Impedance Matching

Note: This lab manual has been created by modifying the original application note developed by Keysight (http://literature.cdn.keysight.com/litweb/pdf/5992-0191EN.pdf)

Introduction

The reception and transmission of small signals into amplifier stages, or the transmission of large signals into loads require careful attention to minimize losses. At RF and microwave frequencies reflections of the propagating wave can drastically undermine the efficiency of transmitted power or the signal-to-noise ratio of transmitted information. Proper matching of impedances is needed to minimize these reflections and insure that any signal which reaches a load is actually absorbed by that load as useful power. Proper impedance matching is a fundamental skill that is central to all RF and microwave engineering. The ability to design and execute proper impedance matches is a crucial and highly sought skill which can make or break a career as well as a specific design. In this lab, some practical laboratory approaches to the problem of impedance matching will be examined.

A quick overview

Consider first the following problem. A load resistance of R_L = 10 Ω is to be fed by a Z_0 = 50 Ω transmission line. If the line were directly connected to the load, this would produce a reflection of Γ = −0.667, which means that the load only absorbs $1-|\Gamma|^2$ = 0.555 of the incident power, and the other $|\Gamma|^2$ = 0.445 fraction gets reflected back to the generator. The voltage standing wave ratio (VSWR) for this situation is 5.00, indicating deep standing waves within the transmission line, and therefore making the line impedance very sensitive to its length, and potentially cause problems for the generating source. One approach to this problem is to add a series matching resistance of R_{sm} = 40 Ω, which will bring the total of $R_{sm} + R_L$ equal to Z_0, as shown in figure 1. This indeed creates a perfect impedance match between the load and the line, with the reflection coefficient now reduced to Γ = 0. However, the introduction of R_{sm} reduces the power that the load R_L receives. Since these two resistances are in series, the load R_L only receives 1/5 of the power leaving the transmission line. The matching network of R_{sm} thus introduces a huge insertion loss of 10 log (5.0) = 7.00 dB.

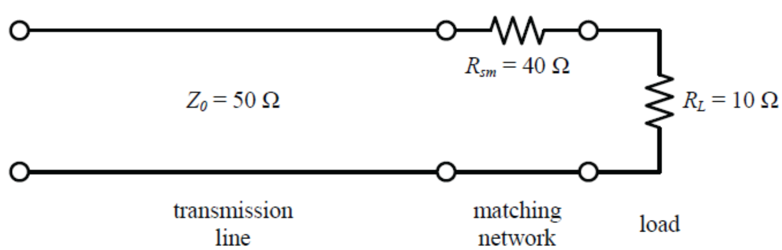

Figure 1

An important benefit of this matching is that it is frequency independent. Although significant power loss is an obvious drawback, resistive elements can be used for broadband matching.

In many cases, the range of frequencies is restricted to a narrow band, and this can allow the use of reactive elements, that is, inductors and capacitors, to achieve low loss impedance matching over that range. Simply adding a single reactive element in series or parallel to a load impedance can cancel any reactive component of the load, but it cannot bring an arbitrary load impedance to equal the desired Z_0 = 50 Ω. To handle arbitrary load impedances with both real and imaginary parts, an additional degree of freedom is required, and this is most easily achieved through the use of an L-network which involves two reactive elements.

The synthesis of these L-networks involves some computations for which the Smith chart is a very handy tool for mapping out the matching strategy and getting initial values for these elements. In practice there will be parasitic elements which may not have been accounted for, as well as other inaccuracies which will cause the final match to be imperfect. **The overall procedure for matching a load to a line** first involves a measurement of the load impedance. Once that is known, a matching strategy can be developed to guide the calculation of the matching elements. These will be nominal values which should be close to the needed values, but perhaps still not exact. Achieving a finer degree of matching then involves adjusting these matching element values while monitoring the reflection coefficient of the line. Thus, some ability to fine tune the matching network is often required. A network analyzer is the preferred tool for both measuring the initial impedance of the load as well as monitoring the reflection coefficient so that it can be nulled out by fine tuning of the matching network.

