

Evaluation of a Polarization Changeover Switch for MSAT
Application

by

Hak K. Chin

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Engineering
in
Electrical Engineering

Winnipeg, Manitoba

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SWITCH FOR MSAT APPLICATION

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A thesis submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
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ABSTRACT

This report presents the design and implementation of an RF SPDT switch. The switch is intended for polarization changeover between RHC and LHC of phased array antennas developed for MSAT applications.

The design was simple and easy to implement. The switch was fabricated on a microstrip line and the series diode switch configuration was used. A computer program was used to predict the performance of the switch. Insertion loss of 0.25 dB, return loss of 17.2 dB and isolation of 23.5 dB were predicted at 860 MHz. Upon actual testing, insertion loss of 0.25 dB, return loss of 23 dB and isolation of 27 dB were measured.

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On a personal note, the author also expresses his thanks to his wife for her patience and understanding over the years.

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Chapter I

INTRODUCTION

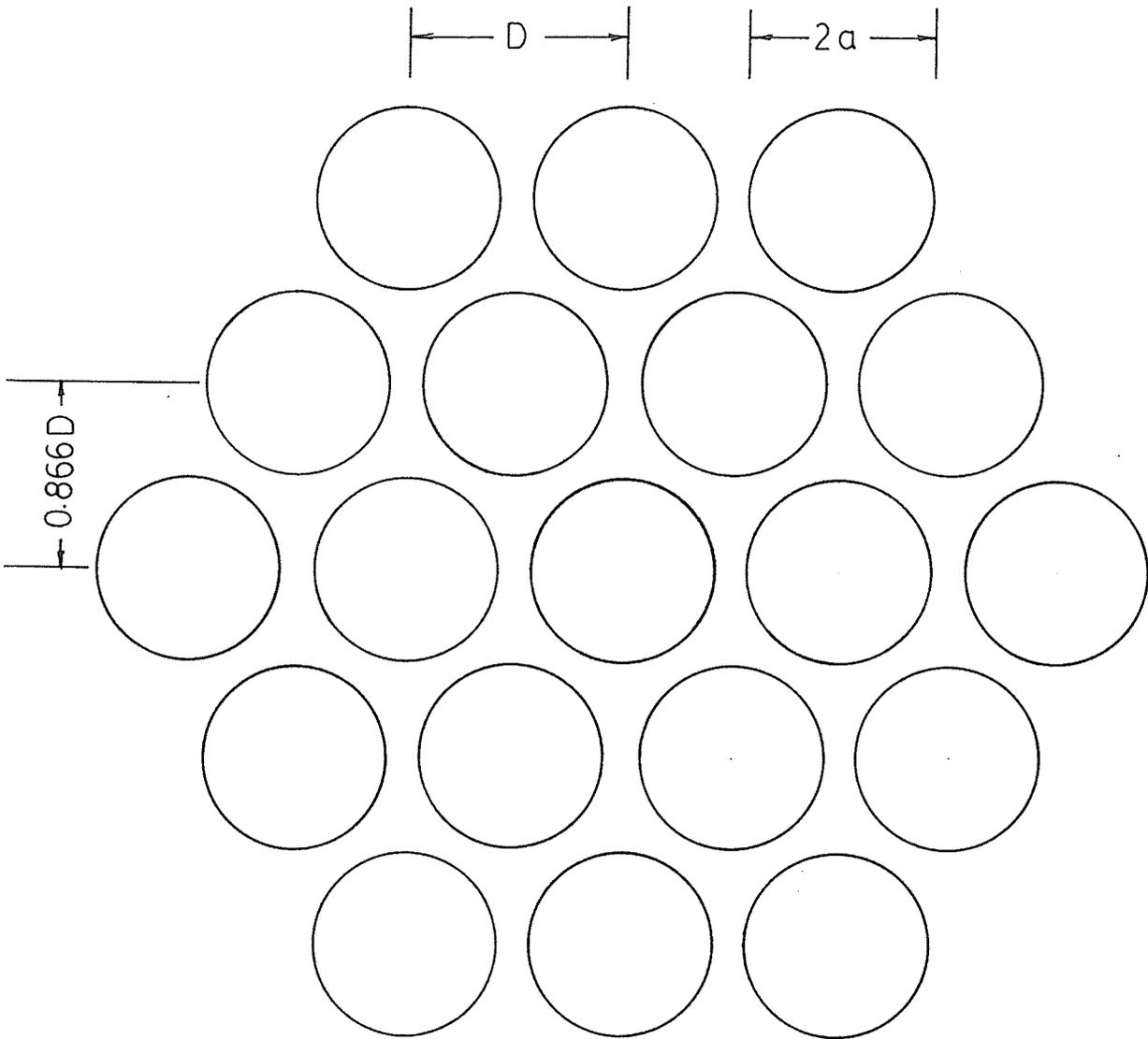
Various types of microstrip phased array antennas for mobile satellite (MSAT) communication are currently being developed at the Department of Electrical Engineering, University of Manitoba. One of the designed arrays consists of nineteen circular microstrip patch elements operating in the TM_{11} mode. In this report, a prototype single pole double throw (SPDT) switch is developed to handle the polarization changeover for the array between RHC and LHC polarization for both the receive and transmit operation. For this particular application, an off-the-shelf RF switch cannot be used because of its limited power handling capability. A narrow band switch which is capable of handling approximately three watts of RF power is needed. Hence, it is more cost effective to implement a switch. Another advantage of developing the switch package is that it can be designed for easy integration into the microstrip phased array.

Figure 1.1 shows the geometric configuration of the 19 element phased array. A block diagram of the MSAT ground station is shown in Fig. 1.2. Tentatively, the antenna is designed to transmit in the 821 - 825 MHz band and receive

in the 866 - 870 MHz band. The switch is designed to operate at a center frequency of 860 MHz with a 6% fractional bandwidth. Hence, the switch can be used to switch both the receive and transmit array. The following are the major design goals for the switch:

- i) power handling capability of approximately 3 watts,
- ii) insertion loss of less than 1/2 dB,
- iii) bandwidth of approximately 6%,
- iv) isolation of approximately 20 dB,
- v) good phase balance between channels,
- vi) linearity at high power level.

The design techniques are discussed in Chapter 2. Computer aided design analysis is presented in Chapter 3 while measurement techniques and test results are presented in Chapter 4.



$$a = 6.79 \text{ cm.}$$

$$D = 16.0 \text{ cm.}$$

Figure 1.1: Geometric Configuration of 19 Element Phased Array Antenna

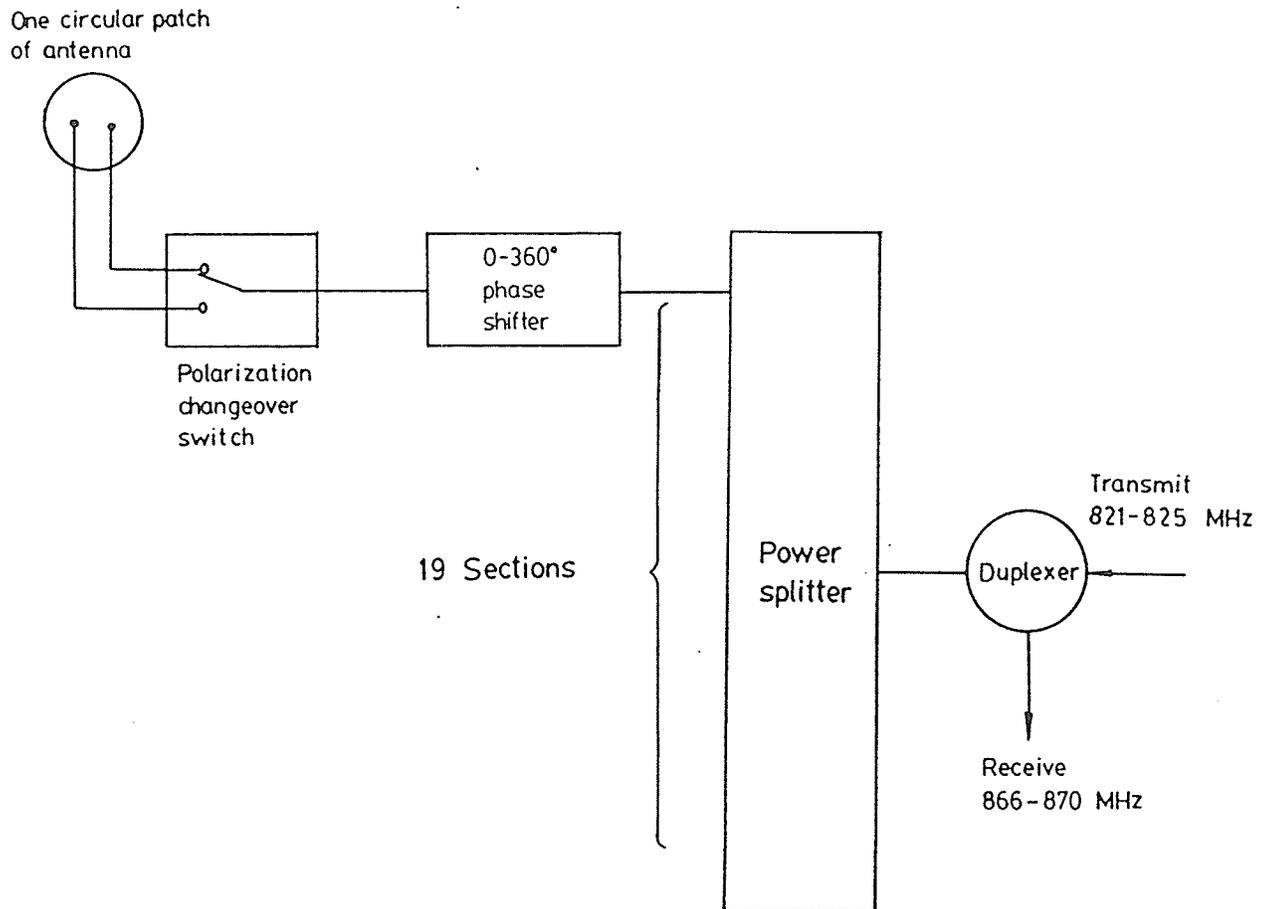


Figure 1.2: Block Diagram of MSAT Ground Station

Chapter II

DESIGN TECHNIQUES

2.1 MICROWAVE SWITCHES

There are three kinds of microwave switches, namely, the diode, ferrite, and electromechanical types. Each switch type has its own unique characteristics. The PIN diode is chosen here as the switching element because of the following advantages:

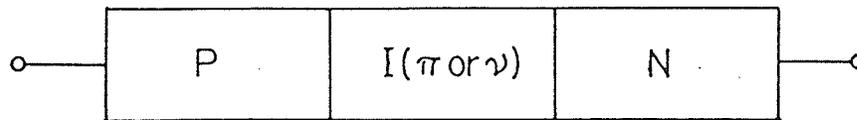
- i) high switching speed,
- ii) good isolation,
- iii) compact size and rugged construction,
- iv) capability of handling high power with little change in diode temperature,
- v) low bias power requirement,
- vi) unlimited lifetime.

The basic technique for using a PIN diode as an RF switch is simple; one or more diodes are incorporated into transmission lines as series or shunt elements. The RF resistance of the diodes can be varied by the application of a bias current, and the flow of the microwave signal is controlled accordingly.

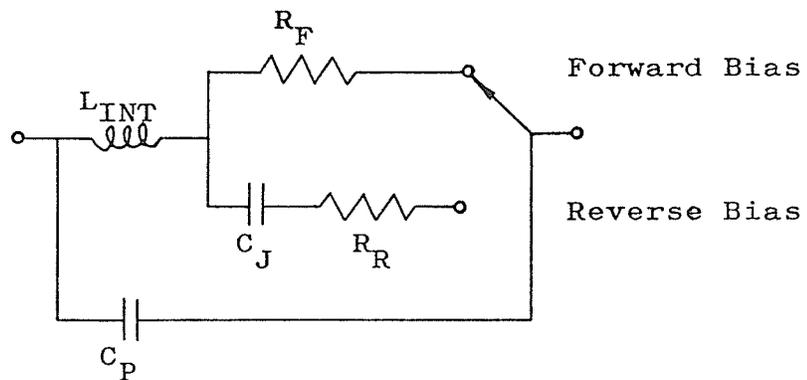
2.2 THE PIN DIODE

A PIN diode is a silicon semiconductor junction similar to that of a pn diode except that a lightly doped π -layer or ν -layer is inserted between the p and n region [1,2]. The most important property of the PIN diode is its behaviour as an almost pure resistance at RF. The diode resistance can be varied over a range of approximately 1 to 10,000 ohms by the application of an appropriate bias current [3]. The PIN diode is used for attenuating, levelling and amplitude modulating an RF signal with the bias current varied continuously. When the bias current is applied in discrete steps, the PIN diode is useful for pulse modulating, phase shifting, and switching RF signals.

Figure 2.1 shows the PIN diode structure and its equivalent circuit model. When reverse or zero biased, the PIN diode can be modeled as a capacitance which is the depletion capacitance of the intrinsic layer. When the diode is forward biased, charges are injected into the intrinsic layer and the conductivity of the diode is proportional to the bias current. In this ON state, the PIN diode can be modeled as a resistance.



a) PIN Model



- C_J - junction capacitance
- C_P - package capacitance
- L_{INT} - internal inductance
- R_F - forward biased junction resistance
- R_R - reverse biased junction resistance

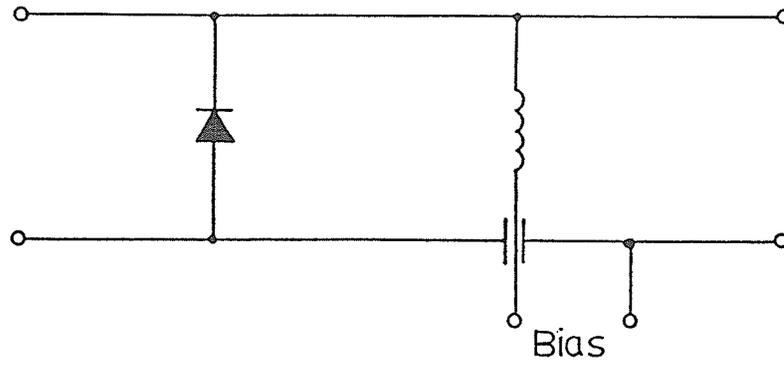
b) Equivalent Circuit

Figure 2.1: PIN Diode Equivalent Circuit

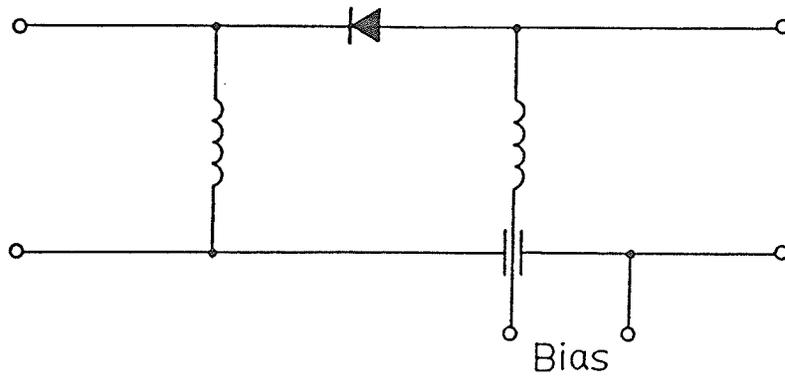
2.3 BASIC SWITCHING CIRCUITS

Two basic diode switch circuit configurations are shown in Fig. 2.2. The shunt switch, Fig. 2.2(a), is ON (RF can pass through with minimum attenuation) when the PIN diode is zero or reverse biased since it presents a high shunt impedance. When the PIN diode is strongly forward biased, RF is reflected back to the source, hence the switch is OFF. On the other hand, the series diode switch, Fig. 2.2(b), is turned on by forward biasing the PIN diode and is turned off by zero or reverse biasing the PIN diode.

As discussed in the previous section, the PIN diode resembles a capacitance when the diode is zero or reverse biased. This diode junction capacitance affects the performance of each switch type differently. For the shunt switch configuration, the ON state is affected when the diode is zero or reverse biased. As the frequency increases, the shunt susceptance presented by the diode increases until the insertion loss rises to an unacceptable level. Conversely, the OFF condition of the series switch configuration is affected. As the frequency increases, more signal leaks through the decreasing capacitive reactance of the diode and the isolation of the switch is reduced. In practice, the degradation in isolation of series diode switches occurs at a much lower frequency than the corresponding degradation of insertion loss of shunt diode switches. Typically, the insertion loss of a shunt switch



a) Shunt diode switch



b) Series diode switch

Figure 2.2: PIN Diode Switch Configurations

will not be affected below 10 GHz whereas the isolation of a series switch drops significantly at frequencies above 1 GHz [4]. Consequently, the series configuration is seldom used at frequencies above 1 GHz.

