RF measurements, tools and equipment

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INTRODUCTION

I am often asked by researchers what kind of equipment is needed to set up an RF lab. The answer depends on what you will be doing in that lab:

- **RF receiver coil arrays**
    1. You will need a network analyzer with at least a full 2 port S parameter capability to do most of the basic measurements. A 4 port analyzer is now also on the market, but still expensive. The 4 port version will tremendously speed up measurements in large array coils.
    2. DC supply to bias diode networks and preamps / DVM
    3. A faraday shielded environment preferably identical to the RF shield of the system that you are building the coils for
    4. An RF Body Transmit coil to apply B and E fields to the receiver coil that are similar to the ones experienced in the bore of the MR system that you are building the equipment for
    5. A temperature measurement device that can measure temperature of components without affecting the applied B and E fields. Example is a Luxtron multichannel thermometer, that uses fiberoptics and temperature sensitive crystals to remotely sense temperature.
    6. Hand made adapters to tune and match baluns, traps, switches, preamps, and so on.
    7. Hand made flux probes that measure B field, as well as probes to measure E field.at the frequency of interest
    8. A large number of small hand tools for cutting, soldering and so on
    9. An Oscilloscope with sufficient bandwidth to be accurate at the frequency of interest
    10. An active FET probe with low input capacitance
    11. A Noise figure meter, if the coil has integrated preamps
    12. A Spectrum analyzer, if the coil has integrated preamps
    13. Computers and analysis software for analysis of field patterns, efficiency, g factor maps, impedance matching and so on. Examples are: Matlab, FDTD, FEM, MoM, Circuit analysis software like e.g. ADS**.**
- **RF Transmit coils and arrays**
    1. All of the above
    2. A power amplifier that can deliver the power needed to set up the desired B field amplitude under loaded conditions
    3. A dummy 50 ohm load that can handle the average power levels that you are testing for
    4. A set of variable attenuators
    5. A waveform generator to generate the desired pulse shapes
    6. A modulator to amplitude modulate the carrier frequency
    7. A 90 degree high power splitter
    8. A set of high power directional couplers
- **RF transmit chain components**:
    1. All of the above
    2. A power meter
    3. A spectrum analyzer
- **RF receive chain components**
    1. All of the above
    2. A noise figure meter

In the following few pages we will go through the most common types of measurements. First we will spend some time on how exactly the RF properties of a component are measured. In the RF world we tend to measure the S parameter matrix of a device, rather than the Voltages, currents and impedances that are common in the low frequency world. Subsequently we move on to discussing the Smith chart, a tool that visualizes the impedance of a

device in a format of lines of constant Resistance, and lines of constant Reactance. We will give examples of measurements using this tool. We will finish with other possible RF measurement capabilities of the network analyzer.

S PARAMETERS AND OTHER MEASUREMENT UNITS
In the RF world we don't work with oscilloscopes and scope probes as often. Instead, the network analyzer is the instrument of choice. The problem with oscilloscope measurements is often that the measurement probe affects the measurement itself, due to its input impedance. Special, expensive FET probes can be applied to minimize this effect. Measurements on the network analyzer are usually made in terms of Scatter parameters or S parameters. Other units that are common are the VSWR, or voltage standing wave ratio, and Γ, or the reflection coefficient. On the network analyzer the S parameters that look at one particular port, S_{NN} can be displayed in the format of a Smith chart (see next paragraph), a particular handy tool. The network analyzer will also determine what the complex impedance of the port is based on the amplitude and phase of the reflected wave. Example: if we want the N port to be 50 ohms real impedance, then the S_{NN} should be <-20 dB. I am assuming here that we are looking at a 50 ohm system, using 50 ohm transmission lines. The impedance measured at the end of a transmission line is not the same as the impedance measured at the beginning of that transmission line, due to phase shift and losses. The beauty of the network analyzer is that we can calibrate the measurement such that the transmission line is taken out of the equation.
A basic explanation of S parameters can also be found on the web at
http://www.sss-mag.com/spara.html#tut
Click on S parameter tutorials
Basic explanations can further be found in (1) thru (5)

