Construction of a Low-Frequency RLB With a Changeable Impedance Level

A new return loss bridge has a conveniently changeable impedance level and an extended low-frequency response.

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INTRODUCTION

An article in the 1993 issue of *ITEM*[1] discussed the advantages of using a return loss bridge (RLB) for evaluating the pass-band responses of 50-ohm passive LC filters. The RLB pass-band response test was shown to be superior to an insertion loss test for detecting a filter component with an out-of-tolerance value. The 50-ohm RLB circuit consisted of one transformer and four resistors and it had a directivity of more than 35 dB from about 6 kHz to 1 MHz. Although the performance capability of this simple passive circuit was adequate for most 50-ohm TEMPEST filter testing, the limited low-frequency performance and the 50-ohm fixed-impedance level of the RLB were obvious disadvantages because filters having impedance levels other than 50 ohms and pass-bands lower than 6 kHz could not be tested.

For operation in the 100-Hz to 10-kHz range, passive filters are frequently designed for impedance levels higher than 50 ohms, and a 500-ohm impedance level is commonly used for audio-frequency filters. A 500-ohm RLB is needed to test these filters. To meet this need, a new RLB design was developed with a low-frequency limit of about 100 Hz and a means of easily changing the RLB impedance level by using different 4-resistor plug-in modules. The 6-kHz low-frequency limit and the fixed-impedance restrictions of the original RLB circuit are eliminated with this new RLB design featuring a 100-Hz minimum frequency and plug-in modules to easily change the RLB impedance level.

BACKGROUND

The original RLB circuit with a fixed 50-ohm impedance level used a bifilar-wound transformer to provide a voltage level which was proportional to the reflected voltage from the unknown impedance. By measuring the reflected voltage level caused by the unknown impedance relative to the open circuit voltage, the return loss of the unknown impedance could be determined directly in decibels. For satisfactory directivity, the transformer reactance had to be about 35 times the impedance of the bridge at the lowest test frequency of 6 kHz. If a new RLB design with a 100-Hz low-frequency limit is to be designed using the same passive configuration, the new transformer reactance will have to be 60 times greater, which means the number of turns on the transformer core will have to be about 7.7 times greater than the original 107 turns. This clearly is impractical.

This dilemma was discussed with Wes Hayward, author of *Intro-*

duction to Radio Frequency Design[2] and an internationally recognized electronics circuit designer. Mr. Hayward recommended that an active RLB circuit be used, and he provided a design consisting of a single integrated circuit (IC) containing four differential input operational amplifiers, ten resistors and two capacitors. I assembled and tested the circuit, and it performed as Mr. Hayward predicted. In order to eliminate the disadvantage of having a fixed impedance level, I assembled the 4-resistor bridge portion of the circuit as a plug-in module consisting of four 1%, 1/4-watt 50-ohm resistors. A second 4-resistor module was assembled with 500-ohm resistors. The RLB impedance level could then be changed simply by plugging in the resistor module having the desired impedance. The rest of the RLB circuit remained unchanged. The performance, versatility and ease of assembly of the active RLB was impressive and will be useful when it becomes necessary to check the return loss of either a low-frequency filter or power line impedance stabilization network (PLISN).

RLB CIRCUIT

Figure 1 shows the schematic diagram of the low-frequency RLB. Three op amps of a National LM324 quad low-power integrated circuit (IC) op amps are used to obtain an output voltage level which is equal in dB to the level of return loss of an impedance connected to the ?Z port. The fourth op amp is unused and is wired to stabilize its output so as to be immune to noise. The four resistors, R1, R2, R3 and R4, are assembled as a plug-in module so the impedance level of the RLB may be conveniently changed without needing to build another complete RLB circuit. Positive and negative voltages are provided for the RLB by two 9-volt batteries which are switched on and off by the double pole, double throw (DPDT) switch, S1. For proper operation, all resistors should have a 1% tolerance. The 0.1-uF capacitors may have a voltage rating as low as 25 volts to minimize their size.

