8

Computer-Aided Design Programs

GENERAL

The process of impedance matching the input and output of high power RF transistors is best performed using computer-aided design programs such as EEsof's TOUCHSTONE™ or Optotek's MMICAD™. This is particularly true when matching involves a band of frequencies instead of a single frequency. It is not the intent of the authors, however, to describe the details of a particular computer-aided design (CAD) program. Detailed instruction manuals accompany any CAD program, and these describe the inputs required and the sequential steps involved in achieving a particular optimized matching network. There is still a place, though, for the use of the Smith Chart as a tool in the initial phase of the matching process. A most unique program to aid the design engineer in using the Smith Chart has been created at Motorola.[1] It has been given the name Motorola Impedance Matching Program (MIMP), and it is available free of charge to anyone who desires a copy.

What the program does is to provide a simple environment for entering and analyzing impedance matching circuitry. It focuses solely on impedance transformations. A standard library of passive circuit elements is provided by MIMP, including various combinations of capacitors, inductors, and transmission lines in both series and shunt configurations. It also contains a unique "distributed capacitance element" that models a capacitor distributed along a transmission line.

The real nucleus of MIMP is its computer-aided Smith Chart. It is uncommon for CAD programs to incorporate the benefits of manipulating actual impedance transformations on a Smith Chart. MIMP's Smith Chart facility provides this electronically. It also displays each circuit element's contribution to the total impedance transformations. Included in MIMP is an auxiliary database in which are tabulated the input and output impedances for many of the RF power transistors contained in Motorola's RF Data Book.

Details of MIMP are contained later in this chapter. Copies of the actual program suitable for use on IBM compatible personal computers can be obtained from Motorola Semiconductor Products by contacting their nearest sales office and requesting DK107. Requirements to successfully use the data disk are an IBM compatible (MS-DOS) personal computer with at least 640K of RAM, a 80286 or higher processor, and a VGA graphics adapter. A "mouse" is recommended.

The following paragraphs describe the combination of MIMP and a CAD program to design matching networks for the input and output of a high power UHF

FREQ MHz	Z_{IN} ohms	$Z_{OL}{}^*$ ohms
400	0.62+j2.8	1.2+j2.5
440	0.72+j3.1	1.1+j2.8
470	0.79+j3.3	0.98+j3.0
490	0.84+j3.4	0.91+j3.2
512	0.88+j3.5	0.84+j3.3
520	0.90+j3.6	0.80+j3.4

FIGURE 8-1

Input and output transistor impedances for MRF658. P_{out} = 65 watts and V_{dc} = 12.5 volts.

transistor. MIMP was used initially to arrive at lumped circuit-matching configurations. The number of matching elements was increased systematically until the desired circuit match (measured in terms of return loss) was obtained across the frequency band of interest. Then the job of optimizing the circuit was turned over to a CAD program for final circuit design, much of which used distributed circuits for element realization. The input circuit was optimized for best match, while the output circuit was optimized for best gain and efficiency simultaneously.

Let's start with the MRF658 RF power transistor. This device is intended to provide 65 watts of output power from 400 to 520 MHz while operating from a 12.5-volt supply. The first step is to take the impedance data supplied by the manufacturer (re-stated in Figure 8-1) and use the impedance matching program (MIMP) to generate lumped element matching networks (see Figure 8-2) to provide high return loss (the goal was 20 dB) over the frequency band from 470 to 512 MHz. In this instance, the number of matching elements was determined experimentally through an iterative process of "cut and try." Filter theory can be used to predict the number of matching elements needed to obtain a "passband" response that covers the desired frequency range and has a "ripple" in the passband no greater than the equivalent specified amount of return loss. However, in this instance, MIMP allows you to start with a single element and add experimentally additional elements until you achieve suitable return loss (an indication of impedance match) over the desired frequency band.

The next step in the design of the amplifier is to convert the design to a microstrip transmission line configuration and add the bias circuitry. Some of this can be accomplished with MIMP and the rest through the use of transmission line equations (such as the one given in Chapter 9, "After the Power Amplifier") that determine a microstrip equivalent for a specified value of inductance L. Figure 8-3