A Smith chart is a polar plot of the reflection coefficient Γ, so that the point at the origin corresponds to Γ = 0, the case for zero reflections and perfect impedance matching of a load to the transmission line. The objective of impedance matching is therefore to land a bullseye in the center of the Smith chart for the range of frequencies that need to be matched.

A computational example will next be developed to illustrate the **procedure for synthesizing an L-type matching network**. Suppose that the load is a complex impedance of Z_L = 20 – j40 Ω, and that the frequency range of interest is centered on 100 MHz. This impedance in practice could be a combination of a 20 Ω resistor and a 40 pF capacitor. A few pF of stray capacitance is quite common for many loads, so this represents a fairly common situation. The objective is to design an L-network of reactive elements which will match this impedance to a Z_0 = 50 Ω transmission line.

The voltage reflection coefficient can be expressed using normalized impedances (i.e. $z_L = Z_L/Z_0$):

$$\Gamma = \frac{z_L - 1}{z_L + 1}$$

Using the values for the load given above, Γ = 0.62 ∠ -97°. We learned in class how to match this load with an element (lumped element or stub) located a specific distance from the load. There are other alternative approaches, which can be used to match a load without inserting elements at a specific distance from the load. For example, referring to Figure 2 below, the use of two inductors can lead to a matched network as long as the equivalent impedance on the right is equal to Z_0. In other words, by writing the equation

$$Z_0 = (Z_L + j\omega L_1) \parallel j\omega L_2$$

one can find that two inductors L_1 and L_2 of 25 nH and 65 nH, respectively, will lead to an ideal impedance matching condition.

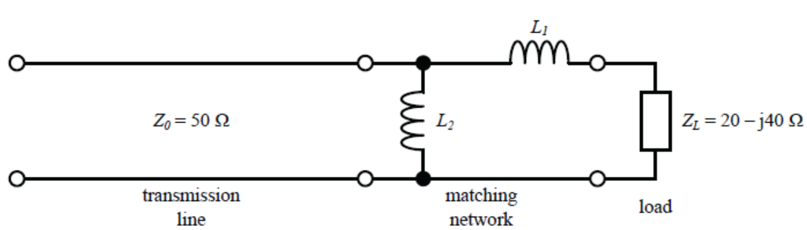

Figure 2

Note that solving the above equation can more easily achieved through online calculators such as Wolfram Alpha: www.wolframalpha.com through the following syntax:
50=((20-i40)+i(2*pi*1e8)*x)*(i(2*pi*1e8)*y)/(((20-i40)+i(2*pi*1e8)*x)+(i(2*pi*1e8)*y)),x>0,y>0
This simply solves the equation above for the two unknowns with the constraints that the results are both positive.

Inaccuracies of measurements, component statistical variations, and unaccounted for parasitic elements will in practice make this only approximate. However, it should be a close starting point which can then be improved upon with a small amount of tuning. This is the point where the process moves into the lab and calculations are supplanted by instrumented measurements.

Learning to measure and match

One of the most powerful applications on the Keysight FieldFox N9913A is the network analyzer (NA). Network analyzers will be discussed in more detail in a subsequent laboratory which will use the full 2-port capabilities of the instrument. For this laboratory, only 1-port measurements will be required.

Scattering parameters, or simply “S-parameters,” are the language of network analyzers. These are the most commonly used system of measurements for characterizing RF and microwave devices. A more detailed look at scattering parameters will be taken up later, but for the present laboratory, the only essential feature to know is that the S_{11} scattering parameter is exactly the same as the reflection coefficient Γ that has been discussed previously. The 11 subscript simply indicates that the S_{11} parameter relates the signal received back from port-1 relative to the signal that was launched into that same port.

