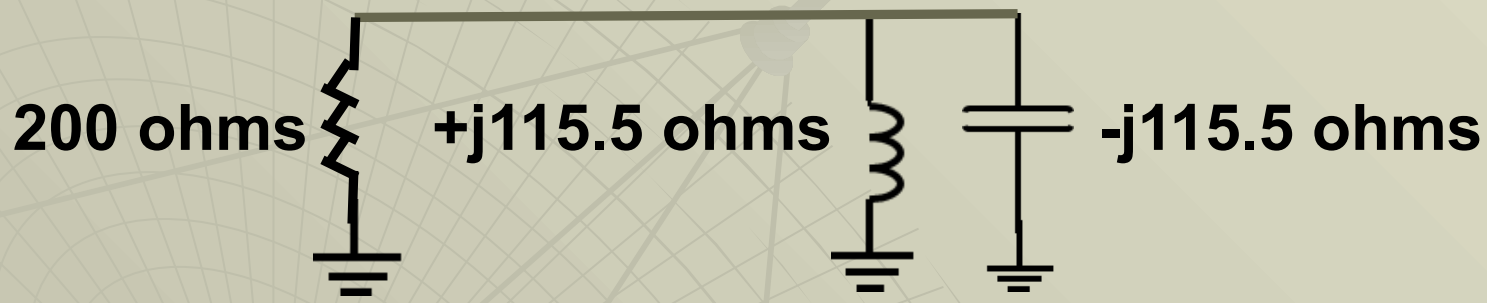
For a series inductor, the circuit is 50 + j86.6 ohms.
Q also = Rp/Xp, and Rp = 200 ohms.
Therefore, Xp = Rp/Q = 200/1.732 = +j115.5 ohms.

COMBINING FOUR ANTENNAS (con't)

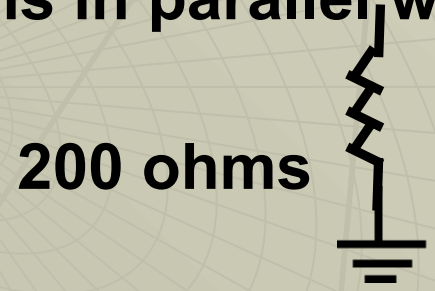


Now place – j115.5 ohms in parallel with +j115.5 ohms leaving only the 200 ohm real impedance.

COMBINING FOUR ANTENNAS (con't)

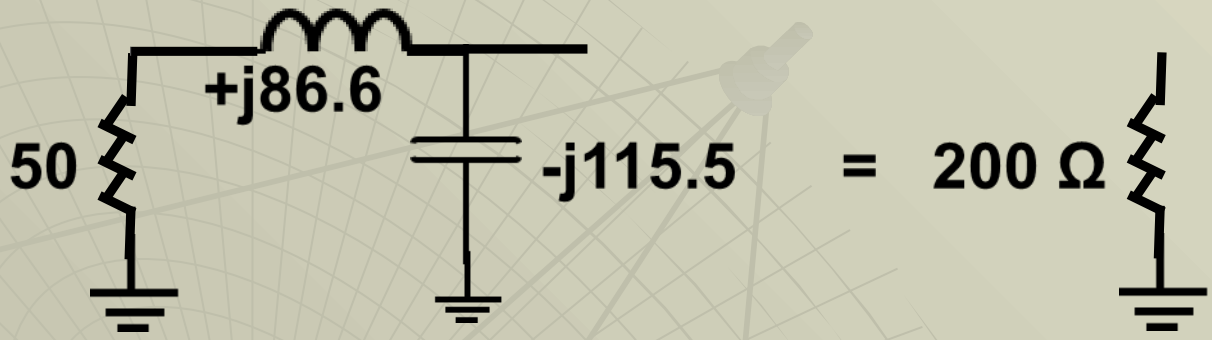


Since +j115.5 ohms in parallel with –j115.5 ohms = ∞, resulting in:



COMBINING FOUR ANTENNAS (con't)

Final matching circuit



Component calculation for +j86.6 at 144 MHz:

$|86.6| = 2\pi f L$ = 6.28 * (144 * 10^6) * L

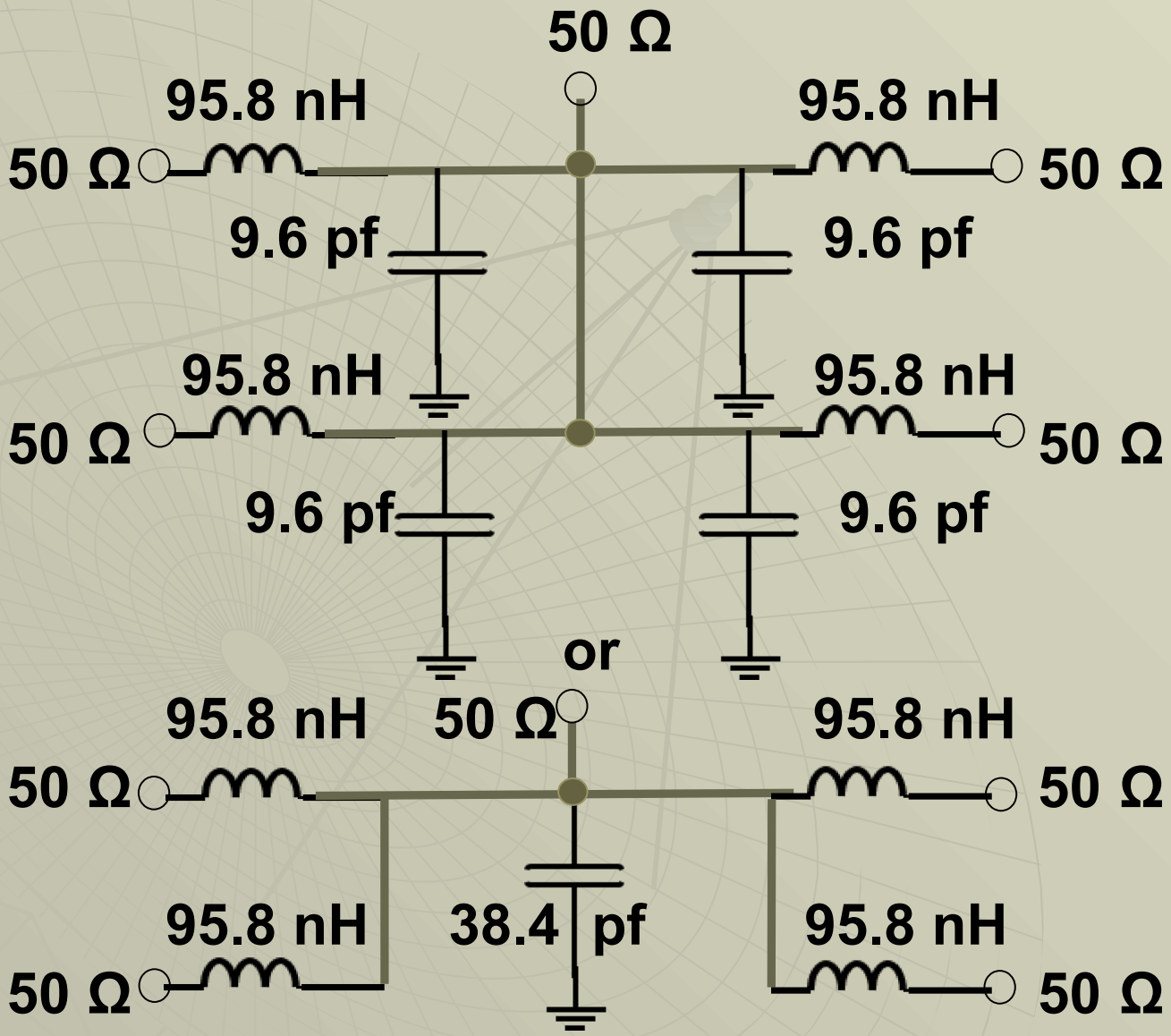
L = 95.8 nH

Component calculation for –j115.5 at 144 MHz:

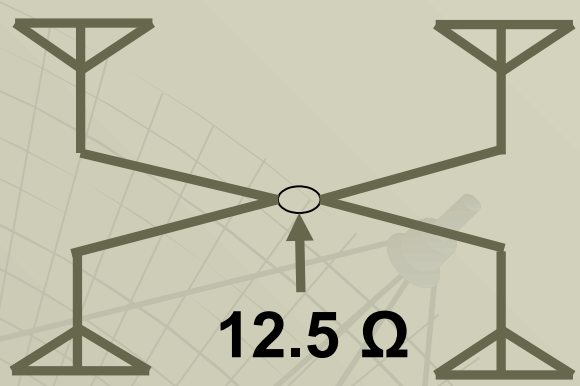
$|115.5| = 1/(2\pi f C)$ = (159 * 10^{-3})/ (144 * 10^6) * C, so:

C = 9.6 * 10^{-12} = 9.6 pf.