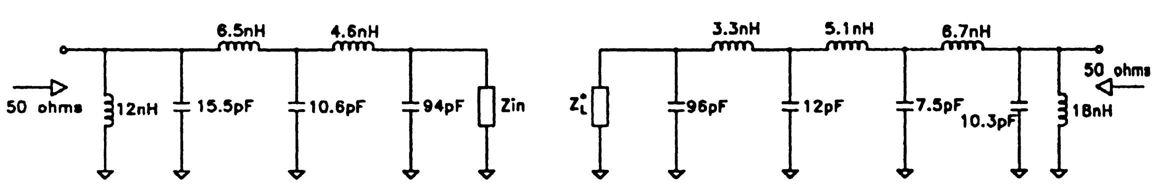
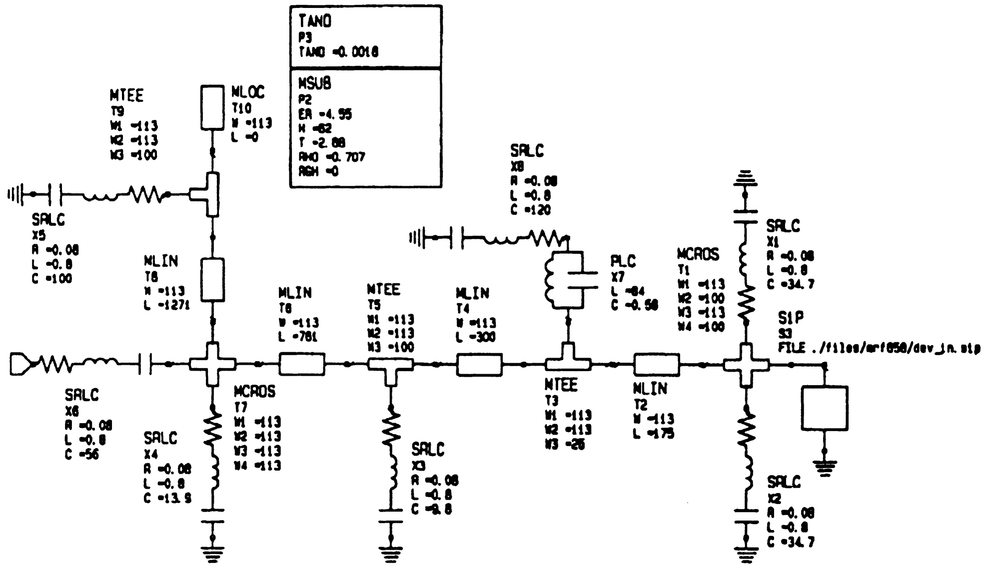
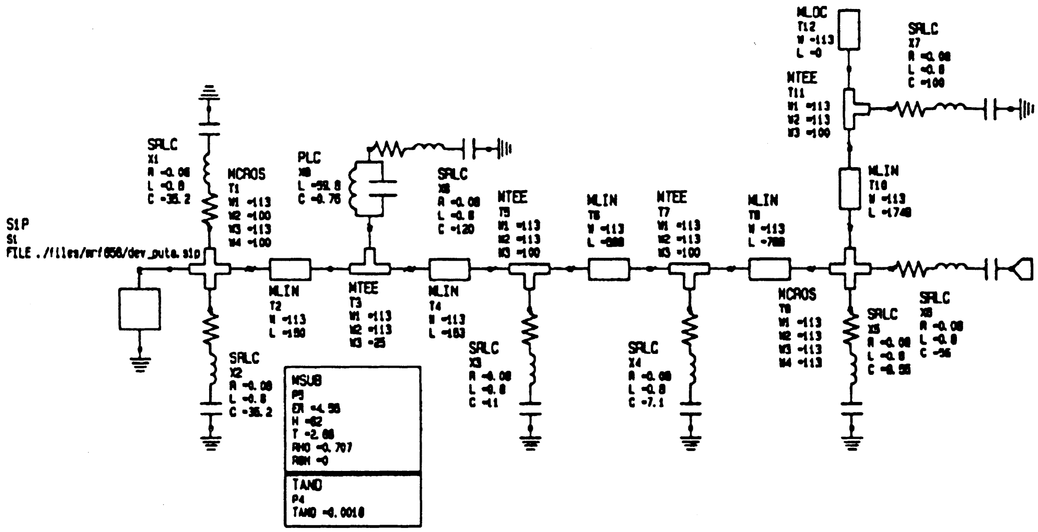


FIGURE 8-2

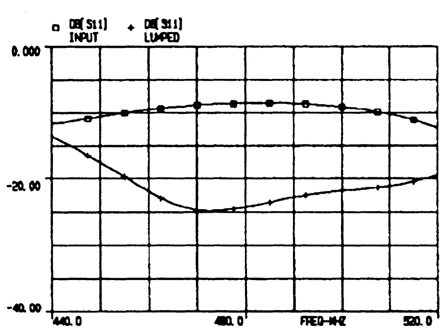
Lumped element matching networks from 470 to 512 MHz, determined experimentally by using MIMP.



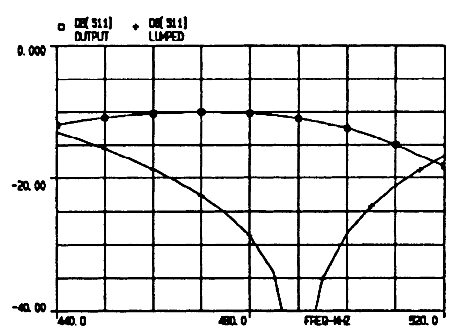
(a)



(b)



(c) Input reflection coefficient



(d) Output reflection coefficient

FIGURE 8-3

Microstrip configuration of amplifier design.

shows the initial microstrip configuration of the design and the predicted performance using the program called ACADEMY™. The need for optimization is readily apparent from Figure 8-3C and D, which show the return loss to be less than desired over the frequency band of interest.

Modifications to the values of some of the matching elements is next accomplished by use of CAD optimizing programs such as TOUCHSTONE™ or MMICAD™. ACADEMY™ will also optimize and automatically generate a board layout from a schematic diagram. Normally, input- and output-matching networks are optimized separately. Usually, the optimization goal for the input network can be stated in terms of return loss. In the example given, the goal was an input return loss (IRL) of at least 18 dB across the frequency band of interest. Generally, the output matching network is optimized for best gain and efficiency across the frequency band.