Figure 2 shows the RLB circuit as assembled on half of a Global Specialties *Experimentor 300 PCB* (printed-circuit board).[3] The Global PCB provides conductive tracks (on the underside of the board) to interconnect all the holes in rows A-E and F-J in each column. In addition, all the holes in row X (and Y) are interconnected so that these separate rows may serve as a common bus such as separate ground or voltage buses. The layout shown in Figure 2 is considered optimum for minimizing the space required for component layout and for simplifying the interconnection of the component leads. The four-resistor module is shown on the left side of Figure 2. The plug-in receptacle is wired on the board at rows "D" and "F" and columns "1" through "4." The socket for the quad op amp is shown in the center of Figure 2. The IC socket is installed on the board so the pin numbers (8-14) agree with the column numbers at the top of the PCB. Before any components are installed, the PCB width must be narrowed so the board will fit within whatever aluminum box is selected to house the assembly.

All components, the resistor plug-in receptacles and the IC socket are placed on the component side of the board with their leads extending through the holes to the conductive tracks on the underside of the board. Figure 3 shows all the components and the 50-ohm plug-in module assembled on half of the *Experimentor 300 PC* board. The six insulated-wire leads are used for the ground connection, plus and minus voltage connections to the DPDT switch and connections to the three signal ports. Holes are drilled near each corner of the PCB for mounting the assembly within the aluminum box.

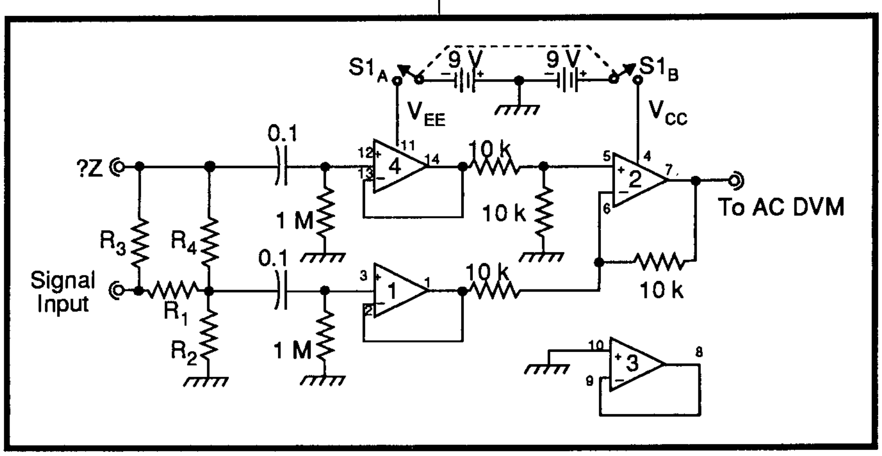

FIGURE 1. *Schematic Diagram of the Active Low-frequency RLB.*
NOTES: 1. All resistance and capacitance values are in ohms and microfarads.
2. All resistors are 1%, 1/4-watt. The values of R1, R2, R3 and R4 must be the same as the impedance of the signal generator.
3. The op amp is a quad low-power LM324N in a plastic DIP package.

RESISTOR PLUG-IN MODULE

Figure 4 shows the parts used in assembling a plug-in module and a completely assembled 50-ohm module. The four resistors are a 1/4-watt, 1%, 49.9-ohm metal-film type available from Digi-Key,[4] Part Number 49.9X at $0.52 for five. The resistors for the 500-ohm module have the same cost and specifications, except the part number is 499X.

The pin-line sockets are Digi-Key part number A208 which comes in a 25-contact socket strip at $2.40 per strip. A pair of four-socket strips are broken off from the 25-contact strip and soldered into holes 1-4 in rows D and F of the PCB as shown in Figure 2. A film of epoxy cement is flowed around each socket on top of the board for additional support.

A pair of 4-pin strip line single in-line pin (SIP) headers is broken off from a 25-contact header strip (Digi-Key Part Number A115, $2.61 each) and plugged into the sockets previously installed on the PCB. The four resistors are then soldered across the header forks as shown in Figure 4. A 17-contact SIP header strip is shown next to the 50-ohm module. The resistor module is then flooded with fast-setting epoxy cement to make a solid assembly, and a half-inch button is fastened on top of the resistor assembly with more epoxy. The button serves as a surface for the fingers to grip when installing and removing the module. Care must be taken to prevent the epoxy from flowing over the pin contacts before the epoxy fully hardens. After the epoxy finally hardens, the resistor module is labelled with the resistance value.