S PARAMETERS (SCATTERING PARAMETERS)
Why are S-parameters used?
S-parameters are a means for characterizing an n-port network circuit. Characterizing such a network by H-parameters, Y-parameters, and Z-parameters requires that some ports are short or open and that voltage and current are measured. As the frequency goes higher and higher, some problems will arise. There is not any readily available equipment to measure total voltage and total current at the ports of the network circuit. It is difficult to realize short and open circuits over a broad band of frequencies. Active devices, such as preamplifiers, often oscillate with a port open or short, making the measurement invalid. S-parameters are usually measured with the device imbedded between a 50Ω load and a 50Ω source so there is very little chance for oscillation to occur. Thus, S-parameters can overcome problems that could occur when H, Y, or Z parameters are measured.
What are S-parameters?
In the high frequency range like RF or microwave, the signal transported between circuits through transmission lines can be considered as a traveling wave. A portion of the incident traveling wave is reflected at the port of a network circuit or load that is connected to the transmission line if the input impedance is not matched to the characteristic impedance of the transmission line so traveling waves in both directions should be considered to characterize network circuit.

Consider a two port network. (Figure 1) E_{i1}, E_{r1}, E_{i2}, and E_{r2} in figure 1 are voltages for the incident wave on port 1 of the two port network circuit, the reflected wave from port 1 of the two port network circuit, the incident wave on port 2 of the two port network circuit, the reflected wave from port 2 of the two port network circuit respectively. S-parameters relate these traveling waves based on the electric properties of the two port network circuit as
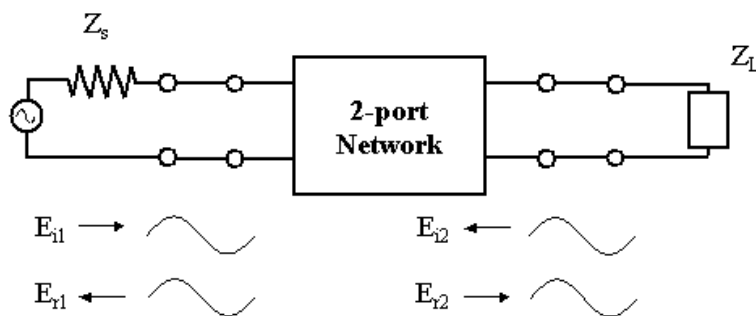

Figure 1

$$b_1 = S_{11} \cdot a_1 + S_{12} \cdot a_2 \qquad (1)$$
$$b_2 = S_{21} \cdot a_1 + S_{22} \cdot a_2 \qquad (2)$$

, where a_1, a_2, b_1, b_2 are traveling waves normalized by the characteristic impedance Z_0 of the transmission line defined as $a_1 = \dfrac{E_{i1}}{\sqrt{Z_0}}$, $a_2 = \dfrac{E_{i2}}{\sqrt{Z_0}}$, $b_1 = \dfrac{E_{r1}}{\sqrt{Z_0}}$, $b_2 = \dfrac{E_{r2}}{\sqrt{Z_0}}$. Notice that the square of the magnitude of these variables has the dimension of power. $|a_1|^2$ can then be thought of as the incident power on port 1. $|b_1|^2$ as power reflected from port 1 and so on. Let's think about the meaning of S-parameters. S_{11} can be measured by measuring the ratio of b_1 to a_1 when terminating the port 2 in an impedance equal to the characteristic impedance of the transmission line because a_2 equals to 0 in this condition. (Eq.[1]) So S_{11} is the input reflection coefficient of the network circuit. S_{21} is measured as the ratio of b_2 to a_1 in the same condition. (Eq.[2]) Then S_{21} is the forward transmission through the network circuit. This could either be the gain of an amplifier or the attenuation of a passive network circuit. S_{22}, S_{12} can be measured in the same way by termination port 1 in an impedance equal to the transmission line. Thus S_{22} is the output reflection coefficient and S_{12} is the reverse transmission coefficient. S-parameters

- relate to familiar measurement like gain, loss, reflection coefficient, etc.
- can be cascaded with multiple devices to predict system performance
- are analytically convenient e.g. for CAD program

S-parameters can be converted to H, Y, or Z parameters if desired.