2.4 SPDT PIN DIODE SWITCH DESIGN

A SPDT switch can be built by combining two PIN diode SPST switches with other circuit elements in such a way that when one diode is turned on the other diode is turned off. Figure 2.3 shows this circuit. The series circuit configuration is used because isolation is not a main concern.

In the circuit shown in Fig. 2.3(b), a positive bias current, I_B , turns on PIN diode D1 and allows RF to flow from A to B. A negative bias current turns on D2 and allows RF to flow from A to C. The SPDT switch is fabricated using microstrip line, with the signal carrying lines and the dc lines etched on the same dielectric substrate. The signal carrying lines have the standard characteristic impedance of 50 ohms. The dc return paths are provided by thin high characteristic impedance quarter-wave transmission lines connected to points B and C. Since the quarter-wave lines are short-circuit terminated, dc current can flow freely but the RF will encounter a very high impedance. For the same reason, dc bias current is fed to point N via a quarter-wave line. The capacitance C2 provides the RF ground and capacitance C1 prevents the dc bias current from appearing at the RF port of the switch.

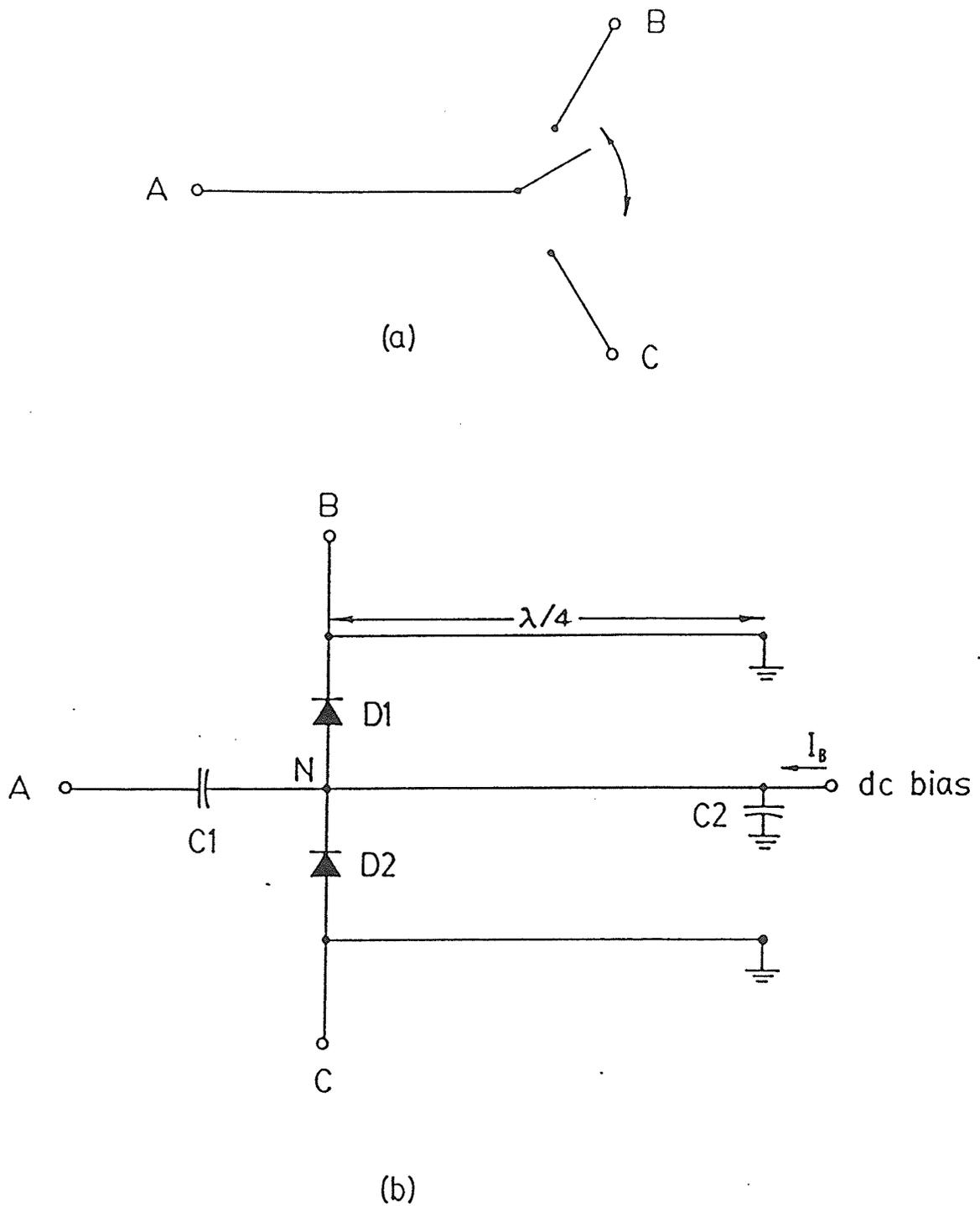


Figure 2.3: (a) Schematic Representation of a SPDT Switch
 (b) SPDT PIN Diode Switch

2.5 MICROSTRIP DESIGN FORMULAE

After the line characteristic impedance and the dielectric substrate have been selected, the task is to determine the needed line widths and the length of the quarter-wave lines. Many scientists have derived accurate formulae for microstrip calculations [5,6,7]. Figure 2.4 presents the

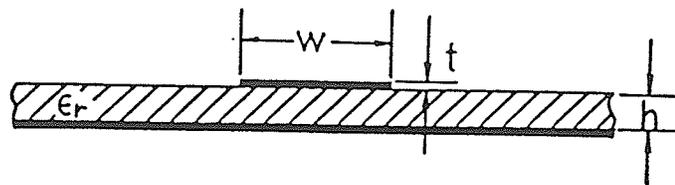


Figure 2.4: Cross-section of Microstrip Line

dimensional parameters of microstrip line. The following is a list of formulae needed to determine the dimensions of the microstrip lines for the switch. The formulae are obtained from reference [6]. For known characteristic impedance Z_0 and dielectric constant ϵ_r , these formulae give the microstrip width-to-height ratio w/h , and the effective permittivity ϵ_{eff} .

For narrow strips ($Z_0 > 44 - 2\epsilon_r$ ohms);

$$\frac{w}{h} = \left(\frac{\exp H'}{8} - \frac{1}{4 \exp H'} \right)^{-1} \quad (2.1)$$

where

$$H' = \frac{Z_0 \sqrt{2(\epsilon_r + 1)}}{119.9} + \frac{1}{2} \frac{(\epsilon_r - 1)}{\epsilon_r + 1} \left(\ln \frac{\pi}{2} + \frac{1}{\epsilon_r} \ln \frac{4}{\pi} \right) \quad (2.2)$$

For $w/h < 1.3$, $Z_0 > (63 - 2\epsilon_r)$ ohms;

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} \left\{ 1 - \frac{1}{2H'} \frac{(\epsilon_r - 1)}{\epsilon_r + 1} \left(\ln \frac{\pi}{2} + \frac{1}{\epsilon_r} \ln \frac{4}{\pi} \right) \right\}^{-2} \quad (2.3)$$

For $w/h > 1.3$, $Z_0 > (63 - 2\epsilon_r)$ ohms;

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 10 \frac{h}{w} \right)^{-0.555} \quad (2.4)$$

When w/h and ϵ_r are known, the following expression gives the value of Z_0 .

For narrow strips ($w/h < 3.3$);

$$Z_0 = \frac{119.9}{\sqrt{2(\epsilon_r + 1)}} \left[\ln \left\{ 4 \frac{h}{w} + \sqrt{16 \left(\frac{h}{w} \right)^2 + 2} \right\} - \frac{1}{2} \frac{(\epsilon_r - 1)}{\epsilon_r + 1} \left(\ln \frac{\pi}{2} + \frac{1}{\epsilon_r} \ln \frac{4}{\pi} \right) \right] \quad (2.5)$$

In the above expressions, the microstrip line thickness t has been ignored. For microstrips having $t/h \leq 0.005$, $2 \leq \epsilon_r \leq 10$, and $w/h \geq 0.1$, the effects of this thickness are negligible. At smaller values of w/h or greater values of t/h the effect of t is more significant.

2.6 FINAL DESIGN

There were two types of substrates available for the switch fabrication. The first type was the Ployguide, a polyolefin substrate manufactured by Electronized Chemical Corporation while the other was the OAK-601 PTFE/Woven Glass substrate manufactured by Oak Laminates. The OAK-601 substrate was chosen because of its more rigid construction. The polyolefin substrate had a tendency to warp and the copper cladding separated from the dielectric easily. The relative permittivity of the OAK-601 substrate is 2.54.

The switch was designed to operate at a center frequency of 860 MHz. The line widths and lengths were calculated using the formulae given in the previous section. The line width of the signal carrying lines were calculated to be 4.48 mm and the bias line length to be 62.19 mm. The bias line width was chosen to be 1.27 mm. The detailed calculations are listed in Appendix A. To reduce the error introduced when laying out the circuit, the circuit was drawn five times the actual size. The circuit layout was then sent to a graphic shop for reduction back to true size. The microstrip line layout is shown in Fig. 2.5 (not actual size).

To allow for line width adjustments, three circuit boards were made. The first board was made with line widths according to the calculated value. The second one was made 5% narrower and the third 5% wider than the calculated line

width. The boards were tested and the board with the best impedance match was picked. Gaps were cut on the microstrip line to accommodate the PIN diodes and the capacitors. The HP 50082-3001 PIN diodes were chosen because their specifications fit our requirements and the diodes were easily available. The diodes and the capacitors were soldered in place and the circuit was housed in an aluminum enclosure. For easy connection, female SMA connectors were mounted at each port of the switch. An AMP Series 30 type low frequency feed-through capacitor was used at the dc bias input terminal. A picture of the finished SPDT switch is shown in Fig. 2.6. A drawing of the metal enclosure is presented in Appendix B.

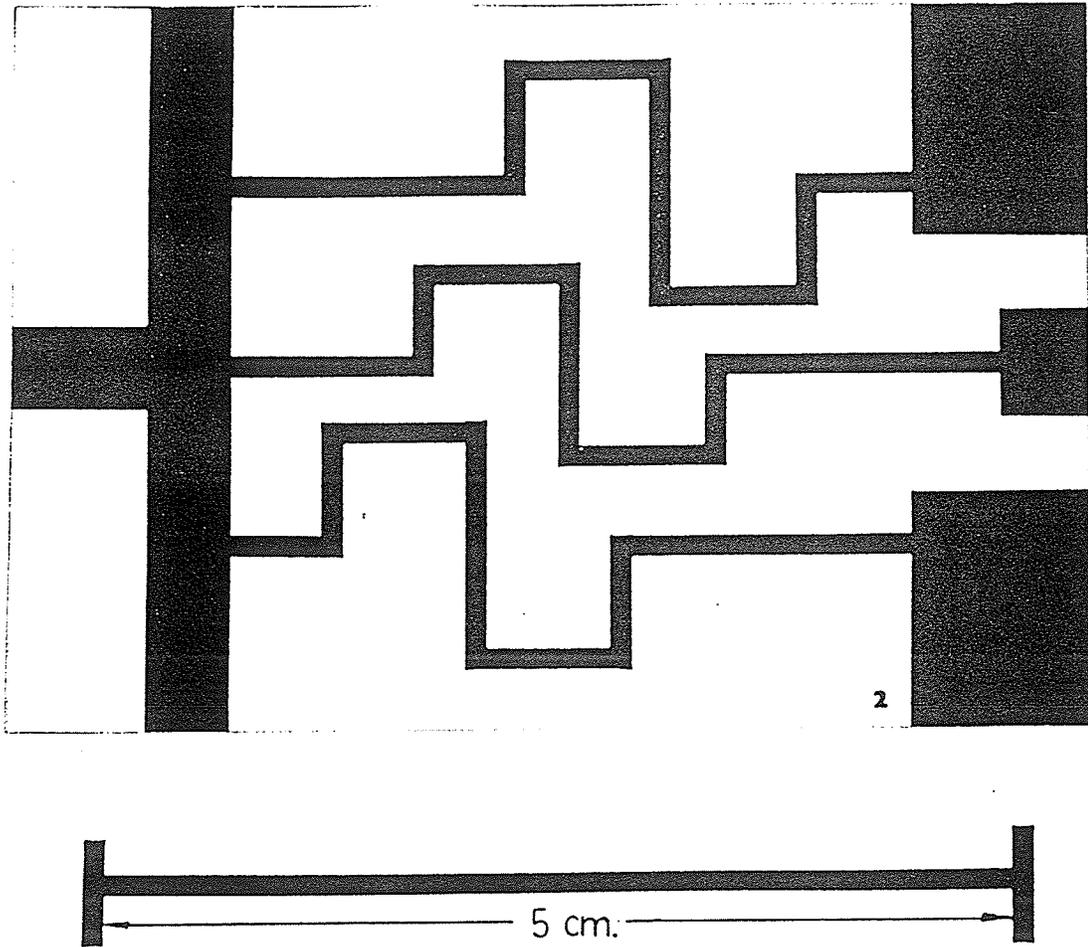


Figure 2.5: SPDT Printed Circuit Board Layout

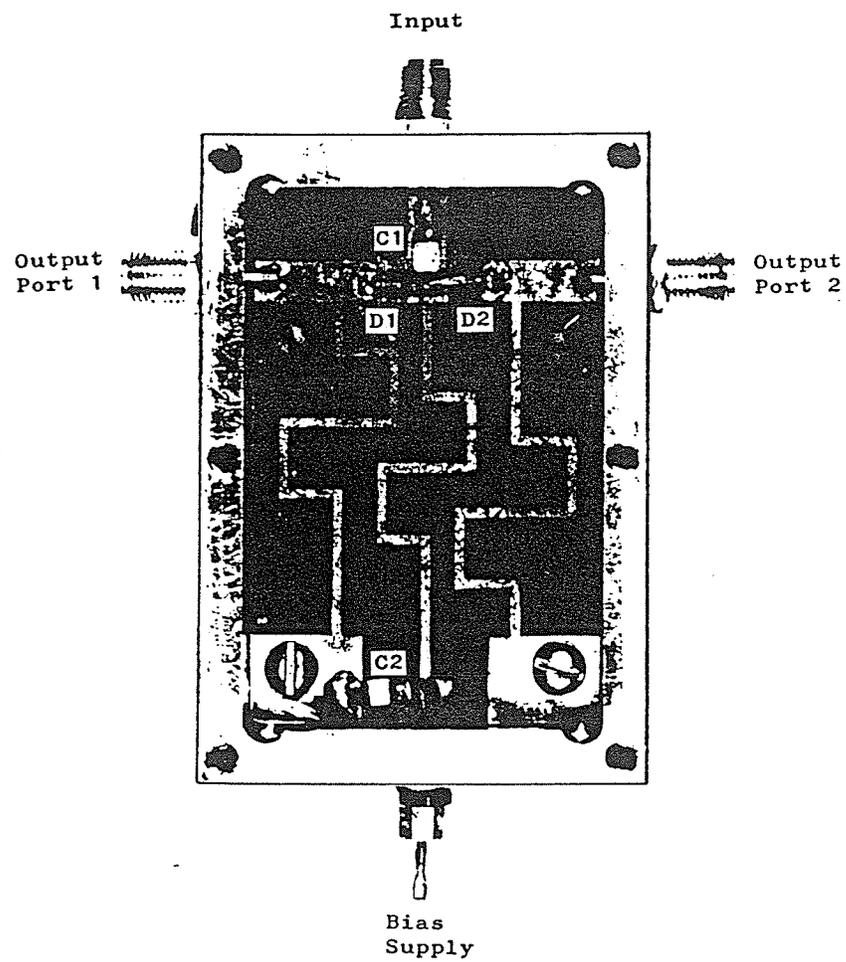


Figure 2.6: The Completed SPDT Switch

Chapter III

COMPUTER AIDED DESIGN ANALYSIS

3.1 INTRODUCTION

To ensure the success of the SPDT switch design and provide a means for easy future design changes, the performance of the switch was determined by computer modeling after the actual implementation and testing of the switch. This was done by gathering the specifications of all circuit components and dimensional information of the switch circuit. The switch insertion loss and return loss for transmission to the two output ports are required over the operating frequency band. Fortunately, this analysis task was simplified with the aid of Touchstone,¹ a microwave simulation and optimization program package supplied by EEsof Inc. The program runs on IBM and IBM-compatible PCs.

3.2 CIRCUIT MODELING

The first step of using the Touchstone computer aided design (CAD) package is to replace the designed circuit elements by circuit models that are recognizable by the computer. Then the circuit is translated into a circuit file - a description of the circuit and instructions to Touchstone

¹ © 1985 by EEsof Inc., Westlake Village, CA.

for measuring the circuit and displaying the results. The designed circuit shown in Fig. 2.5 was broken up into circuit blocks by referencing to the Touchstone element catalog [8]. Figure 3.1 presents the Touchstone circuit model of the designed switch shown in Fig. 2.6. A listing of the circuit file is presented in Appendix C.