In Figure 2, the two jumper wires interconnecting R1, R2 and R3 are shown as part of the plug-in module merely to indicate the connections. Actually, these two jumper wires are connected between the socket pins underneath the PCB as these connections are the same for all the plug-in resistor modules. By installing the jumper wires on the sockets instead of on the resistor plug-in module, the wiring of the plug-in module is simplified and the possibility of inserting the plug-in module in the wrong orientation is eliminated.

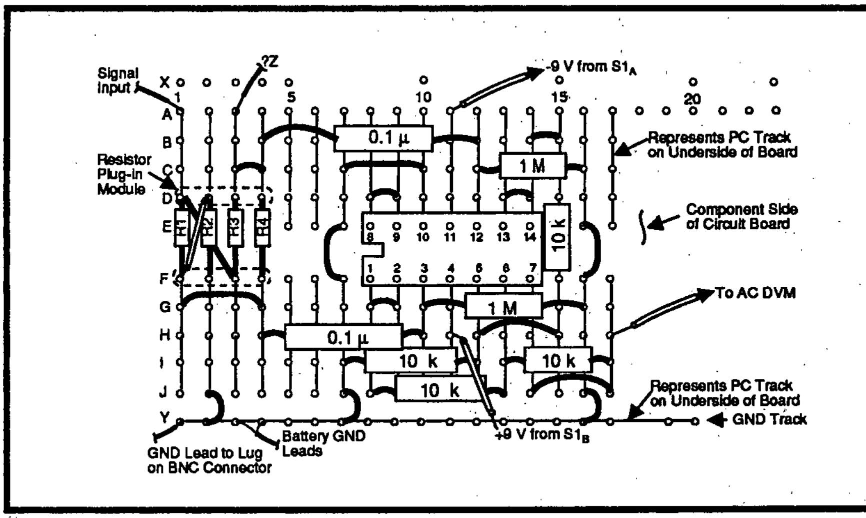

FIGURE 2. Wiring connections of the RLB Components and the Resistor Plug-in Module. Note: The jumper wires between R1, R2 and R3 are connected to the socket pins on the underside of the PCB by connecting tracks A-D1 to F-J3 and A-D2 to F-J1.

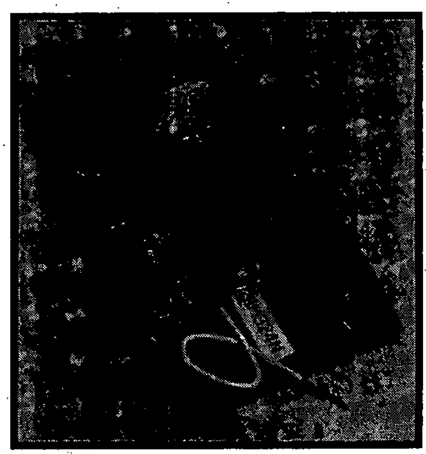

FIGURE 3. RLB Assembled on Half of a Global Experimentor 300 PC Board.

FIGURE 4. RLB 50-ohm Plug-in Module. Also shown are the 1/4-watt 49.9-ohm resistors and the strip line SIP headers and pin line sockets used in the module assembly. Both the header and socket strips have a "break" feature so they can be easily snapped off to any number of positions.