1. Turn on the FieldFox and let it load and launch the default CAT application. Once the CAT application is running, press the Mode button and then press the NA soft key to load and launch the Network Analyzer application.
2. If it is not already selected, press the S11 soft key to measure the S_{11} parameter. For the S_{11} measurements, only port 1 of the FieldFox will be used.
3. Make sure that a Type-N to SMA adapter is attached to port 1.
4. From the Measure menu, press the Format soft key, and then press the Smith soft key to display the S_{11} parameter on Smith chart coordinates. The measured S_{11} data should appear as a yellow trace which runs around the outer unit circle of the Smith chart, perhaps several times. The open circuit condition of port 1 would ideally produce a reflection coefficient of $\Gamma = +1$, but the short section of line created by the Type-N to SMA adapter creates a short section of line whose impedance transformation varies with frequency. The very broad sweep range of the FieldFox shows how much this can affect matters over the full range sweep, which is 4 GHz in this case.
5. Press the Freq/Dist button and change the frequency sweep to a center frequency of 100 MHz and a frequency span of 200 MHz. Notice how the yellow trace has now collapsed to a much shorter arc which lies on the right hand side of the Smith chart. The reason for having this wide of a frequency sweep is so that the yellow trace becomes longer and more visible on the display. The yellow trace lies mainly on the unit circle of the Smith chart and starts at the point $\Gamma = +1$. The display also shows ∞, indicating that this point corresponds to $z_L = \infty$, an open circuit.
6. Attach a shorting cap to port 1. Notice how the yellow trace now jumps over to the opposite left hand side of the Smith chart, close to the point marked “0” which indicates $z_L = 0$, or a short circuit. The yellow trace may not be precisely on the left hand side of the unit circle, but it should be close. The left hand side of the Smith chart corresponds to a reflection coefficient of $\Gamma = -1$, meaning that reflected waves undergo a 180° phase reversal. Using the NA application, the difference between an open and a short is clearly distinguishable.

7. Replace the shorting cap with a male-to-male SMA connector and attach to that an adjustable 500 Ω potentiometer load.
8. The trace will no longer be hugging the unit circle, so reduce the frequency span to 50 MHz to tighten up the length of the trace. By adjusting the potentiometer load, the impedance can be dialed to anywhere from 0 Ω (a short), to 50 Ω (matched), to 500 Ω (not quite an open, but getting there). Experiment with how adjusting the load resistance moves the yellow S_{11} trace across the Smith chart. If the load were an ideal pure resistance, the trace should move along the horizontal axis of the Smith chart. The fact that it lies a little off of the horizontal axis and that it has some length to it indicates the presence of some additional parasitic capacitance and inductance that results from the manner in which the load was constructed.
9. Adjust the load resistance to bring the yellow trace as close as possible to the center of the Smith chart, $\Gamma = 0$. This process will be a little "touchy," indicating the sensitivity of this alignment with this particular value of potentiometer. Once the yellow trace sits over the point $\Gamma = 0$, congratulations, this has now properly matched the load impedance to the $Z_0 = 50\ \Omega$ line! This is the objective of impedance matching. Simply adjusting the load resistance makes impedance matching trivial. The more practical situation is where the load is not adjustable and where it may contain a significant reactive component. For this, an impedance matching network is needed.
10. One last feature to observe with the Smith chart is the effect of the transmission line length. The previous loads were connected to port 1 using only the male-to-male connector which is in effect a very short length of line. Remove the connector and connect an 24 inch long SMA cable to port 1, leaving its end open circuited.

    <u>Capture screenshots of the measurements above and explain what you observe in the traces near 100 MHz for the four cases (open load, shorted load, matched load using a potentiometer, and open load connected through a 24-inch cable).</u>

11. **The end objective of this laboratory is to properly impedance match an arbitrary experimental load to a 50 Ω transmission line. To start the process, the first step is to measure the impedance of this load over the frequency range of interest.** The experimental load is made up of a 100 Ω resistor in parallel with a 22 pF ceramic capacitor, both soldered to a female SMA connector. Replace the adjustable potentiometer load with the experimental load, as shown in figure 3. The center frequency for the impedance matching will be 100 MHz, and to get a better picture of how this match is working, a frequency span of 20 MHz will be used. Configure the FieldFox frequency sweep for this frequency range of 90 to 110 MHz. The measured S_{11} parameter data should appear as a short yellow trace in the lower half of the displayed Smith chart.

Figure 3

12. To obtain numerical data, press the Marker button. If it is not already there, move the marker to 100 MHz and record the marker coordinates. In the Smith chart format, the marker does not give the value of S_{11}; rather, it gives the value of the load impedance Z_L, based upon $Z_0 = 50\ \Omega$. As an example, at 100 MHz, the measurement might yield $Z_L = 24.5 - j37.6\ \Omega$. Just below the

marker coordinates, the marker data also displays the component value that would be associated with the imaginary part of the load impedance. In this case, the display shows 42.30 pF. Record the values for the load that is being used, these will be needed later.