PIN DIODE MODEL

A model of the HP-3001 PIN diode suitable for use by Touchstone was developed based on the manufacturer's specifications and actual measurement on a PIN diode embedded in series in a short microstrip line with no additional circuitry (i.e., biasing was applied via the network analyzer) [9].

The component values listed in Fig. 3.2 were partly obtained from the manufacturer's specifications and partly derived using Touchstone. The component values were adjusted to make the characteristics predicted by Touchstone coincide with the measured characteristics of the embedded diode since the complete component values of the diode model could not be obtained from the PIN diode catalog.

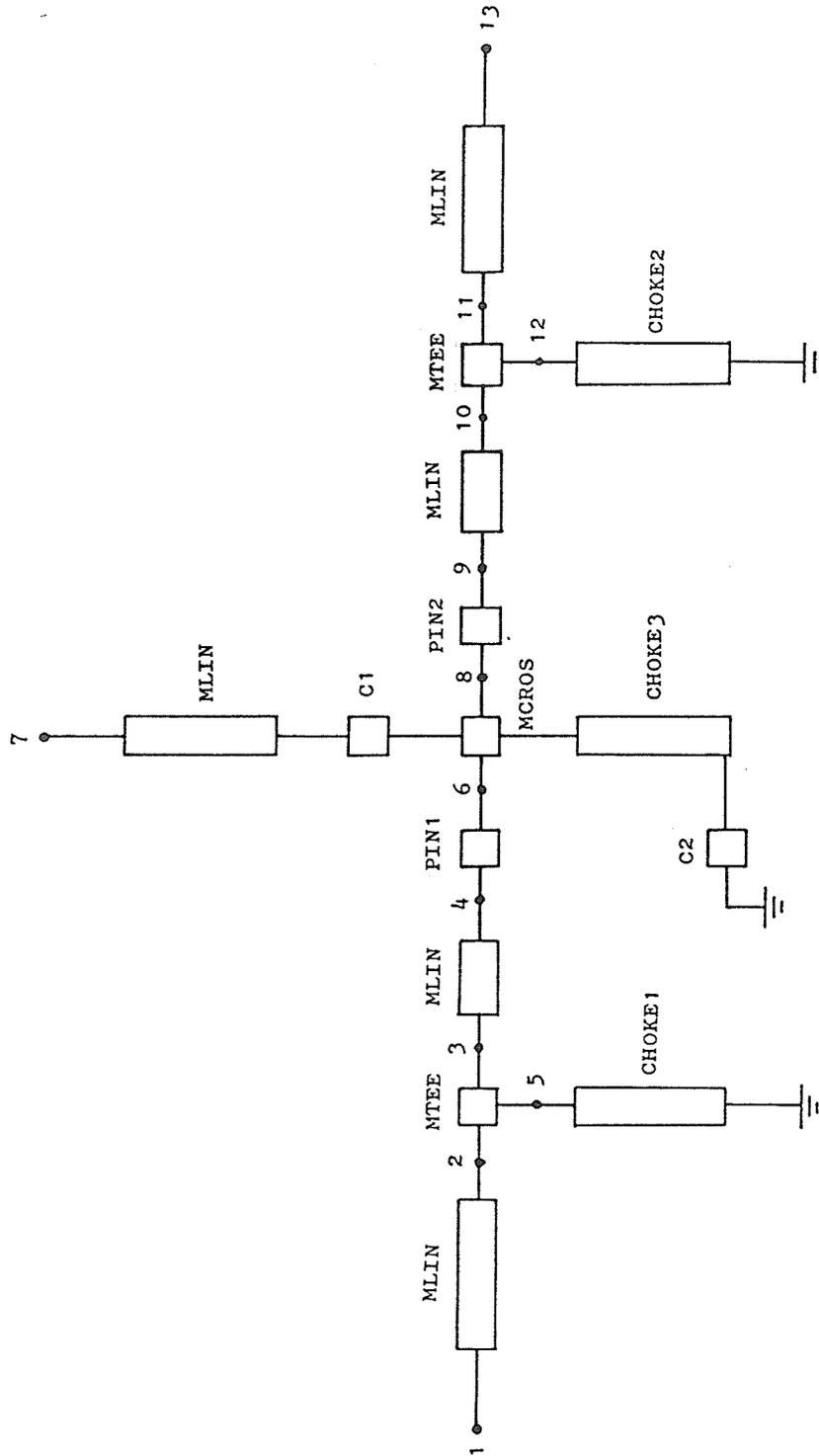
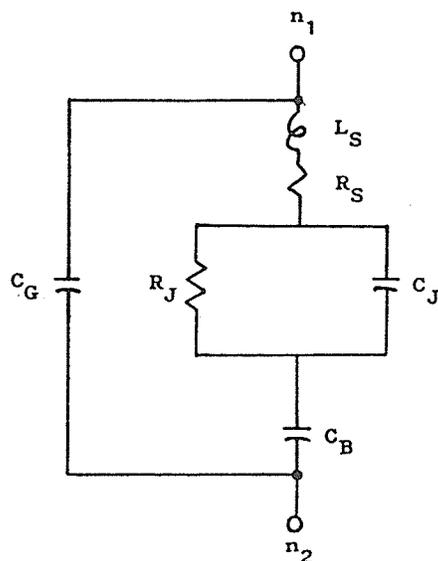


Figure 3.1: Computer Circuit Model of SPDT Switch



- C_J = junction capacitance, 0.08 pF
 R_J = junction resistance, 0.1 ohm ON, 10 k Ω OFF
 R_S = diode series resistance, 0.9 ohm
 L_S = bond wire inductance, 2.5 nH
 C_B = by pass capacitance, 1000 pF
 C_G = capacitance of gap across which diode
 is connected, 0.13 pF

Figure 3.2: Computer Model of HP-3001 PIN Diode

3.4 RESULTS OF COMPUTER ANALYSIS

The Touchstone program predicted that the switch circuit using a microstrip line width 5% wider than the calculated width would have the best performance. Figure 3.3 shows the predicted insertion loss of the switch over the frequency range 800 to 900 MHz. The return loss and isolation over frequencies 800 to 900 MHz are shown in Fig. 3.4 and Fig. 3.5, respectively. From the Figures, an insertion loss value of 0.25 dB, return loss of 17.2 dB and isolation of 23.5 dB were predicted at 860 MHz. Hence, computer analysis verifies that the design is practical.

Further computer analysis show that the insertion loss of the switch at 860 MHz with the OFF state arm removed was 0.2 dB which implied that 0.05 dB was lost in the OFF state arm. By removing all transmission line losses and mismatch losses from the circuit, an insertion loss of 0.09 dB was predicted for the switch. This value agreed with the calculated insertion loss caused by the 1 ohm forward residual resistance of the PIN diode.

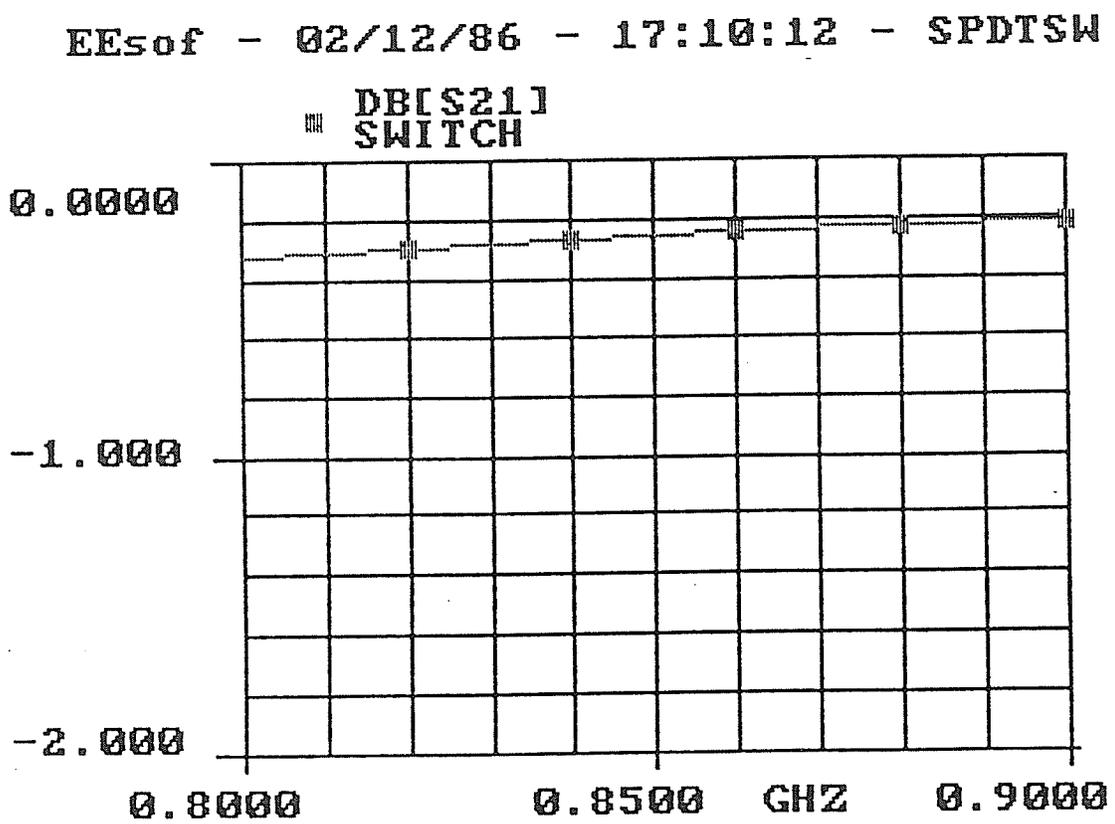


Figure 3.3: Insertion Loss Predicted by Touchstone

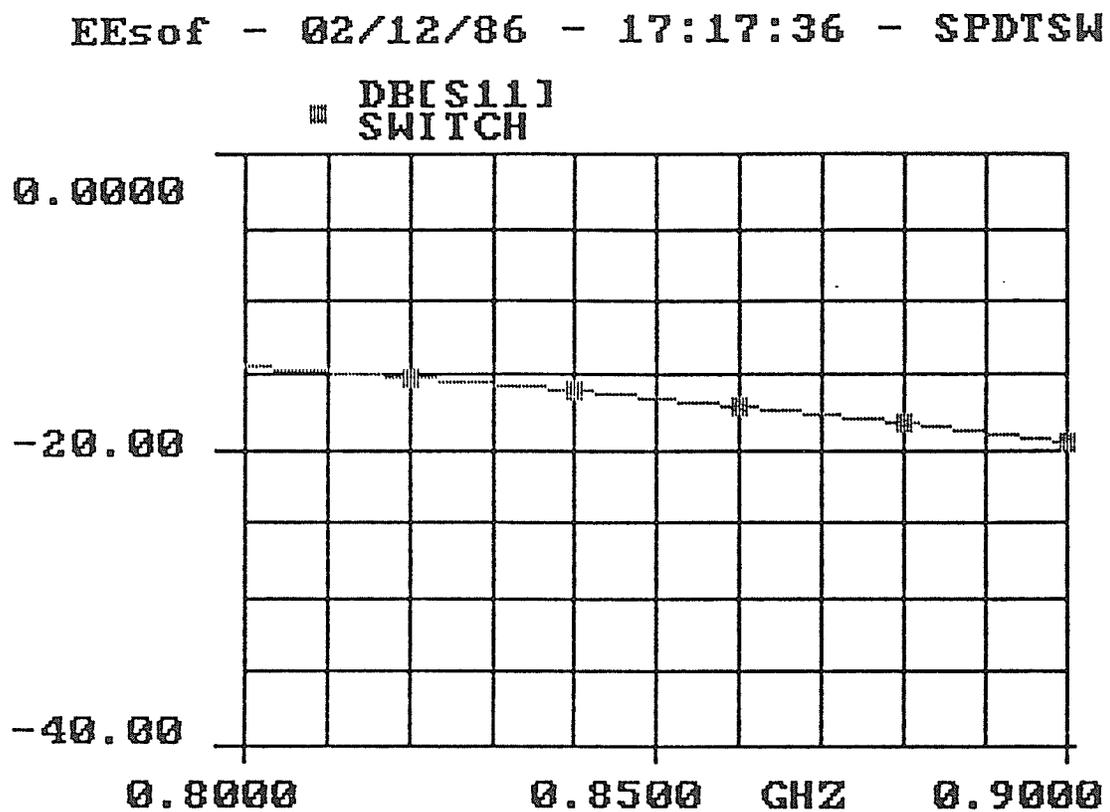


Figure 3.4: Return Loss Predicted by Touchstone

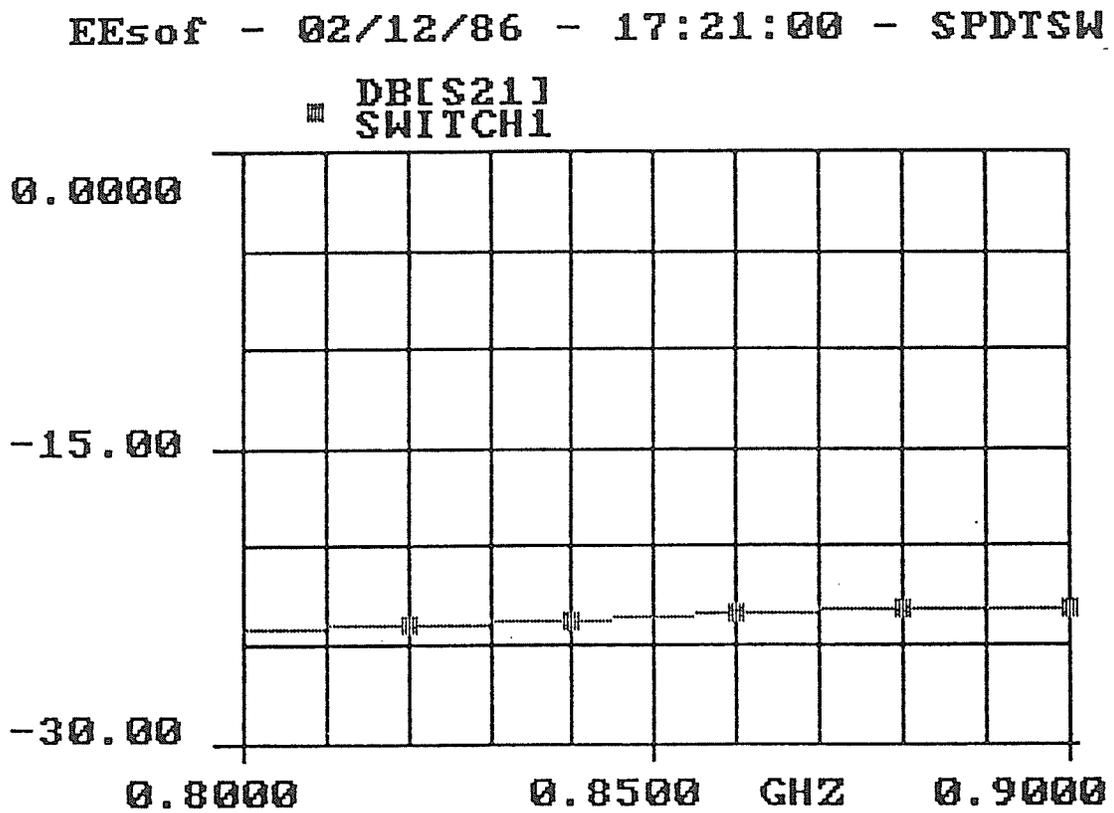


Figure 3.5: Isolation Predicted by Touchstone

Chapter IV

MEASUREMENT TECHNIQUES AND TEST RESULTS

4.1 INTRODUCTION

At this point, another important phase of the design work is needed - testing the switch. For the switch to be acceptable for practical use, it must be tested to check whether it meets the required specifications. The following are performance parameters of the switch which need testing:

- i) characteristic impedance,
- ii) insertion loss,
- iii) isolation,
- iv) return loss,
- v) phase difference between the two signal paths of the switch,
- vi) power handling.

4.2 TEST PROCEDURES AND RESULTS

To evaluate the performance of the switch the following instruments were used to measure the performance of the switch:

- i) Sweep Oscillator (HP 8690A),
- ii) Network Analyzer Mainframe (HP 8410A),

- iii) Output Display Plug-In Units: Phase-Magnitude Display (HP 8412A), Polar Display (HP 8414A),
- iv) S Parameter Test Set (HP 8745A),
- v) Harmonic Frequency Converter (HP 8411A),
- vi) Universal Extension (HP 11604A),
- vii) Microwave Frequency Counter (Systron Donner 6030),
- viii) Power Meter (HP 436A),
- ix) Power Sensor (HP 84818),

In addition to the above instruments, a variety of cables, connectors and adapters were utilized.

The HP 8410A Network Analyzer System was used to measure the characteristic impedance, insertion loss, isolation, return loss and phase difference of the switch. The general test set up is shown in Fig. 4.1. Before any measurement can be made, the instruments must be properly calibrated. For the above measurements, the sweep oscillator (HP 8690A) was set to sweep between 800 and 900 MHz. The S-parameter switch was set to S_{11} or S_{21} according to the measurement of interest.