INSTALLATION OF THE PCB IN AN ALUMINUM BOX

Figure 5 shows the assembled return loss bridge on its PCB installed in an aluminum box with two 9-volt batteries. The box containing the RLB assembly was obtained from Mouser,[5] Part Number 537-J-877, 4-1/4 x 2-1/4 x 1-1/2 inches for $3.17. A box with almost the same dimensions is available from DIGI-KEY, Part Number L102, 4 x 2-1/4 x 2-1/4 inches for $4.58, or a BUD box, 4-1/4 x 2-1/4 x 1-1/2 inches, Part Number CU-

3016A, can be used. Any box is suitable as long as the length is not less than 4 inches and the width is not less than 2-1/4 inches. The 2-1/4 inch minimum width is necessary so the two batteries and their terminal clips will fit within the sides of the box cover. A single dab of silicone sealer on the bottom of each battery was used to secure the batteries to the inside of the cover. The common ground leads of the batteries connect to the ground terminal of the PCB and the positive and negative battery leads connect to the DPDT switch. Cardboard spacers about 1/8-inch thick were placed under each end of the board to keep the resistor leads underneath the board from touching the aluminum case. Four 6-32 machine screws and nuts were used at each corner of the board to secure the board in the case.

BNC coaxial connectors were used for the signal ports because it was anticipated that standard 50-ohm coaxial cables with BNC connectors would be used for making all external signal connections between the RLB and the signal generator, the ?Z load and the ac digital voltmeter (DVM). However, if the external cabling to be used has phono connectors, this connector type can be used on the RLB box instead of the more expensive coaxial connector. Because the highest frequency will never exceed 100 kHz, inexpensive shielded wire with phono connectors will suffice for the signal interconnections.

PERFORMANCE TESTING OF THE RLB

After the RLB assembly is installed in the aluminum box and all wiring is completed, the RLB must be tested to confirm that it is operational and that it gives the correct return loss of an impedance connected to the ?Z port. First, the directivity of the RLB is checked over the 100-Hz to 100-kHz frequency range. To do this, plug in the RLB 500-ohm resistor module. Connect a 500-ohm signal generator to the signal input port and a digital ac voltmeter (having an ac voltage bandwidth of at least 100 kHz) to the port labelled "AC DVM." The ?Z port remains open circuited at this time. A suitable DVM for this test (and the one used by the author) is the FLUKE hand-held digital multimeter, Model 8060A. This meter has a true-RMS ac voltage capability with a 100-kHz bandwidth and a relative dB option. The following example is based on using the Model 8060A DVM.*

Turn on the RLB power switch and apply a 1-kHz audio signal of about 1 volt rms to the SIGNAL INPUT port. Set the DVM voltage range switch to 2 volt and vary the signal generator amplitude control so the DVM indicates an ac level between 0.195 and 0.199 volts. Change the DVM range switch to 200 mVolt and then push the "dB" and "REL" buttons on the DVM. An indication of zero dB should be observed. This reading indicates that the return loss for an open-circuit ?Z port is zero dB, and it is the level against which all other levels are referenced. Connect a 500-ohm load, accurate to within 1%, to the ?Z port and sweep the signal generator from 100 Hz to 100 kHz without changing the generator level control. The return loss or directivity of the RLB should be greater than 45 dB up to 10 kHz, and greater than 40 dB from 10 kHz

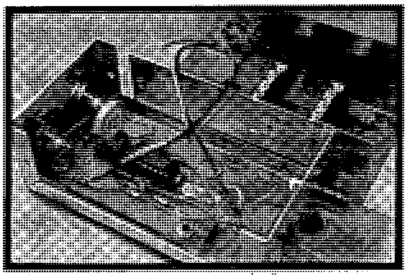

FIGURE 5. Complete RLB With Two 9-volt Batteries Installed in an Aluminum Box.

to 80 kHz. From 80 kHz to 100 kHz, the directivity should be greater than 30 dB.

After the RLB directivity is confirmed, resistors of different values should be connected to the ?Z port so the measured return loss level can be compared with a calculated value. For example, a resistive load of 750 ohms should give a return loss of 14 dB, and a 963-ohm load should give 10 dB.

