AC 2009-2000: A LABORATORY EXPERIENCE IN IMPEDANCE MATCHING USING TRANSMISSION LINE STUBS

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A Laboratory Experience in Impedance Matching using Transmission Line Stubs

Abstract
Impedance matching is a fundamental concept of RF circuit design. The proper application of impedance matching circuits allows for maximum power transfer between devices with minimum reflection of input signals. This concept is traditionally presented in mathematical form in conjunction with a Smith chart presentation. This paper presents a laboratory approach which uses these traditional forms of presentation in conjunction with real-time visualizations and low cost hardware demonstrations to present impedance matching concepts in multiple forms to address a range of student learning styles.

This paper details a successful laboratory experience focused on presenting impedance matching concepts at frequencies near 100 MHz through the design, simulation and measurement of a stub matching network. The procedures include hand and Smith Chart calculations reinforced using Applied Wave Research's Microwave Office to provide interactive simulations of the network. The designs and simulation results are then verified through the construction and measurement of the impedance matching system on a spectrum or network analyzer.

The laboratory exercises are designed to be performed in two hours. The exercises have been completed by 64 undergraduate students working in pairs over a period of two years with a completion rate over 90%. The laboratory presents concepts in multiple presentation forms to accommodate a range of student learning styles. This paper presents procedures, student perspectives and performance results on this laboratory experience.

Introduction

The concept of impedance matching has historically been poorly understood by students in our program. While students are often able to follow an algorithmic approach which ultimately leads to a numerical solution, in the end they are routinely unaware of the role and contributions of each component in the matching network. This inability to relate mathematical expressions to the physical components in a network propagates through to later topics and courses which explore more advanced RF filter applications which commonly interchange between transmission lines and discrete inductances and capacitances. The purpose of this laboratory experience is to reinforce the relationship between the mathematics used in the design of single stub impedance matching networks and the physical components in the network. This is supported with the addition of interactive simulations using Microwave Office to complement existing mathematical and hardware presentations.

Background

This laboratory is designed to be completed in a two-hour laboratory session for those successfully completing pre-laboratory exercises. While a number of RF simulation packages may be used to perform the listed simulations, the real-time tuning capabilities of Microwave Office provide for a high degree of interactivity which is a primary component of this

experiment. Minimal equipment requirements include a RF frequency generator and a spectrum analyzer; however, the use of a vector network analyzer with s-parameter capabilities provides additional opportunities to reinforce concepts demonstrated in the design and simulation phases of this laboratory. The frequencies and impedances used in this procedure were selected to match existing coaxial cable and load inventories in the laboratory; however, these values can easily be modified to support different cables or loads.

Implementation

In preparation for laboratory activities, students are first required to locate the manufacturer's datasheet for the coaxial cable used in the laboratory experiment to determine the nominal velocity of propagation. The cable used in this procedure was Belden 7806R 50Ω which has a nominal velocity of propagation of $0.77c$[1].

The first step of the laboratory requires students to determine a narrowband impedance matching network to match a 50 Ω source impedance to a 25 Ω load impedance at a frequency of 74 MHz.
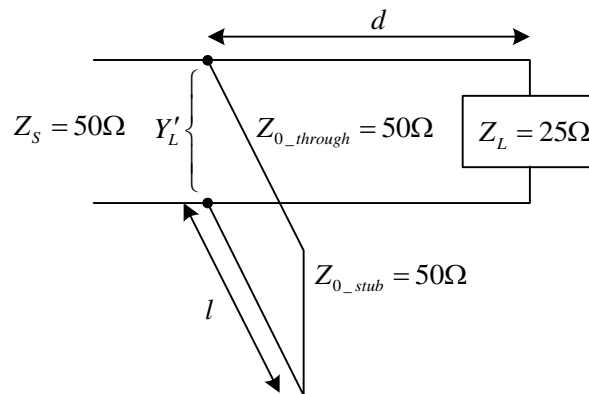

Figure 1 - Single Stub Impedance Matching Network

One possible approach is to design an impedance matching network using mathematical expressions. This can be accomplished through algebraic manipulation of widely available transmission line input impedance expressions, although this process can become tedious without some guidance. Previous attempts using this method have resulted in limited success as most students quickly become lost in the mathematics. Presentation of a fully completed example can provide a reference which students can be related back to when using the less mathematically rigorous process provided by the Smith chart.

