Incorporating cost-efficient radio frequency experiences in engineering technology programs

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Abstract: *As the number of applications using wireless technologies continues to increase, it is necessary to educate and train students in our engineering technology programs in the particularities of radio frequency. Because the behavior of circuit elements in this frequency range is much different from how they act at low frequencies, experimental learning is a critical tool in their education. This paper describes experiences using a low-cost antenna analyzer for students to learn the characteristics of transmission lines as they experiment with the analyzer.*

I. Introduction

With the increasing use of radio frequency technologies such as Wireless networks, ZigBee and RFID for example, in addition to the already established applications such as radio, TV, and cellular telephony among others, it is possible to foresee an increase in the demand of engineers and technologists trained in radiofrequency communications [1]. Therefore, the professional success of our students depends on their ability to understand and work with these technologies. Because engineering technology programs are characterized by an extensive hands-on experience, it is critical in the education of our future graduates to have extensive laboratory experience in radio frequency technologies.

Students have difficulties in fully understanding the behavior exhibited by the different circuit elements in the radio frequency range. At these frequencies, the electronic components behave in a manner that is very different from the manner students have learned in the initial courses: resistors become more than just resistors; short-circuits are no longer short-circuits; cables no longer have the same voltage at all the points in the line, etc. This situation creates a double problem for our students: In the first years of their college education they struggle to learn the voltage-current relationship in circuit elements: resistors, capacitors, inductors, short- and open-circuits. When starting to study radio frequency concepts, we ask them to forget what they have learned and look at the same elements from a totally different and sometimes seemingly opposed point of view.

While it is true that when introducing the circuit elements in the basic courses most of us explain to the students that we are using an idealistic model and the real behavior of these components can be very different, the truth is that during the rest of the course we only use the ideal model, never mentioning again the more complex behavior of these components. However, when studying radio frequency topics, students not only have to learn a new set of rules, but they also have to understand which ones of the "old rules" still apply and which ones need to be re-examined.

Given this new paradigm of seemingly contradictory approaches to characterizing circuit elements from the point of view of the students, experimental learning becomes crucial for them to understand the new concepts brought up by the behavior of circuit elements at radio frequencies. Learning occurs when students are able to observe the effect of changing different parameters have on the variable being measured. They need to experiment, modify amplitude, frequencies, phase, etc. in order to observe the changes that they produce, which in turn will cement what they are learning. However, radio frequency equipment requires a more sophisticated infrastructure, tends to be fairly expensive and is complex to use, having a step learning curve. This results in students often not being allowed to manipulate the equipment on their own because of its complexity and especially by the fear that incorrect settings in the instrument may cause some damage to the instrument itself or to other expensive equipment. This may turn most experiments in simple demonstrations set up by the instructor in which the students are only data takers instead of being involved in setting the appropriate parameters for the instrumentation being used. It can be easily seen that this is not the best approach to enhance student learning as they are not fully participating in the experience itself.

Some educators have proposed to use software packages that simulate the behavior of specific instrumentation or the whole radio frequency system as a low-cost alternative to using the actual instruments [2]. They claim by using the simulation software, students will be able to learn the concepts that they would have learned from the experimental measurements. However, this approach needs to be taken with extreme caution and if used, it should be limited to only the introductory concepts. Simulation approaches should be taken with caution, maybe only used in the first experimental activities or introductory courses as it has been shown that the benefits of using simulation tools alone are limited [3].

It seems then clear that there is a need and reason for using low cost and easy to use test instrumentation in our laboratories, especially for experimental learning activities in radio frequency. Although this type of instrumentation may not have all the power and potential associated to professional test equipment, it can nevertheless become ideal to use in our academic laboratories. Simplicity and ease to use, associated with relatively low cost, are factors that will encourage instructors to design experimental activities in which the students will be able to understand how the equipment works easily and will not feel afraid to change parameters as needed [4]. With this main idea in mind, the goal of this paper is to discuss and present the potential use of a low-cost antenna analyzer to development experimental activities for students in the area of radio frequency and in particular experiences to characterize transmission lines.

II. The Antenna Analyzer

This paper is focused on the uses of the antenna analyzer AIM 4170 manufactured by Array Solutions [5]. This product was first developed by the radio amateur market although it has been used by professional broadcast engineers. This unit, shown in Figure 1, allows the measurement of complex impedance of a transmission line or an antenna, the measurement of reflection coefficient, insertion losses and other parameters of interest. As shown in Figure 1, the unit itself is very simple. The front panel contains a ON/OFF switch, two LED indicators and a single BNC connector. The back panel contains the power supply connection and a DB9 connector for a serial cable from the control computer. The instrument configuration is done by software.

The user can select the range of frequencies for the sweep -starting frequency, ending frequency and step-. This unit can also act as a fixed radio frequency source by generating a single frequency within its operating range, selected by the user. The output values are shown graphically on the screen as graphs, either in conventional form or as Smith Charts. In addition to the graphical output, it can also generate a text file containing the measured parameters at each frequency in the sweep. This file can then be imported by other software to further study the data, manipulate it or to create customized graphics.

Figure 1: Antenna Analyzer AIM 4170 from Array Solutions.

The user can select which one of the following parameters should be displayed: Impedance Magnitude, Impedance Phase, Reflection Coefficient, Return Loss, Stationary Wave Ratio, Series Load Circuit or Parallel Load Circuit. The user can select the parameters to plot, from a single one to all of the above. In addition to the unit, its power supply and a CD containing the software and operation manual, the manufacturer also includes three terminations. These terminations shown in are an open-circuit, a short circuit and a purely resistive load of 200 Ω as shown in Figure 2.