Example of S parameter measurement in a RF systems of a MRI system
  Here we show some examples of S-parameter measurements in the RF design in MRI.:

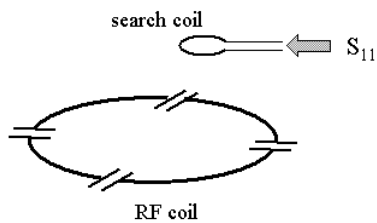1 Detection of the resonant frequency of RF coil

Figure 2
RF coil absorbs the most power radiated from a search coil at its resonant frequency. Thus S_{11} measured with a search coil has a dip at the resonant frequency of the RF coil.
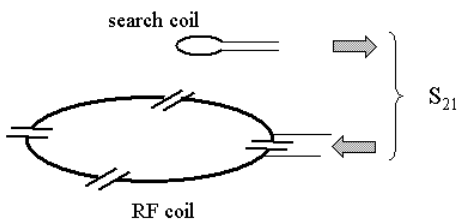
2 Measure B1 map of a RF coil

Figure 3
A driven RF coil produces EM fields. The B component can be measured by a search coil with the normal direction of the search coil plane through S_{21}

3 Impedance matching

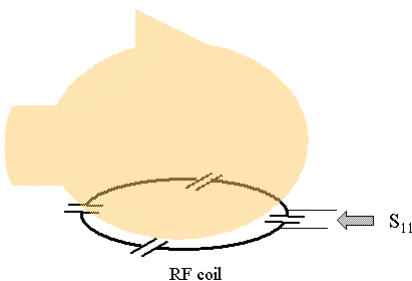
Figure 4
The reflection coefficient is measured by S_{11}. An impedance matching circuit is tuned so that S_{11} is small enough under load condition.

4 Measure the gain of a preamplifier

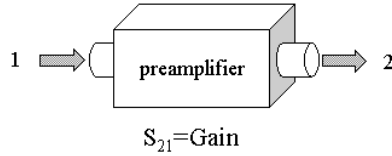Recalling the relationship between reflection coefficient and normalized impedance

Figure 5

The gain of the preamplifier is measured as S_{21} when the input port is port 1 and the output port is port 2.

S_{21}=Gain

THE SMITH CHART AND ITS ORIGIN

The Smith Chart originated as a transmission line calculator, so some relevant results must be recalled. For a length l of lossless transmission line, fed by source S, and terminated in load impedance Z_l, we write the spatially dependent incident and reflected voltage amplitudes as:

$$V_i(x) = E_{il} \exp ik(x - l) \tag{3}$$

$$V_r(x) = E_{rl} \exp - ik(x - l) \tag{4}$$

The voltage reflection coefficient at any point on the line is defined as the ratio of reflected to incident voltage $\rho(x) = V_r(x)/V_i(x)$; the factor of l in the exponentials allows us to write: $\rho(l) = E_{rl}/E_{il}$ -- in general a complex quantity. The spatially dependent incident and reflected currents are given by dividing with the characteristic impedance Z_0, and reversing the sign for the reflected current.

$$I_i(x) = \frac{E_{il}}{Z_0} \exp ik(x - l) \tag{5}$$

$$I_r(x) = -\frac{E_{rl}}{Z_0} \exp - ik(x - l) \tag{6}$$

Then at the load, by simple circuit theory, having added the incident and reflected currents to obtain the total currents (and likewise the voltages), we write the line-terminating load impedance in terms of the voltage reflection coefficient:

$$Z_l = V(l)/I(l) = \frac{V_i(l) + V_r(l)}{I_i(l) + I_r(l)} = \frac{V_r(l)\{1 + \rho(l)\}}{\frac{V_r(l)}{Z_0}\{1 - \rho(l)\}} = Z_0 \frac{\{1 + \rho(l)\}}{\{1 - \rho(l)\}} \tag{7}$$

The key is that a particular terminal impedance is now expressed in terms of the voltage reflection coefficient, and the line characteristic impedance. More generally, defining the *normalized impedance* at any point on the line as $\zeta(x) \equiv Z(x)/Z_0$, we have the *defining equation* for the Smith Chart:

$$\zeta(x) = \frac{\{1 + \rho(x)\}}{\{1 - \rho(x)\}} \tag{8}$$

that is, the normalized impedance at any point along the line expressed as a function of the complex voltage reflection coefficient at that point. Writing the complex ρ as $u + iv$ and the complex ζ as $R + iX$, and performing some simple algebraic manipulations (including completing the square) yields a pair of equations for circles, when R is held constant while X varies, and *vice versa*:

$$(u - \frac{R}{1 + R})^2 + v^2 = \frac{1}{(1 + R)^2} \qquad \text{(circle of constant resistance)} \qquad (9)$$

$$(u - 1)^2 + (v - 1/X)^2 = 1/X^2 \qquad \text{(circle of constant reactance)} \qquad (10)$$