COMBINING FOUR ANTENNAS (con't)

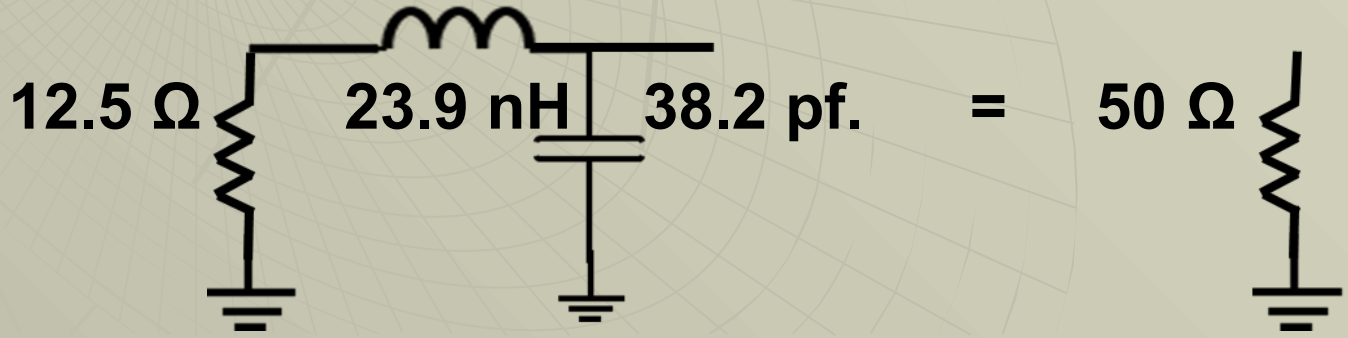


COMBINING FOUR ANTENNAS SIMPLIFIED

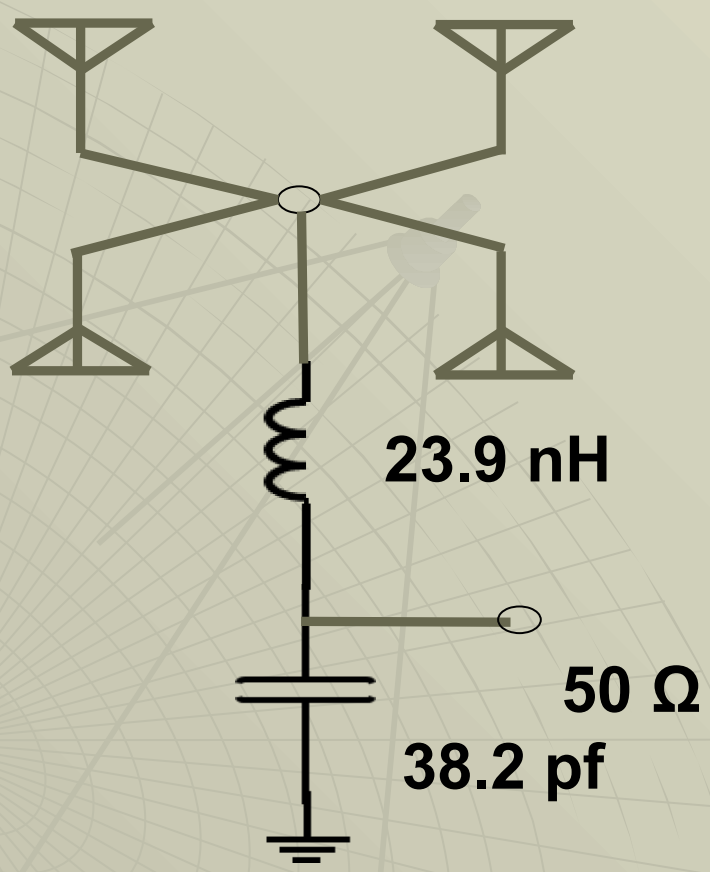


Make all feedline the exact same length. Now match 12.5 Ω to 50 ohms using a series inductor and parallel capacitor.

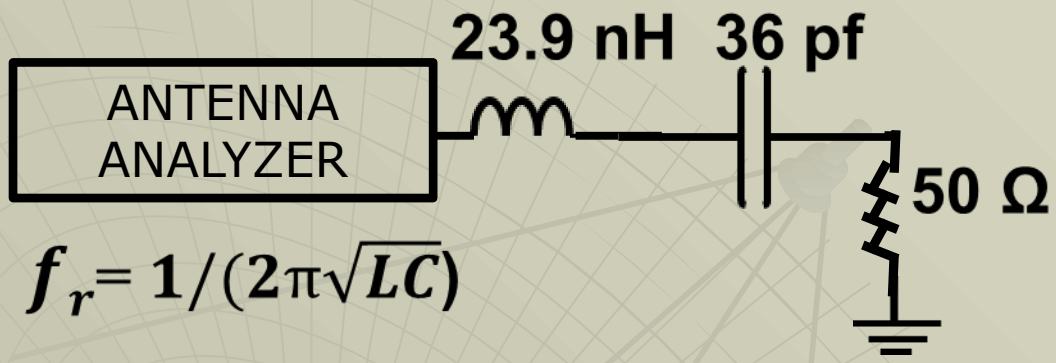
Rp = Rs (Q^2 + 1), Q = 1.732, Xs = 23.9 nH, C = 38.2 pf.



COMBINING FOUR ANTENNAS SIMPLEFIED



WHEN IS YOUR INDUCTOR 23.9 nH?



$$f_r = 1/(2\pi\sqrt{LC})$$

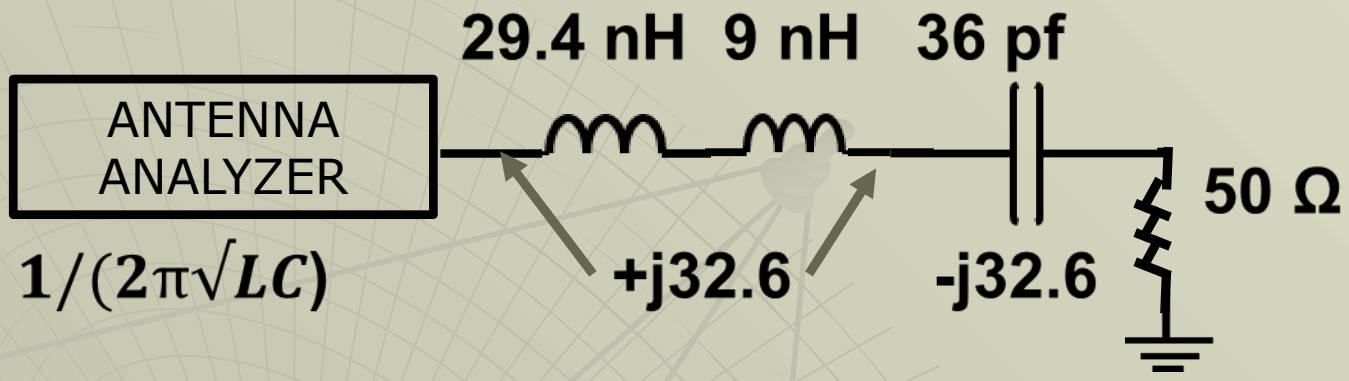
$$f_r = 159 * 10^{-3}/(\sqrt{23.9 * 10^{-9} * 36 * 10^{-12}})$$

$$f_r = 154.6 \text{ MHz}$$

To account for 9 nH of internal lead inductance for the 36 pf capacitor:
L = 29.4 nH + 9 nH = 38.4 nH, and

$$f_r = 135.2 \text{ MHz}$$

WHEN IS YOUR INDUCTOR 23.9 nH, con't?