4.2.1 Measurement of Characteristic Impedance

The very first step in implementing the SPDT switch was to lay out on the substrate the microstrip signal lines and dc bias lines. As mentioned in Chapter Two, three circuit boards were made. The characteristic impedance of each board was measured to determine the best line width.

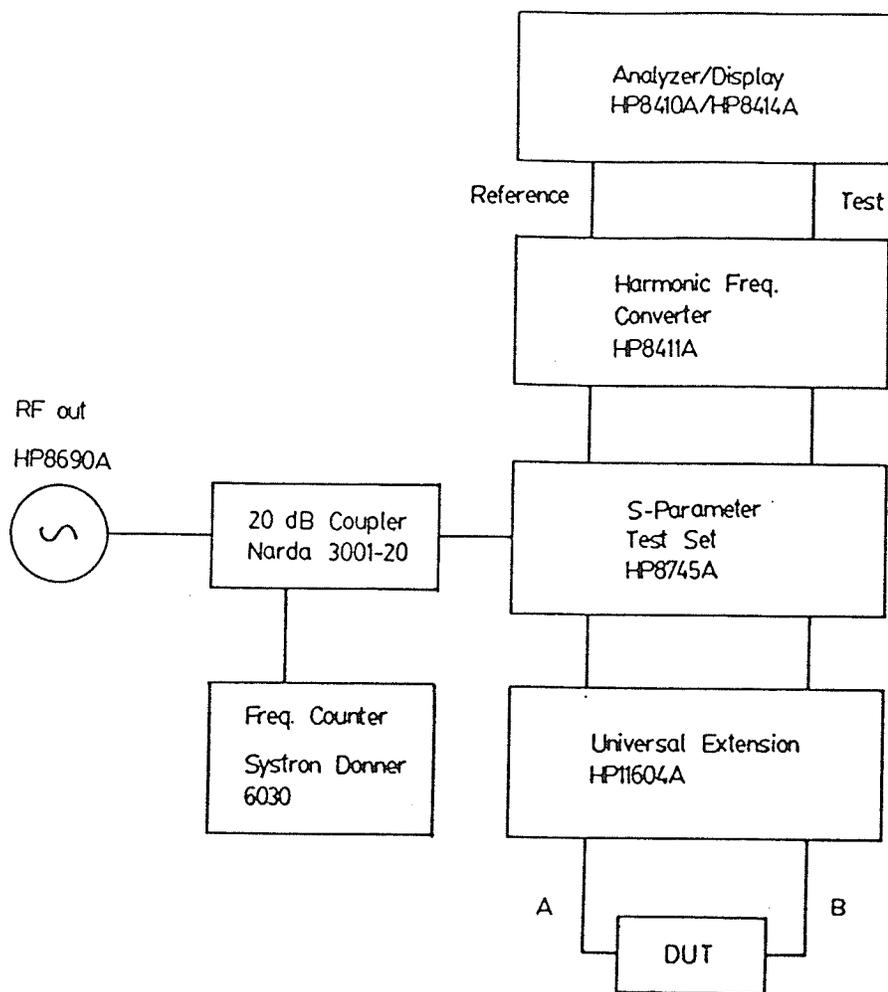


Figure 4.1: General Test Set Up

The characteristic impedances of the three circuit boards were observed on the Smith Chart overlay. The impedance of the circuit board with a line width 5% wider than the calculated value was closest to 50 ohms over the frequency range 800 to 900 MHz. Therefore the SPDT switch was fabricated on this particular board.

The measured result agreed with that predicted by Touchstone. Further investigation show that the calculated line width did give the best impedance response but only when the dc bias lines were removed. The wider line compensates for the effect of discontinuities introduced at the junctions of the dc bias lines to a better degree than the narrower lines. Hence, the wider line gave better overall performance. Figure 4.2 shows the wide-line circuit impedance response over the frequency range 800 to 900 MHz.

4.2.2 Measurement of Insertion Loss and Isolation

One parameter of major interest of the SPDT switch is insertion loss. Insertion loss is a measure of the loss of signal through the switch via its ON state path. In a series switch, the insertion loss is primarily determined by the forward resistance of the diode. Other losses include the microstrip loss and the mismatch loss.

The switch was inserted between the arms of the Universal Extension (HP 11604A) as shown in Fig. 4.3. A bias current of 50 mA was used to turn on the diode that was under test.

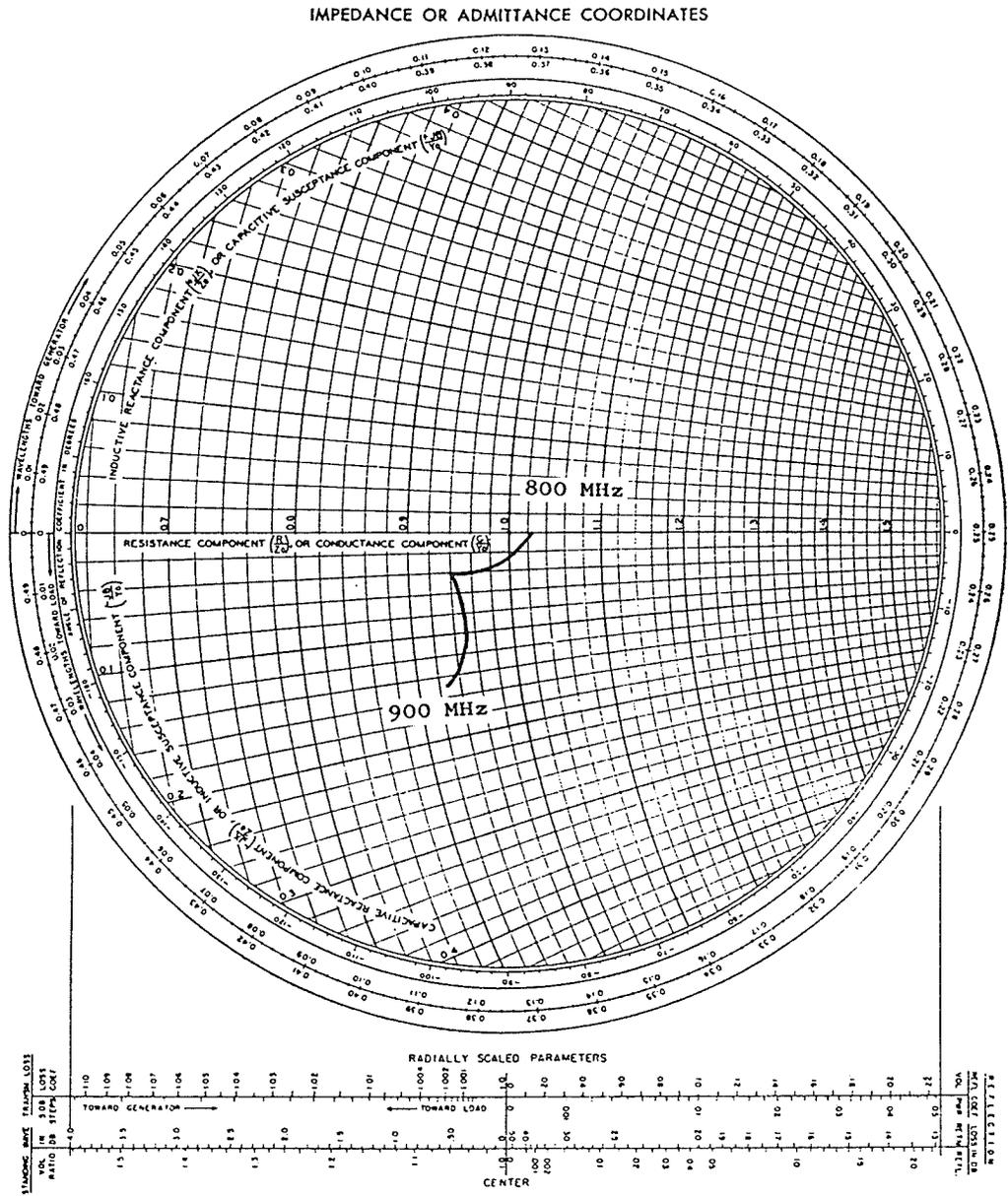


Figure 4.2: Characteristic Impedance of Signal Path

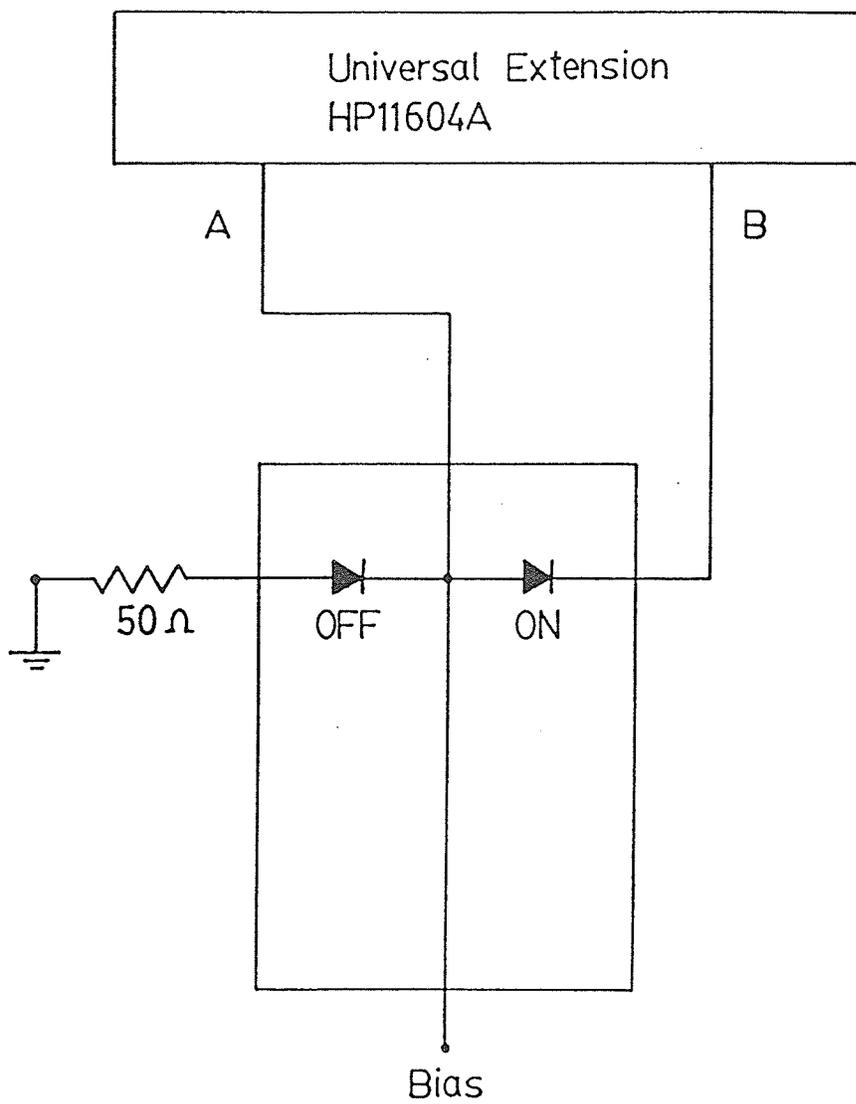


Figure 4.3: Connection of Switch to the Universal Extension

The insertion loss S_{21} on the Phase-Magnitude Display was read. Then the bias current was reversed and the insertion loss of the other arm of the switch measured.

Isolation is a measure of signal leakage between the input and output via an OFF state path. The isolation of the switch was measured using the same set up as above except that the insertion loss readings were taken at each OFF state arm of the switch.

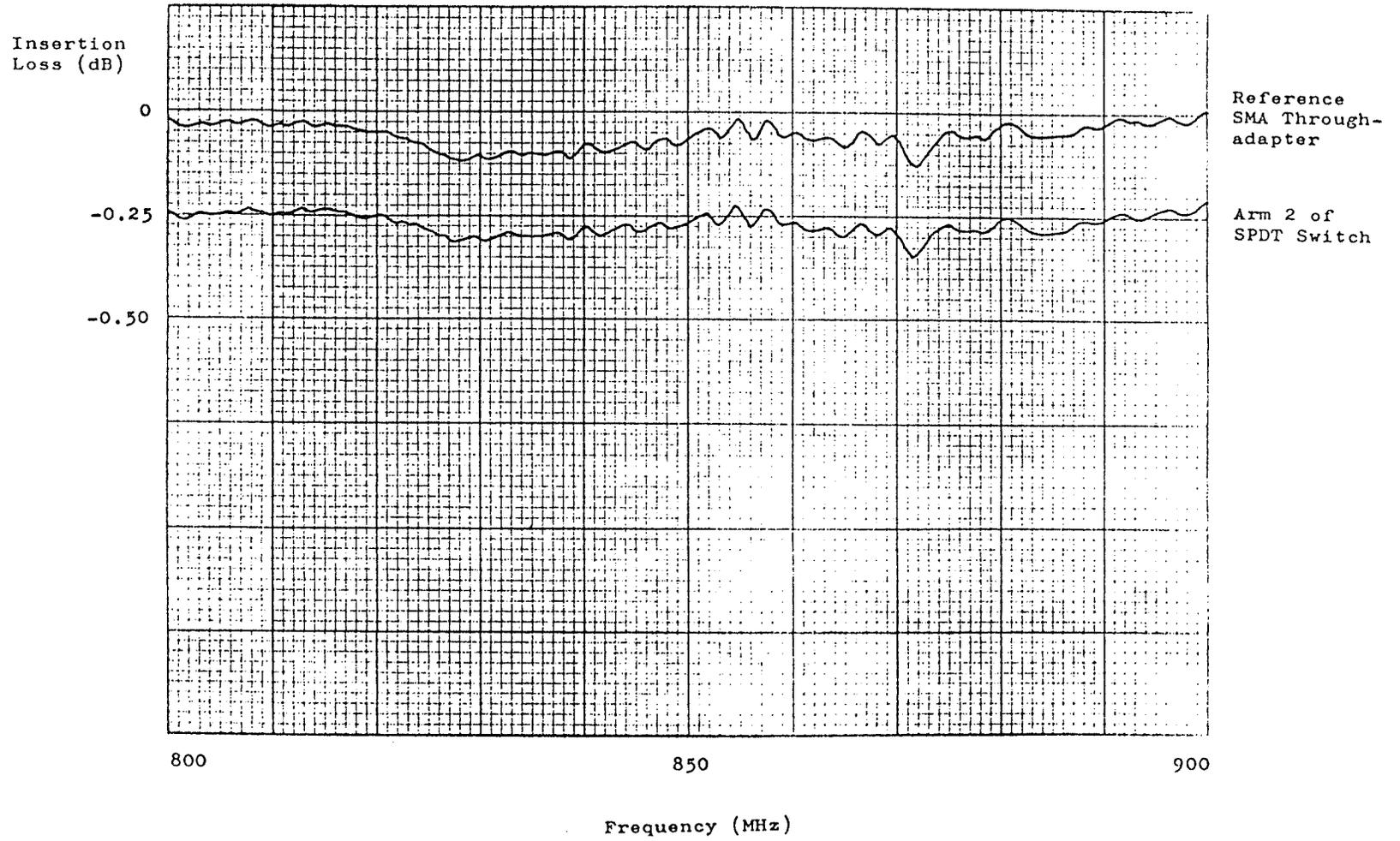
The insertion loss of both arms of the switch at 860 MHz was measured to be 0.25 ± 0.05 dB. For reference, the insertion loss of the switch was compared to that of a Narda Model 59 SMA through-adapter. Figure 4.4 shows the insertion loss of arm 2 of the switch versus frequency.

An isolation value of at least 27 dB was measured for both arms of the switch as shown in Fig. 4.5. This degree of isolation satisfies the design requirement. The measured insertion loss of 0.25 dB at 860 MHz agreed with the predicted value shown in Fig. 3.3. The measured isolation was better than the predicted value of 23.5 dB at 860 MHz as shown in Fig. 3.5.