To calculate the return loss corresponding to a particular resistance, and if the resistance is larger than the reference impedance (in this case, the reference impedance is 500 ohms) divide the resistance by the reference

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**Note: For proper operation of the RLB, the impedance of the generator must be the same as the resistance of the RLB plug-in module. If a 600-ohm generator is the only audio signal source available, its impedance can be changed to 500 ohms by placing a 3000-ohm resistor across its output terminals, or a 600/500-ohm minimum loss resistance pad of 245 ohm and 1225 ohms can be used. If the RLB with its 50-ohm resistor module is to be checked and the only audio signal source is a 600-ohm generator, then a 600/50-ohm matching transformer and minimum-loss matching pad can be used. The design and assembly of a suitable 600/50-ohm matching transformer and a minimum loss matching pad is described in Reference 6.*

impedance. If the reference is larger, divide it by the resistance. The result will be the standing wave ratio (SWR) which is always greater than one. To find the return loss corresponding to the calculated SWR, refer to p. 240 of Reference 1 where Table A1 lists 27 values of SWR from 1.020 to 2.660 with the corresponding return loss values. Also given are equations relating reflection coefficient, SWR, return loss and attenuation.

RLB APPLICATIONS

The primary function of the low-frequency RLB described in this article is to check the passband return loss response of a passive LC filter having a specific design impedance level. *Remember, the impedance of the signal generator must be the same as the impedance of the plug-in module and the filter.* Also, the filter output must be terminated in its design impedance in order for valid results to be obtained.

When the test signal frequency is swept across the filter passband, the return loss should theoretically never drop below the calculated minimum return loss of the filter; however, a drop of a few decibels below the design value is seldom a reason for concern. If, however, the return loss minimum is 4 dB or more below the calculated minimum return loss, one or more of the filter components may need checking for an out-of-tolerance value or the design may have been incorrectly calculated. In either case, the cause for the lower than normal minimum return loss should be determined and the problem corrected. The filter passband return loss test is a sensitive check for confirming that the filter was correctly designed and assembled.

Another application of the low-frequency RLB is to check the SWR of low-frequency PLISNs which are used to stabilize the power line impedance of an equipment under test (EUT) when it is being TEMPEST tested. The RLB discussed in ITEM 1993 was capable of testing the SWR of PLISNs only down to 6 kHz, but with the low-frequency active RLB, PLISNs can now be checked down to 100 Hz.

MEASURING THE RETURN LOSS OF REACTIVE LOADS

Although the RLB is usually used to evaluate loads that are primarily resistive, the bridge will also measure the return loss of impedances that have a significant reactance associated with them. For example, the input impedance at the powerline receptacle of a PLISN is primarily resistive in the center portion of its operating range, and consequently the return loss is generally higher than 20 dB. However, at the low and high ends of the PLISN frequency range the input impedance becomes increasingly reactive as a consequence of the stray capacitances and inductances associated with the PLISN coupling and isolation circuits. It is therefore advisable that the TEMPEST engineer and technician be aware of the relationship between return loss and reactive loads and understand how the phase angle of a load impedance affects its return loss.

Although the reference impedance for PLISNs is 50 ohms, the following discussion will use 500 ohms as the reference impedance since the need to check a 500-ohm filter prompted this article. Nevertheless, the comments associated with the 500-ohm impedance are equally applicable to the 50-ohm reference impedance or any other impedance level. The use of a 500-ohm reference impedance is particularly convenient because it can be changed to 50 ohms just by moving the decimal point one place. The corresponding return loss can be determined whether the reference impedance is 50 or 500 ohms.

Return loss can be considered a figure of merit indicating how closely a measured impedance matches a reference impedance, both in magnitude and phase angle. If the reference impedance is 500 ohms resistive, an impedance of 500 ohms having a phase angle of zero degrees will have a theoretical return loss of infinity. In the case of the RLB discussed in this article, the return loss will be equal to the RLB directivity. If the 500-ohm impedance has increasingly larger phase angles, the return loss will decrease in a corresponding manner. Figure 6 shows the relationship between return loss and impedance magnitude for phase angles of zero to 35 degrees in five degree increments. From this graph, it is obvious that return loss is sensitive to phase angle. For example, if a 500-ohm impedance has a phase angle of only ten degrees, the return loss is 21.2 dB. However, if the phase angle were zero, the impedance could vary between 420 and 595 ohms while having the same minimum return loss.