Figures 8-4 and 8-5 show the schematic diagrams optimized by MMICAD™ and ACADEMY™. Figure 8-6 shows the final schematic diagram of the amplifier, and Figure 8-7 is a diagram of the actual circuit layout. Finally, Figure 8-8

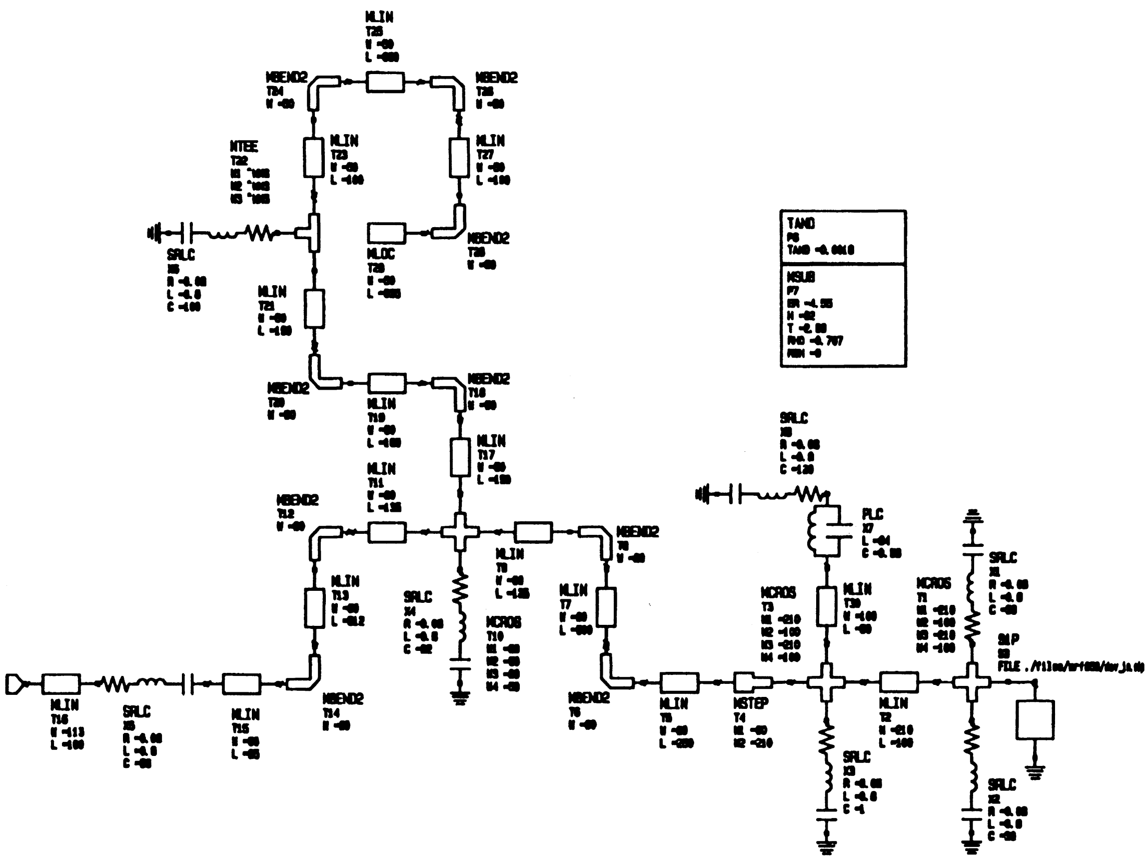


FIGURE 8-4

Optimized input-matching network from ACADEMY™.

