Impedance Matching

Laboratory 04 Manual
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1 Laboratory Objective

You have previously learned that, for best performance, it is important to operate transmission lines under matched conditions (i.e., terminated into their characteristic impedance Z_0). If this is not done, maximum transfer of power from the transmission line to its load will not occur (some of the incident wave power will be reflected back towards the generator). Since in many situations one may be forced into accommodating a load that has a complex impedance Z_L that is not equal to Z_0, it is important to have available techniques for transforming Z_L into Z_0. This process of transforming Z_L into Z_0 is called impedance matching, and we will consider it in detail in this laboratory.

In this laboratory you will use the Smith Chart to design impedance matching networks. To be successful you will then need to have studied in detail the material covered in Sec. 9-6 and 9-7 of our textbook[1]. Once the design process is complete, you will computer-simulate the performance of your circuit, construct the corresponding matching network, and measure its performance using the NanoVNA-F.

It is always very useful to numerically simulate the operation of any designed circuit before constructing it. This allows you to to verify the circuit performance as well as to catch errors before committing time and other resources to hardware. This is also true for the work associated with this laboratory, and hence we will carry out numerical simulations. With this in mind, a useful sophisticated software for handling high-frequency circuits in association with the Smith Chart is the SimSmith software[2]. You can download SimSmith, together with its operation manual and additional useful information, from the website:

`http://www.ae6ty.com/Smith_Charts.html`

You may also want to watch the introductory video provided in the above web site, and also on the web site[3]:

`https://www.w0qe.com/`

A particularly useful operation summary document can be found inside the SimSmith help menu. To access it, select on the top banner the tab "help," and from it select "papers," "old Documents," and then "primer."

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[1]D. K. Cheng, *Field and Wave Electromagnetics*, Second edition, Addison-Wesley Pub. Co., 1989.
[2]SimSmith is free and was written by Mr. Ward Harriman.
[3]These instructional SimSmith videos were developed Mr. Larry Benko.

As a result of this laboratory you will need to generate and submit a laboratory report for grading. The report should have each of its sections and subsections numbered according to this laboratory manual, and be a detailed document with all your design efforts, calculations, Smith Charts clearly depicting the hand drawings associated with your design process, numerical simulations and corresponding pictures of SimSmith, measurement results, conclusions, drawings, plots, relevant photos of all constructed components (to showcase your very important high-frequency craftsmanship), and printouts of any developed software.

Note that, to maximize the learning experience, the laboratory has been designed to be carried out individually, hence each person in the class received their own individual lab kits. Consequently, the experiment and the corresponding report has to be done completely individually.

2 Transmission Lines' Velocity Factor and Characteristic Impedance Measurement

Before learning how to match arbitrary loads, it is useful to first understand how to match a transmission line, if you have available the choice of using any terminating impedance Z_L that you desire. With this in mind, in this section you will again explore the fact that the input impedance Z_i of an arbitrarily terminated transmission line of length ℓ, is provided by[4]

$$Z_i = Z_0 \frac{Z_L + Z_0 \tanh(\gamma\ell)}{Z_0 + Z_L \tanh(\gamma\ell)},\tag{1}$$

where Z_0 and $\gamma = \alpha + j\beta$ are the characteristic impedance and the propagation factor of the transmission line, respectively. In particular note that Eq. 1 shows that the transmission line will be matched (i.e., render $Z_i = Z_0$), regardless of the value of $\gamma\ell$, if a load of impedance $Z_L = Z_0$ terminates the line.

When matching using transmission line elements, at the very start it is of cardinal importance to have in hand reliable numerical values for both the velocity factor VF as well as the characteristic impedance Z_0 of the lines involved. Although in previous laboratories you have already measured both VF and Z_0, using various methods, in this section you will again measure both VF and Z_0. This way, in addition of learning some alternate useful measurement techniques, you will have the opportunity to assure that you indeed already have in hand the correct VF and Z_0 values before marching ahead.

1. For this section initial measurements you will be needing the calibration that you previously stored in the position 1 of the NanoVNA-F (i.e., the calibration that was done right at the port 1 of the NanoVNA-F, using the male standards). Make sure that the stored calibration is still reliable and recalibrate the NanoVNA-F again only if it isn't.

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[4]From Sec. 9-4 of D. K. Cheng, *Field and Wave Electromagnetics*, Second ed., Addison-Wesley Pub. Co., 1989.

2. To start you will be measuring the velocity factor *VF* and the characteristic impedance Z_0 of one of the two ~200 mm long RG316 coaxial test cables that come in the NanoVNA-F box. Locate then the test cable, and connect it to the calibrated port 1 of the NanoVNA-F.