4.2.3 Measurement of Return Loss

The return loss is a measure of the fraction of incident power which is reflected back toward the source. This measurement provides an indication of how well the switch is matched. The return loss is given by

Figure 4.4: Insertion Loss of Switch



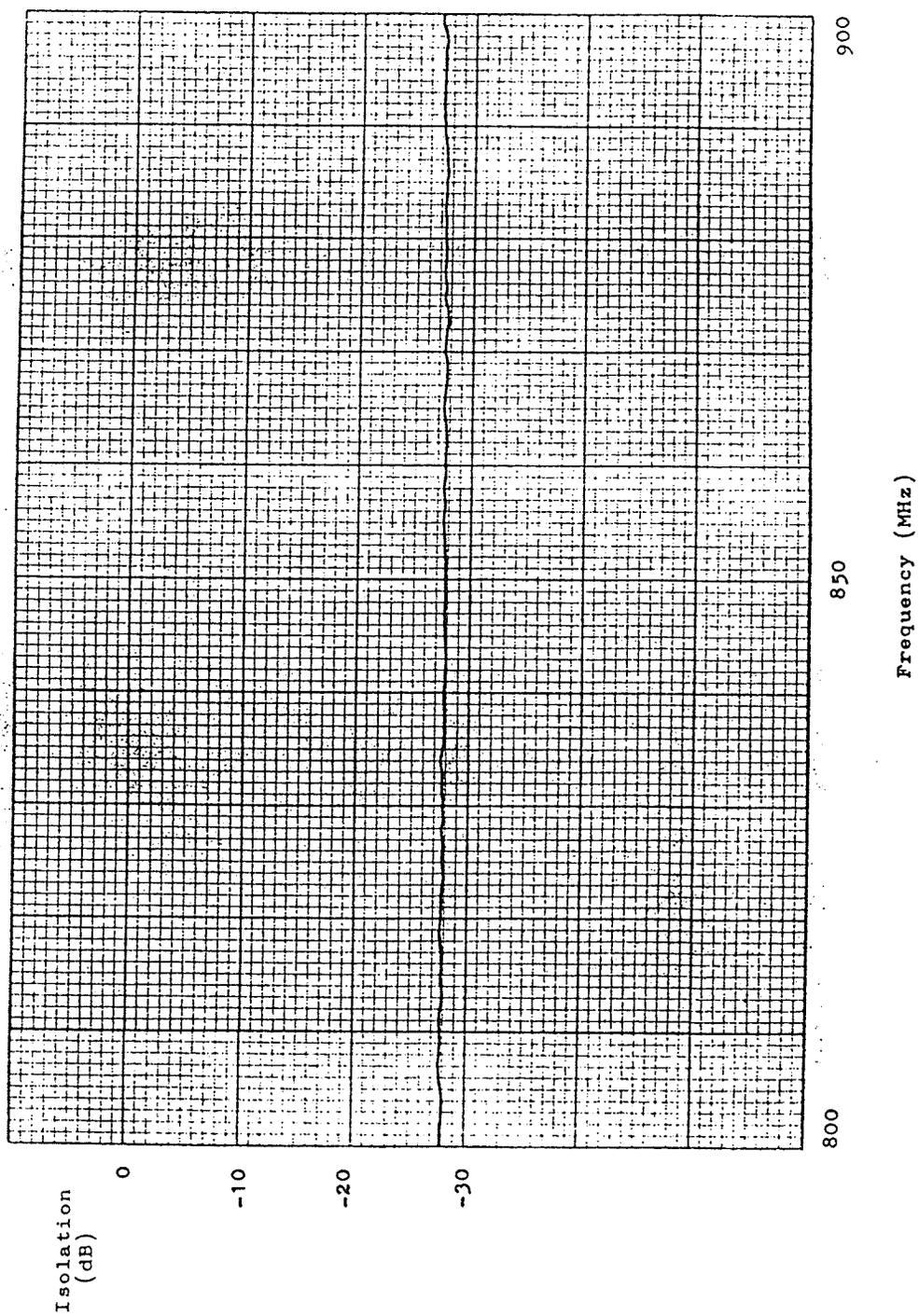


Figure 4.5: Isolation versus Frequency

$$L_r = 20 \log \frac{1}{|S_{11}|} \quad (4.1)$$

The measurement set up as shown in Fig. 4.1 was again used except that the S-Parameter unit was set to read S_{11} . One side of the switch was turned on by forward biasing the PIN diode with a 50 mA bias current. The return loss was read off the Phase-Magnitude Display. The bias current was then reversed and the return loss of the other arm of the switch was measured.

Arm 1 of the switch was measured to have a return loss of 26 dB while a value of 23 dB was obtained for arm 2 of the switch. The difference in return loss between the two arms is probably due to a slight difference in characteristics of the two PIN diodes. These values compare favourably with that for a Narda Model 59 adapter which has a return loss of about 30 dB. The measured return loss was better than predicted (see Fig. 3.4) by about 6 dB.

Figure 4.6 and 4.7 show the reflection coefficient of arms 1 and 2 of the switch, respectively. These measurements were made in addition to the return loss measurements and show that the switch is well matched.

The insertion loss, L_i , of the switch can be broken up into two components, the Z_0 -mismatch loss, L_{m0} , and the dissipation loss, L_d . These are related to scattering parameters as follows:

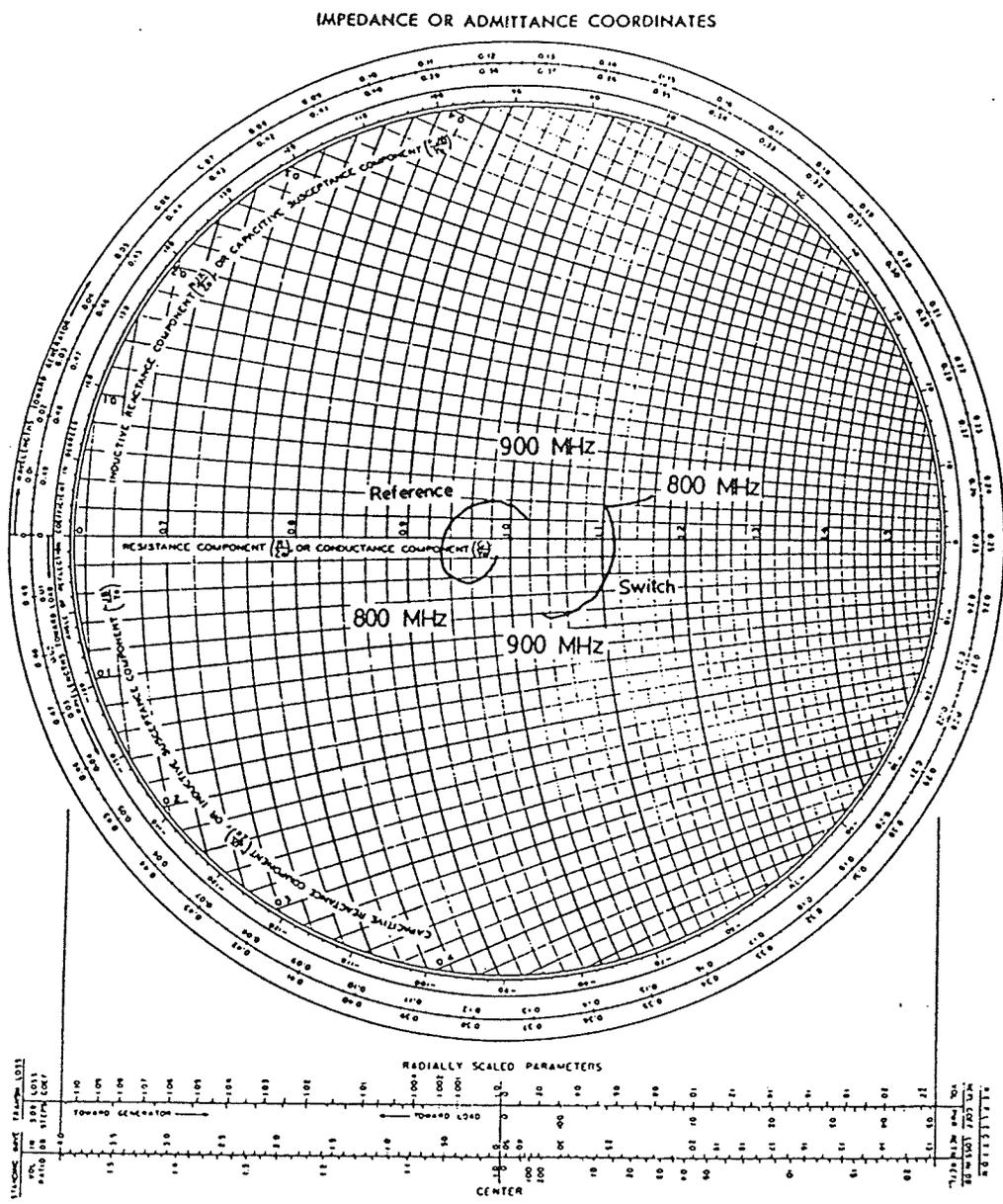


Figure 4.6: Reflective Coefficient of Arm 1 of Switch

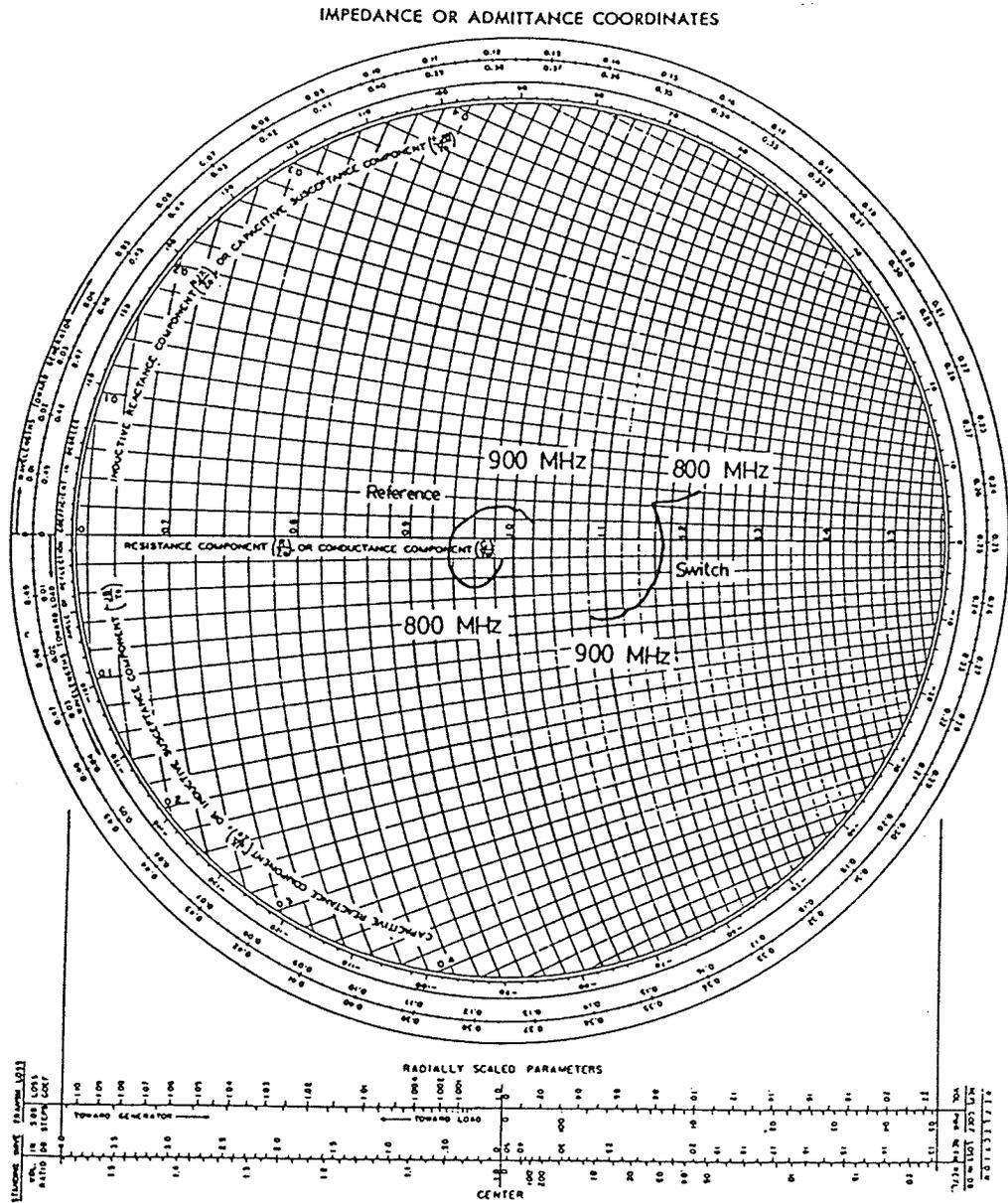


Figure 4.7: Reflective Coefficient of Arm 2 of Switch

$$L_i = L_d + L_{mo} \quad (4.2)$$

where

$$L_i = 10 \log \frac{1}{|S_{21}|^2} , \quad (4.3)$$

$$L_d = 10 \log \frac{1 - |S_{11}|^2}{|S_{21}|^2} \quad \text{and} \quad (4.4)$$

$$L_{mo} = 10 \log \frac{1}{1 - |S_{11}|^2} \quad (4.5)$$

For the switch, $L_i = 0.25$ dB; using (4.2), yields $|S_{21}| = 0.972$. From return loss measurement, $|S_{11}| = 0.071$; using (4.4), $L_{mo} = 0.0218$ dB. Hence, $L_d = L_i - L_{mo} = 0.228$ dB. Since the dissipation loss forms the major part of the insertion loss, we can conclude that the switch is well matched.

4.2.4 Measurement of Phase Difference

The same set up used for previous measurements was employed. The Polar Display Plug-In unit was used with the Network Analyzer. The S-Parameter select switch was set at S_{21} . The two arms of the switch were turned on successively and connections made to the analyzer so that the phase of the

signal at each output port could be read off the face of the Polar Display.

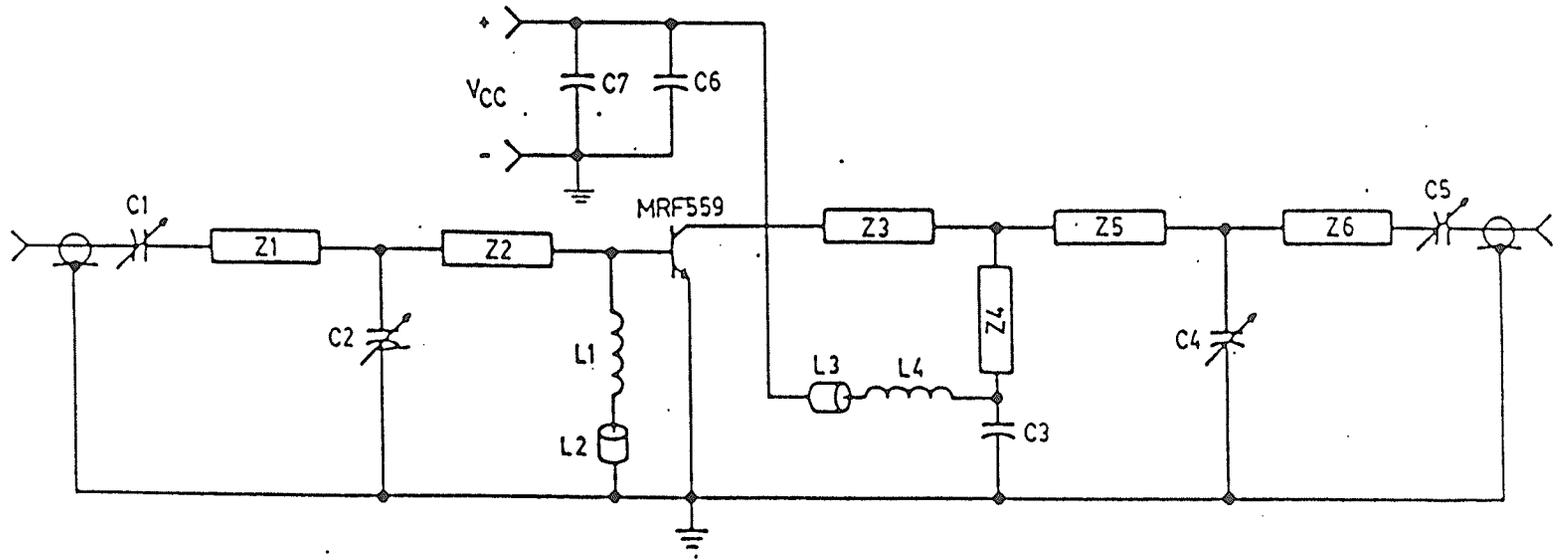
The signal phase difference between the two arms of the switch was very small and could not be resolved by the test instrument. The line length of each path through the switch was approximately 80 electrical degrees. Hence, the switch exhibits good phase balance between the two arms.

4.2.5 Measurement of Power Handling

This is one of the most important parameters of the designed SPDT switch. The major reason that commercially available SPDT switches are not suitable for the proposed application is their limited power handling capability. For the MSAT application, a switch that can handle 3 watts of RF power is needed while most commercial switches can only handle about 100 milliwatts.