13. Now, onward to the problem of matching this experimental load to a 50 Ω transmission line. The critical piece of information is the impedance of the load at the desired matching frequency of 100 MHz: Z_L = 24.5 – j37.6 Ω, or something close to this value. This value is similar to the value of Z_L = 20 – j40 Ω that was used in the prior example, so that previous L-network design should serve as a good starting point for matching this experimental load. The prior L-network design required 65 nH and a 25 nH inductors. As mentioned earlier, simply selecting these components based upon their low frequency values will almost certainly produce something quite different at 100 MHz. Perhaps something not even close. The challenge is to synthesize these values at the frequency they are needed to operate.

Measurement assignment

To construct the previously designed matching network, a means is needed to connect the matching components into the transmission line, as both series and parallel (shunt) elements. This proves increasingly difficult as the frequency increases, but it can still be accomplished at 100 MHz with some creativity. An impedance matching breadboard has been constructed for this purpose as shown in figure 4.

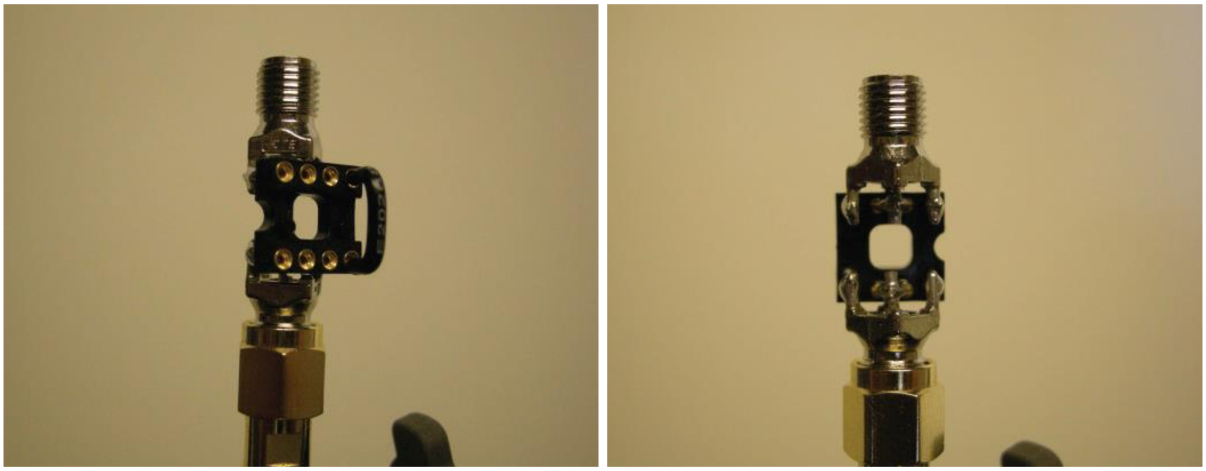

Figure 4

The impedance matching breadboard is constructed from a pair of female SMA PCB connectors that are soldered to a DIP-8 machine pin socket. On each side, the two middle pins are connected to the center pin of the SMA connector, and the two outer pins are connected to the housing or shield of the SMA connector. This configuration allows all possibilities for inserting leaded components into the transmission line. To ensure that both of the SMA housings or shields are electrically connected, a short wire is needed to jumper these across the DIP-8 socket. This is shown in figure 4, with the short black wire connecting pins 4 and 5 of the DIP-8 socket. The L-network described previously can be implemented by inserting L_1 between pins (2,3) and (6,7), and inserting L_2 between pins 1 and (2,3).