3. To perform the *VF* measurement, start by leaving the end connector of the coaxial cable open-circuited (to create a very large $|Z_L|$). Note that in principle you would need to connect the open calibration standard to the cable end in order to create a reliable open circuit. However, since our operation frequencies are relatively modest (i.e., under 1.5 GHz), the stray capacitance associated with leaving the coaxial cable open provides a very large reactance. Hence, and as the NanoVNA-F readings indicate, the open end works well to implement a large $|Z_L|$.

   Now observe the S_{11} trace displayed on the Smith Chart of the NanoVNA-F screen, as the frequency increases. As long as the transmission line electrical length is relatively short, its loss factor α can be neglected and hence $\gamma\ell \approx j\beta\ell$. In this circumstance both Eq. 1 and the NanoVNA-F display show that Z_i is pretty much purely reactive and hence its associated Smith Chart trace lies almost on a circle (*i.e.*, $|S_{11}| \approx 1$). The S_{11} path actually slowly spirals down towards the center of the Smith Chard though, an inexorable consequence of the small but nevertheless non-zero α.

   Use Eq. 1 to calculate the smallest value of ℓ/λ, where λ is the transmission-line wavelength, that will make Z_i a short circuit.

4. If the previous item wavelength was in free space (i.e., $\lambda = \lambda_0$), what would be the lowest frequency f_{s0} that would make the Z_i of your RG316 coaxial test cable a short circuit? Provide the value of f_{s0} in MHz.

5. Use the NanoVNA-F Smith Chart display, together with the frequency marker, to determine the lowest frequency f_s where the cable input impedance becomes an short circuit. Then use this measured f_s value, together with the previously computed f_{s0}, to determine the *VF* of the coaxial cable. Make sure to compare this *VF* value with both your previously measured results and the manufacturer provided value.

   Note that, to precisely determine f_s (and hence *VF*), you are going to have to narrow the frequency sweep range of the VNA accordingly.

6. Considering now the characteristic impedance Z_0 measurement, locate the 200 Ω trimming potentiometer that has been provided in the laboratory kit and familiarize yourself with its operation. For this you may want to connect the potentiometer to the SMAF-DIP8-SMAF test fixture and measure it by itself, and also take a good look at the potentiometer data sheet. This small potentiometer is commonly referred to as a trimpot (an abbreviation of the words *trim*ming *pot*entiometer).

7. Replace the short circuit at the end of the coaxial cable by the SMAF-DIP8-SMAF test fixture with the trimpot, to provide an adjustable resistive termination for the cable. Then use the S_{11} trace displayed on the Smith Chart of the NanoVNA-F

screen to adjust the potentiometer to obtain the lowest possible reflection coefficient over the 50 kHz – 200 MHz frequency range, and hence obtain the desire Z_0 value of the cable.

Observe that of course the potentiometer has undesirable parasitc reactances, as well as the SMAF-DIP8-SMAF test fixture, and hence it does not provide a reliable pure resistance value if the frequency gets too high. However, with great care it is possible to adjust the potentiometer to yield a very small reflection coefficient over the limited 50 kHz – 200 MHz frequency range.

Note that the NanoVNA-F allows you to control the radius of the Smith Chart outermost circle (normally it is $|S_{11}| = 1$), and hence magnify what is happening at the chart center region, to provide better resolution. To do this you first need to use the menu to select the Smith Chart (green) trace by going to "DISPLAY," "TRACE," and then selecting "TRACE 2." Once on Trace 2, select "BACK," "SCALE," and "SCALE/DIV." A numerical keyboard will appear and you can then type in the desired value for the $|S_{11}|$ of the outermost Smith Chart circle. For example, typing 0.5 x1 on the keyboard will set the NanoVNA-F FS parameter to 0.5, indicating that the Smith Chart outer circle corresponds to $|S_{11}| = 0.5$. The NanoVNA-F top left green label should now read "S11 SMITH 0.5FS," successfully confirming that the full scale of the Smith Chart is set to 0.5.

Provide the measured value of the characteristic impedance Z_0 of the RG316 coaxial cable and compare this value with both your previously measured results and the manufacturer provided value.

8. Let's now use a similar procedure to determine the velocity factor and the characteristic impedance of the ~200 mm long parallel wire transmission line that you constructed on a previous laboratory. For this you will need to connect the SMAM-SMAM adapter directly to port 1 of the NanoVNA-F and connect the SMAF-DIP8-SMAF test fixture to it.