To confirm that the RLB will correctly indicate the return loss of a reactive load, a series circuit was tested consisting of a 483-ohm resistor and a 1.23-uF capacitor. The calculated reactance of the

1.23-uF capacitor at 1000 Hz is -j129.4 ohms, and the series combination of this reactance and the 483-ohm resistor is 500 ohms with a phase angle of 15 degrees. When this series-connected circuit was connected to the RLB ?Z port and a 500-ohm signal generator was set to 1000 Hz, the return loss of this load was measured to be 17.8 dB, which is within 0.2 dB of the calculated value.

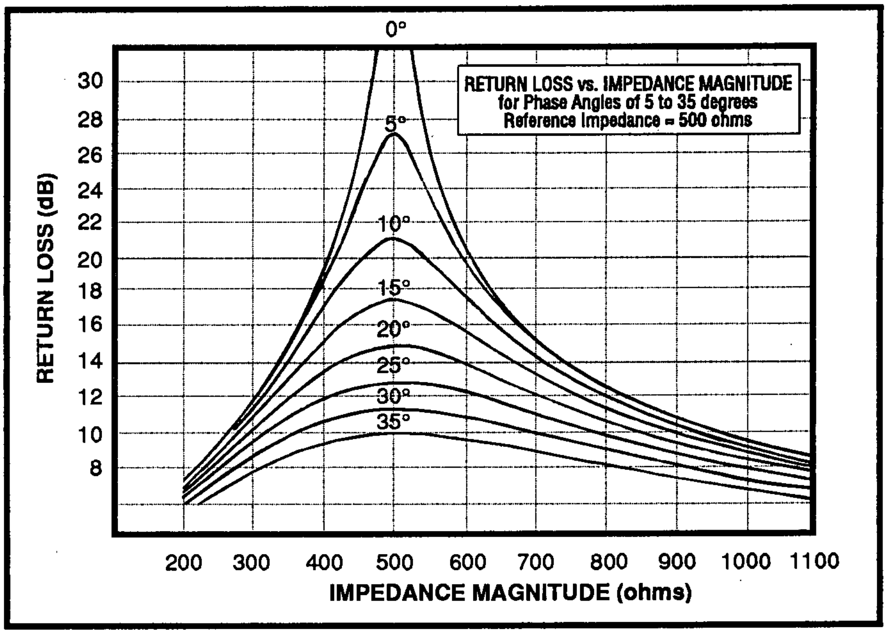

FIGURE 6. Plots of Return Loss versus Impedance Magnitude for Phase Angles of 5 to 35 Degrees in 5-degree Increments. The Reference Impedance is 500 ohms.

The calculated value is obtained from Figure 6 by noting the return loss level where the 15-degree curve intersects the 500-ohm y-axis. If the signal generator frequency is changed to 383 Hz, the calculated return loss for the same load is about 9.75 dB (from Figure 6 at an impedance of 589 ohms at an angle of 35 degrees), while the RLB-measured return loss is 9.9 dB. Again, the measured return loss is within 0.2 dB of the calculated value. These examples demonstrate that the RLB will give valid results when determining the return loss of reactive loads.

Appendix A lists a BASIC program that can be used to calculate the data points used in plotting the curves of Figure 6. Table A1 shows an abbreviated table of data which results when the BASIC program is run on a computer with a printer.

SUMMARY

The disadvantages of the 6-kHz low-frequency limit and the fixed 50-ohm impedance level of the return loss bridge (RLB) discussed in the previous issue of ITEM have been eliminated with a new return loss bridge having a conveniently changeable impedance level and an extended low-frequency response down to 100 Hz. The improved and more versatile performance of the new RLB design is accomplished with an active circuit featuring a 4-resistor plug-in module for changing the impedance level of the bridge. Sufficient details are included to permit any interested reader to obtain the parts and assemble the circuit on an inexpensive and commercially available PCB. Test procedures are described so it may be confirmed that the completed RLB is operating properly. Curves of return loss vs. impedance magnitude and phase angle plus a short BASIC program are included so the return loss of reactive loads can be independently determined. The TEMPEST test engineer and technician will find the active RLB useful for testing filters and PLISNs over the 100-Hz to 100-kHz frequency range.