Figure 2: Load terminations included with the Antenna analyzer: Open circuit, short circuit and 200 Ω resistive load.

The main limitation of this antenna analyzer is its frequency range. While professional analyzers and RF generators allow measurements up to several GHz, the maximum operating frequency for the AIM 4170 is 170 MHz. However, it is necessary to consider its affordability (less than $500 at the time of writing this paper) and the fact that 170 MHz is a high enough frequency to observe how the behavior of circuit elements in this frequency range is much different than at low frequencies. This makes it an attractive unit to be used for educational purposes.

III. Electrical length of transmission lines

Students in EET programs are familiar with using coaxial cables to connect function generators, oscilloscopes and other testing equipment. Because these electronic experiences use low frequencies, typically below 100 kHz, and the cables are relatively short, the effects of transmission lines can be neglected. In this situation it is adequate to assume that the voltage at both ends of the cable is the same; that is, the coaxial cable is transparent to the signal. For this reason, it is difficult for them to understand how there are situations in which the voltage measured at different points of the cable are different. Being used to visualize a coaxial cable as a line with zero resistance and transparent to the signal, understanding the same cable as a transmission line in which the voltage changes depending on the position where it is measured and in which the impedance seen from the cable depends on the length of that cable is a difficult step.

For this reason, any experimental work in radio frequency concepts should first focus on helping students understand the reality of transmission lines. The following describes several experimental activities on effects of transmission lines that can be easily carried out using the AIM4170 Antenna Analyzer.

This experience is based on the use of one coaxial cable 144 cm long. This experience could be complemented by repeating the same steps using coaxial cables of different lengths in order for the students to contrast the results obtained. The velocity factor (VF) for the coaxial cable used is 0.66. A more complete and detailed table several parameters for different transmission lines can be found in other texts, for example in [6].

The Electrical Length of the transmission line depends on the frequency of the signal being transmitted through the line and can be calculated as:

$$EL = \frac{L}{\lambda} \qquad (1)$$

with L being the physical length of the transmission line and λ the wavelength of the signal.

The wavelength of the signal (λ) is in turn dependent on each transmission line through its velocity factor (VF) as:

$$\lambda = \frac{v_p}{f} = \frac{c \cdot VF}{f} \qquad (2)$$

with c being the speed of light in the vacuum ($c = 3\ 10^8$ m/s).

The term v_p denotes the propagation velocity of the electrical signal within the transmission line. For a VF = 0.66 the propagation velocity results in $v_p = 2\ 10^8$ m/s.

Using the concept of electrical length it is now possible to calculate the frequencies at which the electrical length of the transmission line used in this experience is equal to one, one half and one quarter of the wavelength. This is summarized in the table below:

Coaxial Cable (144 cm long)	
One Wavelength (EL = λ)	138 MHz
One Half wavelength (EL = λ/2)	69 MHz
One Quarter wavelength (EL = λ/4)	34.5 MHz

Table 1: Frequencies for specific values of EL.

The relationship between the impedance input impedance (near-end impedance) and the impedance at the termination of the line (far-end impedance) depends, among other factors, on the electrical length of the line as shown below [7]:

$$Z_{in} = Z_o \left[\frac{Z_R \cos\beta + j\, Z_0 \sin\beta}{Z_o \cos\beta + j\, Z_R \sin\beta} \right] \qquad (3)$$

with Zo being the characteristic impedance of the line, Z_R the impedance of the termination at the far-end and β the electrical length of the line in expressed degrees. It is possible to see that equation (3) is a complex equation from which students may have difficulties understanding its physical meaning. The equation, however, becomes extremely simplified when the electrical length of the transmission line is equal to a half wavelength (β = 180º) and when it is equal to a quarter of a wavelength (β = 90º).

With β = 180º, the input impedance is:

$$Z_{in\ (\beta=180^\circ)} = Z_R \qquad (4)$$

This means that when the electrical length of the transmission line is equal to a half wavelength, the impedance seen at the near-end (Zin) is equal to the impedance at the termination (Z_R). This situation repeats itself for multiples of 180º, meaning that Zin = Z_R also when the electrical length of the line is equal to a full wavelength, one a half wavelengths, etc.

On the other hand, with β = 90º, the input impedance is:

$$Z_{in\ (\beta=90°)}=\frac{Z_0^2}{Z_R} \qquad (5)$$

In this situation, the input impedance seen from the near-end is equal to the inverse of the impedance at the termination of the line. This means that at this specific frequency, a short circuit at the far-end will be seen as an open-circuit at the near-end. Conversely, an open-circuit at the far-end will be seen as a short circuit at the near-end. This situation repeats itself when the electrical length of the line is an odd multiple of λ/4.

When the electrical length of the line is neither λ/2 , λ/4 or an integer multiple, equation (3) results in a complex number. This means that in these cases, the input impedance to the line has an inductive or capacitive behavior. This is the basis for impedance matching, in which by choosing the appropriate length of a transmission line it is possible to match the impedance of a termination to the desired input impedance. However, as EET graduates are not involved in designing matching networks, this situation will not be considered in this paper. It is however very important for EET graduates to be aware of the potential problems that may arise when cabling networks and in particular when the length of their cables is an odd multiple of a quarter wavelength as shown by equation (5). This is becoming more important with the increasing use of RFID systems operating in the UHF band, as well as cellular telephony for which their wavelengths is just few inches long. In fact, several questions in the examination for RFID certification exam focus on the effects of cable length on the integrity of the signal.