Locate the ~200 mm long parallel wire transmission line and properly connect it to the row of pins of the SMAF-DIP8-SMAF test fixture that is closer to the Port 1 of the NanoVNA-F, leaving the end of the line open. Similarly to what you did in a previous item for the RG316 coaxial cable, report the obtained values of f_{s0} and f_s, and hence calculate and report the desired velocity factor VF of the parallel wire line. Please make sure to compare this value with your previously measured results.

9. To measure the characteristic impedance of the parallel wire line, connect the 200 Ω potentiometer to the row of the SMAF-DIP8-SMAF test fixture pins that is further away from the Port 1 of the NanoVNA. Then connect the open end of the parallel wire line to the row of pins of the SMAF-DIP8-SMAF test fixture that has the potentiometer, and adjust the potentiometer to provide a relatively stable impedance over the entire 50 kHz – 200 MHz frequency range.

To achieve the desired result it is helpful to put the frequency marker at 200 MHz and use the Smith chart with a magnified scale (e.g., set the NanoVNA-F FS Smith

Chart parameter to 0.5), to *minimize the overall dimensions* of the displayed impedance wiggle as the frequency sweeps between 50 kHz and 200 MHz. The reason for this is that, since the parallel wire Z_0 is not 50 Ω, what you are trying to achieve here is an almost constant resistive impedance at the beginning of the parallel-wire transmission line, since this will only happen when the parallel wire transmission line is terminated by its characteristic impedance Z_0.

Provide the measured value of the characteristic impedance Z_0 of the parallel wire transmission line and compare this value with your previously measured results.

3   Matching With Lumped Elements

In the previous section you experimented with matching a transmission line using a terminating resistance equal to the line characteristic impedance. This is the ideal matching situation since it provides a broad-band match (this is what needs to be done, for example, when transmission lines are used to carry pulses in digital circuits). However, in many applications this may not be possible or even necessary; one may only need to operate the transmission line in the time-harmonic regime and over a limited frequency range. In this section you will explore matching under these circumstances.

Generally speaking two basic principles are involved into the design of matching networks: use of components to change the magnitude of the impedances involved (i.e., produce step up and step down transformations), and use of components to cause reactance changes. This last effect is accomplished through the use of components with reactances of opposing sign (e.g., an inductive reactance can be reduced by adding a capacitive reactance in series to it). Note that *the usage of resistances is never recommended or desired*, since they create otherwise avoidable power loss.

When designing matching networks it should always be kept in mind that simplicity is of cardinal importance (i.e., matching should be accomplished with a minimum number of added components), since even the addition of only reactive components always brings in some parasitic resistance, and hence some power loss, and power loss is never desirable.

Matching using reactive elements is inherently a narrow band technique. The reason is that it employs capacitive and inductive stored energies to provide reactance cancellations, and since reactances depend on frequency, good cancellation only occurs near the design frequency. A corollary of this comment is the fact that broadband matching has then to be accomplished using components and techniques that avoid stored energy. However, such approach will not be pursued in the current laboratory.

In this section we will be performing matching using lumped elements (i.e., inductors and capacitors), and in the next section the matching will be accomplished using sections of transmission lines. Since lumped components invariable bring with them parasitic reactances, and you are limited by your hands on how small and accurately you can make circuit components, manual matching with lumped components is usually a low-frequency endeavor. Of course you can also implement lumped-components matching using integrated circuit techniques, and in such case the hand construction limitations are lifted, but this is not the case of this laboratory.

Although the NanoVNA-F is pretty much a self contained instrument, as you move forward please keep in mind that you can always enlist the NanoVNASaver software to assist you with your measurement tasks. This is often desirable, other times just convenient, but sometimes it is actually needed; the decision is of course dictated by the circumstances.

When using the SimSmith software to simulate your circuit, you must note that the scale of its Smith Chart is determined by the Z_0 value present in the generator block box (blue rectangle on the right of the circuit located the top left of the screen). The red and blue Smith charts display impedances and admittances, respectively. When you first start SimSmith it opens with $Z_0 = 50\,\Omega$, but you can change Z_0 to any value you desire. If you set Z_0 to $1\,\Omega$, for example, the red and blue Smith Charts will effectively display normalized impedance and admitance values, respectively.

We all learn Smith Charts with normalized impedance and admittance values, as this is how books have them. This is just a matter of publisher convenience though, since this way just one (printed) chart fits all applications. However, normalized values are somewhat inconvenient and increase the opportunity for errors (as opposed to actual impedance and admittance values in Ohms and Siemens, respectively). Since software can easily allow for the flexibility that removes this inconvenience, SimSmith allows you to do so.