This experiment forgoes the mathematical process in favor of a Smith chart design. At this point in the course students have some experience with fundamental Smith chart concepts and several Smith chart impedance matching network designs have been presented in the course lecture. This portion of the laboratory typically takes one hour to complete. Detailed procedures for single stub matching network design using a Smith chart are available in a number of texts[2,3,4] and are not presented in this paper. The single stub network can produce 4 possible base solutions which reoccur at higher frequency multiples. In this exercise the optimal solution is presented as that which requires the shortest length of series and shunt transmission line. The

Smith chart solution for the open stub matching network appears in Figure 2 with a summary of all possible solutions appearing in Table 1.
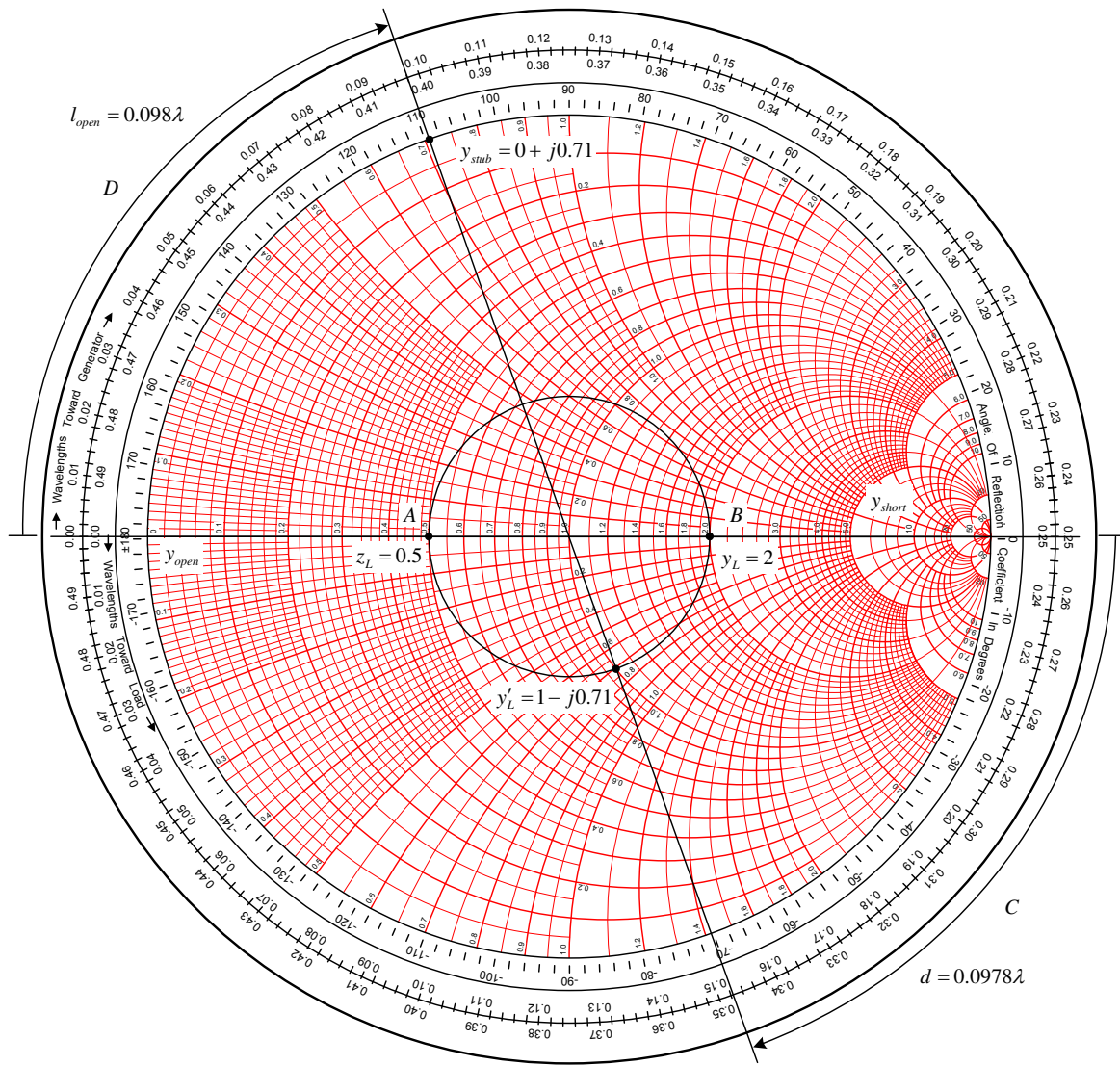