$f_r = 1/(2\pi\sqrt{LC})$

$f_r = 159 * 10^{-3}/(2\pi\sqrt{38.4 * 10^{-9} * 36 * 10^{-12}})$

$f_r = 135.2\ \text{MHz}$

$|X_L| = 2\pi f L = 6.28 * 135.2 * 10^{6} * 38.4 * 10^{-6}$

$|X_L| = +j\ 32.6$

$|X_C| = \frac{1}{2\pi f C} = 159 * 10^{-3}/(135.2 * 10^{6} * 36 * 10^{-12})$

$|X_C| = -j\ 32.6$

@ 135.2 MHz: +j32.6 –j32.6 + 50 = 50 Ω

USE COMPLEMENTARY L MATCHING FOR HIGHER IMPEDANCE TRANSFORMATIONS

EXAMPLE 2 – Multi step impedance transformation

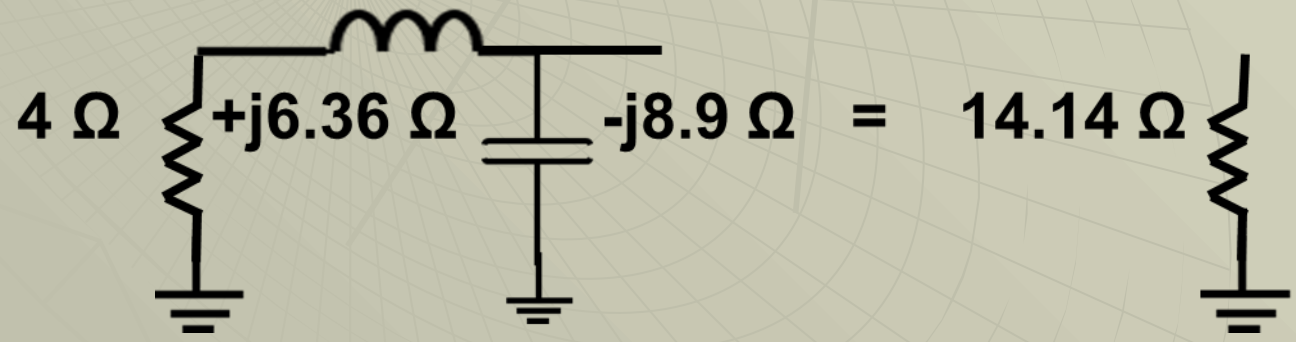
Solid state PA device typically is ~ 4 Ω. Since this is > 4:1 (50/4 = 12.5), use two impedance transformations and use complementary L sections: i.e. if first transformation is series L and parallel C, the second transformation should be series C and parallel L.

Also, the interstage impedance should be the "geometric mean" impedance for the same percentage step to the beginning and ending impedance values.

DETERMINE THE "GEOMETRIC MEAN" IMPEDANCE

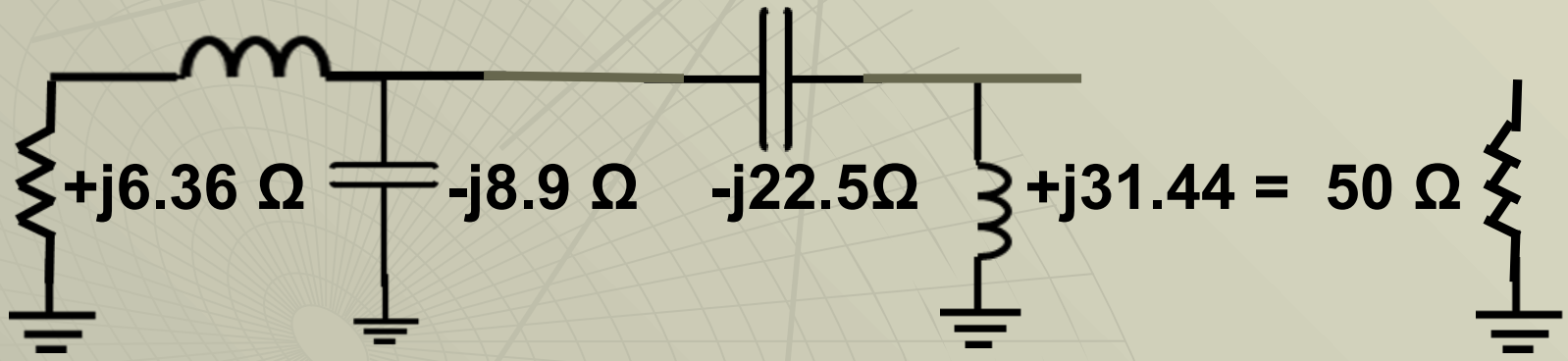
The geometric mean impedance = $\sqrt{4 * 50}$ = 14.14 Ω.
The 1st stage impedance ratio is 14.14/4 = 3.535, and the 2nd stage impedance ratio is also 50/14.14 = 3.535; both less than 4:1!

1st stage transforms 4 Ω to 14.14 Ω with an inductor.
$R_p = R_s (Q^2 + 1)$, $14.14 = 4(Q^2 + 1)$, Q = 1.59.
Q = Xs/Rs, Xs = Q*Rs = (1.59*4) = +j6.36
Xp = Rp/Q = 14.14/1.59 = +j8.9 Ω
Therefore, use –j8.9 Ω to resonate +j8.9 Ω.



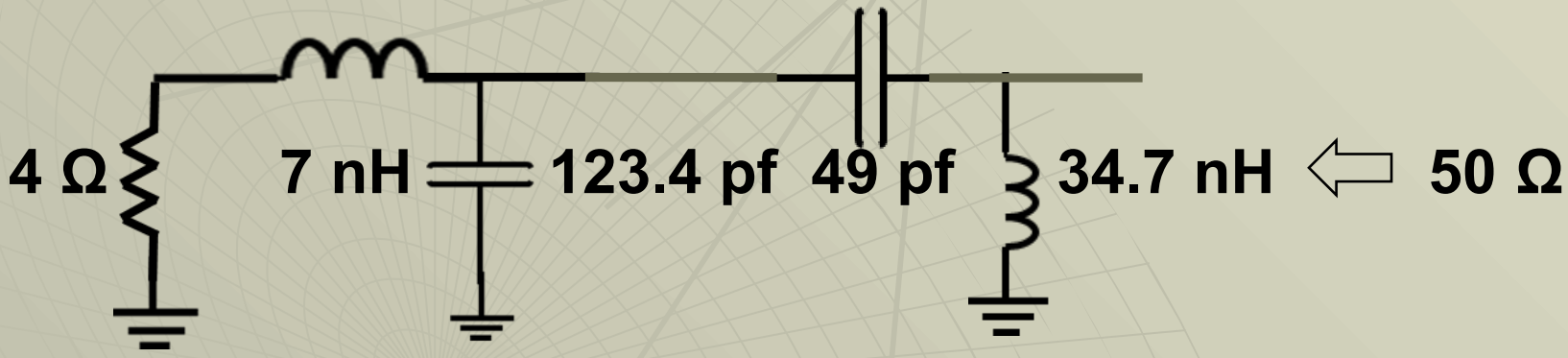
2nd STAGE TRANSFORMATION TO 50 OHMS

2nd step transforms 14.14 Ω to 50 Ω with a capacitor.
$R_p = R_s (Q^2 + 1)$, $50 = 14.14(Q^2 + 1)$, $Q = 1.59$.
$Q = X_s/R_s$, $X_s = Q*R_s = (1.59*14.14) = -j22.5$
$X_p = R_p/Q = 50/1.59 = -j31.44\ \Omega$
Therefore, use $+j31.44\ \Omega$ to resonate $-j31.44\ \Omega$.