APPENDIX A

The following BASIC Program calculates Return Loss vs. Impedance and Phase Angle.

```
10 LPRINT " |Z| R.L. ANGLE RESIST REACT R.C."
20 LPRINT " (ohm) (dB) (deg) (ohms) (ohms) (%)"
30 FOR AA= 5 TO 15 STEP 5    :'PHASE ANGLE IN DEGREES
40 FOR Z = 450 TO 550 STEP 50 :'IMPEDANCE MAGNITUDE IN OHMS
50 A = AA/57.29578  :'CONVERTS DEGREES TO RADIANS
60 RO = 500        :'REFERENCE IMPEDANCE LEVEL IN OHMS
70 R = COS(A)*Z    :'RESISTANCE IN OHMS OF Z-MAG.
80 X = SIN(A)*Z    :'REACTANCE IN OHMS OF Z-MAG.
90 LR = (R^2+X^2-RO^2)/((R+RO)^2+X^2) :'REAL COMPONENT OF RHO

100 LI = (2*X*RO)/((R + RO)^2 + X^2)  :'IMAGINARY "  "
110 RHO=(LR^2+LI^2)^.5  :'REFLECTION COEFFICIENT MAGNITUDE
120 RET=-8.68589*LOG(RHO) :'RET LOSS FROM REFL. COEFF. MAG.
130 LPRINT USING " ####"; Z;  :'PRINTS Z MAGNITUDE IN OHMS
140 LPRINT USING " ##.#"; RET; :' "  RETURN LOSS IN dB
150 LPRINT USING " ### "; AA; :' "  ANGLE IN DEGREES
160 LPRINT USING " ###.#"; R;  :' "  RESISTANCE (OHMS)
170 LPRINT USING " ###.#"; X;  :'PRINTS REACTANCE (OHMS)
180 LPRINT USING "  ##.#"; RHO*100 :' "% REFL COEFF MAG.
190 NEXT Z : LPRINT : NEXT AA  : END
```

|Z| (ohms)	R.L. (degrees)	Angle (ohms)	Resistance (ohms)	Reactance (ohms)	R.C. (%)
450	23.3	5	448.3	39.2	6.8
500	27.2	5	498.1	43.6	4.4
550	23.8	5	547.9	47.9	6.5
450	19.8	10	443.2	78.1	10.2
500	21.2	10	492.4	86.8	8.7
550	20.0	10	541.6	95.5	10.0
450	17.0	15	434.7	116.5	14.2
500	17.6	15	483.0	129.4	13.2
550	17.1	15	531.3	142.4	14.0

***TABLE A1**. Calculated return losses for given values of impedance and phase angle. Included are the corresponding values of resistance, reactance and percentage of reflection coefficient. The BASIC program used to calculate this table and the curves in Figure 6 is shown below. If a duplicate of the data used to plot the curves in Figure 6 is needed, the FOR statements in LNs 30 and 40 must be modified to include the impedance and angle ranges plotted in Figure 6.*

REFERENCES

1. E. Wetherhold, "Design and Construction of a 9-kHz Highpass Filter and Assembly of a Return Loss Bridge for Filter and PLISN Testing," *ITEM* 1993, pp. 220-240.
2. W. H. Hayward, *Introduction to Radio Frequency Design*, Englewood Cliffs: Prentice-Hall, Inc., 1982.
3. Global Specialties. An Interplex Electronics Company, 70 Fulton Terrace, New Haven CT 06512. 1-800-572-1028. Telephone to request *Test & Design Instrumentation* Catalog.
4. Digi-Key Corporation, 701 Brooks Ave. South, P.O. Box 677, Thief River Falls, MN 56701-0677. 1-800-344-4539. Telephone to request a free catalog.
5. Mouser Electronics, Central Distribution Center, 2401 Highway 287 North, Mansfield, TX 76063-4827. 1-800-346-6873. Telephone to request a free catalog.
6. E. Wetherhold, "Simplified Attenuator and Impedance Transformer Design," *ITEM* 1992, pp. 26-38.

ACKNOWLEDGEMENTS

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