Figure 2 - Smith Chart Design of Stub Matching Network (Solution 1)

Table 1 - Stub Matching Network Solutions

Solution	d (λ)	l (λ)	Termination
1	0.0978	0.098	open
2	0.0978	0.348	short
3	0.4022	0.348	open
4	0.4022	0.098	short

As is evident from the detailed Smith chart in Figure 2, this process can become involved for novices students. These students often indicate that they become lost in the procedure and are unable to properly describe the operation of the matching network unless previously exposed to the full process multiple times in lecture.

Once the initial Smith chart design is completed, the circuit response can be verified using Microwave Office. The software's component tuning feature allows for real-time updates to the Smith chart as component properties in the matching network are modified. This interactive visual presentation serves to reinforce concepts presented in the initial Smith chart design method and provides additional focus to the role of each element in the matching network.

In Microwave Office, a new project is created with a single analysis frequency of 74 MHz. Ports representing the source and load impedances are first added to the project. A 50 Ω series transmission line with no electrical length is then added between the ports. This transmission line represents the series transmission line in the stub matching network.

The tune tool is then be used to modify the electrical length of this line variable between the range of 0 λ and the previously calculated series line length of 0.098 λ. With the Smith chart in the active display, the tune tool can slowly increase the electrical length of the series line. This allows students to observe the input impedance of the network travelling in an arcing motion to y'_L (Figure 3). The role of this transmission line in the network is to match the real component of the load impedance to the real component of the source impedance. Over 92% of students were able to describe this relationship in follow-up analysis questions. Students were then asked to adjust the maximum value of the tune tool significantly beyond the calculated series line length to explore the periodic nature of the match, allowing for the discovery that the same point is reached with each additional 0.5 λ of series electrical length.

Most students observed that an additional solution to the network exists at this stage, following a symmetrical path in the negative reactive region of the Smith chart.

The quality factor of the match can be quickly determined by dividing the imaginary portion of the value at y'_L by the real value, with most students demonstrating an awareness that the quality factor of all four possible solutions is the same value for this type of matching network.

Input Impedance

Variable Tune
Tune ┌ ..ic 1:d
Nom-> 0.098
Max-> 0.098
Close
Save
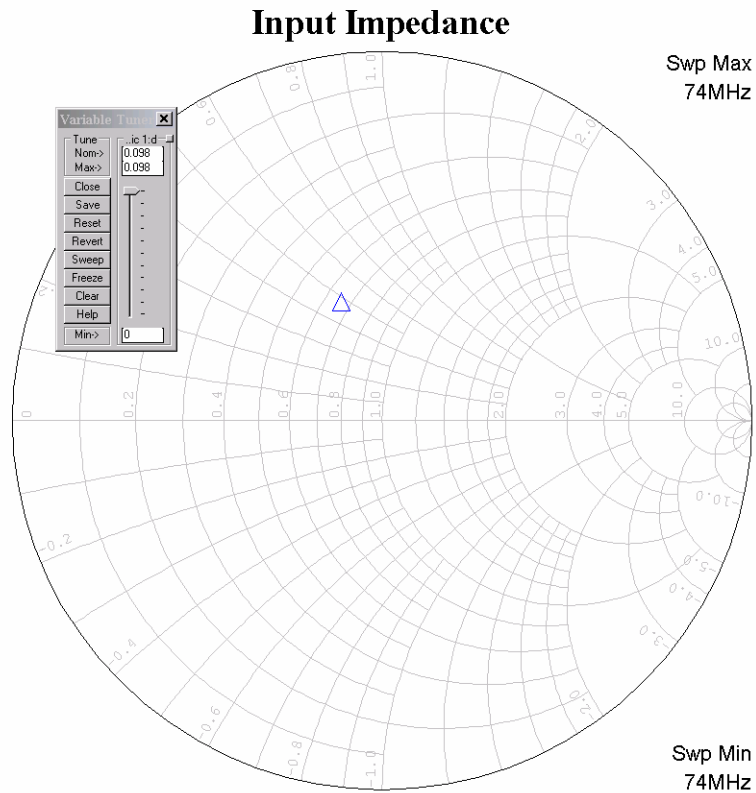Reset
Revert
Sweep
Freeze
Clear
Help
Min-> 0