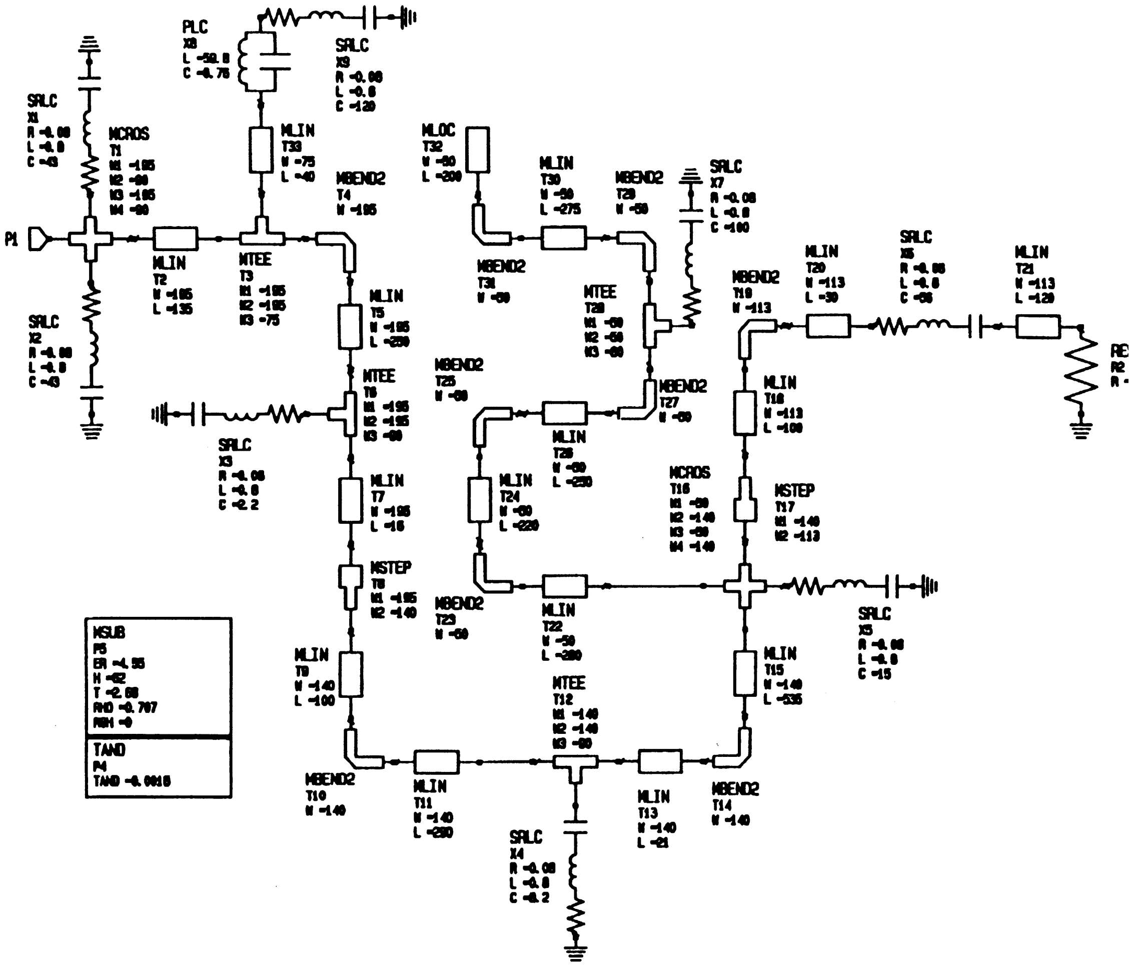


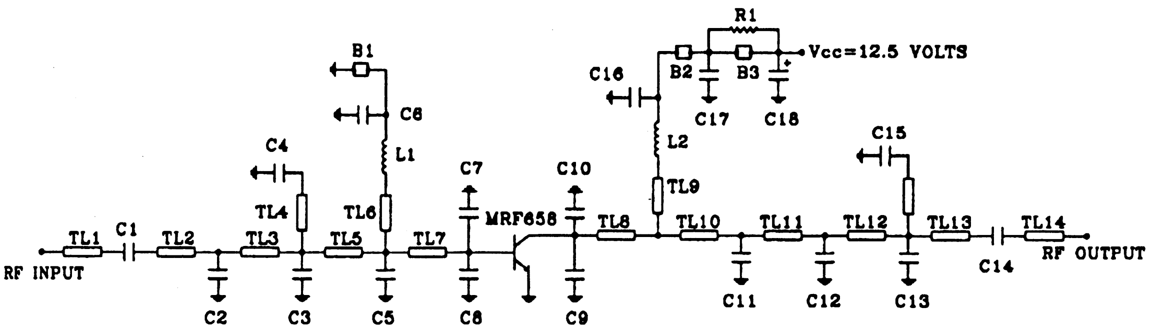
FIGURE 8-5

Optimized output-matching network from ACADEMY™.

shows the performance obtained from a series of amplifiers constructed from the ACADEMY™ circuit layout.[2]

INSIDE MOTOROLA'S IMPEDANCE MATCHING PROGRAM

MIMP is a specialized form of CAD specifically developed for RF power amplifier circuit design. It provides a simple environment for entering and analyzing impedance matching circuitry. Commercially available programs include a multitude of circuit elements and provide numerous analytical capabilities. However, MIMP focuses *only* on impedance transformations. This is typical of most RF power amplifier design problems, since data sheets for RF devices only present large signal impedances measured at a single combination of frequency, voltage,



C1=56pF	C10=43pF	L1=84.0nH
C2=1.5pF	C11=5.6pF	L2=59.8nH
C3=18pF	C12=8.2pF	B1=Short Ferrite Bead
C4=100pF	C13=13pF	B2=Short Ferrite Bead
C5=5.6pF	C14=56pF	B3=Long Ferrite Bead
C6=120pF	C15=120pF	R1=4x39 ohms in Parallel
C7=39pF	C16=120pF	Circuit Board Parameters:
C8=39pF	C17=.18uF	h=1/16"
C9=43pF	C18=10uF	Er=4.55

FIGURE 8-6
Schematic diagram of a completed Class C UHF power amplifier.

power level, and power dissipation. These impedances generally must be transformed to another set of impedances, such as 50 Ω or the input/output impedance of another device. To do this, MIMP provides a standard library of passive circuit elements, including various combinations of capacitors, inductors, and transmission lines in both series and shunt configurations. It also contains a unique