1. Start by recalling the NanoVNA-F calibration that you made for use with the SMAF-DIP8-SAMF test fixture. We will be using the test fixture to implement the required matching circuit connections in the neighborhood of an operation frequency $f = 200$ MHz (narrow-band matching). Don't forget to verify the quality of your calibration.

2. The load Z_L to be matched will be constructed by connecting a 25.5 Ω 1/4 W resistor in series with a 5 pF capacitor (i.e., $Z_L = R_L - jX_C$). Both components came with your laboratory kit and we will be using them without clipping off any part of their leads.

    To construct Z_L twist one of the leads of the resistor together with one of the leads of the capacitor and then bend the twisted pair away from the other two individual leads. This is the desired Z_L.

    As you have learned in previous laboratories, the constructed Z_L will unavoidably have its own parasitic reactances, and they will be considered below. However, you can start by easily minimizing the load parasitic capacitance by keeping all the wires far removed from each other.

3. Now connect the two unbent individual leads of your complex impedance load Z_L to the test fixture and measure and report its complex impedance Z_L at the frequency $f_m = 200$ MHz. You will be matching Z_L at this frequency f_m (the subscript m refers to matching). Since this f_m is relatively low, we will consider the stray capacitance and inductance (C_f and L_f, respectively) of the test fixture as part of Z_L (they are then already included in your measured Z_L value).

    Observe that, even though at f_m your measured impedance Z_L indicates that the load is just a resistor R_L in series with a capacitor C_L, this is only true at f_m.

4. Measure the load Z_L and from the results determine its equivalent circuit for frequencies f in the range $0 \leq f \lesssim 300$ MHz,. Provide the SimSmith drawing of the equivalent circuit developed (it clearly shows all the numerical values of its components). Also simulate the equivalent circuit in SimSmith, provide the results obtained, and compare them with NanoVNA-F measured results. Hint: did you notice the existing resonance?

   To make the SimSmith software scan in frequency you need to set its "sweep" box to "y" (on the middle left of the screen) and input the required parameters in the corresponding fields (to the left of the "y").

   When implementing the load equivalent circuit in SimSmith, please note that you should never simply add the reactance of the load as a number in the load reactance box. If you do this, the load reactance will be assumed fixed, and hence not change with frequency, and this is never what happens in practice. Leave instead the load reactance box with a zero value, and input all the individual components of your load equivalent circuit as separate entities.

   In case you are wondering, it is possible to connect SimSmith directly to the NanoVNA-F, calibrate it, and then easily compare measured and simulated results using SimSmith. If you want to use this feature (it is highly recommended that you use it to develop your Z_L equivalent circuit), you can find its details inside the SimSmith help menu. To access it, select on the SimSmith top banner the tab "help," and from it select "Less Used Manuals" and then "nanoVNA connect manual."

5. When done with the previous item, move the Z_L to the row of pins connected to the SMA connector that is farther away from the Port 1 of the NanoVNA-F. Since this will leave only one free pin connected to the center coaxial conductor that is currently not connected to the Port 1 of the NanoVNA-F, our matching circuit will have to start with a series component (we will be needing the free pin shortly for this series component). This process will also free the row of pins that is closer to the Port 1 of the VNA.

   Observe that now your load has in parallel with it the capacitance associated with the test fixture open female SMA connector coaxial cable. Use what you learned in previous laboratories to estimate the value of this parasitic capacitance C_p and then determine its associated reactance X_p at 200 MHz. We will also ignore the effect of this C_p, since the 200 MHz operation frequency is relatively small. However, since the C_p reactance undesirably adds to Z_L, by neglecting it you will be reducing the accuracy of your work a little bit.

6. Your next task is to use a Smith Chart to design a purely reactive circuit that will match the above measured complex Z_L to $Z_0 = 50$ Ω, at 200 MHz. Start by plotting the measured Z_L value in the Smith Chart, and make sure to properly label this point as P_1 (please see an example in the Smith Chart of the next page).

   I recommend that you print a clean version of the annotated Smith Chart of the next page, since you must use it for designing the matching circuit. Note that this