These concepts and impedance transformations that radio frequency professionals encounter in their professional life can be initially difficult to understand for our students. By allowing students to experiment with radio frequency signals and transmission lines beyond being passive data takers, we will ensure their understanding of these concepts and their ultimate success.

IV. Experimental activities for transmission lines

IV.a Impedance transformation for EL = λ/2

The goal of this experimental activity is for the students to evaluate the effects of the transmission line with its electrical length is equal to half the signal wavelength. In particular, this experience is focused on how the impedance at the far-end of the transmission line is seen from the near-end. When evaluating impedance transformations with the far-end loaded with an open-circuit or short-circuit, it is a good idea to use the terminations provided with the antenna analyzer instead of merely leaving the far end of the coaxial cable disconnected or shortcircuiting it. By always using these terminations, the effects of their respective BNC connectors will be present in all the measurements and therefore it will be easier to compare the effects of different terminations.

According to equation (4) when EL = λ/2 the transmission line is transparent from the impedance point of view. That is, the input impedance is equal to the impedance of the termination.

According to Table 1, for the coaxial cable used as transmission line, EL = λ/2 at 69 MHz. To compensate for possible errors in the use of VF and the capacitance introduced by the terminations, students should perform the initial measurements over a wider frequency range and later tune in the region of interest.

Figure 3 shows the plot from the antenna analyzer when the transmission line is terminated with an open circuiot. The graph in green shows the magnitude of the input impedance while the purple graph displays its phase. It is important to note that although the transmission line is loaded with an open-circuit, the impedance seen at the near end is finite, with a value of 2,500 Ω. This finite value is due to the attenuation losses in the cable. At this point, it would be an interesting experience for the students to experiment using several coaxial cables with the same length but different quality and therefore different attenuation losses. With these experiences, students would be able to observe the effect of different construction parameters on the attenuation losses for the line and also the effect of the attenuation losses on the measured value of input impedance.

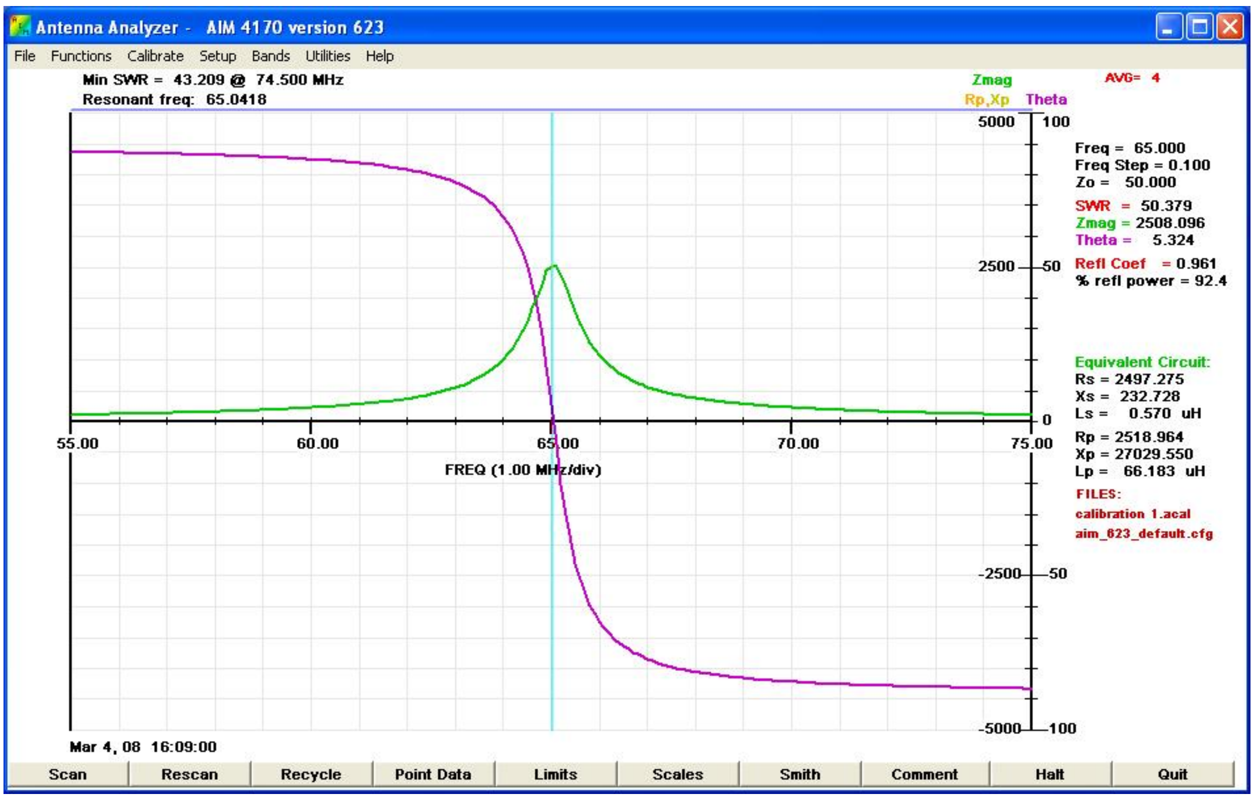

Figure 3: Plot of Z_{in} versus frequency with ZR = ∞ for EL = λ/2.

Figure 3 shows that the actual frequency that makes EL = λ/2 is 65 MHz, slightly lower that the frequency predicted in Table 1. As stated earlier, this discrepancy can be attributed to choosing the correct value for the velocity factor as well as the additional capacitance introduced by the open-circuit termination shown in Figure 2.