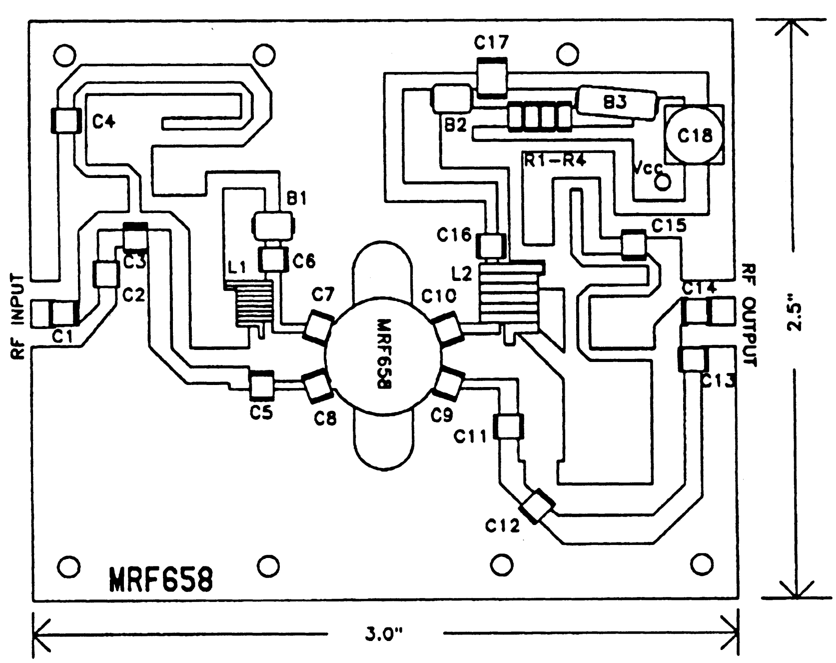


FIGURE 8-7
Diagram of an assembled RF power amplifier.

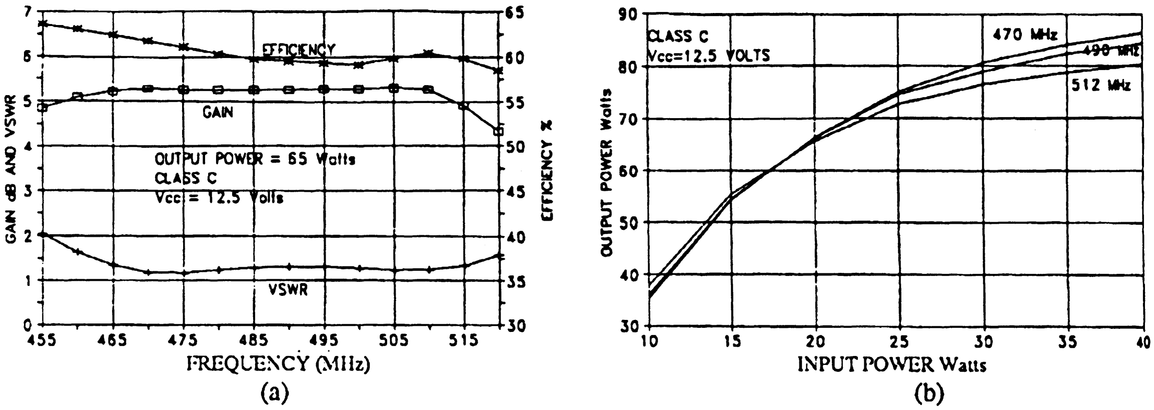


FIGURE 8-8

(a) Average gain, VSWR, and efficiency for six amplifiers, and (b) output power versus input power.

distributed capacitance element that models a capacitor distributed along a transmission line.

The real nucleus of MIMP is its computer-aided Smith Chart. It is uncommon for CAD programs to incorporate the benefits of manipulating actual impedance transformations on a Smith Chart. If commercially available programs were used merely for impedance matching, a typical final result of a computer run would be S_{11} versus frequency. To supplement this, many RF designers still keep a Smith Chart, compass, straight edge, and pencil handy so they can pictorially represent each circuit component's contribution to the total transformation. MIMP's Smith Chart facility provides this service electronically. It also displays each circuit element's contribution to the total impedance transformations. Here are some additional advantages of the Smith Chart display function:

1. The Smith Chart can be instantly "re-normalized" to any characteristic impedance. All impedances (with interconnecting arcs) are automatically recalculated and displayed.
2. There is an option for overlaying constant return loss circles for any complex source impedance independent of the normalized characteristic impedance. (Most other programs constrain the use of constant return loss circles to the center of the Smith Chart.)
3. Multiple transmission line transformations (each with different characteristic impedances) are displayed simultaneously and in exact graphical relationships to each other, independent of the Smith Chart's normalized impedance. (Drawing transmission line transformations by hand requires an iterative denormalize/renormalize/replot/redraw procedure.)
4. A tabular impedance display is provided to view the impedance at any "node."

5. Constant Q arcs can be added to the Smith Chart.
6. Real-time changes in the impedance transformation are displayed, while individual circuit elements are tuned. This utility is provided to perform manual circuit optimization. A scalar display of input return loss is updated simultaneously as an additional tool for optimization.
7. If Motorola's RF power transistors are used in the design, then an auxiliary database containing the input and output impedances for many such devices can be accessed.

MIMP DESCRIPTION

MIMP is divided into three screens: the *impedance entry screen*, the *circuit entry screen*, and the *Smith Chart display*. A mouse is recommended for easy entry and manipulation of data, although there are keyboard equivalents for most of the mouse functions.