NORMALIZED IMPEDANCE AND ADMITTANCE COORDINATES

1 + j 2

P3

P2

P1

RADIALLY SCALED PARAMETERS

TOWARD LOAD — >   <— TOWARD GENERATOR

CENTER

ORIGIN
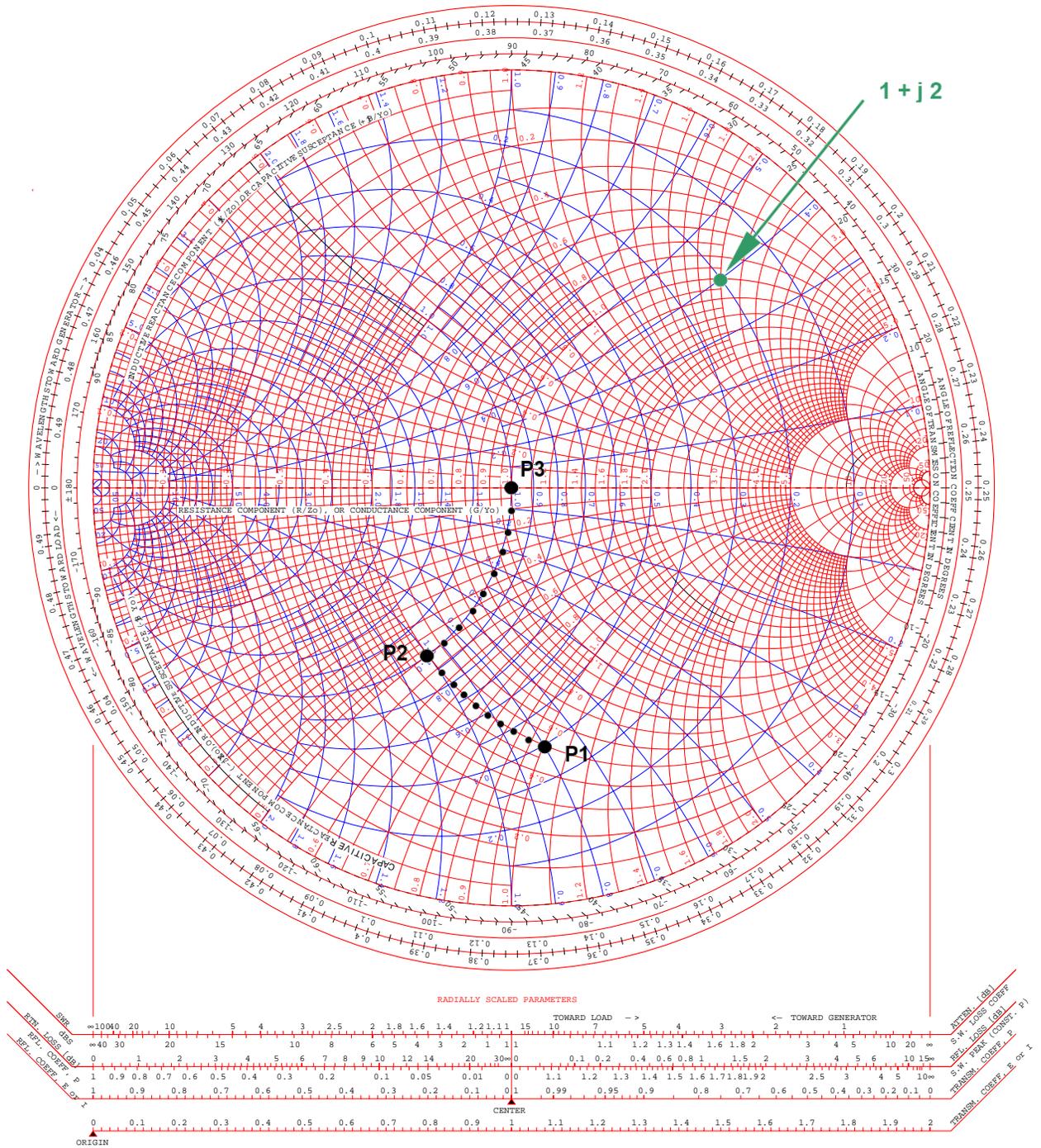
chart is slightly different than the one you learned in class, and is also a bit more confusing at first, as it conveniently shows both impedance and admittance circles simultaneously (in red and blue, respectively). Its advantage is that it allows you to operate with impedances and admittances concurrently. To see how, consider for example the normalized impedance $\tilde{Z} = Z/Z_0 = 1.0 + j\,2.0$, which has normalized resistance $\tilde{R} = 1.0$ and normalized reactance $\tilde{X} = +2.0$. The corresponding normalized admittance value is, using a calculator, $\tilde{Y} = 1/\tilde{Z} = 0.2 - j\,0.4$, which has normalized conductance $\tilde{G} = 0.2$ and normalized susceptance $\tilde{B} = -0.4$. Now, if you use the red scales (they are associated with the red Smith Chart) you can plot this impedance $\tilde{Z}$ in the red Smith Chart (at the location of the green point, indicated by the green arrow), and you can then read the corresponding value of $\tilde{Y}$ effortlessly (on the scales associated with the blue circles), and vice versa. Note that the numerical conductance and susceptance values associated with the blue chart are also shown in blue, and in particular observe that the susceptance values of the top semicircle of the blue chart are to be read as negative values (unfortunately this important detail is not indicated anywhere in the provided scales).