The next issue is to find elements for L_1 and L_2. This is a situation where building works better than buying. Both inductors will be crafted by hand from some short lengths of solid hookup wire. Solid #24 gauge wire works best for this, since that fits well into the machine pin DIP socket receptacles. The first step is to re-measure the load with the impedance matching breadboard in place. Complete the connections from the Fieldfox to the load by using two short pieces of wire on the breadboard. We are repeating the measurement of the load with the breadboard in place, since the breadboard will add parasitic resistance/reactance that alters the value you recorded earlier for the load alone. Now that you have the load impedance to match, calculate the values of the inductors needed to match the experimental load you measured. Note that if your breadboard/load combination results in a reactance that is too large (greater than -j25 Ohm), you may not be able to match the impedance with 2 inductors. If that is the case (the online calculator yields no solution), don't match the load at 100 MHz, but instead raise or lower the frequency such that the reactance to match is <-j25 Ohm and/or the matching calculation yields a 2 inductor solution. This new frequency will be the one you will work with from now on to match the load.

The next step is to gain some feel for how much wire or coil is needed to create the required inductance values. The self-inductance of #24 solid wire is roughly 23 nH per inch, so not very much is going to be required. The best strategy is to experiment with some different lengths, simple hairpins versus open loops versus coils of a few turns, and test these on the FieldFox to find their inductance values at the frequency you are matching the load. The inductance measurement can be found by switching the measurement format to Smith, and connecting the test wire across the Fieldfox output directly at the SMA connector (no other fixture attached). Figure 5 shows some of the possibilities for length of wire/coil you may need.

Inductors made in this fashion are tunable. By bending their geometry, their inductance can be adjusted to the precise value that is needed for the match. The inductance of a loop is proportional to its area, so simply opening and closing the size of the loop, along with changing the length of the wire in the loop, will provide quite a bit of adjustment. For multi-turn coils, the number of turns and their spacing apart provides additional adjustment. The objective is to develop a wire inductor that provides some tuning range around the nominal values of L_1 = 25 nH and L_2 = 65 nH. Note that L_1 is not going to involve much more than about 1 inch of wire.

Once suitable wire inductors have been found, connect up the impedance matching breadboard to produce the network of figure 2. Add the experimental load using a second male-to-male SMA connector and test the result out on the FieldFox. If all has gone well, the resulting yellow trace of S_{11} should be closer to a minimum magnitude and phase at your matching frequency. Tune up the matching network by bending the inductors slightly to adjust their values and move the Smith chart trace as close as possible to the origin at your matching frequency. This can be also visualized as being lowest VSWR when viewed in the VSWR format. It is helpful to place the marker on 100 MHz (or your matching frequency) and try to move the bottom of the green diamond on to the center of the Smith chart. Figure 6 shows the final configuration.

Be sure to record a screen image of the final impedance match. This is something to be proud of. As a final thought, consider how difficult this process would be without having a network analyzer!