Once the program is "launched" on the computer, the screen in Figure 8-9 is displayed. This is the Impedance Entry screen, which is separated into four basic sections:

1. frequency table
2. load impedance table

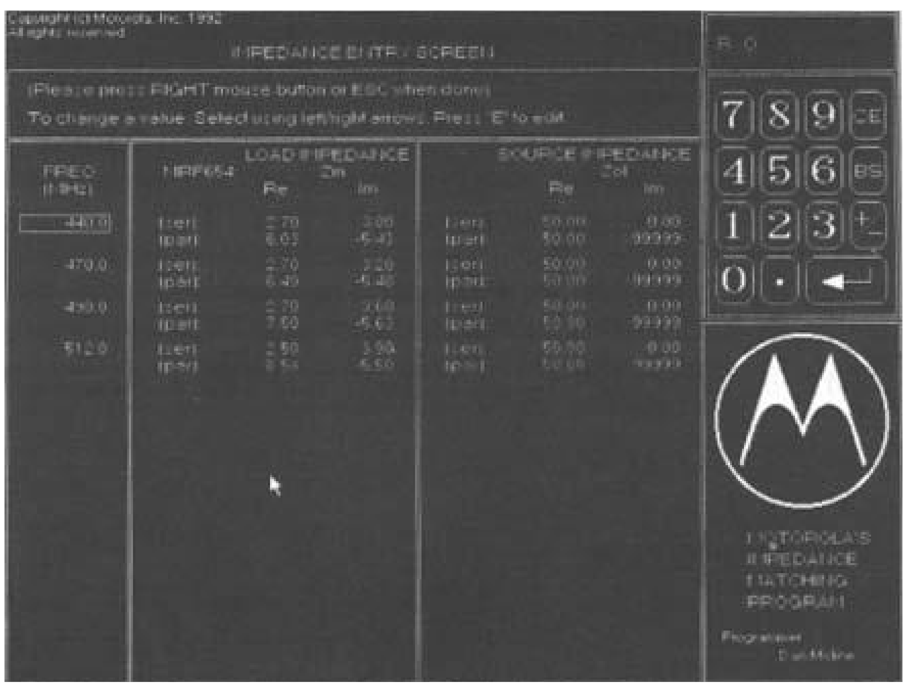


FIGURE 8-9

The Impedance Entry screen in MIMP.

3. source impedance table
4. data entry keypad

MIMP first prompts the user for the number of frequencies to be entered. The program will only accept values less than or equal to 11. (If zero is entered, the program advances to a standard device entry sequence, as will be described later.) After the number of frequencies has been supplied, each frequency should be entered sequentially, starting with the lowest value. When the last frequency has been entered, the user is prompted to supply the load impedance data for each frequency. An option to specify 50 Ω is supported by pressing the ENTER key. After all the load impedance data is furnished, the source impedance data is requested. Again, there is an option to display 50 Ω by pressing ENTER. (Parallel equivalents are calculated and displayed for all impedances.) After the data is entered, the user may proceed to the Circuit Entry screen or edit any of the frequency or impedance data.

If a standard device is to be selected as the load impedance, users can select from the 2N, MRF, JO, and TP prefixes and then enter the remainder of the number. The program next prompts the user to select either the device's input or output impedance as a load. If the requested device is included in the database, the impedance information is displayed at their corresponding frequencies. The source impedance is entered manually. Editing can be performed on any fre-

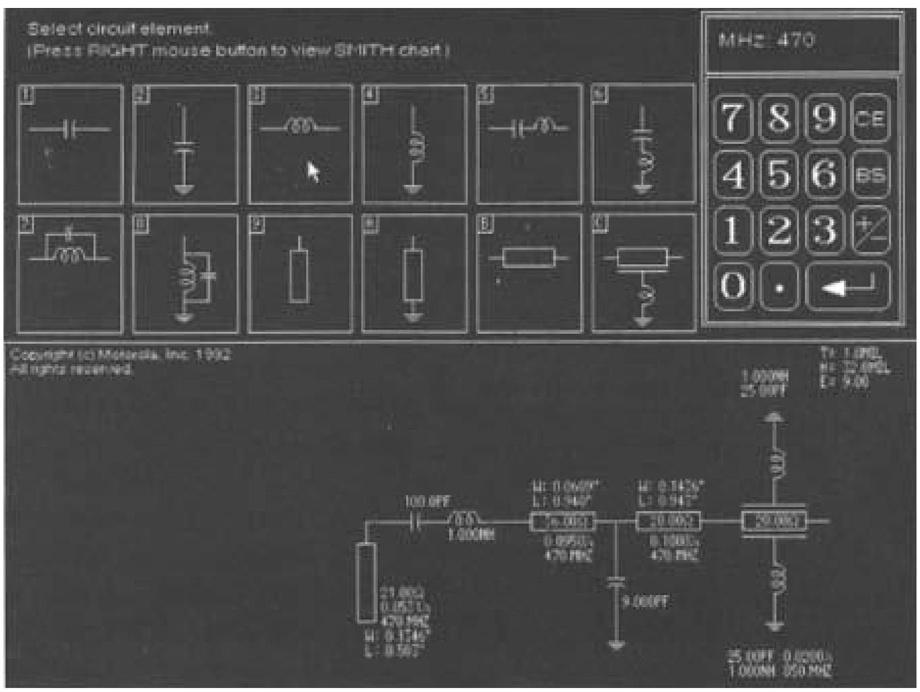


FIGURE 8-10
The Circuit Entry screen in MIMP.