Our capacitive load Z_L can be matched by adding a series inductive reactance X_1 to it (this will move the point P_1 to a convenient new location P_2, along a constant resistance circle), and then adding a parallel inductive reactance X_2 (which will move the point P_2 to the point P_3, along a constant conductance circle, to the very center of the Smith Charts). Figure out what needs to be done, use the Smith Chart to determine the required X_1 and X_2 values, and from them calculate the corresponding inductances L_1 and L_2.

Observe that, since the reactance X_2 needs to be added in parallel with the input of your circuit, for this step it was convenient to use the blue admittance Smith Chart, to easily move the point P_2 to point P_3 by adding a negative susceptance B_2 to it (the movement takes place clockwise along a constant conductance blue circle).

Please make sure to include in your report the hand-drawn, annotated, and properly labeled (i.e., clearly showing P_1, P_2, etc.) Smith Chart that shows all your design work.

7. Simulate your circuit in SimSmith and therefore verify the validity of its design. Make sure to provide a printout of the SimSmith simulation with your report.

8. Use what you have learned in previous laboratories to construct the L_1 and L_2 inductors and carefully adjust them to the required reactance values using the NanoVNA-F.

   As you already know from previous laboratories, the inductance of low-frequency inductors can be precisely calculated, and equations to do so have been derived and are available in the literature. For the current purposes a very useful and accurate result can be obtained from Nagaoka's formula[5], assuming a cylindrical

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[5]F. W. Grover, *Inductance Calculations*, Dover Pub., Inc., 1962, pag. 143.

single-layer inductor of length not large compared to its diameter. This yields

$$L = \frac{\mu_0}{2} \, 2b \, N^2 \left[\ln\left(4\,\frac{2b}{h}\right) - \frac{1}{2} \right], \tag{2}$$

where L is the inductance value, $2b$ is the inductor diameter (the cylinder diameter, measured relative to the wire center), h is the inductor length (the cylinder height, again measured relative to the wire center), and N is the number of turns. Although Nagaoka's original work is quite general, to arrive at the above formula it has been assumed that $h/2b \lesssim 1$.

I suggest that you use Nagaoka's formula primarily for guideline though, since in the cases at hand the inductors will be physically quite small, and hence their construction precision will probably not be stellar. In other words, any observed differences between calculated and measured inductance values will pretty much be all due to your construction practices (you can expect very good agreement between predicted and measured inductance values though, if somehow you manage to be very precise with your hands).

Even though in a previous laboratory you had constructed and measured inductors using the NanoVNA-F, in here the task is slightly different. You now have to make two inductors with specific inductance values. The way to successfully accomplish this task is to observe that the value of the inductance is determined pretty much by the length of the insulated 26 AWG wire used. Hence keep careful and precise track of the lengths used by measuring them before you coil the wire. Then remove ∼4 mm of the insulation from the wire extremities, carefully and precisely coil the wire, and use the NanoVNA-F to determine the inductance obtained, at the operating frequency. If the measured inductance turns out to be excessive, straighten back the wire, cut a bit of its length (I suggest about 1 mm at a time), remove the insulation from the cut end, coil back the wire, and repeat this process until you get to the desired inductance value.

A convenient form to use for coiling the inductors is the conical end of a sharpened pencil, since it allows you to easily control the diameter of the inductors. This is useful because eventually you have to mount the inductors in the test fixture, and for this the inductors' terminals have to end up at the proper locations. As a last comment, to avoid unnecessary confusions use wires of different colors for the two inductors.

9. Connect the components of the matching circuit to the test fixture and measure its performance. Make sure to try to align the inductors' axes perpendicularly to each other, to minimize unaccounted for magnetic coupling effects.

10. What is the lowest measured reflection coefficient Γ_{min}, in dB, and what is its corresponding frequency f_{min}? How close did you get to the $f_m = 200$ MHz design frequency? Comment on any discrepancies.

11. Assuming that the maximum tolerable reflection coefficient Γ_e is -10 dB, what is the measured operation frequency bandwidth BW of your circuit, in percent (i.e.,

$BW = (\Delta f / f_{min}) \times 100$)? Compare the measured BW with the SimSmith predicted value and discuss.

To precisely determine the BW, a total of 301 points spread over the the the NanoVNA-F full 50 KHz to 1 GHz operation range is too coarse a sample set. I then suggest that for this item you operate the NanoVNA-F over a much smaller band (perhaps 150 MHz to 250 MHz), so you can have a denser set of frequency points and hence a finer BW measurement resolution. Of course, if you have been using the NanoVNASaver software, you may already have a sufficiently denser set of frequencies in place.