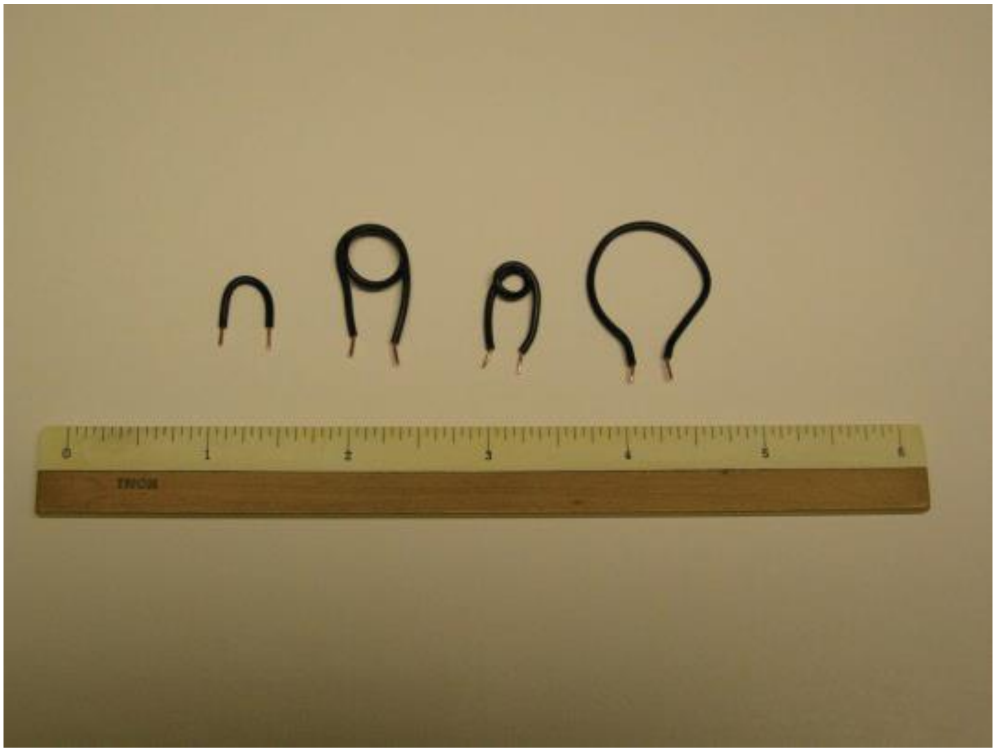

Figure 5

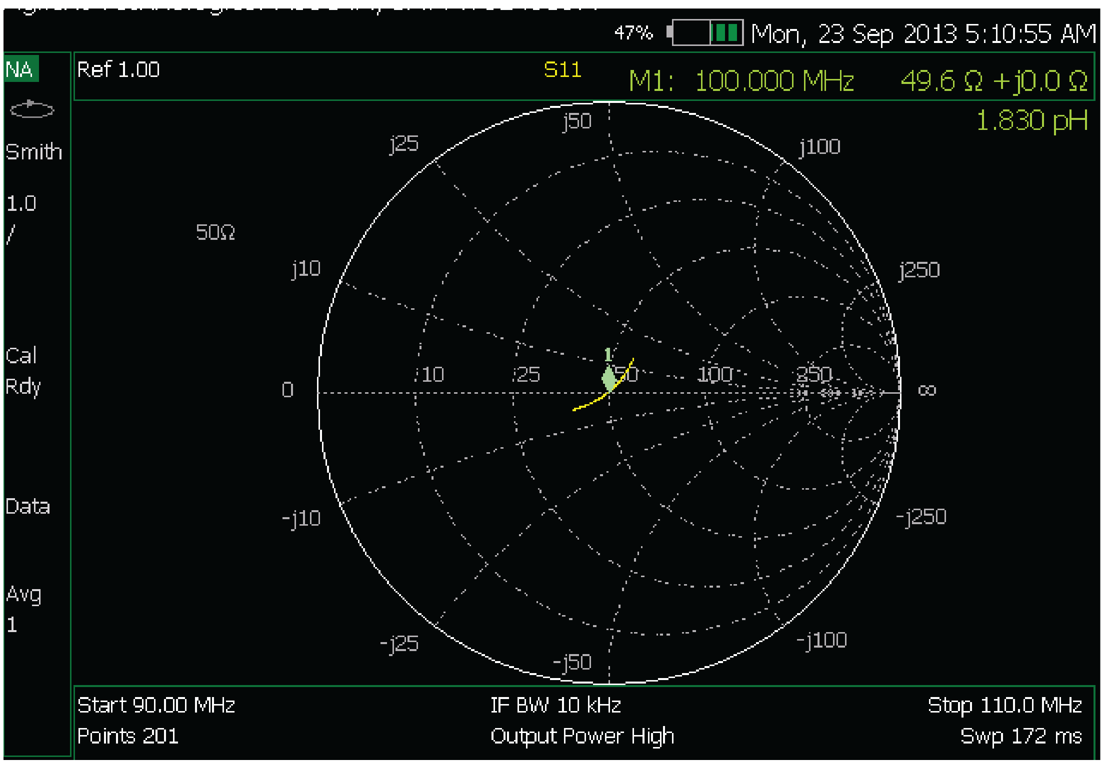

Figure 6

Grading scheme

This lab is out of 15 marks.

- 4 marks for answering questions from the Learning to Measure and Match section
- 8 marks for answering questions from the Measurement Assignment
- 3 marks for INDIVIDUALLY answering additional questions about this lab found on eClass.

All questions can also be found on eClass, where you will enter your answers. Note that all group members may have similar answers, EXCEPT for the questions indicated that are to be answered INDIVIDUALLY, where each group member is expected to have their own answer.