quency or impedance before proceeding to the Circuit Entry screen. Figure 8-10 shows the Circuit Entry screen. It is separated into three parts:

1. the component library
2. data entry keypad
3. circuit display area

A component is selected by clicking it with the mouse or pressing the appropriate keys. Immediately after a component is selected, the numeric keypad is activated and the user is prompted to enter component values. Inductors are recognized in nanohenries and capacitors in picofarads, and inductive/capacitance reactance can be specified.

A transmission line is defined by its characteristic impedance in ohms and its electrical length in fractions of a wavelength. The electrical length needs to be referenced to a specific frequency in MHz. Transmission lines (microstrip) may also be classified in physical terms. MIMP will prompt users for the conductor's width and length. Whenever the first transmission line is selected (whether defined in electrical or physical properties), MIMP will also request information on relative dielectric constant, dielectric thickness, and conductor thickness.[3] This information is assumed to be the same for all subsequent transmission lines and is displayed in the upper right-hand corner of the display. To change these values, all existing transmission line data must be deleted.

Most CAD programs assume that a capacitor has no width; that is, it contacts the circuit at a single point. As frequencies increase, this assumption introduces a significant error in circuit analysis, particularly at low impedances. Since a capacitor is typically mounted on a transmission line, a significant phase shift can occur across its width at higher frequencies. (A 100-mil capacitor can have an electrical width of 0.02 λ at 1 GHz if mounted on Al_2O_3.) This error can be reduced by modeling a capacitor as a "distributed" component. On most CAD programs, this involves subdividing the capacitor and transmission line into several smaller sections to comprehend the collective capacitive effects and transmission line transformation. MIMP provides a component, called the DISTRIBUTED CAPACITOR, which first prompts the user for a capacitor value along with any accompanying series lead inductance. It next asks for the characteristic impedance of the transmission line on which the capacitor is mounted. Finally, it asks for the transmission line's electrical length (in fractional wavelengths) for that portion of the transmission line on which the capacitor is mounted. MIMP then calculates the combined effect of the two.

Figure 8-11 shows the Smith Chart display. It is divided into four sections:

1. the Smith Chart
2. the menu bar
3. the nodal impedance display
4. the scalar input return loss graph

The Smith Chart graphically displays the impedances transformed by each shunt or series element. These impedances are represented by small "x" letters.

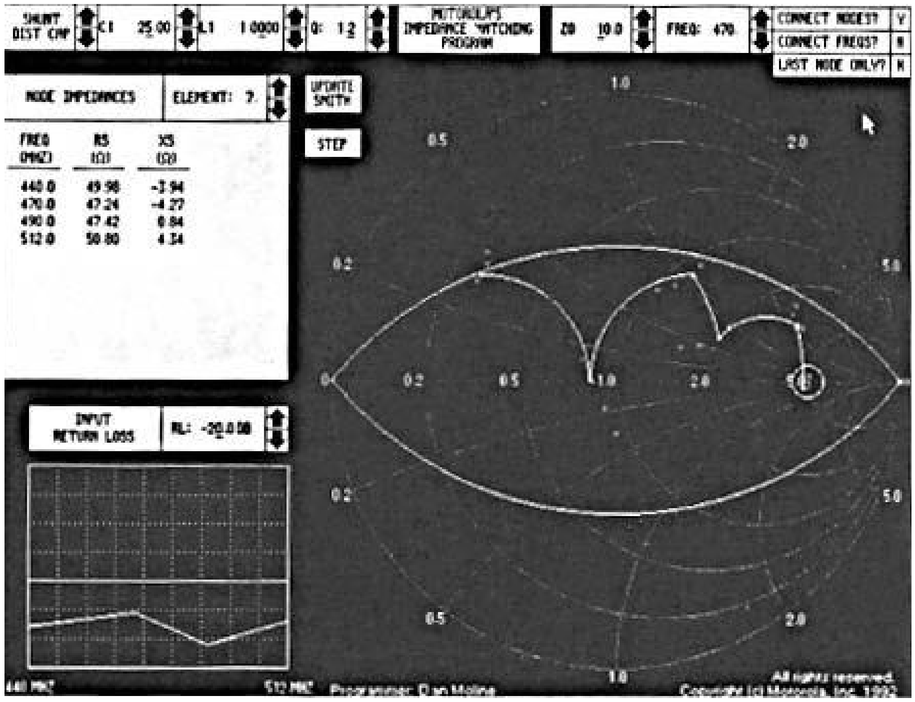


FIGURE 8-11

The Smith Chart display screen in MIMP.

Each frequency is depicted by a different color. If there are multiple series or shunt elements, the combined effect of all elements is lumped together as one element.