This difference between the calculated and the measured frequencies serves as an introduction for students to observe and measure the effects that different connectors and adaptors have on the transmission line. Figure 4 shows the results obtained repeating the same measurements in three different situations: using the open circuit termination supplied with the instrument, leaving the line with no termination and connecting one of the BNC adaptors shown in Figure 6. The curve at the left of Figure 4, with a resonant frequency of 65 MHz has been obtained with the open-circuit termination supplied with the instrument that is the one also used in the previous experiment. The bold curve on the right has been obtained by leaving the cable without any termination, and the curve in the middle was obtained terminating the cable with one of the BNC adaptors shown in Figure 6. From Figure 4, it can be seen that when leaving the cable without any terminations, the resonant frequency is 68.5 MHz that is very close to the calculated values of 69 MHz. It can also be seen how as the capacitive load in the line increase, the value of the reflected impedance in the near end decreases.

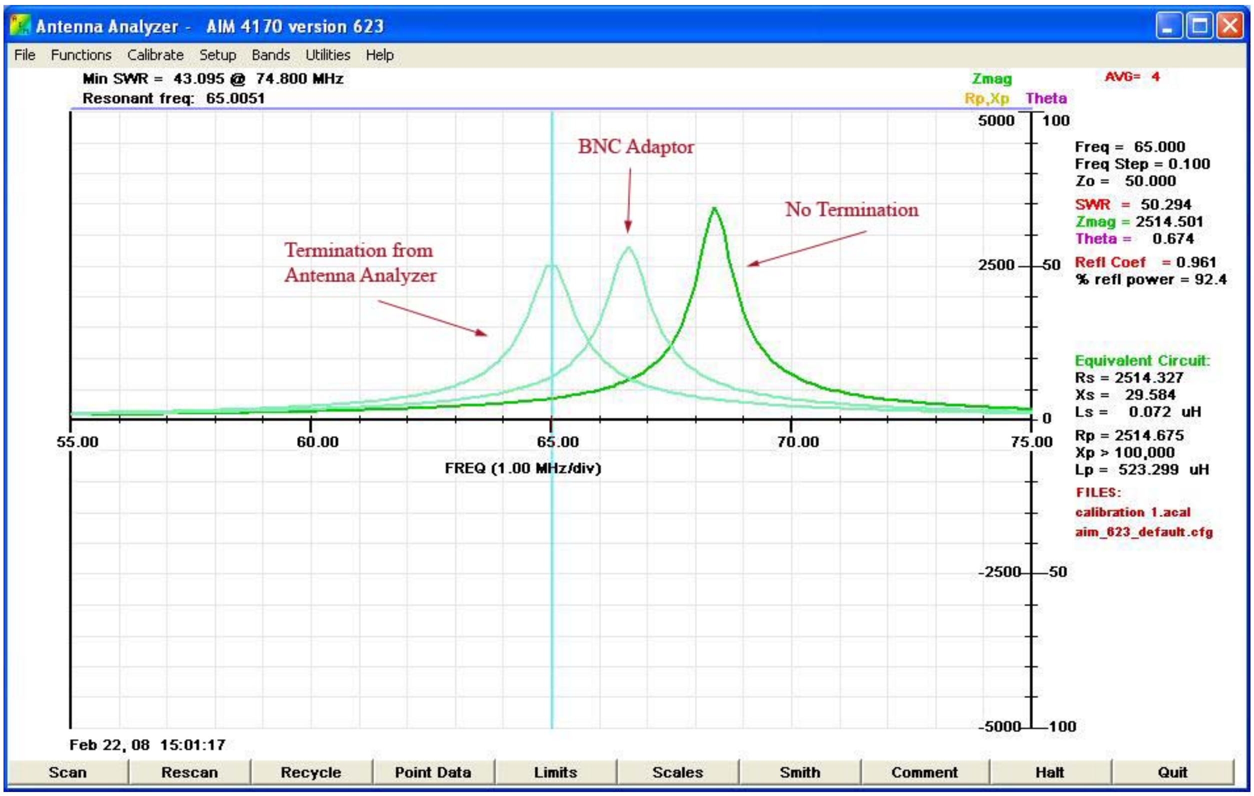

Figure 4: Effect of different terminations on the resonant frequency for the transmission line.

Figure 5 shows the graphs obtained repeating the same measurements using the BNC adaptors shown in Figures 6 and 7. Once again, the bold curve on the right represents the transmission line with no terminations that is used for comparing purposes with the graphs obtained when using the BNC adaptors.