To experimentally determine the power handling capability of the SPDT switch, a medium power RF source was required. For this purpose, a two stage RF amplifier capable of supplying 20 watts was constructed. The Motorola MRF 559 NPN silicon high frequency transistor was used for the first stage amplification. The amplifier circuit shown in Fig. 4.8 was based on the test circuit provided in the manufacturer's data manual [10]. The circuit board layout is shown in Fig. 4.9, OAK-601 substrate was used as the printed circuit board material. SMA connectors were used at the input and output

Figure 4.8: Driver Circuit for MHW820-1 Power Module



C1,C2,C4,C5—1.0-10 pF Johanson
 C3,C6—0.001 μ F Chip Capacitor
 C7—1.0 μ F Tantalum
 L1,L4—4 Turns #26 AWG, 0.31D, 4mm Long
 L2,L3—Ferrite Bead
 Microstrip— $\epsilon_r = 2.54$

Z1—50 Ω 10.23 mm
 Z2—30 Ω 13.38 mm
 Z3—50 Ω 13.65 mm
 Z4—50 Ω 8.19 mm
 Z5,Z6—50 Ω 8.53 mm

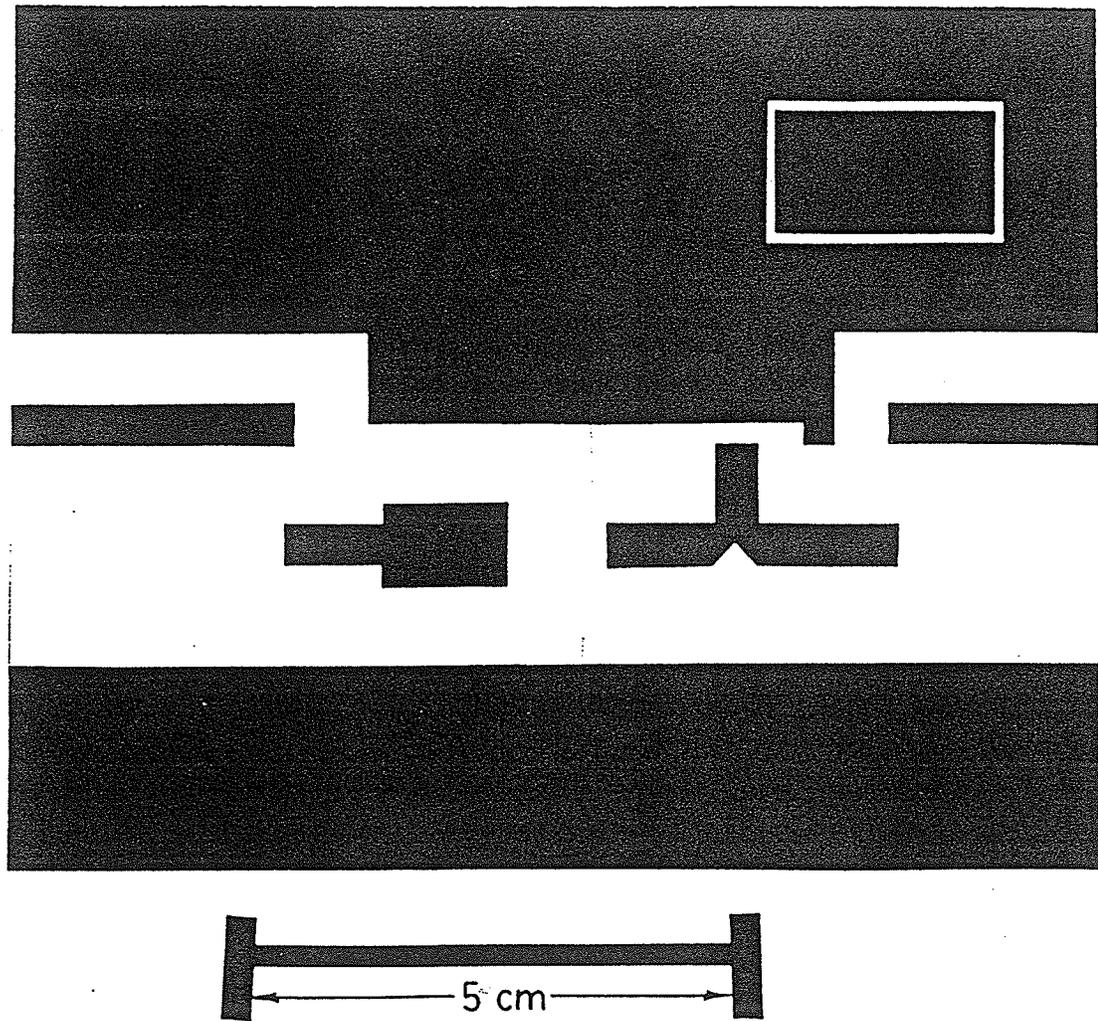


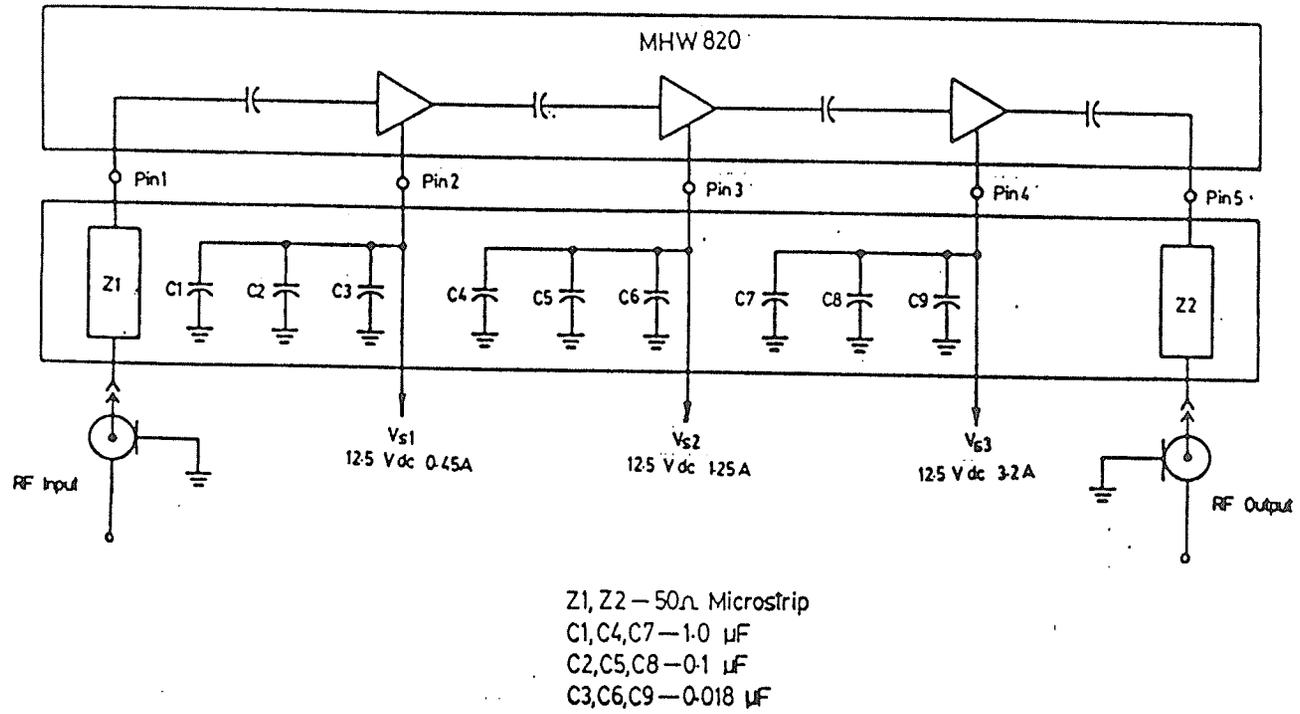
Figure 4.9: Driver Circuit Board Layout

ports for external connections. The amplifier was designed to operate at 860 MHz, with an output of 26 dBm obtained for an input of 17 dBm. The second stage used the Motorola MHW820-1 UHF Power Amplifier Module as the active component. The circuit design was also based on the manufacturer's data manual [10]. The amplifier circuit is shown in Fig. 4.10 and the circuit board layout in Fig. 4.11. As before, OAK-601 was used as the microstrip substrate. An SMA connector was used at the input port while an N connector was used at the output port to handle the high output power. The MHW820-1 amplifier module was mounted on an 4x3.5x0.5 inch aluminum slab for heatsinking. For output level control, Vs2 and Vs3 were kept at 12.5 Vdc while Vs1 was adjusted to give the required output power. A maximum power of 20 watts was obtained at 860 MHz. Pictures of the finished amplifiers are shown in Fig. 4.12.

Figure 4.13 shows the test set up for power measurements. To evaluate the performance of the switch over a period of time, the HP 436A Power Meter was interfaced with the HP 85 computer. A program was written to monitor the power flowing through the switch and the voltage across the PIN diode continuously. The program listing can be found in Appendix D.

Figure 4.14 shows the output power level of the switch versus time at various input power levels at 860 MHz. The power versus time graphs show that the switch can handle

Figure 4.10: 806-870 MHz 20 W Power Amplifier



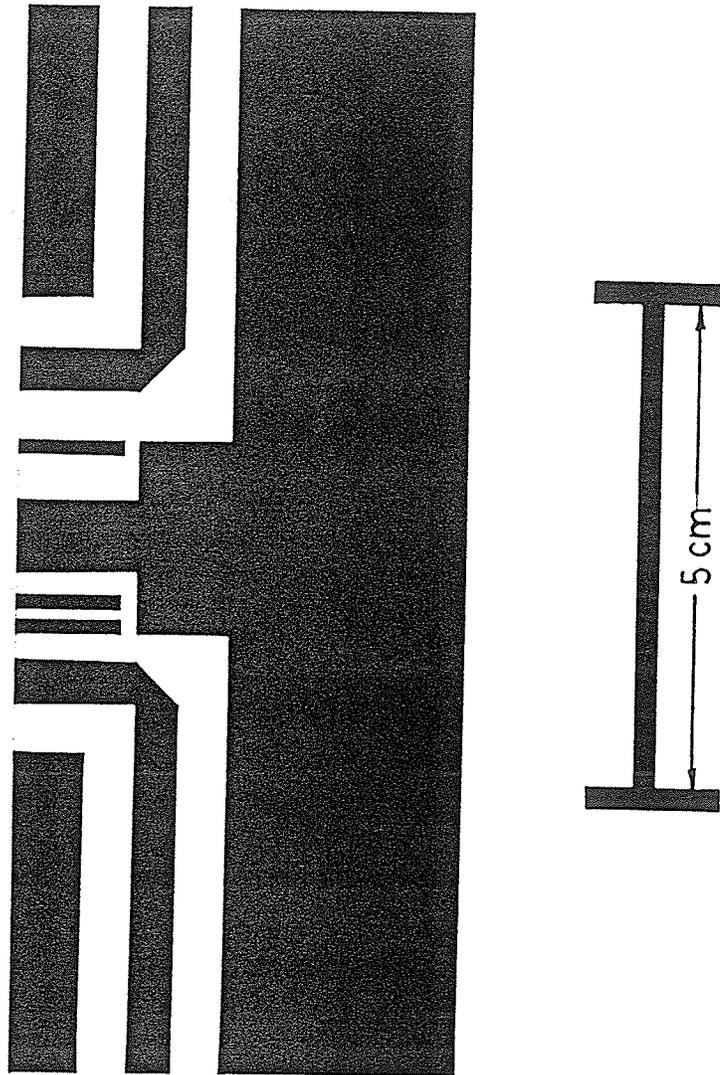
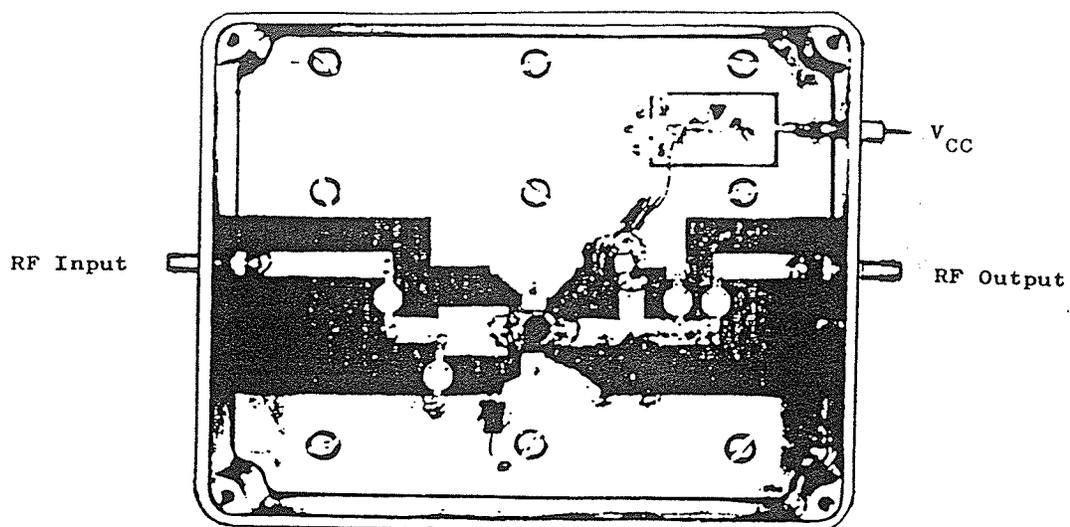
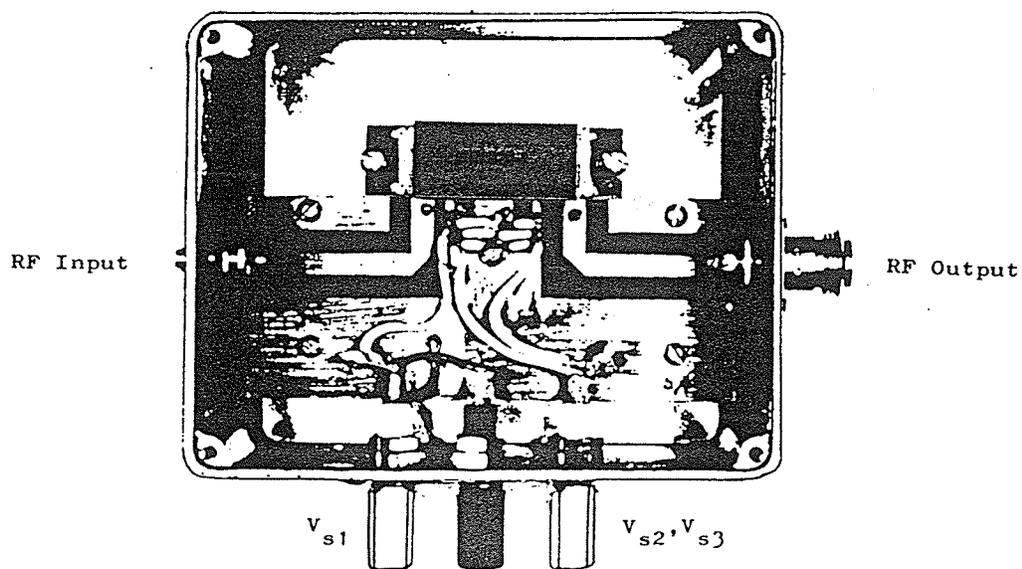


Figure 4.11: Power Amplifier Circuit Board Layout



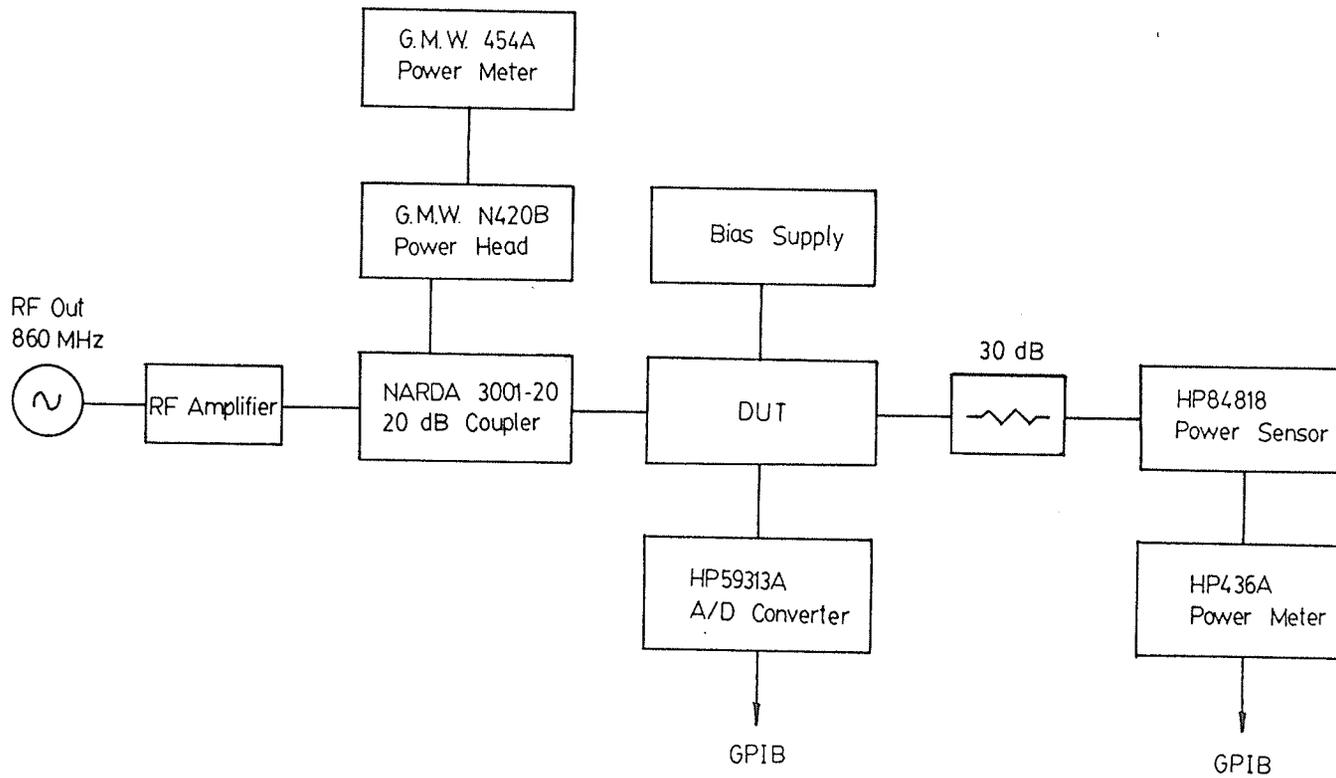
Driver



Power Amplifier

Figure 4.12: The Completed Power Amplifier

Figure 4.13: Power Measurement Test Set Up



3 watts of RF power continuously without stress. In fact, the switch survived a 12-watt input which was applied intentionally for a duration of 100 second with no apparent damage to the diode. The switch could also handle high power transfer with a mismatched load (VSWR = 4.2) connected to the output of the switch. For input levels of 2, 4, and 6 watts, the output remained steady over a long period of time. The insertion loss of 0.25 dB calculated from the power measurements agreed with the insertion loss measured earlier with the network analyzer. At higher input power levels, the output power dropped as the PIN diode warmed up.