These are illustrated pictorially: Figure 6 shows the right
half of the complex impedance plane (i.e. for positive *R*)
with three vertical lines showing constant resistance of 0.1,
1 and 10 ohms; also six color matched horizontal lines
showing reactances of ± 0.1, ± 1, and ± 10 ohms (the
negative reactances have dashed lines.) The corresponding
Smith Chart circles are shown (with color matching) in Fig.
7. A black outer circle *of unit magnitude* circumscribes the
chart, and also bounds all possible values of ρ for passive
loads, since for a passive device, the modulus of the
reflected voltage cannot exceed that of the incident. A black
line horizontally bisects the chart, dividing it (as soon we
shall see) into regions of positive and negative reactance.
The circles of constant resistance lie entirely within the
circumscribed area, and penetrate equally into regions of
positive and negative reactance. The reactance circles form
a spray, emanating from the right-most point of the
bounding circle, and are disposed in matched pairs of positive
and negative values (same color, solid and dashed lines), having
reflection symmetry with respect the horizontal bisector. Observe
that the negative values (dashed lines) all fall in the lower half of
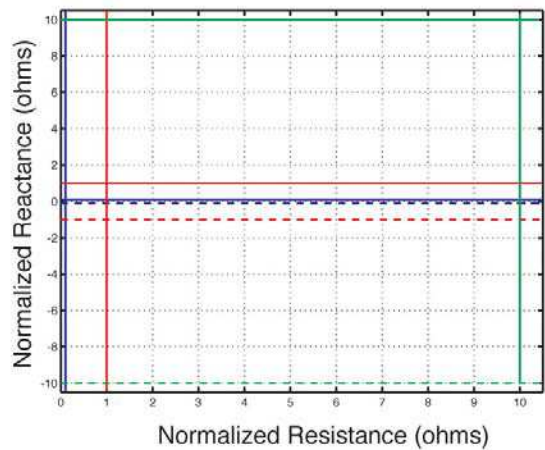the chart.

Fig. 6: Right half of impedance plane, with
lines of constant resistance and reactance as
explained in the text

The figure also shows a small rosette of 'Steiner circles', i.e. families of
circles tangent at a point. The similarity to the Smith Chart is
immediately apparent.

Other points worthy of notice: The Smith Chart can be considered as
simply an overlay for the complex reflection coefficient displayed in
polar coordinates. On commercially available charts (e.g. in .pdf format)
the circles are labeled with their appropriate resistance or reactance value.
The center (black dot in the figure) is the point zero reflection (or perfect
match) corresponding to a purely resistive load equal in value to the
characteristic impedance of the line, Z_0.   As we have presented our
derivation, this corresponds to a normalized impedance $\zeta=1$; and many
Smith Charts follow this scaling. However, charts are also available
without normalization, i.e. scaled to read ζZ_0, where Z_0 is most usually
50 ohms. Conversion from the normalized chart is made simply by
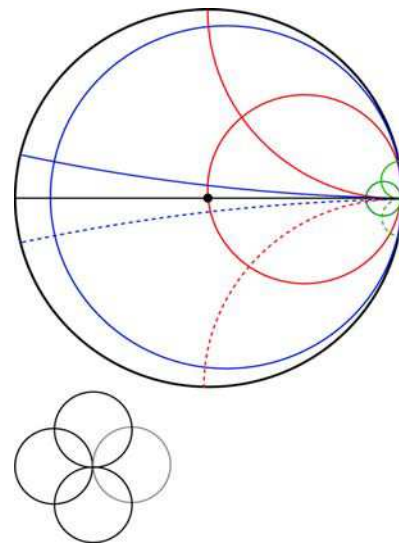multiplying all impedance values by Z_0 .

Also: higher values of impedance cluster to the right, and the
rightmost point represents an open circuit; conversely, the
leftmost represents a short to ground.

Fig. 7: Above: Smith Chart circles of constant
resistance and constant reactance, color
matched with Fig. 6; details in text. Below:
Example of 'Steiner Circles' so-called: families
of circles tangent at the origin. Refer to text.

Finally, the entire development of the theory can be done in
terms of admittance rather than impedance; the result is a chart of similar form, but with the constellations of circles
emanating from the left instead of the right. Examples are given below in the discussion of applications. The
normalized chart is of particular use when admittance and impedance reckoning are both required, since a pair of
printed charts can be overlayed (with one reversed) and viewed on a light box. The conversion factor for the
normalized admittance chart to a 50 ohm system is 20 mmho.