By the way, the sweep range of the NanoVNA can be changed through its menu tree. Go to "STIMULUS" and then "START," to adjust the starting frequency, and then "STOP," to adjust the stop frequency. You can also control the sweep by specifying the desired center frequency and the span. And don't forget to check if you need to recalibrate, if you significantly change the sweep range.

To determine the BW using the SimSmith software you will need to make it scan in frequency. It will also be helpful to add a VSWR circle to the chart (i.e., add a VSWR Mark to the Chart), corresponding to the $|\Gamma| = -10$ dB value.

As a final comment, the measured and SimSmith predicted BW should agree well. If they don't, and you did not make any design mistakes, there are pretty much only two possibilities: you did not construct your inductors carefully enough, or you are not using a good broadband model for the load Z_L in SimSmith. Either way, please do not march ahead without addressing the problem.

12. What percent of the incident power is lost by a -10 dB reflection coefficient (lost because it is returned to the generator)?

    As you can see from the above power lost because of mismatch number, a -10 dB reflection coefficient can usually be tolerated in practice. However, it is highly desirable to operate with a smaller number. In this lab the expectation is that your matching circuit will provide at least -20 dB at f_{min}, and if you do a good job constructing the matching circuit elements you can even achieve a reflection coefficient around -30 dB at f_{min}.

4   Matching With Transmission Line Elements

Although the lumped circuit technique of the previous section works well, as you just found out it relies on very carefully made inductors and capacitors (note that, even though capacitors did not need to be constructed in the particular situation tackled previously, they are necessary when the load is inductive). This difficulty can be minimized by using transmission lines sections in lieu of lumped elements. In this section you will explore this alternative by designing and constructing a matching network using only transmission line elements.

One alternative to accomplish the above is simply to replace the two inductors by shorted transmission line sections. However, you will not be pursuing this alternative

in this section. Instead you will implement the matching technique that employs a section of transmission line together with a single stub in parallel with it (discussed in Sec. 9-7.2 of our textbook[6]). This technique will be used to match the same Z_L load that was constructed in the previous item to 50 Ω, at the same $f = 200$ MHz operation frequency. And when done you will measure the overall performance of the matching circuit.

Because the stub eventually connects in parallel to the transmission line, you will be using the Smith Chart entirely in admittance mode. I suggest then that you use the simpler Smith Chart provided in the next page for your design. Furthermore, because it is relatively easy to work with parallel-wire transmission lines made with insulated 26 AWG wire, you will use them to transform both the load admittance as well as to implement the stub. You have previously measured both the characteristic impedance as well as the velocity factor of the 26 AWG parallel-wire transmission line (in a previous section as well as in previous laboratories), and now you are going to need these values.

Observe that, even though the parallel-wire transmission line does not have a 50 Ω characteristic impedance, it can and will be used it implement a match to the 50 Ω coaxial cable. Also observe that there are multiple alternative transmission-line lengths that will carry out the matching job, but the best lengths are invariably the shortest ones, since they provide the the lowest losses and frequency dependence.

1. Start your design process by calculating the admittance Y_L of the measured load value Z_L, and then plot the normalized $\tilde{Y}_L$ value in a clean Smith Chart, labeling its location P_1 (note that an example of a P_1 point location is already depicted in the Smith Chart).

   Because the matching network will be entirely constructed using parallel-wire transmission lines, all the required admittance normalizations should be relative to the parallel-wire line characteristic admittance.

2. Use what you learned in previous experiments to determine the length ℓ of a parallel-wire transmission line made with insulated 26 AWG that will transform Y_L to an admittance with a conductive part equal to 1/50 S, and label this new point location in the Smith Chart by P_2.

3. Determine the length ℓ_s of a parallel-wire open-circuited stub (made using the 26 AWG insulated wire) that will cancel the susceptance of point P_2. In other words, determine the susceptance that will bring the point P_2 to the horizontal axis of the Smith Chart (label this point point P_3). Note that the point P_3 is the matched impedance location, and it is not located at the center of the Smith Chart, since you are matching to 50 Ω.

   Please make sure to include with your report the hand-drawn, annotated, and properly labeled (i.e., clearly showing P_1, P_2, ℓ_s, etc.) Smith Chart that shows all your design work.

4. Simulate your circuit in SimSmith and therefore verify the validity of its design. Make sure to provide a printout of the SimSmith simulation with your report.