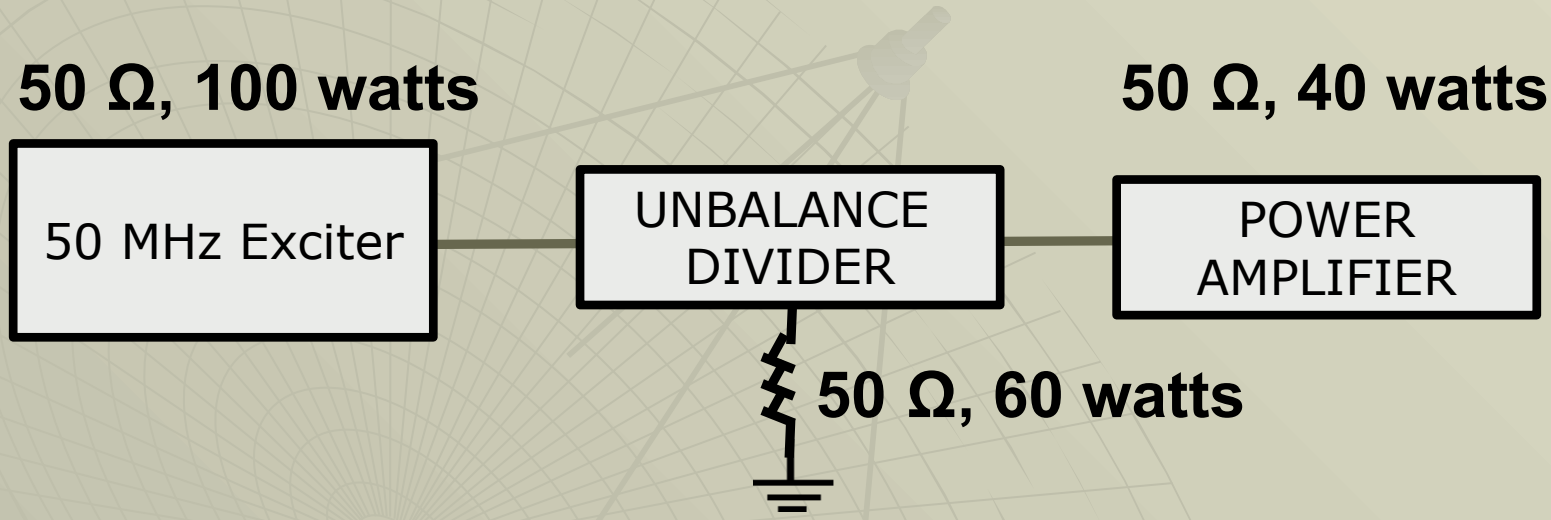
DETERMINE COMPONENT VALUES FOR 144 MHZ

+j6.36 Ω = 7 nH
-j8.9 Ω = 123.4 pf
-j22.5 Ω = 49 pf
+j31.4 Ω = 34.7 nH



UNBALANCED POWER DIVIDER

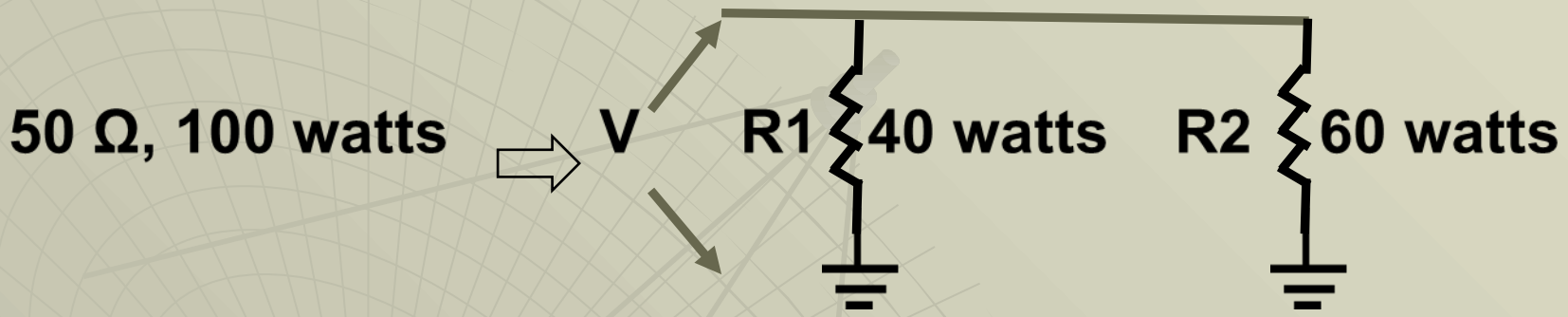
EXAMPLE 3: USED TO DIVIDE POWER FOR UNEQUAL LEVELS AND MAINTAIN 50 OHMS FOR EXCITER.



Exciter has 100 watts output. PA requires 40 watts. Need to dissipate 60 watts into 50 Ω termination and still present 50 ohm load to the exciter.

UNBALANCED POWER DIVIDER, con't

Determine impedances for desired power split.



$$R = 50\Omega = \frac{R1 * R2}{R1 + R2}$$

$$P = \frac{V^2}{R}, \quad P_1 = \frac{V^2}{R_1}, \quad P_2 = \frac{V^2}{R_2}$$

$$V^2 = 40\,W * R_1 = 60\,W * R_2$$

$$R_1 = 1.5R_2$$

UNBALANCED POWER DIVIDER, con't

$$R = 50\Omega = \frac{R_1 * R_2}{R_1 + R_2}$$

Substituting 1.5 R_2 for R_1

$$50\Omega = \frac{1.5R_2 * R_2}{1.5R_2 + R_2},$$

$$125R_2 = 1.5\ R_2^2$$

$$1.5R_2 = 125$$

$$R_2 = 83.3\ \Omega$$

$$R_1 = 125\ \Omega$$

The 50 Ω input to the PA should be matched to 125 Ω, and the 50 Ω input to the termination should be matched to 83.3 Ω.