SMITH CHART APPLICATIONS

The main application of the Smith chart is impedance matching. In order to understand how to work with the Smith chart, the following definitions are needed: Impedance Z is

$$Z = R + jX \quad [ohm] \quad\quad\quad (11)$$

In which R is the resistance, and X is the reactance. In Fig 8 there are lines of constant resistance, the red circles, and lines of constant reactance, the red lines. Positive reactance, or inductance is the top half of the chart, and negative reactance or capacitance is the bottom half. Like wise, the green portion of the chart represents Admittance Y in which

$$Y = 1 / Z \quad [mho] \quad\quad\quad (12)$$

Admittance consists of a real and imaginary part as in

$$Y = G + jB \quad [mho] \quad\quad\quad (13)$$

Here G is called the conductance, and B is called the susceptance. The top half of the green chart represents negative susceptance, and the bottom positive susceptance. The horizontal straight line going through the center of the chart is the Real axis (i.e. zero reactance). The center of the chart is whatever the calibrated load is, but in most applications it is 50 ohms (1/50 mho) real. This can be changed in the calibration / normalization procedure of the analyzer.

Impedance matching is made quite easy using the Smith chart tool. Before I give examples, first a few words about why impedance matching is necessary:
Consider a transmit chain containing a power amplifier with an output impedance of 50 ohms real. The RF pulses are transported to the whole body transmit coil via 50 ohm transmission lines. In order for all the power to end up in the coil, producing B field (but also some losses) the impedance looking into the coil needs to be 50 ohms real to prevent reflections at the end of the transmission lines.
Another example: In the receive chain, the preamplifiers need to see certain impedance at the input in order to perform at their best noise figure. Looking into the receive coil(s) we need to see that impedance.

Fig 8: Smith chart, definition of lines

Green: Admittance chart
Red: Impedance chart
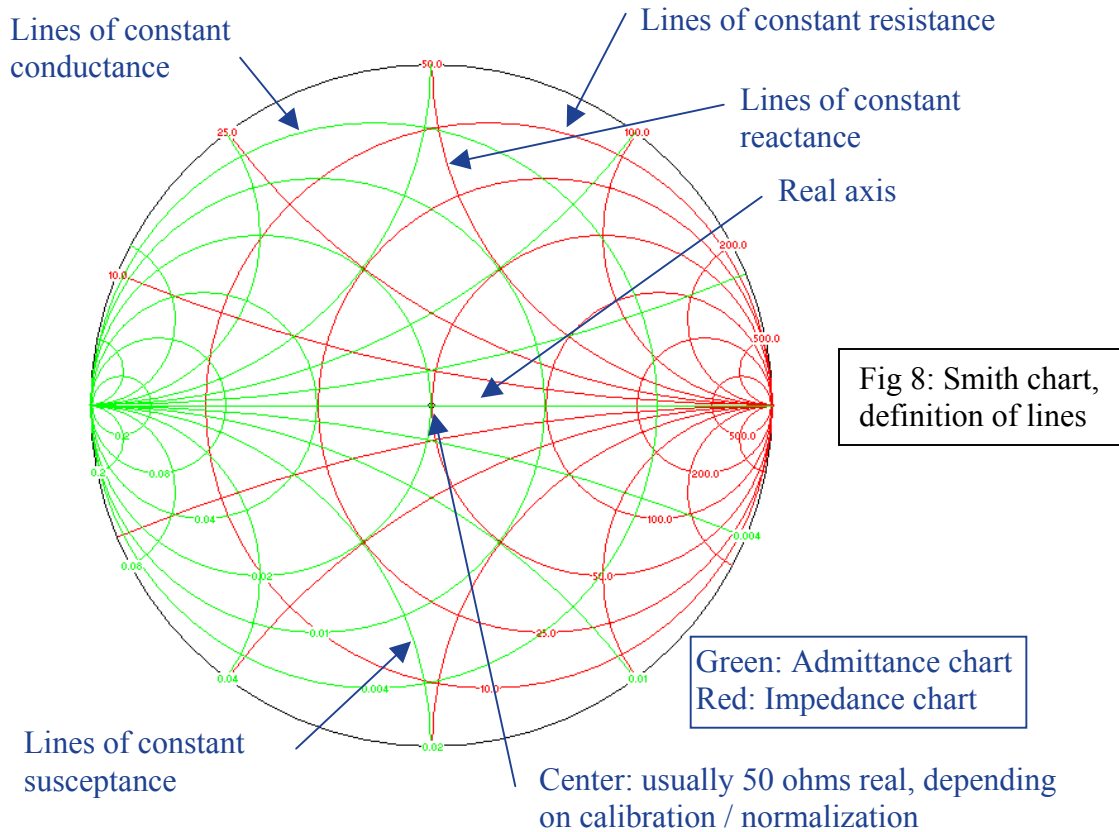
Consider a linear 64 MHz whole Body transmit coil, a 1 port device. Connect it to a network analyzer. Calibrate out the transmission line connecting the coil with the analyzer, so we measure true impedance as seen at the input of the coil. Select an S_{11} measurement, and under "Format", select "Smith Chart". Sweep the frequency from 60 to 70 MHz and put the marker on 64 MHz. Assume that the impedance of the coil, loaded with a patient is 100 – j25 ohms, and we have to make that look like 50 ohms real by adding reactance to the input network. In the Smith chart we will be following the red constant resistance circles in a clock wise fashion, if we add series inductance to the input. Adding series capacitance will follow the constant resistance circles in an anti clock wise fashion. Adding shunt capacitance means we will be following the green constant conductance circles in a clock wise fashion, and finally, adding shunt inductance corresponds to moving counter clockwise along a green constant conductance circle. We can also manipulate the impedance by adding 50 ohm transmission line to the input. Adding the series transmission line we will move along a circle that is centered around the center of the Smith chart. Most transmission lines are lossy, so in our MRI coil application we try to avoid building matching networks with them.