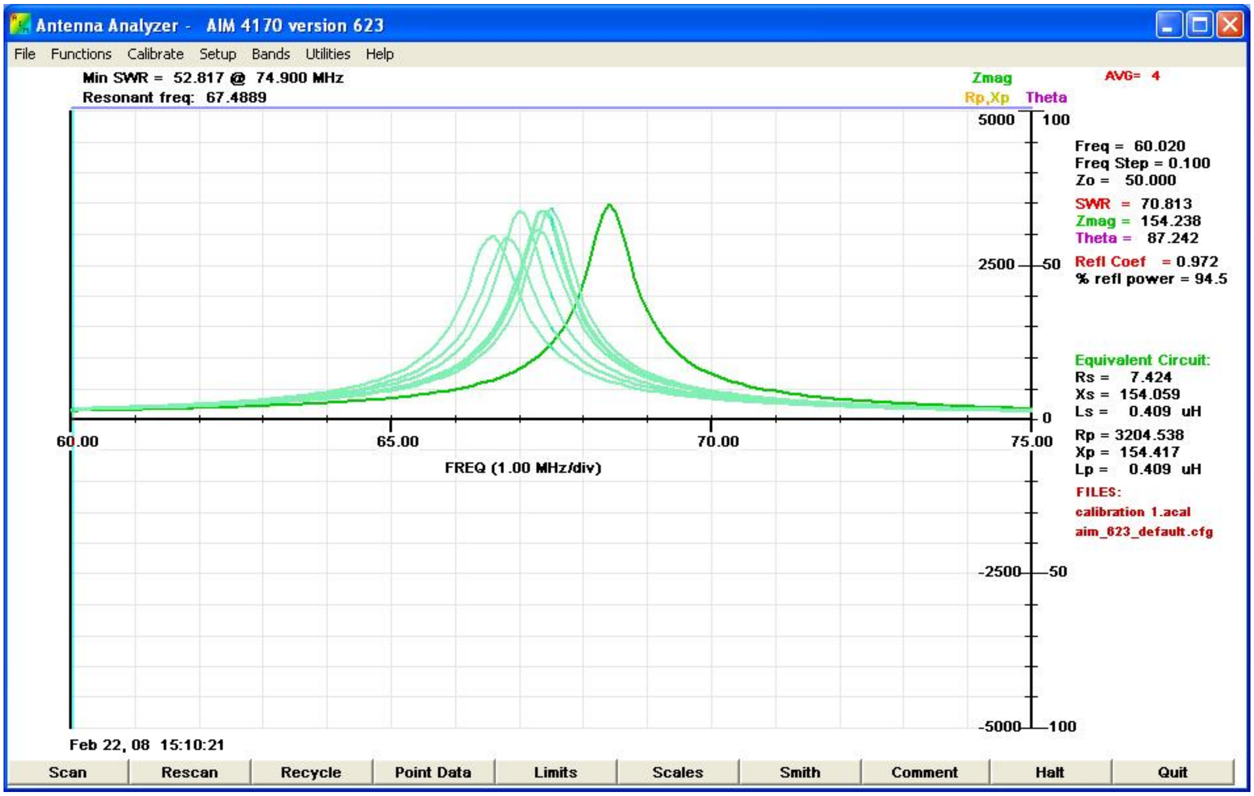

Figure 5: Effect of different adaptors on the resonant frequency for the transmission line.

Through these experiments, students learn that connecting adaptors to a transmission line results in changes in the characteristics of that line that cannot always be predicted. Moreover, these experiences tell them to avoid using these types of connectors whenever possible.

Figure 6. Several BNC adaptors.

Figure 7. Several BNC adaptors.

As explained in the description of the antenna analyzer, in addition to being able to do a frequency sweep, it can also operate at a single frequency source. This feature, especially in the radio frequency range becomes very useful for students to visualize and understand that the signals do not have the same phase along different points in the transmission line. For example, Figure 8 shows the signals measured at the near-end of the transmission line (top trace) and far-end (bottom trace) when EL = $\lambda/2$. This figure shows that while the amplitude of the signals is very similar, they are shifted by 180º.

Figure 8 depicts a situation that is very different from the situation students are used to work at low frequencies. At low frequencies, because EL << λ it is possible to neglect the effects of the transmission line, resulting in the signal being the same at the different points of the line. Students can therefore understand that the conditions in which they are working in traditional AC courses is very different to the conditions in which they work in radio frequency.