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[6]D. K. Cheng, *Field and Wave Electromagnetics*, Second edition, Addison-Wesley Pub. Co., 1989.
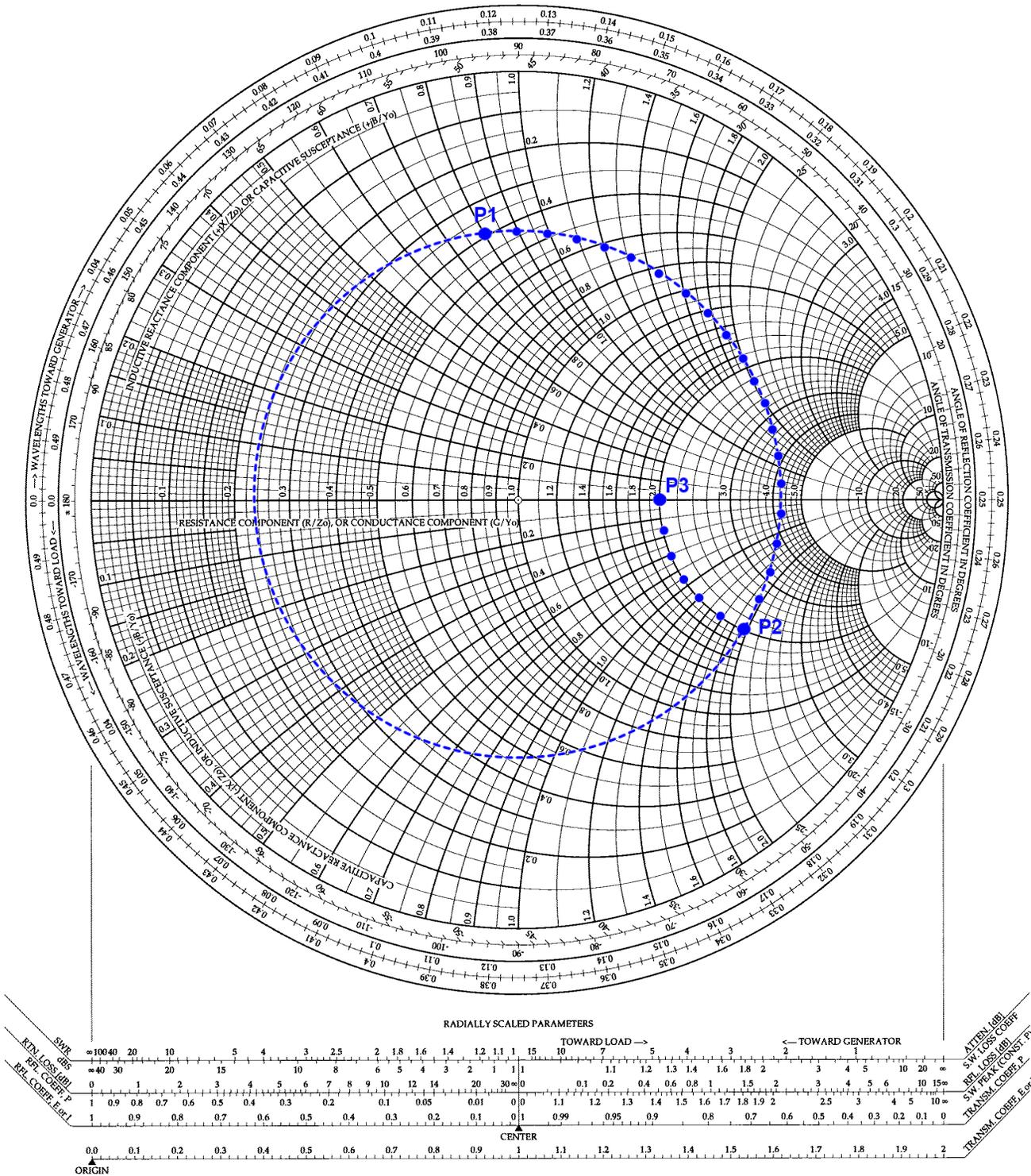
5. With the load Z_L on the same test fixture location as before, construct the transmission line of length ℓ and connect it between the two connectors of the test fixture.

6. Construct the stub of length ℓ_s and properly connect it to the test fixture.

7. What is the lowest measured reflection coefficient Γ_{min}, in dB, and what is its corresponding frequency f_{min}? How close did you get to the 200 MHz design frequency? Comment on any discrepancies.

8. Assuming again that the maximum tolerable reflection coefficient Γ_e is -10 dB, what is the operation frequency band BW of your circuit, in percent? Compare the measured BW with the SimSmith predicted value and discuss.

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