To get to the 50 ohm real point (center) we need to get onto the 50 ohm impedance circle, or the 1/50 mho circle as soon as possible, and then just add reactance to move from there to the center of the chart. In our example of the Body coil e.g. we start with Z = 100 –j25 ohm at point 1 in fig 9, we then add a shunt capacitance of 18.9 pF to get onto the 50 ohm circle in point 2, and then we add a series inductance of 130.4 nH to follow the 50 ohm circle towards the center of the chart in point 3. So the final circuit will look like in fig 10, and looking into the coil we will now see approximately 50 ohms real. Other matching / impedance transformation problems can also easily be solved in the same manner.
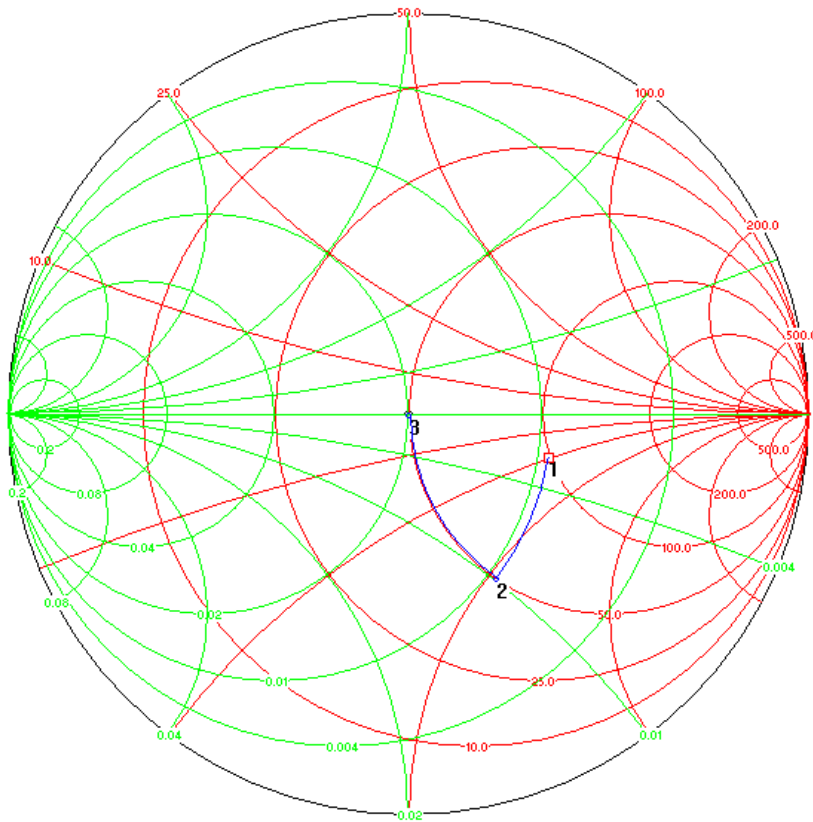
Fig 9: Smith chart: impedance matching