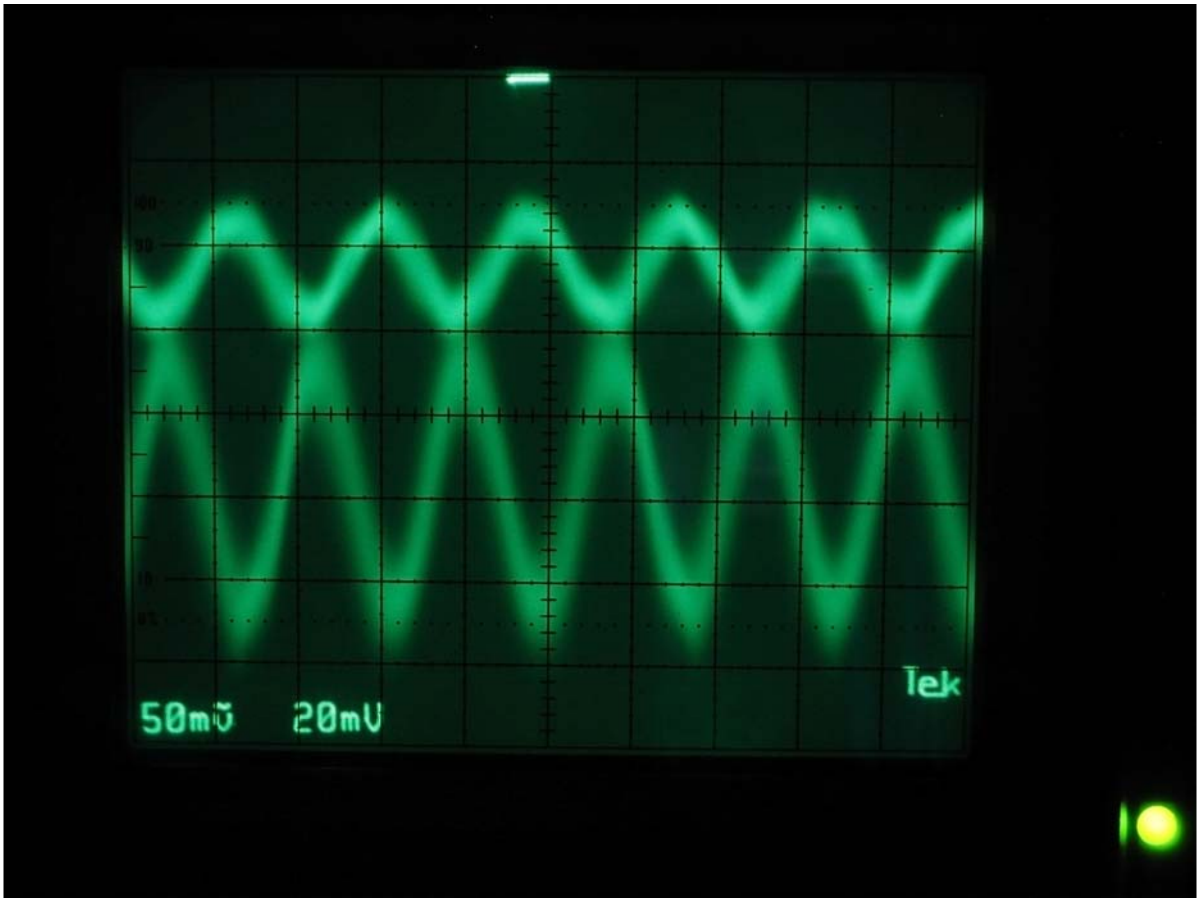

Figure 8. Signals at the far-end and near-end of the transmission line for El = λ/2.

The graph shown in Figure 9 depicts the impedance of the transmission line, also in the range of EL = λ/2 but in this case loaded with a short circuit. The graphs shows that the input impedance seen at the near-end is equal to the impedance connected at the far-end, in this case a shortcircuit. This result is in agreement with the assumption that when the electrical length of the transmission line equals half of a wavelength, the line is transparent and the input impedance is equal to the impedance of the load or termination.

Figure 9: Plot of Z_{in} versus frequency with ZR = 0 for EL = λ/2.

IV. b) Impedance transformations at quarter wavelength

When the electrical length of the transmission line is equal to one quarter of a wavelength, the situation changes considerably. Equation (5) shows that the input impedance in this case is equal to the inverse of the load impedance scaled by a factor. This means that if the impedance at the far-end of the transmission line is a short circuit, the near-end will see an open circuit. Conversely, if the impedance at the far-end is an open circuit, the input impedance at the near-end will be a short circuit. This impedance transformation can be confusing to our students as they are used to see a short circuit as always a short circuit and the same with an open circuit.

Therefore, the experiences described in this section help students to understand the behavior of transmission lines when their electrical length is one quarter of the signal wavelength. The instructor should strongly emphasize this impedance transformation and encourage students to experiment with different load impedances, resistive and reactive.

According to Table 1, for the coaxial cable used in this experience, EL = λ/4 when f = 34.5 MHz. Similarly to the procedure carried out earlier, students should initially choose a wider frequency range to take into account potential sources of error.

Figure 10 shows the plot of input impedance versus frequency for EL = λ/4 when the far-end of the transmission line is loaded with an open circuit. The graph shows how the open circuit at the far-end is transformed into a short circuit at input (near-end). The frequency that causes EL = λ/4 is equal to 32 MHz. This frequency is also lower than the frequency that was calculated, similar to the half wavelength case. Once again, the capacitance introduced by the termination affects the characteristics of the transmission line.

Figure 10: Plot of Z_{in} versus frequency with ZR = ∞ for EL = λ/4.

The graph shown in Figure 11 shows the input impedance when the transmission line is terminated with a short circuit. In this case, following equation (5) the near-end impedance should be infinity. However, similarly to the half wavelength case, the attenuation losses in the transmission line originate the finite value of input impedance with an approximate value of 4,300 Ω.