Figure 3 - Microwave Office Tune Tool and Smith Chart

Students are then asked to add a open-terminated shunt transmission line to the network. They can use the tune tool again to observe how the stub adjusts the input impedance from y'_L to a matched network though manipulation of the stub's electrical length. When asked about the role of this line in the network nearly all students were able to accurately conclude that the line counteracts the imaginary component of the impedance at the input of the series transmission line (d).

To further reinforce that the combination of series and shunt transmission lines have provided a complete match, students are asked to place an additional series transmission line at the front end of the matching network (Figure 4). Students quickly determine that varying the electrical length of this series line has no impact on the observed impedance of the system.

The frequency dependant nature of the match is then explored by changing the simulation from a single frequency to a swept-frequency analysis. In this example the frequency is swept from DC to 74 MHz, the design frequency for the matching network (Figure 5).

d=0.098
l_open=0.098
arbitrary=1

COAX2
ID=CX2
EL=arbitrary*360 Deg
Fo=74 MHz
Z=50

PORT
P=1
Z=50 Ohm

COAX2
ID=CX1
EL=d*360 Deg
Fo=74 MHz
Z=50

PORT
P=2
Z=25 Ohm

COAX2
ID=CX3
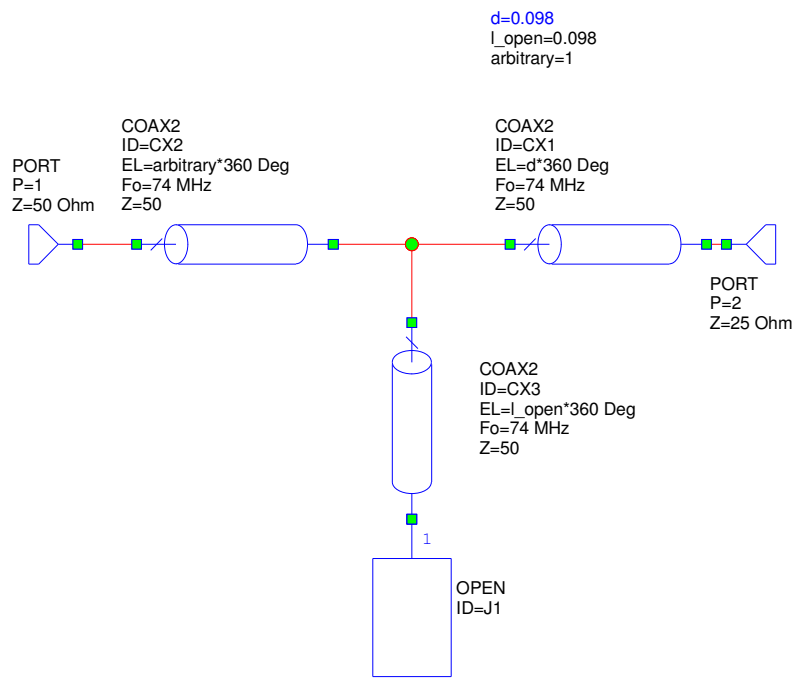EL=l_open*360 Deg
Fo=74 MHz
Z=50