It is obvious how we determine the amount of reactance needed to get from point 2 to point 3, because we can just read it from the chart. Point 2 happens to have a negative reactance of 52.4 ohms (and a resistance of 50 ohms), so we need +52.4 ohms in series to get to point3, and this happens to be a 130.4 nH inductor at 64 MHz. How do we know that it takes 18.9 pF to get from point 1 to point 2? This is a bit more complex, but not too bad: from the green admittance chart we can read that we need to add 7.6 E-3 mho of susceptance, which is the inverse of reactance, so the needed reactance is -131.5 ohms, and at 64 MHz this is a 18.9 pF capacitor.

Although matching is the main application of the Smith chart, there are many others. I do not have the space in this short syllabus to go into detail, but fortunately, there are many excellent books that will educate you about those, especially (3) through (5). Among the other applications are: Figuring out the complex impedance of a network, by just graphically adding up all the reactances and susceptances, figuring out the VSWR of a particular port and so on. Instead of figuring this all out with a ruler, pencil and paper

Fig 10: Matching network

Smith charts, it is much better to get an electronic Smith chart calculator. This is freeware, you can find on the web at e.g. **http://www.hta-be.bfh.ch/~dellsper/downloads.htm**, but also at **www.rfcafe.com**, where you will find many other handy RF tools. Many tutorials on Smith charts can also be found on the web.
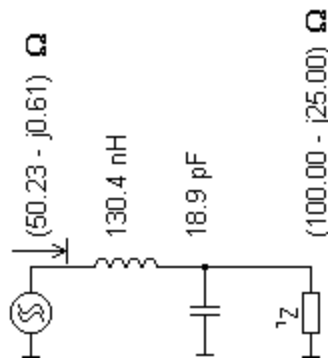
OTHER RF MEASUREMENTS
I cannot possibly go into detail on all possible RF measurements in this limited space, but there is one other important measurement common to all RF labs, and that is how to measure the Q of a circuit, and an RF coil in particular: Using the network analyzer this is most accurately done with a S_{21} measurement, and a log magnitude format. The two ports of the analyzer are connected to two 50 ohm non resonant flux probes that are sensitive to

mostly B field components. These two probes are then lightly coupled to the RF coil to be measured, to not influence the Q of the device. On the display, we will see the typical Lorentzian shape as in fig 11, where the frequency is on the horizontal axis, and the log of the transmission sensitivity (from probe 1 to probe 2) on the vertical axis. Obviously there will be more flux going through probe 2 when probe 1 excites the RF coil exactly at its frequency of resonance. Now simply take the center frequency of the peak and divide it by its –3dB bandwidth to get the Q. Alternatively we can connect port 2 of the analyzer to a tuned and 50 ohm matched coil via its input network, and inject flux into the coil via port 1 and a flux probe. We now also get a Lorentzian as the response, but the –3dB bandwidth will be twice as big, because the coil gets loaded with the 50 ohm impedance of the analyzer transformed into series resistance of the coil by the input matching network. This will double the series resistance of the coil, and since Q is reactance divided by resistance, the Q will drop by a factor 2

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(5) Caron, Antenna Impedance matching, ISBN 0-87259-220-0, 1993 ARRL
(6) Agilent technology application note 154, "S-parameter Design"
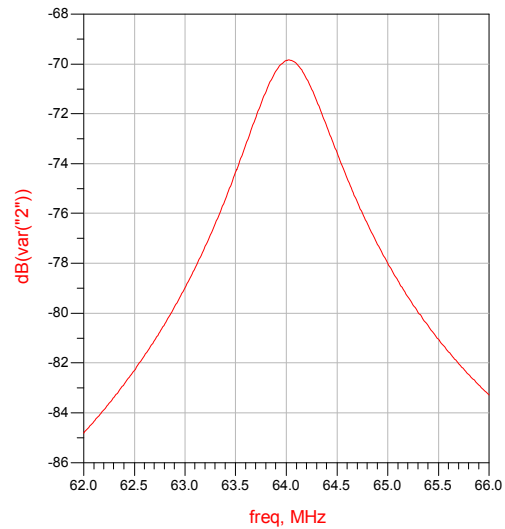(7) HP application note 95-1, "S-parameter technique"

Fig 11: Q measurement S_{21} Lorentzian