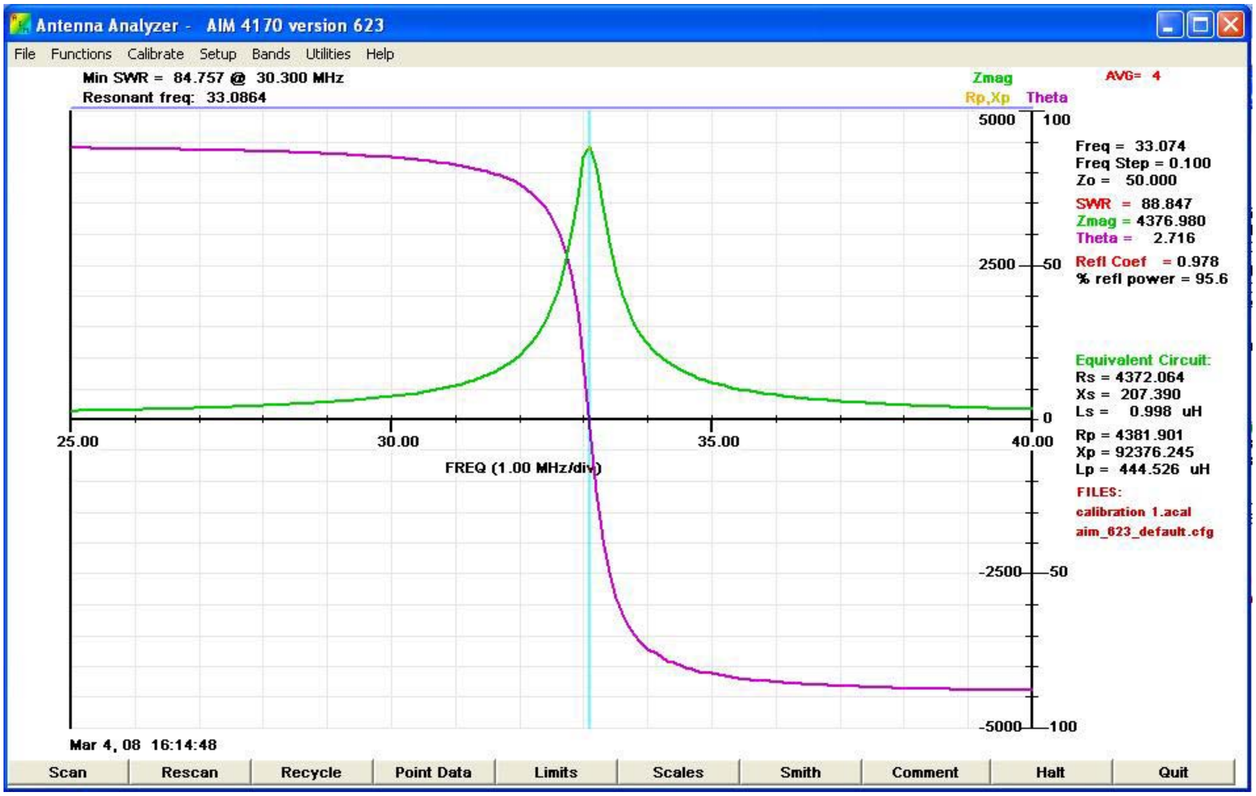

Figure 11: Plot of Z_{in} versus frequency with ZR = 0 for EL = λ/4.

Figure 12 shows the signals obtained with an oscilloscope at the far-end and near-end of the transmission line. It is then possible to observe how these two signals are 90º shifted. The traces also show that the amplitude of the signal are very different due to the fact that one of the ends of the transmission line sees an open circuit while the other end sees a short circuit.

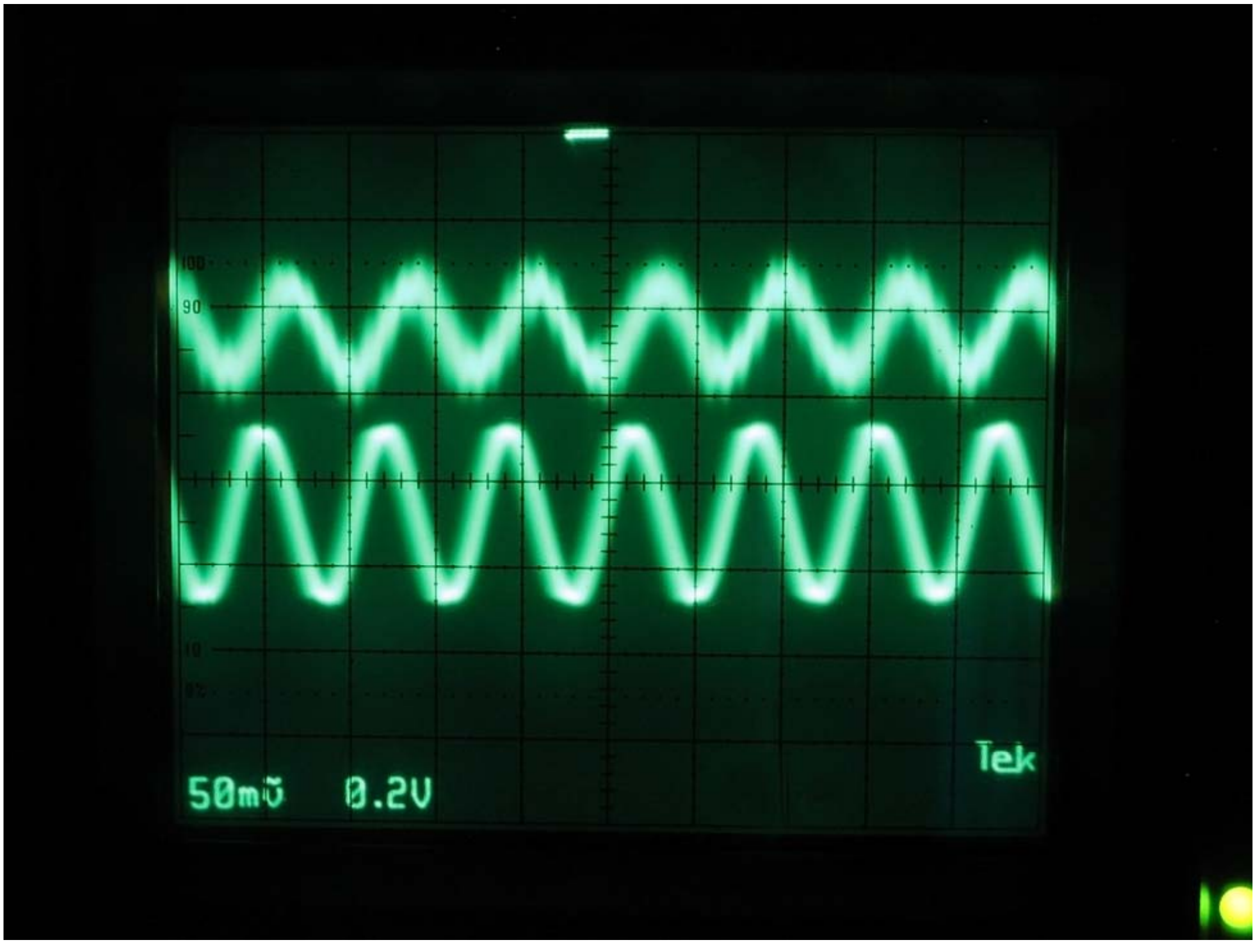

Figure 12. Signals at the far-end and near-end of the transmission line for El = λ/4.