OPEN
ID=J1

Figure 4 - Open Stub Network in Microwave Office
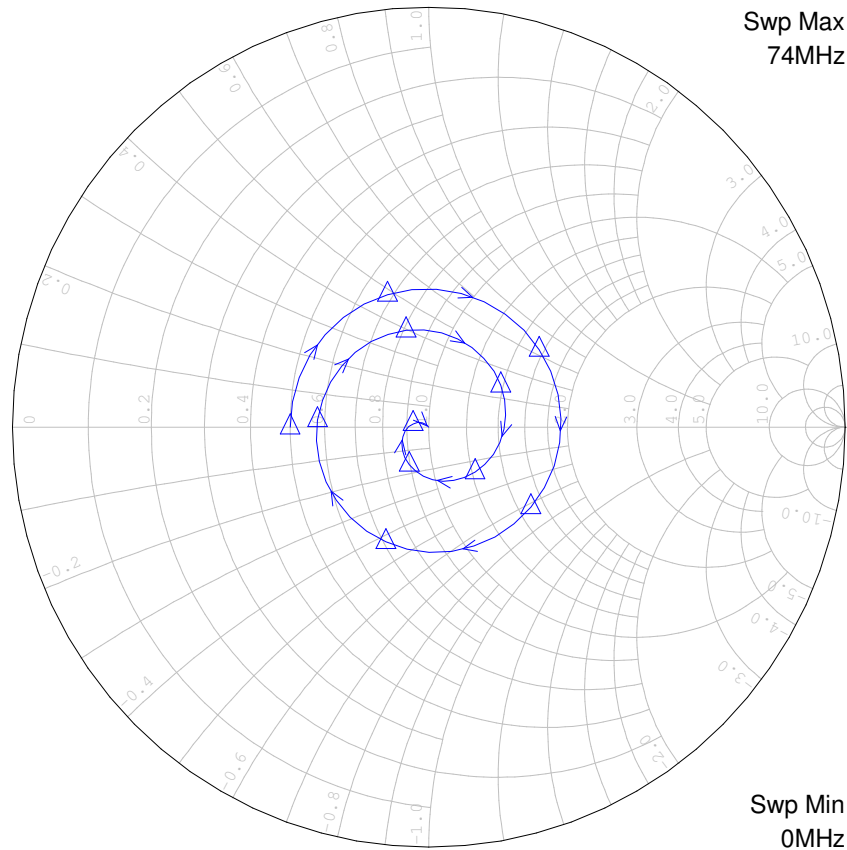
Input Impedance vs Frequency

Figure 5 - Frequency Response of Matching Network

The maximum frequency can be increased to demonstrate that the match appears again at higher frequencies, which is attributable to the periodic nature of this type of matching network. This response can be further explored in the hardware portion of the laboratory on an appropriately equipped network analyzer.

After completing all simulations for Solution 1, students are asked to repeat the simulations for the remaining solutions. This process takes approximately 30 minutes to complete.

Upon completion of the hand design and the simulation, the matching network is further examined in a physical demonstration. This requires converting the previously determined ideal electrical lengths into physical lengths of coaxial cable which serve as the transmission lines in this example. Using the velocity of propagation specified for the cable, the necessary lengths of cable are determined for Solution 1.

$$\ell_{series} = \frac{0.77c}{74MHz}(0.0978) = 30.6cm \approx 1ft$$

$$\ell_{open} = \frac{0.77c}{74MHz}(0.098) = 30.6cm = 1ft$$

$$\ell_{short} = \frac{0.77c}{74MHz}(0.348) = 1.09m = 3.56\,ft$$

The matching circuit is constructed using the specified lengths of coaxial cable, BNC Tee connectors and load (Figure 6). The circuit is connected to a spectrum analyzer using the tracking generator as the circuit's source. A properly calibrated network analyzer, if available, can be used to provide a native Smith chart presentation of the data.
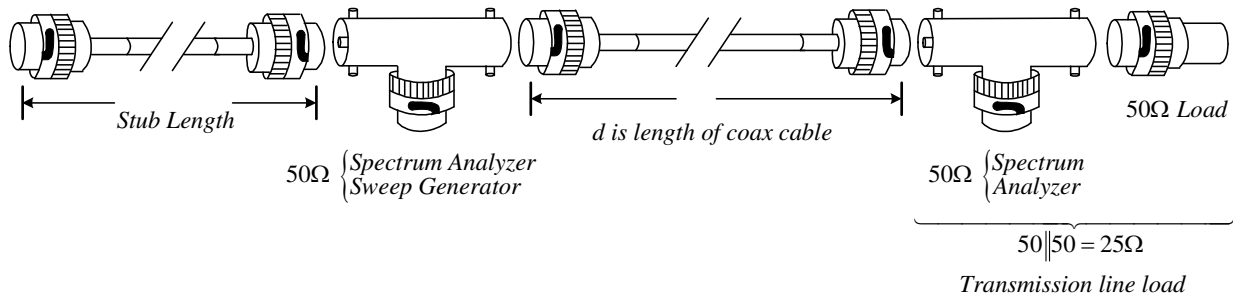