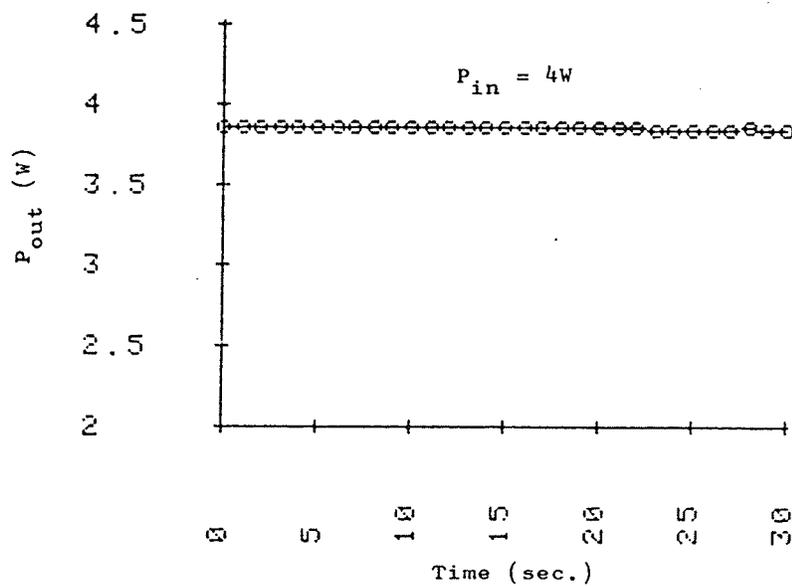
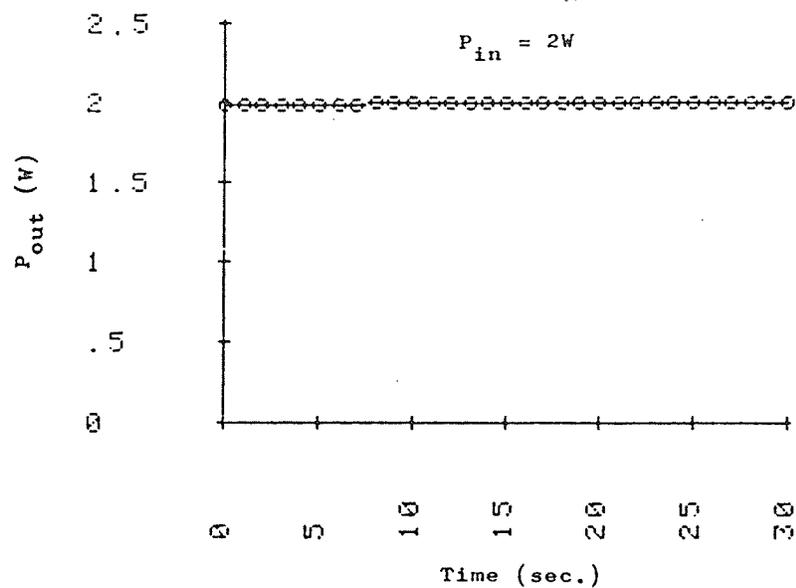


Figure 4.14: Output Power Level at Various Input Power Levels

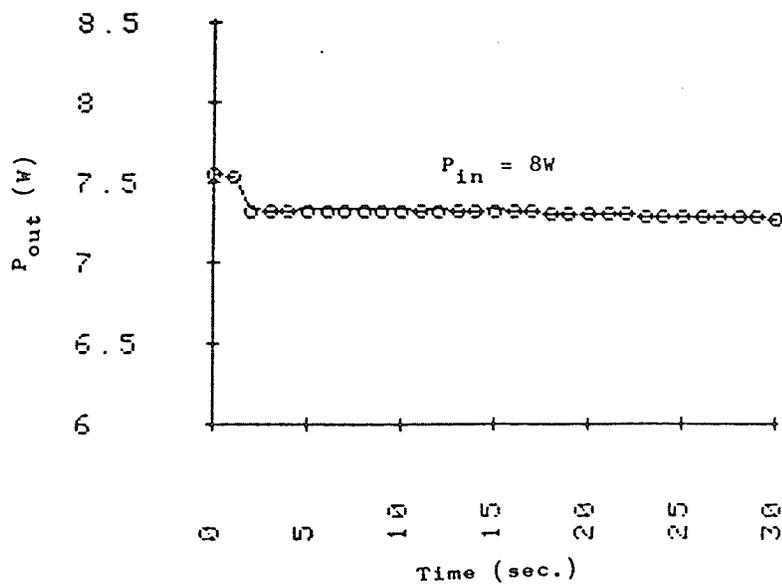
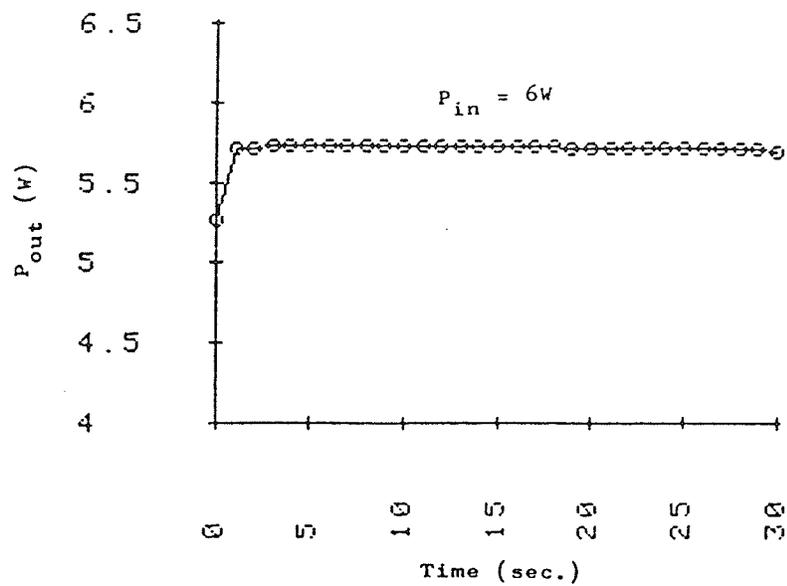


Figure 4.14 (Cont'd): Output Power Level at Various Input Power Levels

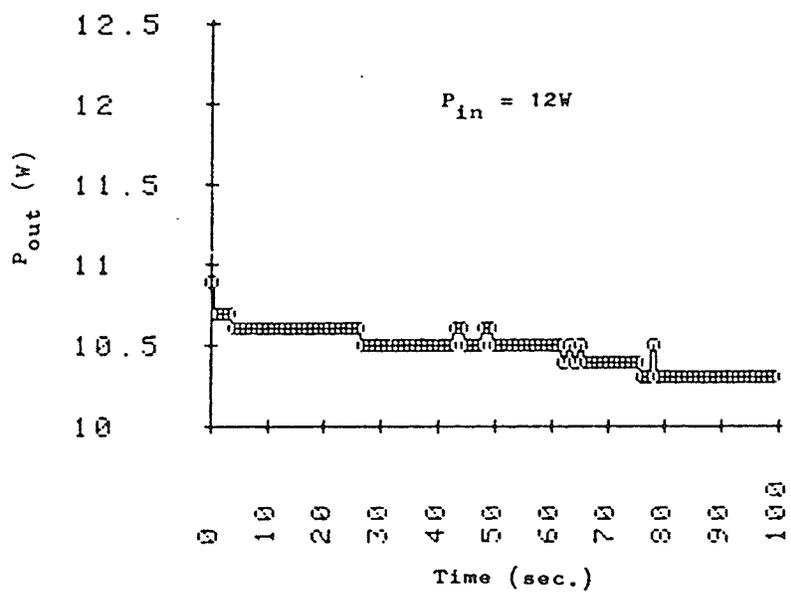
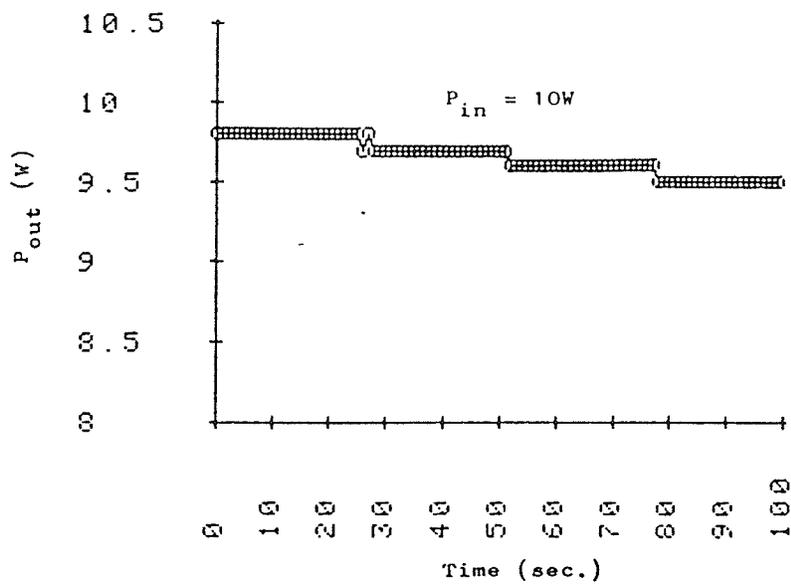


Figure 4.14 (Cont'd): Output Power Level at Various Input Power Levels

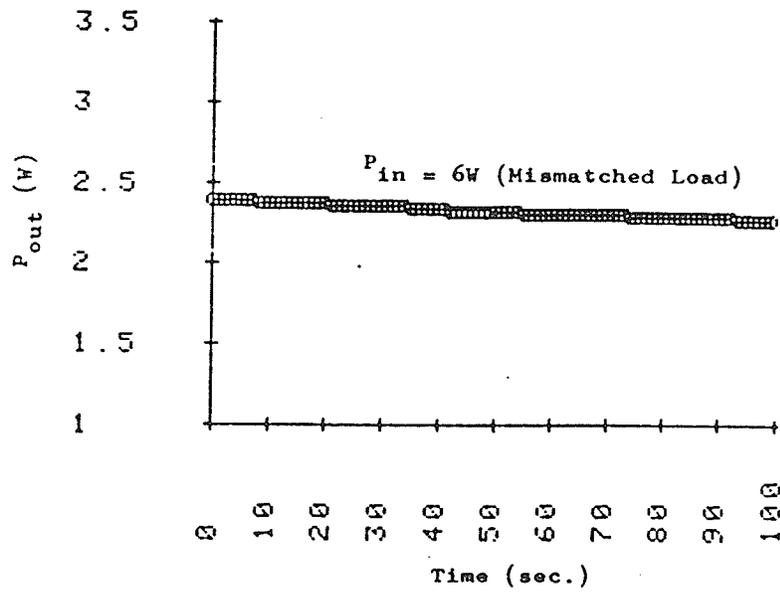
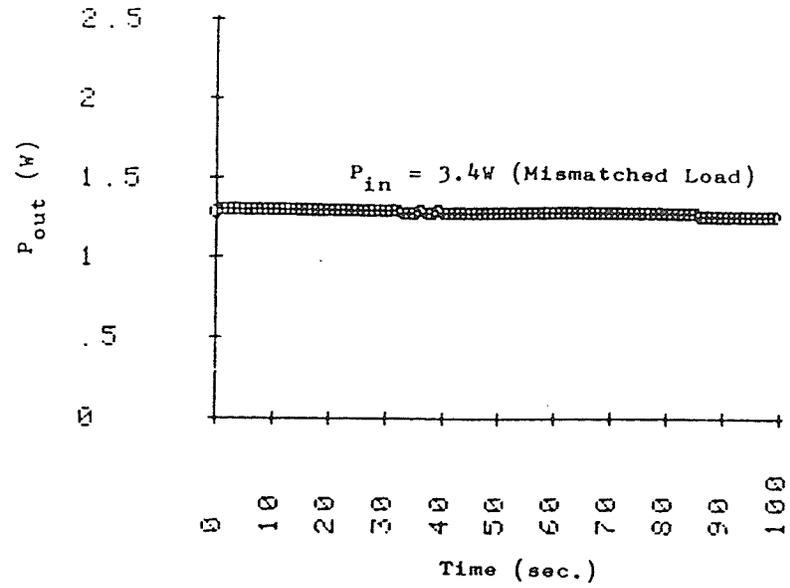


Figure 4.14 (Cont'd): Output Power Level at Various Input Power Levels

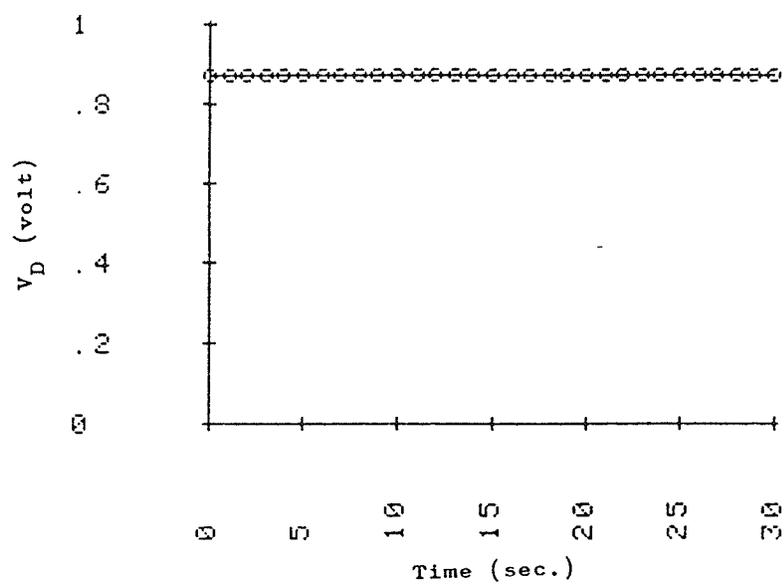


Figure 4.15: Diode Voltage Vs Time

Chapter V

CONCLUSION

A prototype SPDT switch has been designed and implemented. The designed switch has an insertion loss of 0.25 dB, isolation of 27 dB and a return loss of at least 23 dB at 860 MHz. The switch is also capable of handling 3 watts continuous power. The design is simple and expandable - an array of switches can be fabricated on one circuit board. Hence, the design is suitable for its intended application.

The design technique is also applicable to the implementation of a 4-bit switched line digital phase shifter which is another component of the beam forming network of the MSAT antenna. A by-product of this design, the two stage 20-watt RF amplifier, can be used to test other components developed for the MSAT project.

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9. Smegal, R., Chin, H., "MSAT Phase Shifter Progress Report I", Internal Report, Department of Electrical Engineering, University of Manitoba, Winnipeg, January 1986.
10. Motorola RF Data Manual, Third Edition, Motorola Inc., U.S.A., 1983.