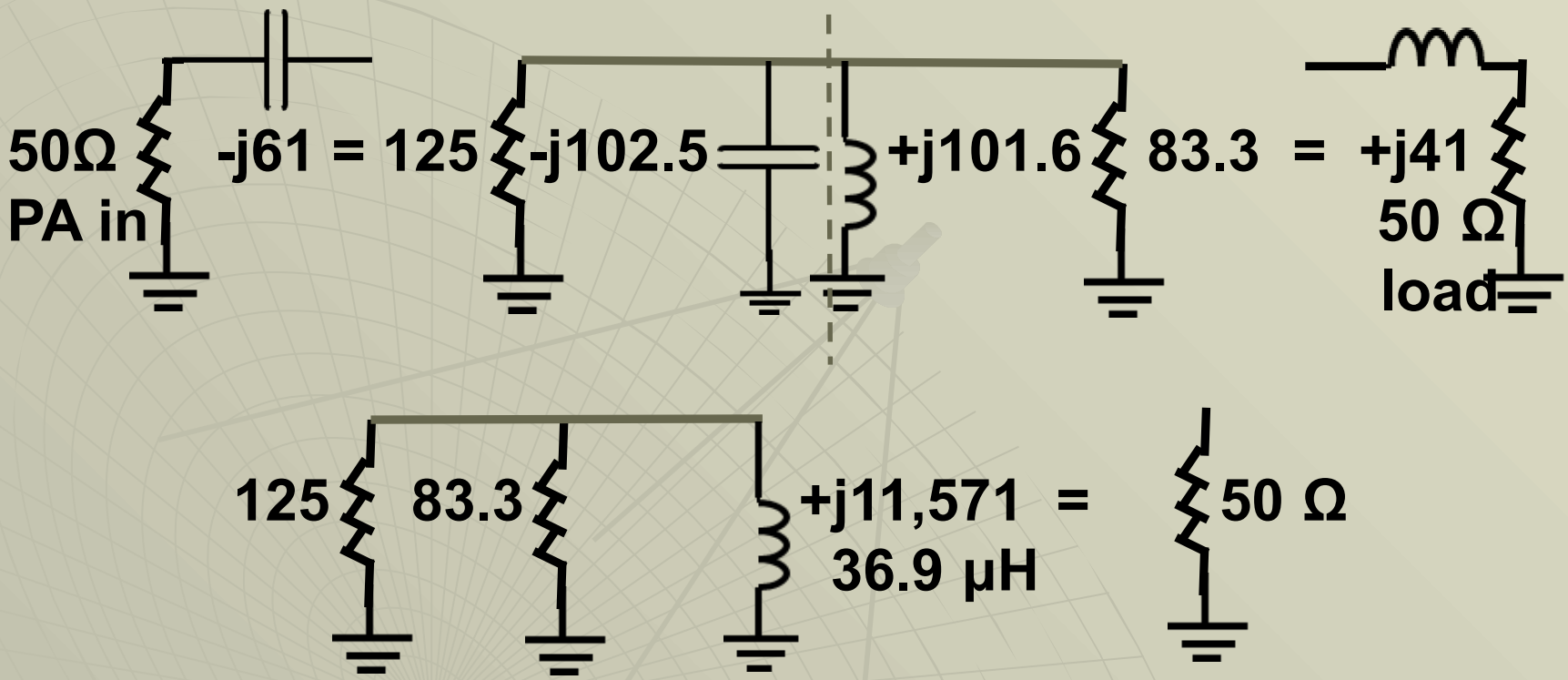
UNBALANCED POWER DIVIDER, con't

For the PA side to match 50 Ω to 125 Ω :
$R_p = R_s (Q^2 + 1)$, $125 = 50(Q^2 + 1)$, $Q = 1.22$.
For a series capacitor, $X_s = Q*R_s = (1.22*50) = -j\,61$, and
$X_p = R_p/Q = 125/1.22 = -j102.5\ \Omega$.

For the 50 Ω termination side to match 50 Ω to 83.3 Ω:
$R_p = R_s (Q^2 + 1)$, $83.3 = 50(Q^2 + 1)$, $Q = 0.82$.
For a series inductor, $X_s = Q*R_s = (0.82*50) = +j41$, and
$X_p = R_p/Q = 83.3/0.82 = +j101.6\ \Omega$.

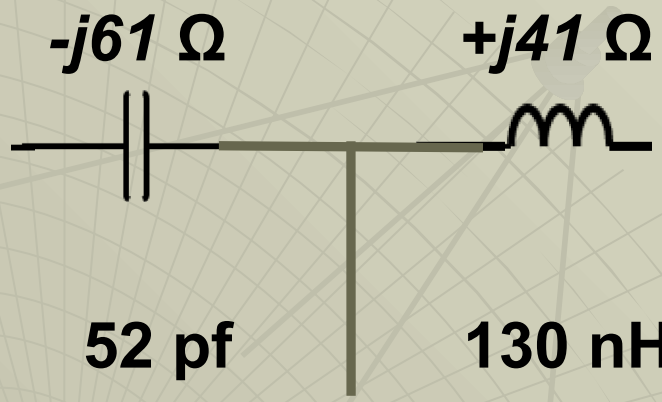
Since the parallel reactance toward the PA is –j 102.5 and the parallel reactance toward the termination is +j101.6, i.e. approximately the same, these can be used to compensate for each other with the parallel combination!

UNBALANCED POWER DIVIDER, con't



FINAL UNBALANCED POWER DIVIDER CKT.

@ 50 MHz:

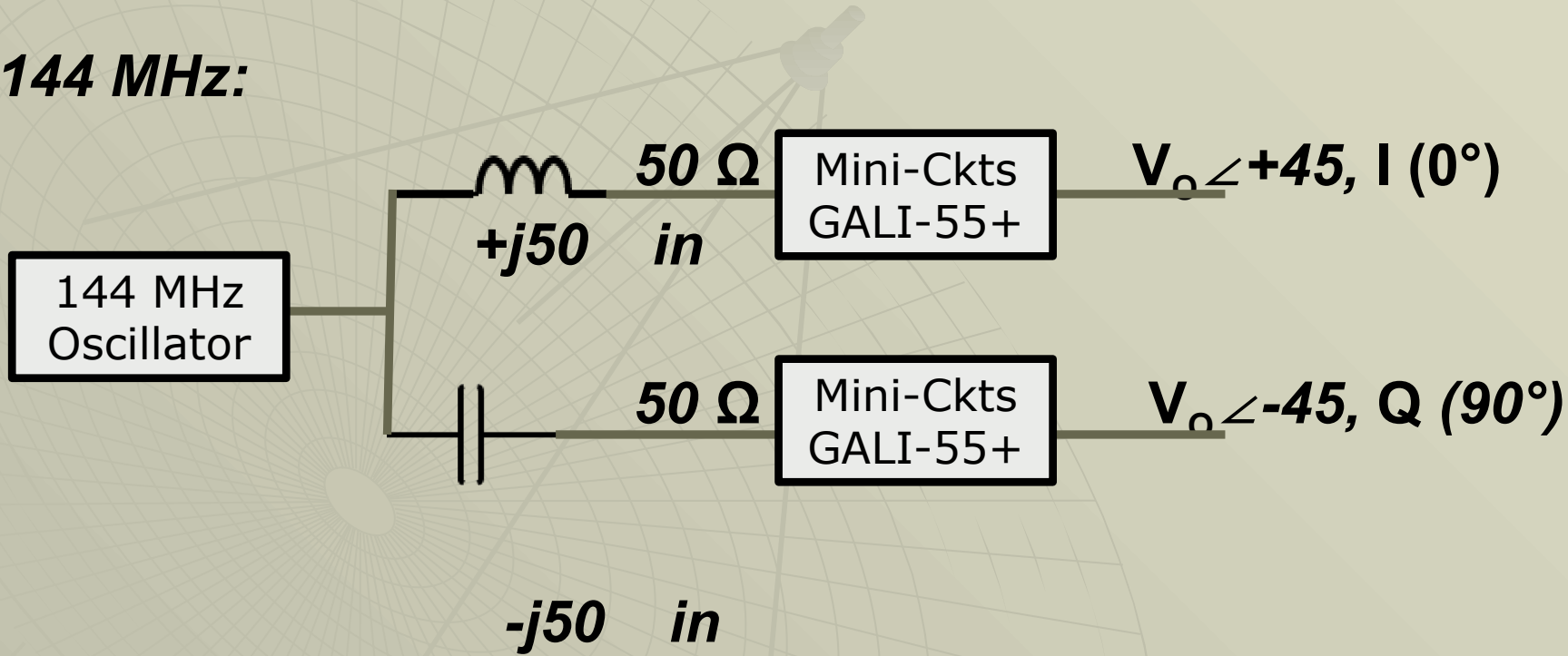


100 watts from transceiver

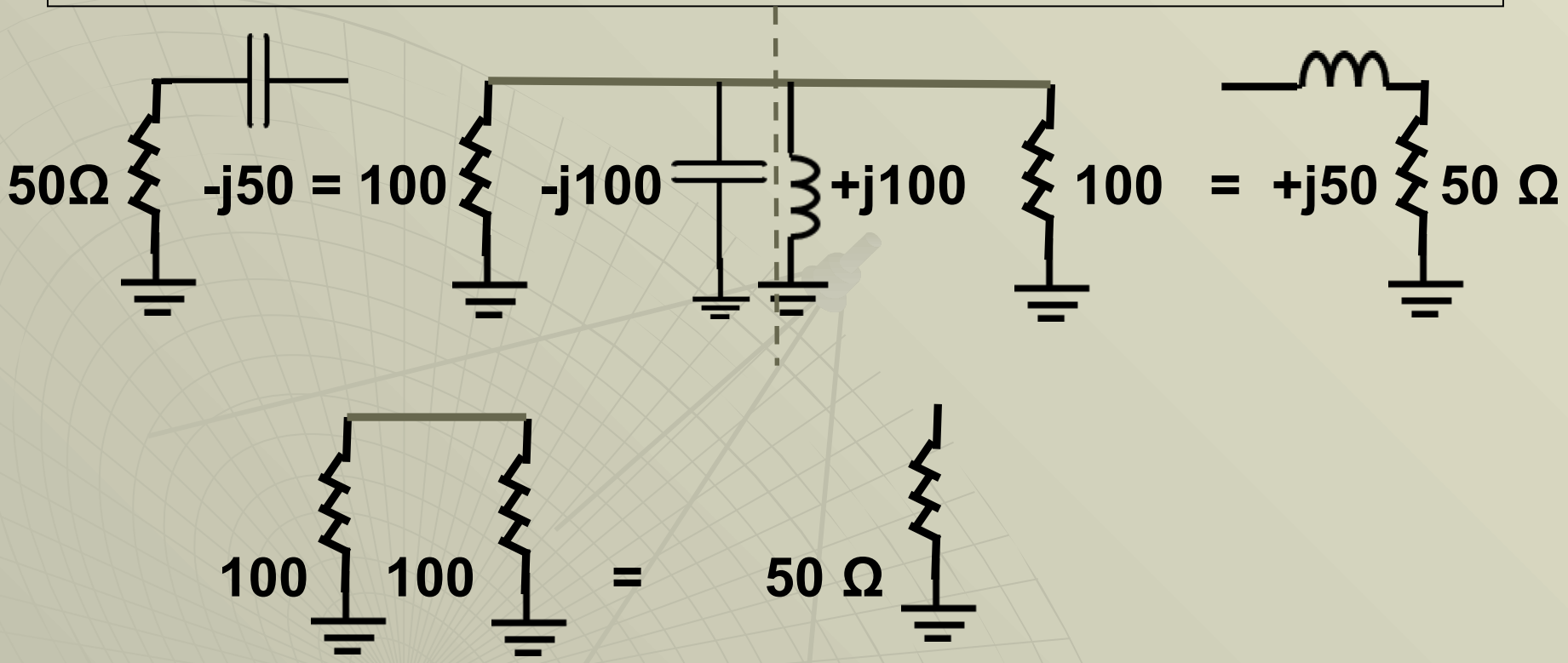
I AND Q GENERATION FOR SDR OR SSB

EXAMPLE 4: GENERATION OF I AND Q SIGNALS

@ 144 MHz:

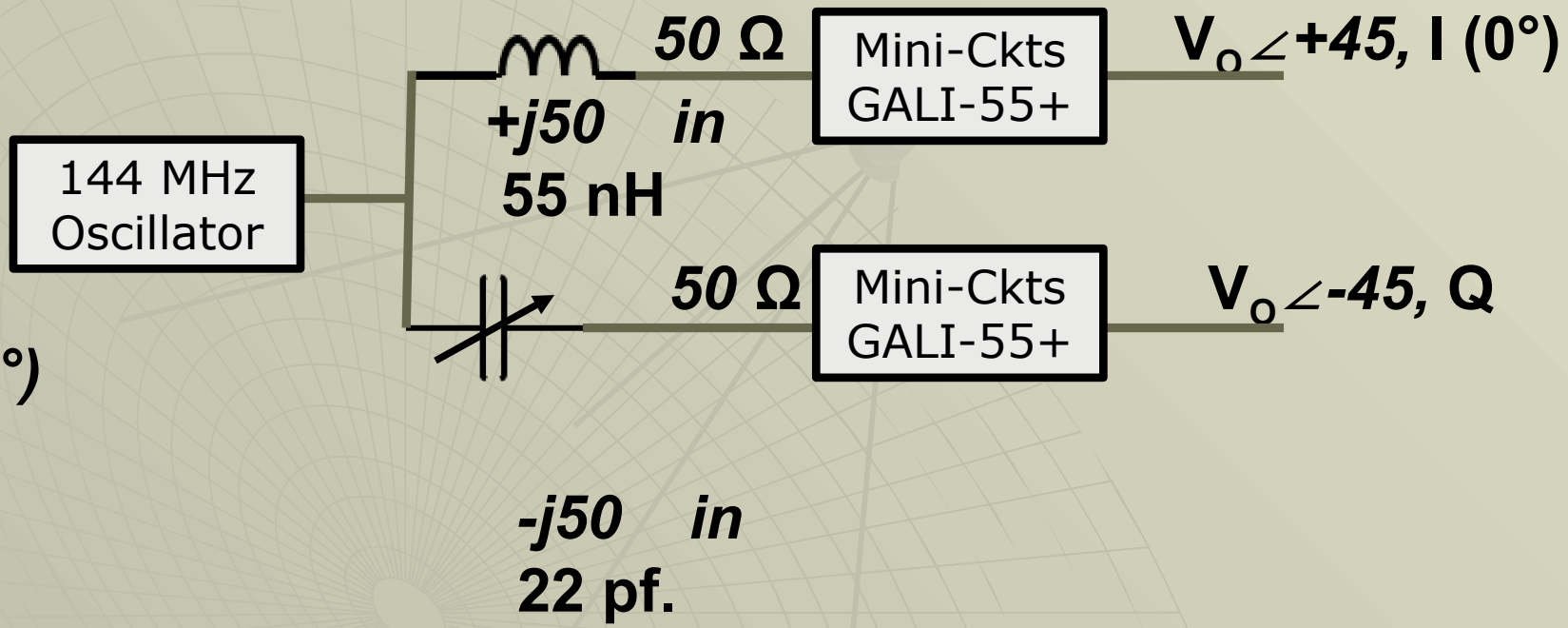


I AND Q GENERATION, con't

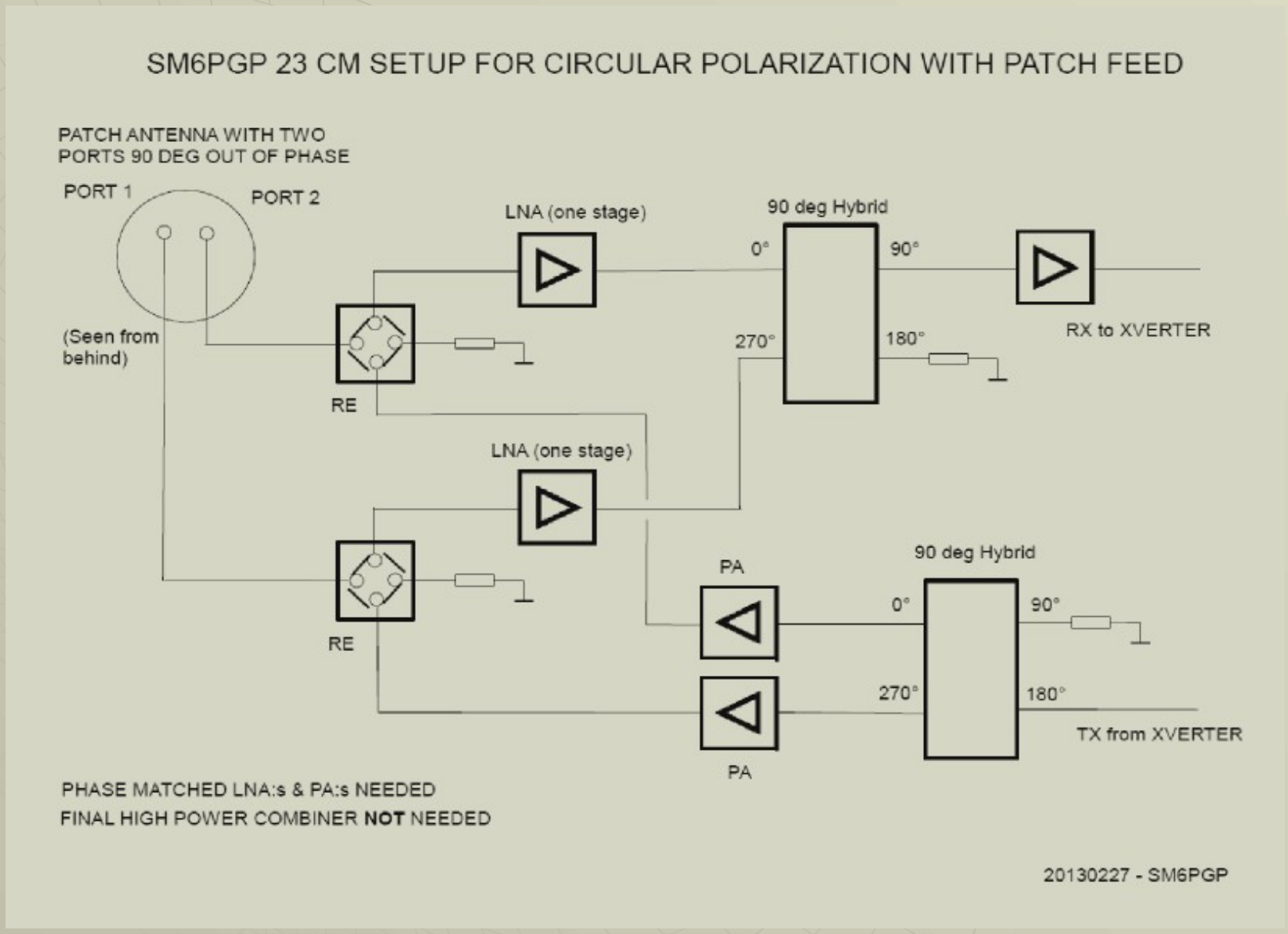


I AND Q GENERATION, con't

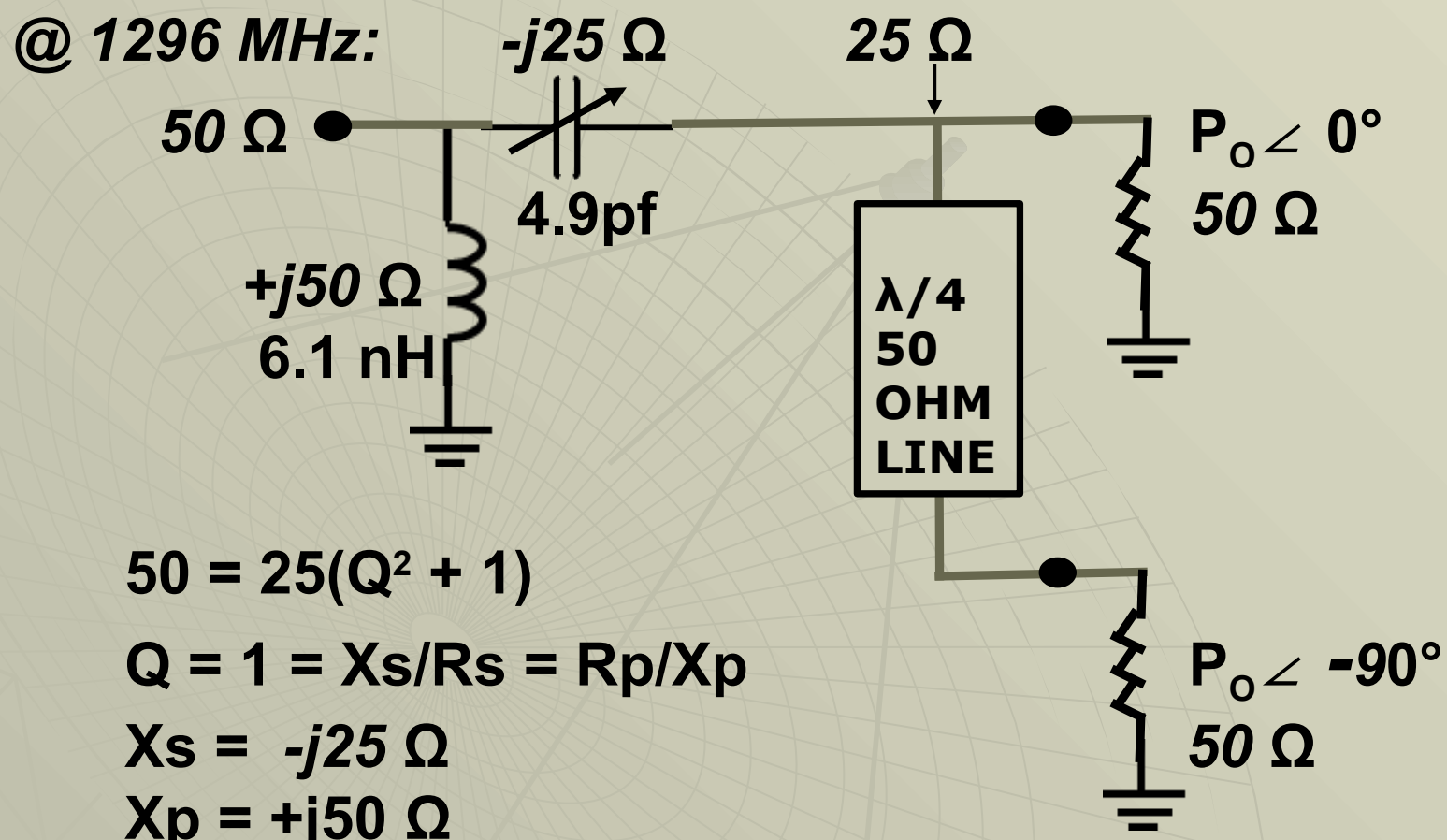
@ 144 MHz:



SM6PGP/SM6FHZ CIRCULAR POLARIZATION



1296 MHz QUADRATURE COUPLER



$50 = 25(Q^2 + 1)$

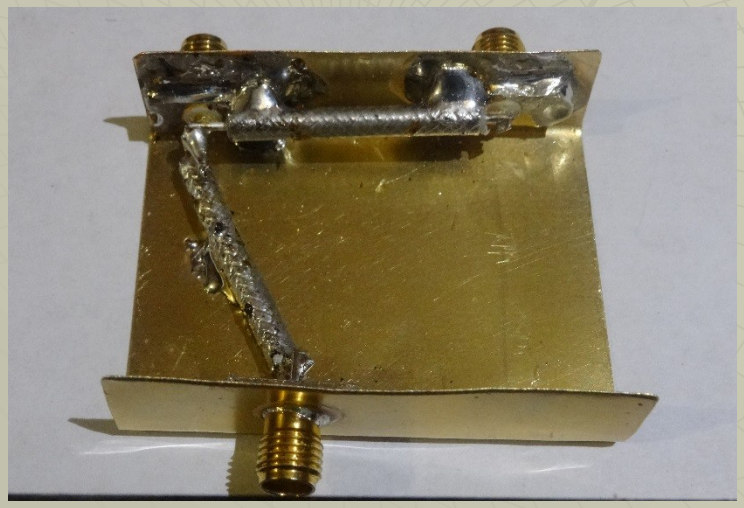
$Q = 1 = Xs/Rs = Rp/Xp$

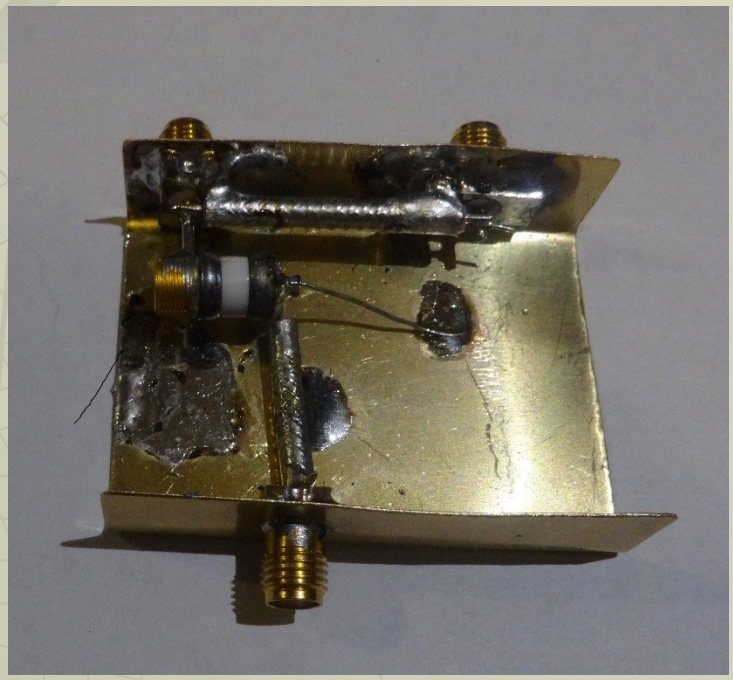
$Xs = -j25\ \Omega$

$Xp = +j50\ \Omega$

1296 MHz QUADRATURE COUPLER







LNA OPTIMUM SOURCE IMPEDANCE

EXAMPLE 5: DESIGN INPUT MATCH FOR MINIMUM NF

Typical source impedance from min. NF contour on Smith Chart:

Min. NF source Impedance =

0.82 +j 0.18 (normalized)

= 41 + j9

∴ load impedance =

41 - j9, complex conjugate

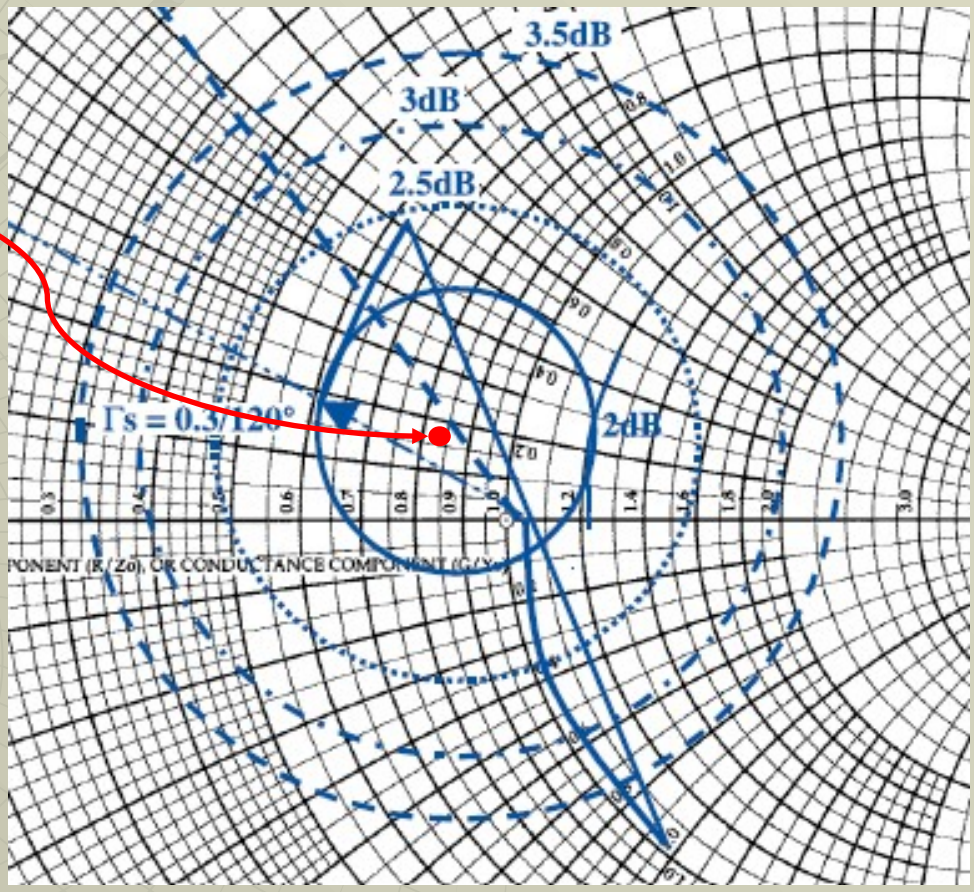
Q = 0.22, $Q^2+1 = 1.048$

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

= 41*1.0484) = 43

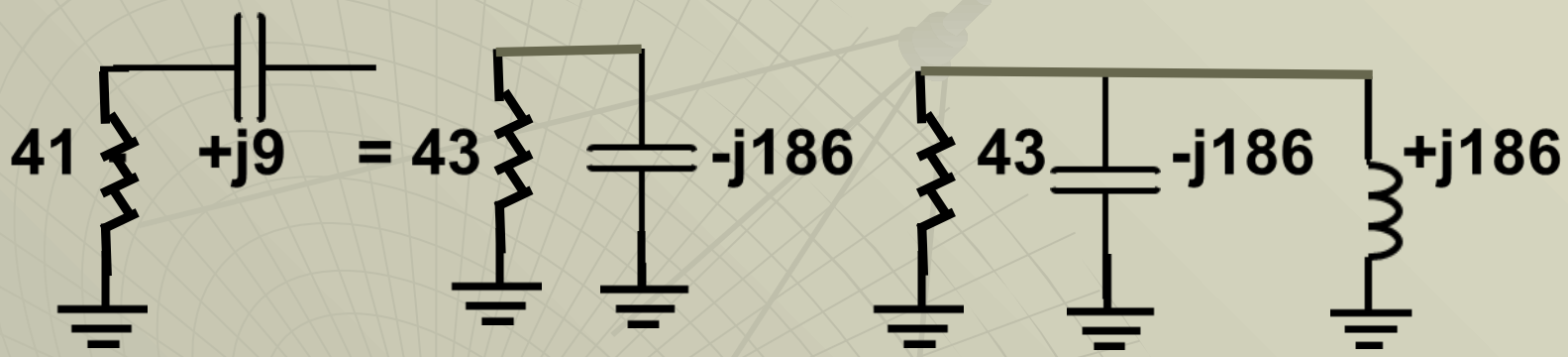
Xp = Rp/Q = 43/0.22

= j186

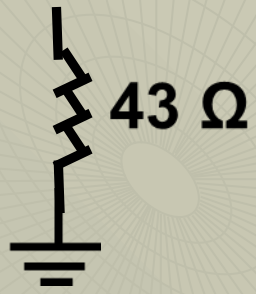


LNA OPTIMUM SOURCE IMPEDANCE, con't

Use +j186 to resonate –j186. At 1296 MHz, +j186 = 0.023 µH or 23 nH, yielding:



Leaving



This is sufficiently close to 50 Ω, or a λ/4 line ($\sqrt{50 * 43} = 46.4\Omega$) can be added between the 43 Ω and 50 Ω input to achieve the 50 Ω match. (This would be academic.)

SUMMARY

- ***EXAMPLE 1: Combining 4 antennas***
- ***EXAMPLE 2: Two step impedance transformation for greater impedance ratios***
- ***EXAMPLE 3: Unbalance power divider***
- ***EXAMPLE 4: Generation of I and Q signals***
- ***EXAMPLE 5: LNA input circuit for minimum noise figure***

QUESTIONS?