Figure 6 - Coaxial Matching Network

The resulting display (Figure 7) illustrates the periodic match between the source and the load, with the best match providing maximum power transfer. Alternating terminations between a shorted stub and an open stub is useful to demonstrate that the best impedance matching frequencies in one case are the poorest frequencies for the complementary type of termination.
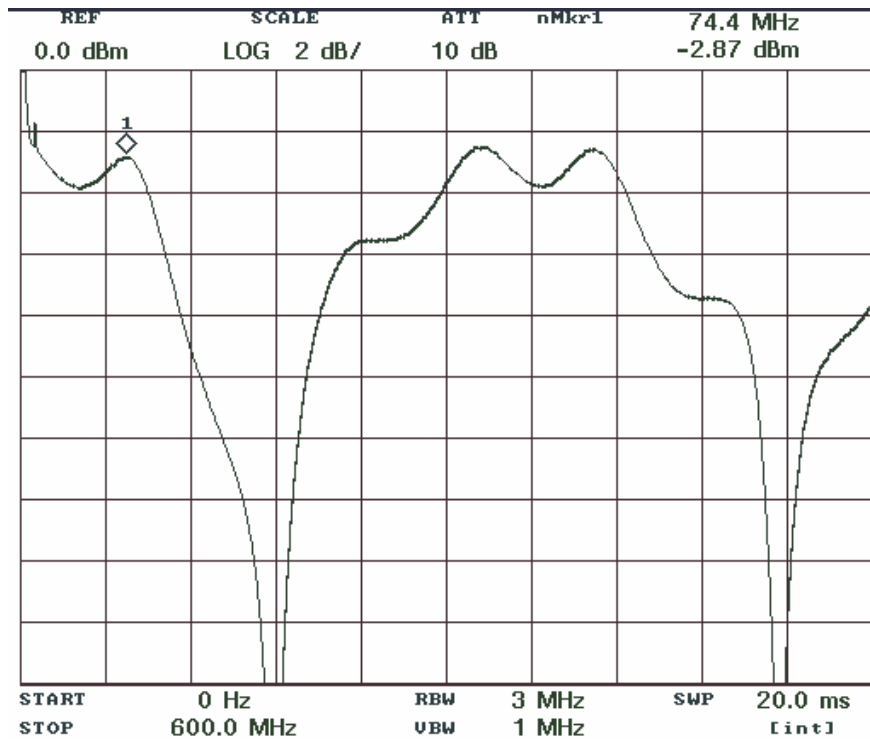

Figure 7 - Frequency Response of Coaxial Matching Network

Results

The use of multiple methods in the presentation of impedance matching allows for improved understanding of concepts by a greater number of students. Student response to the laboratory is very positive. The most common response in follow-up interviews indicate that initial uncertainties in determining matching solutions upon entering the lab are addressed through this experiment. A majority of students have demonstrated a preference for using the interactive tune tool compared with the hand-drawn Smith chart. Upon completion of this lab, most students (86%) state an improved understanding of how an impedance matching solution is achieved. Student performance on impedance matching questions in course exams has improved by nearly 17% with the introduction of this laboratory.

Conclusions and Recommendations

The presentation of impedance matching concepts using multiple reinforcing forms of presentation provides a means of demonstrating concepts to a wider range of student learning styles than traditional methods. The addition of interactive simulation allows for a greater appreciation of the role that each element plays in a matching solution and promotes increased student engagement in the laboratory. The minimal resource requirements of this laboratory experience allows for inexpensive hardware demonstrations of concepts, which are often presented solely in calculation or simulation.

Bibliography
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