IV. c) Impedance transformations over a higher frequency range.

It is also important for the students to understand that the conditions for impedance transformations seen earlier are not limited to the frequencies that make the electrical length of the coaxial cable equal to λ/4 or λ/4, but also its multiples. This is shown in Figure 13 that depicts the impedance seen at the input of the transmission line when its far-end is loaded with a short circuit.

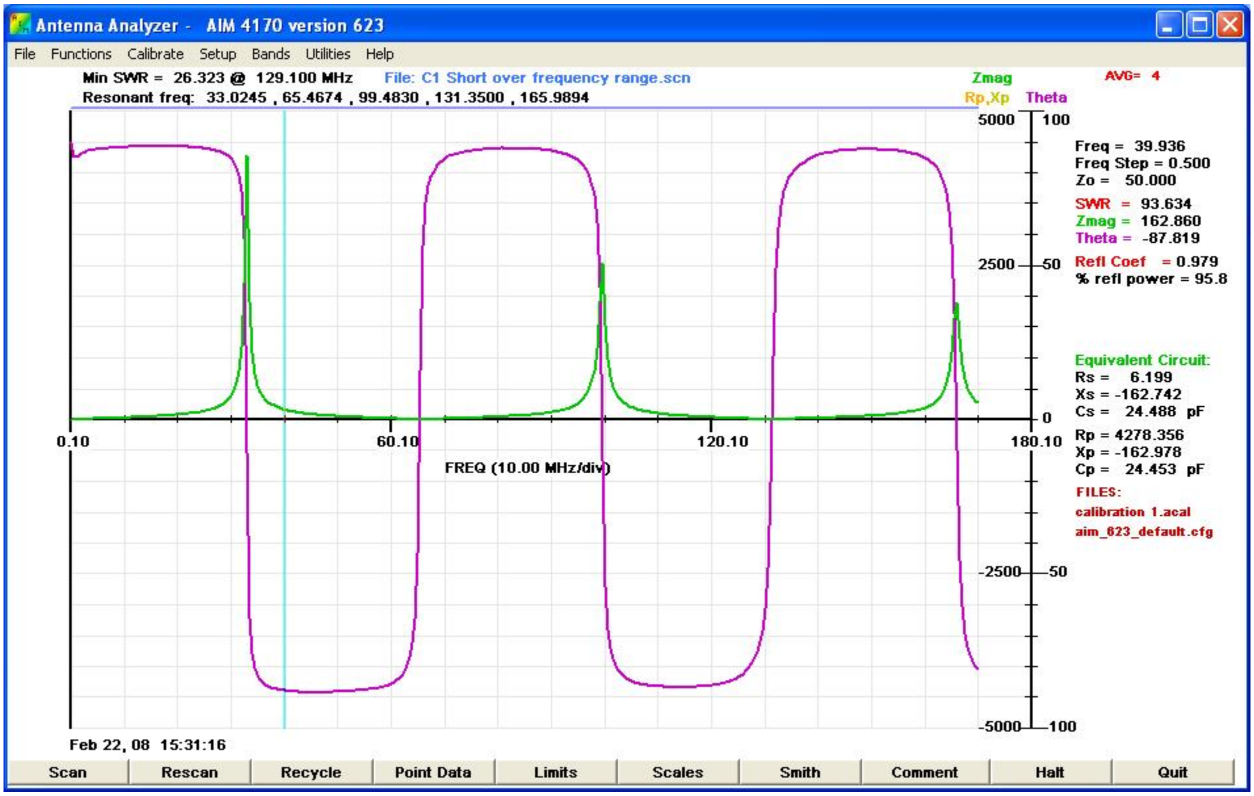

Figure 13. Input impedance over a wide frequency range ($Z_R = 0$).

As it was seen in Figure 11 the first peak occurs at 33 MHz that corresponds to EL = λ/4. At this frequency the short circuit at the far-end of the transmission line is seen as an open circuit at the near-end. The peak is repeated at 99 MHz (EL = 3 λ/4) and 165 MHz (EL = 5 λ/4). In addition to observing how the high input impedance peaks repeat themselves at odd multiples of a quarter wavelength, students can also visualize how the attenuation losses increase as the frequency increases, resulting in a lower value of measured input impedance. Figure 9 showed that at 65.6 MHz, EL = λ/2 and therefore the input impedance is equal to the impedance of the termination. This is also shown in Figure 13, also depicting the same situation at 131 MHz that corresponds to EL = λ. This graph gives students a visual understanding of how the transmission line transforms the impedance of the termination and can help them select the appropriate length of transmission lines for their purposes.

V. Conclusion

As the need for engineers and technologists trained in radio frequency communications is posed to increase in the near future, it is necessary to help our current students become proficient in understanding and working its instrumentation and testing equipment. While professional instrumentation may be out of reach for most of our academic institutions due to its cost, complexity and required infrastructure, it is nevertheless possible to design useful experimental activities using low equipment.

This paper has described academic experiences using such equipment, in particular analyzing how the characteristics of transmission lines are dependent on their electrical lengths. The system used in this paper is suitable for students to experiment in several conditions due to its versatility and ease to use. Furthermore, it allows instructors to design experimental activities in which the students take a leading role in approaching their solution. This learner centered approach to experimental education is essential for students to develop their skills in this growing are of Engineering Technology.

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