There are several default conditions set whenever the Smith Chart display is entered. The conjugate of the source impedance is shown by a series of yellow “x” letters encircled by a −20 dB return loss circle (the conjugate is the desired transformed impedance). The Smith Chart is initially normalized to 10 Ω. The constant Q arcs are set to 0, and the nodal impedances are listed for the last node. The first circuit element is selected for tuning. These default conditions may be altered by making selections from the menu bar and by using the mouse or keyboard to change the conditions and values. The menu bar is also used to select and tune the various circuit elements.

The nodal impedance display shows the actual transformed impedance produced by each circuit element. Multiple series or shunt elements are lumped together. (Note: these are not really nodal impedances. It is the transformed circuit impedance, starting from the load up to and including the selected element.) Different points in the circuit can be selected, and as the “node” is changed, the corresponding “x” letters are highlighted.

The return loss display shows on a scalar chart how well the transformed impedance matches the source impedance. The reference return loss is indicated by the yellow line on the scalar display and the yellow circle on the Smith Chart display. If the source impedance is frequency dependent, the circles on the Smith Chart will be relocated for each frequency.

SMITH CHARTS AND MIMP

The accepted practice for plotting impedance transformations on Smith Charts requires that each circuit impedance be first normalized to its respective transmission line's characteristic impedance. Once normalized, the impedances can be plotted (and transformed) on a similarly normalized Smith Chart. Each time a new transmission line is encountered in the circuit, the impedances must then be denormalized using the old Z_0 and renormalized with the new Z_0 before additional graphical manipulations can be accomplished. The normalized Smith Chart (typically 1 Ω) remains unchanged with each new transmission line transformation. This results in a series of noncontiguous impedance transforms whose visual relationships have little or no value. See Figure 8-12.

One of the unique features of MIMP's Smith Chart display is its ability to have various transmission lines with different characteristic impedances displayed together on one Smith Chart. Instead of constantly denormalizing and renormalizing circuit impedances and plotting them on the same normalized Smith Chart, the reflection coefficient plane for each transmission line transformation is renormalized instead. The locus of points representing the transmission line's impedance transformation is remapped into this new plane. The origin of the reflection coefficient (RC) plane is repositioned along the real axis, and the magnitude of the RC is rescaled. In effect, a second Smith Chart of an adjusted

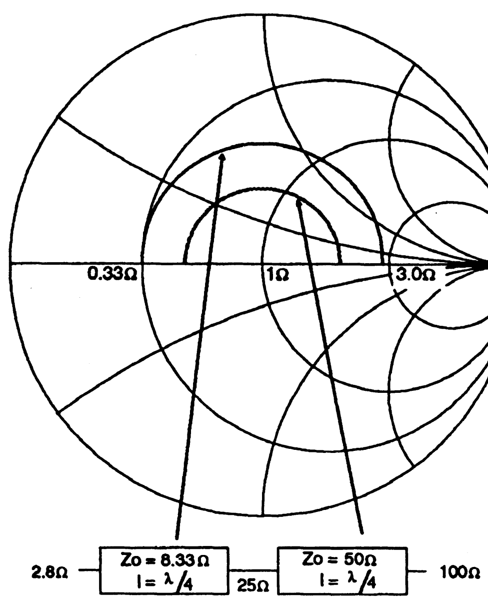


FIGURE 8-12

Conventional impedance transforms for different values of Z_0.

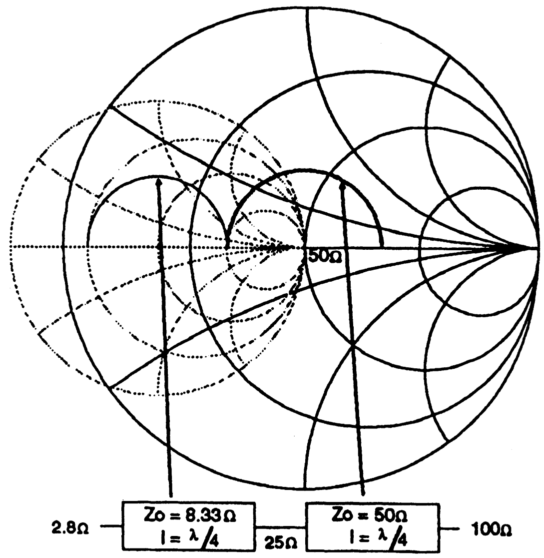


FIGURE 8-13

MIMP display for impedance transforms with different values of Z_0.

size is overlayed on the original Smith Chart. Figure 8-13 shows this. This approach permits multiple transmission lines to be displayed on the same Smith Chart in a contiguous flow, while maintaining exact graphical relationships between the various transformations. Because of the additional calculations, this technique is obviously more applicable for CAD than by hand. Once the program is set up to handle these calculations, all impedance transformations maintain their relative positions as the relative characteristic impedance of the Smith Chart is changed. MIMP also allows the user to specify any relative Z_0 for the Smith Chart.

References

[1] Dan Moline, "Impedance Matching Program," *RF Design*, January 1993.

[2] Robert Baeten, "Computer Aided Design of A Broad-Band, Class C, 65 Watt, UHF Amplifier," *RF Design*, March 1993.

[3] E. Hammerstadt and O. Jensen, "Accurate Models for Microstrip Computer Aided Design," *IEEE International Microwave Symposium Digest*, June 1980.