Appendix A

CALCULATION OF LINE WIDTH AND LENGTH

Substrate: Oak-601

$$h = 1.588 \text{ mm}$$

$$t = 0.07112 \text{ mm}$$

$$\epsilon_r = 2.54$$

Calculation of line width for $Z_0 = 50$ ohms:

using Eqn. 2.2,

$$H' = 1.228$$

Substituting H' into Eqn. 2.1, we get

$$w/h = 2.826$$

Multiply by h , yields

$$w = 4.486 \text{ mm}$$

Calculation of quarter-wave choke length:

Choose $w = 1/20" = 1.27 \text{ mm}$

Using Eqn. 2.5, ($w/h = 0.8$)

$$Z_0 = 99.27 \text{ ohm}$$

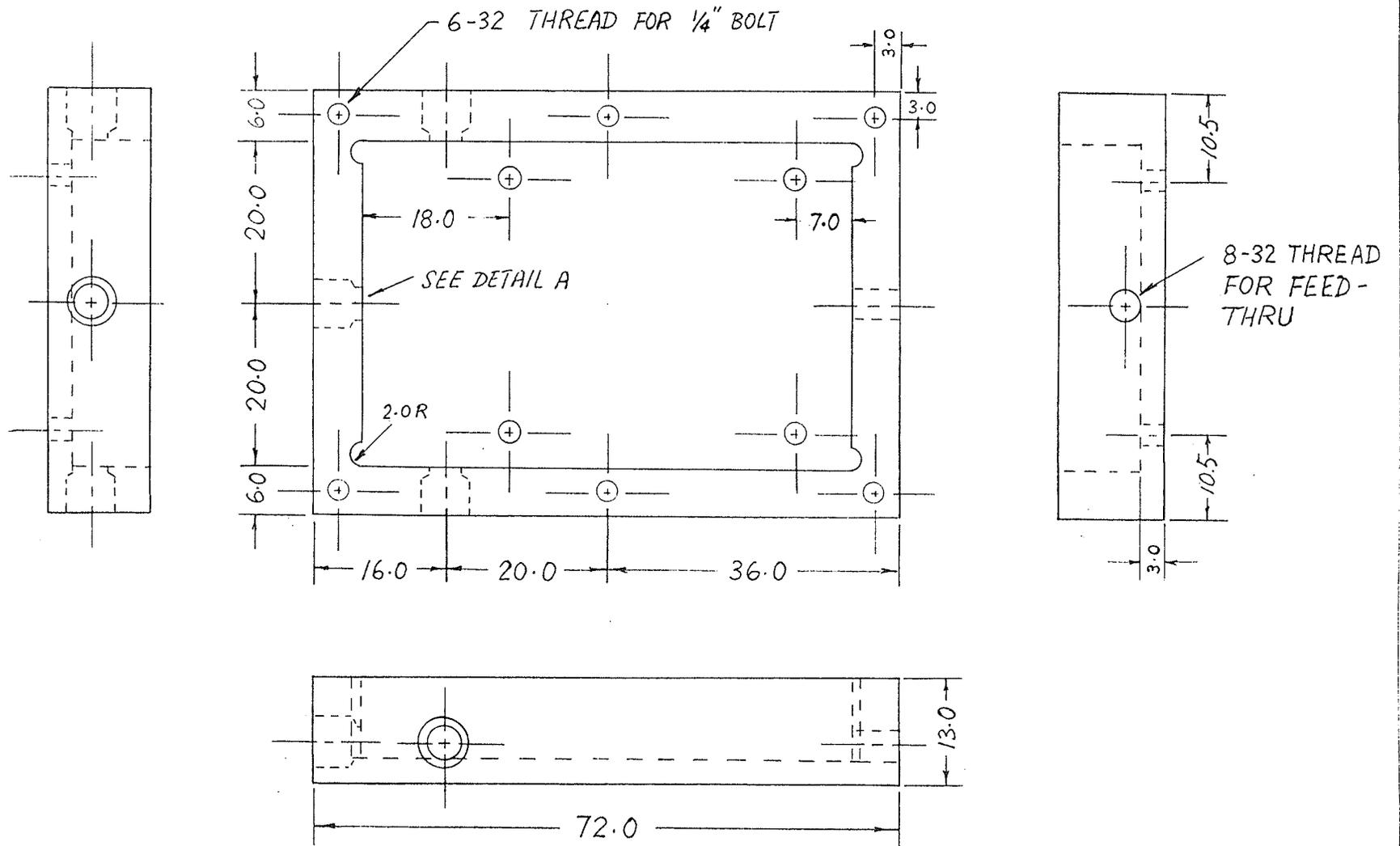
Using Eqn. 2.3,

$$\epsilon_{eff} = 1.966$$

The quarter-wave choke length is,

$$300/4(0.86 \sqrt{1.966}) = 62.19 \text{ mm}$$

Appendix B
DRAWING OF METAL ENCLOSURE



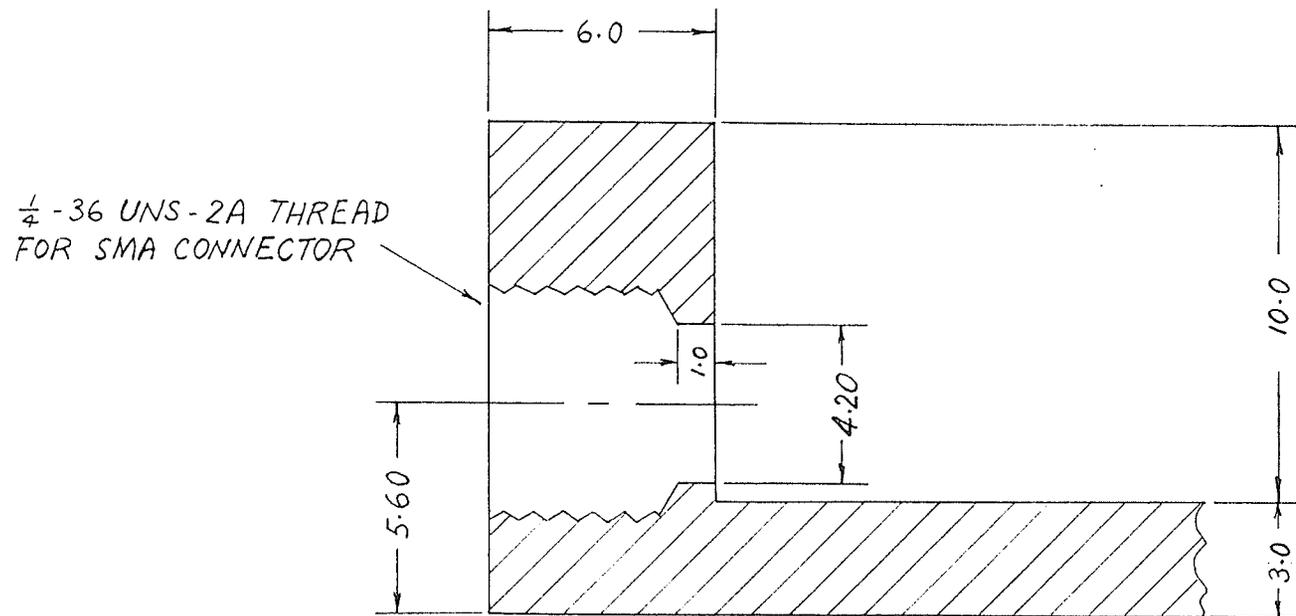
MAT'L: ALUMINUM
 SCALE: 1mm=0.75mm

SPDT SWITCH ENCLOSURE

SHEET 1 OF 2

DRAWN BY: H. K. CHIN

DATE: 1986-02-04



DETAIL A
 SCALE: 1 mm = 0.2 mm

SPDT SWITCH ENCLOSURE

SHEET 2 OF 2

DRAWN BY: H. K. CHIN

DATE: 1986-02-04

Appendix C

TOUCHSTONE CIRCUIT FILE LISTING

VAR

wc1=1.27
wml=4.71

DIM

lng mm

CKT

msub er=2.54 h=1.588 t=0.07112 rho=.7069 rgh=0.001
tand tand=.0022

! ***** define network to represent choke line bends (90 deg.)
mbend 1 2 w^wc1 ang=90 m=0
def2p 1 2 bendo

! ***** define choke terminating capacitor
mtee 1 2 3 w1^wc1 w2=5 w3=5
open 2
ribbon 3 4 w=2.36 l=0.6 rho=.6645 ! silver ribbon leads
srhc 4 5 r=0.1 l=0.5 c=75
ribbon 5 6 w=2.36 l=0.6 rho=.6645
shor 6
def1p 1 cap2

! ***** define input choke section
mlin 1 2 w^wc1 l=10
bendo 2 3
mlin 3 4 w^wc1 l=3.8
bendo 4 5
mlin 5 6 w^wc1 l=6.8
bendo 6 7
mlin 7 8 w^wc1 l=8.8
bendo 8 9
mlin 9 10 w^wc1 l=6.8
bendo 10 11
mlin 11 12 w^wc1 l=3.7
bendo 12 13
mlin 13 14 w^wc1 l=15.2
def2p 1 14 chok2

! ***** define output #1 choke
mlin 1 2 w^wc1 l=4.9
bendo 2 3
mlin 3 4 w^wc1 l=5.0
bendo 4 5
mlin 5 6 w^wc1 l=6.6
bendo 6 7
mlin 7 8 w^wc1 l=12.2
bendo 8 9
mlin 9 10 w^wc1 l=6.7
bendo 10 11
mlin 11 12 w^wc1 l=5.0
bendo 12 13
mlsc 13 w^wc1 l=15.2
def1p 1 chok1

```
! ***** define output #2 choke
m1in 1 2 w^wcl l=14.9
bend0 2 3
m1in 3 4 w^wcl l=5.0
bend0 4 5
m1in 5 6 w^wcl l=6.7
bend0 6 7
m1in 7 8 w^wcl l=12.4
bend0 8 9
m1in 9 10 w^wcl l=6.7
bend0 10 11
m1in 11 12 w^wcl l=5.0
bend0 12 13
mlsc 13 w^wcl l=5.2
def1p 1 chok3

! ***** input choke terminated with cap2 ****
chok2 1 2
cap2 2
def1p 1 ichok

! ***** define input section including X-connection and choke (ichok)
mcros 1 4 3 2 w1^wml w2^wml w3^wml w4^wcl
sr1c 4 5 r=0.1 l=0.5 c=100
m1in 5 6 w^wml l=6
ichok 2
def3p 1 3 6 input

! ***** define pin diode in on state *****
pin 1 2 cj=0.1 rj=0.1 rs=0.9 ls=2.5 cb=1000 cg=.13
def2p 1 2 pin1

! ***** define pin diode in off state *****
pin 1 2 cj=.1 rj=10000 rs=0.9 ls=2.5 cb=1000 cg=.13
def2p 1 2 pin2

! ***** assemble the switch *****
m1in 1 2 w^wml l=9
mtee 2 3 5 w1^wml w2^wml w3^wcl
m1in 3 4 w^wml l=3.5
pin1 5 6
chok1 5
input 6 8 7
pin2 8 9
match 9
def2p 1 7 switch

! ***** define switch for isolation measurement
m1in 1 2 w^wml l=9
mtee 2 3 5 w1^wml w2^wml w3^wcl
m1in 3 4 w^wml l=3.5
pin1 4 6
chok1 5
input 6 8 7
pin2 8 9
```

Touchstone (TM) -Ver (1.32-Lcd 100) -Targ (IBM-PC/AT) -Ser (16195-2212- 1000)
SPDTSW.CKT 02/12/86 - 17:09:31

```
m1in 9 10 w^wml l=3.5  
mtee 10 11 12 w1^wml w2^wml w3^wml  
m1in 11 13 w^wml l=9  
chok3 12  
match 1  
def2p 7 13 switch1
```

OUT

```
switch s11  
switch db[s21] gr1  
switch db[s11] gr2  
switch1 db[s21] gr3
```

FREQ

```
sweep 0.8 0.9 .02
```

GRID

```
range .8 .901 .01  
gr1 -2 0 .2  
gr2 -40 0 5  
gr3 -30 0 5
```

Appendix D

PROGRAM LISTING FOR MONITORING POWER AND VOLTAGE

```

1 ! PROGRAM FOR MONITORING
  POWER AND VOLTAGE.
2 !
3 ! V(I,1) IS TIME IN SEC.
4 ! P(I,1) IS TIME IN SEC.
5 ! V(I,2) IS THE VOLTAGE READ
  FROM THE A/D CONVERTER.
6 ! P(I,2) IS THE RF POWER.
7 !
8 OPTION BASE 1
9 INTEGER I
10 DIM V(100,2),P(100,2)
11 CLEAR
12 DISP "ENTER FULL SCALE VOLTA
  GE FOR A/D CONVERSION"
13 DISP
14 DISP "ASSURE PROPER RANGE JU
  MPERS ARE SET"
15 INPUT K1
16 K2=K1/1022
17 DISP
18 DISP "ENTER SCALING FACTOR F
  OR A/D CONVERSION"
19 DISP "ENTER 1 FOR ACTUAL VOL
  TAGE"
20 INPUT K3
21 K2=K2*K3
22 DISP
23 DISP "ENTER ATTENUATION AT
  POWER SENSOR"
24 INPUT K4
25 CLEAR
26 DISP "SELECT FUNCTION"
27 ON KEY# 1,"CAL" GOTO 33
28 ON KEY# 2,"START" GOTO 72
29 ON KEY# 3,"STORE" GOTO 119
30 KEY LABEL
31 GOTO 30
32 !
33 ! A/D CONVERTER CAL.
34 !
35 CLEAR
36 DISP "ENTER CHANNEL NUMBER &
  TURN OFF POWER REF"
37 INPUT C
38 IF C=4 THEN C=8
39 IF C=3 THEN C=4
40 !
41 ! POWER METER CAL.
42 !
43 OUTPUT 713 ;"Z1T"
44 OUTPUT 713 ;"9A+T"
45 ENTER 713 USING "B,B,B,9Z" ;
  G,A,M,P
46 IF G>=84 THEN 44
47 CLEAR @ DISP "TURN ON POWER
  REF" @ DISP
48 DISP "ENTER POWER RANGE SETT
  ING, 1/2/3/4/5"
49 INPUT R

```

```

50 OUTPUT 713 ;R,"A+T"
51 ENTER 713 USING "B,B,B,9Z" ;
   G,A,M,P
52 IF G=82 THEN 55
53 IF G=83 THEN 58
54 GOTO 61
55 BEEP
56 DISP "OVER RANGE, REENTER RA
   NGE"
57 GOTO 48
58 BEEP
59 DISP "UNDER RANGE, REENTER R
   ANGE"
60 GOTO 48
61 CLEAR
62 DISP "ONCE ZERO IS SET SELEC
   T NEW FUNCTION KEY"
63 OUTPUT 706 USING "#,K,K" ; "
   H",C,"AJ","F"
64 ENTER 706 USING "#,W" ; V1
65  $V1=K2*V1$ 
66 DISP
67 DISP "READING IS ";V1;"VOLTS
   "

68 DISP
69 DISP "READING IS ";P;"WATTS"
70 KEY LABEL
71 GOTO 50
72 !
73 ! DATA COLLECTING
74 !
75 CLEAR @ DISP "# OF POINTS RE
   QUIRED"
76 INPUT N0
77 DISP "ENTER TIME INTERVAL BE
   TWEEN POINTS(SEC.)"
78 INPUT T0
79 DISP "ENTER CHANNEL NUMBER"
80 INPUT C
81 IF C=3 THEN C=4
82 IF C=4 THEN C=8
83  $T8=T0*1000$ 
84 I=0
85 DISP "ENTER POWER RANGE SETT
   ING, 1/2/3/4/5/"
86 INPUT R
87 CLEAR @ DISP "PRESS CONT WHE
   N READY"
88 PAUSE
89 I=I+1
90 OUTPUT 706 USING "#,K,K" ; "
   H",C,"AJ","F"
91 ENTER 706 USING "#,W" ; V1
92  $V(I,2)=K2*V1$ 
93 OUTPUT 713 ;R,"A+T"
94 ENTER 713 USING "B,B,B,9Z" ;
   G,A,M,P
95 IF G=82 THEN 98
96 IF G=83 THEN 100
97 GOTO 102

```

```

98 BEEP @ DISP "OVER RANGE, REE
   NTER"
99 GOTO 85
100 BEEP @ DISP "UNDER RANGE, RE
    ENTER"
101 GOTO 85
102 J=I-1
103 T1=T0*J
104 V(I,1)=T1
105 P(I,1)=T1
106 P(I,2)=P*10^(K4/10)
107 DISP T1;V(I,2)
108 DISP T1;P(I,2)
109 DISP
110 IF I<N0 THEN 114
111 DISP "SELCT FUNCTION"
112 KEY LABEL
113 GOTO 111
114 WAIT T8
115 GOTO 89
116 !
117 ! STORE DATA
118 !
119 CLEAR
120 DISP "THERE WERE";I;"POINTS
    COLLECTED"
121 DISP @ DISP
122 DISP "ENTER FILE NAME FOR VO
    LTAGE DATA"
123 INPUT A$
124 CREATE A$,13,128
125 ON ERROR GOTO 122
126 DISP "ENTER FILE NAME FOR PO
    WER DATA"
127 INPUT B$
128 CREATE B$,13,128
129 ON ERROR GOTO 126
130 ASSIGN# 1 TO A$
131 ASSIGN# 2 TO B$
132 PRINT# 1 ; I,V(,)
133 ON ERROR GOTO 122
134 ASSIGN# 1 TO *
135 PRINT# 2 ; I,P(,)
136 ON ERROR GOTO 126
137 ASSIGN# 2 TO *
138 DISP @ DISP
139 DISP "TRANSFER COMPLETED"
140 OFF ERROR
141 END

```