NPSEC-93-007

NAVAL POSTGRADUATE SCHOOL

Monterey, California

Widebanding Techniques for VHF Antennas – II

by

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March 1993

Approved for Public Release; Distributed Unlimited

Prepared for: Naval Postgraduate School, Monterey, CA

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This report was prepared and funded by the U.S. Army Communications and Electronics Command.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION: Unclassified

1b RESTRICTIVE MARKINGS:

2a SECURITY CLASSIFICATION AUTHORITY:

2b DECLASSIFICATION / DOWNGRADING SCHEDULE:

3 DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S): NPSEC-93-007

5 MONITORING ORGANIZATION REPORT NUMBER(S):

6a NAME OF PERFORMING ORGANIZATION: Dept. of Elec. & Comp. Eng. Naval Postgraduate School

6b OFFICE SYMBOL (If applicable): EC/JS

7a NAME OF MONITORING ORGANIZATION: Naval Postgraduate School

6c ADDRESS (City, State, and ZIP Code): Monterey, CA 93943-5004

7b ADDRESS (City, State, and ZIP Code): Monterey, CA 93943

8a NAME OF FUNDING / SPONSORING ORGANIZATION: U.S. Army CECOM

8b OFFICE SYMBOL (If applicable):

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c ADDRESS (City, State, and ZIP Code): Center for C3 Systems, Fort Monmouth, NJ 07703

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification): WIDEBANDING TECHNIQUES FOR VHF ANTENNAS -- II (U)

12 PERSONAL AUTHOR(S): Keem B. Thiem and RamaKrishna Janaswamy

13a TYPE OF REPORT: Technical

13b TIME COVERED: FROM 10/1/92 TO 3/30/93

14 DATE OF REPORT (Year, Month, Day): March 1993

15 PAGE COUNT: 133

16 SUPPLEMENTARY NOTATION: The views expressed in this report are those of the author and do not reflect the official policy or position of the Department of Defense or the United States Government.

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number):

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

For a variety of mechanical and electrical reasons, the U.S. Army prefers to use a wire antenna for its mobile applications in the HF and VHF bands. However, due to the rapid fluctuation of impedance with frequency, a simple wire antenna is not suitable. This research will look into the aspects of electronic switching of the antenna length and electronic switching of the accompanying tuning network for frequency hopping applications. Two separate schemes will be studied. The first one involves a chosen wire antenna loaded with PIN diodes. The diodes will be selectively switched ON or OFF at different frequencies to control the input impedance of the antenna. In the second scheme, a monopole antenna of fixed length will be considered and data on its input impedance over many sub-bands within 30 to 90 MHz will be generated. Tuning networks composed of resistors, inductors and capacitors will be designed over each sub-band. The various networks will then be connected via PIN diodes and selectively switched to provide matching over a much wider band.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a NAME OF RESPONSIBLE INDIVIDUAL: Ramakrishna Janaswamy

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22c OFFICE SYMBOL: EC/JS

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

ABSTRACT

For a variety of mechanical and electrical reasons, the U.S. Army prefers to use a wire antenna for its mobile applications in the HF and VHF bands. However due to the rapid fluctuation of impedance with frequency, a simple wire antenna is not suitable. This research will look into the aspects of electronic switching of the antenna length and electronic switching of the accompanying tuning network for frequency hopping applications. Two separate schemes will be studied. The first one involves a chosen wire antenna loaded with PIN diodes. The diodes will be selectively switched ON or OFF at different frequencies to control the input impedance of the antenna. In the second scheme, a monopole antenna of fixed length will be considered and data on its input impedance over many sub-bands within 30 to 90 MHz will be generated. Tuning networks composed of resistors, inductors and capacitors will be designed over each sub-band. The various networks will then be connected via PIN diodes and selectively switched to provide matching over a much wider band.

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I. INTRODUCTION

A. BACKGROUND

For a variety of mechanical and electrical reasons, the U.S. Army prefers to use a monopole antenna for mobile applications at HF and VHF bands. However, a simple conducting wire antenna being electrically small is extremely narrow band with respect to both its input impedance and radiation pattern. To improve its bandwidth, the antenna is usually loaded with resistance or reactance along its length. Lumped loading or tapered resistive loading have been employed in the past as some of the techniques of loading the antenna. An attempt had been made by Janaswamy [Ref. 1] to design a broadband monopole antenna by using the continuous resistive profile proposed by Wu and King [Ref. 2]. The resistively loaded antenna can produce significant matching bandwidth, but at the expense of extreme reduction in the efficiency of the antenna. A new loading technique that uses inductive loading in addition to the resistive tapering has been proposed by Little, Ramahi and Mittra [Ref. 3]. The new tapered inductive loading is employed primarily to counteract the high capacitive reactance at the lower end of the frequency band and thus increase the radiating power of the antenna [Ref. 3].

B. RESEARCH DEFINITIONS

This research will attempt to design a broadband monopole antenna with a relatively high efficiency over the frequency band of 30 to 90 MHz. Two separate designs will be considered. In the first design, the electrical length of the monopole will be switched electronically by means of PIN diodes so as to maintain an approximately flat input impedance. A tuning network will be designed to effectively compensate for the impedance variations of the monopole and provide a relatively flat gain over the desired band. In the second design, a monopole antenna of fixed length will be considered. Since it is difficult to design a single matching network over the entire band, we divide the frequency band of 30 to 90 MHz into a number of sub-bands. Tuning networks will be designed separately for each sub-band. The networks will then be combined using PIN diodes which will be selectively switched ON or OFF to provide matching over a large band.

In both of the above schemes, the instantaneous bandwidth of the system comprised of the antenna and tuning network is narrow, but the system is switched electronically so that it effectively 'hops' with the radio. In both of the designs a 1.5 m long monopole antenna will be considered and the VSWR as seen from a 50 ohm generator will be maintained less than 2:1 ratio.

Current state-of-the-art techniques and commercially available design and simulation codes will be used in aiding this research. The WIRE program [Ref. 4] will be used to obtain input impedance, radiation patterns and current distribution of the monopole antenna. The MATCHNET program [Ref. 5] will be employed to synthesize the matching networks. The EEsof TOUCHSTONE program [Ref. 6] will be used to simulate and optimize individual and combined responses of the matching networks resulting from MATCHNET. Detailed discussions on the capabilities of each code and its applications are given in Appendices A, B and C.

II. DESIGN SCHEMES

In this chapter the two design schemes, the diode parameters, and the Bode-Fano criterion will be discussed. The diode parameters and its equivalent circuit will be discussed in Section A. Locations of the diodes on the antenna and its input impedance at the feed point for two different loadings will be discussed in Section B. In Section C, a brief description of the second design scheme will be given. Finally, the Bode-Fano criterion will be discussed in Section D.

A. PIN DIODE PARAMETERS

A commonly used device in switching applications is a PIN diode. The device has two states, one having a very low impedance obtained by switching the diode ON, and the other having a very high impedance obtained by switching the diode OFF. A device with small capacitance can be created by inserting an intrinsic (i-) region between the p- and n-type layers. The breakdown voltage is also high if the i-region is wide. The forward biased resistance, on the other hand, can be as low as that of a p-n junction diode [Ref. 7].

Figure 2.1 illustrates the equivalent circuit of the PIN diode for our applications. The signal takes the bottom path when the device is switched ON and top path when it is switched OFF. In the ON state the diode has a relatively small impedance of 3 ohms, and in the OFF state it has an extremely high impedance. We have decided to use the circuit parameters of a glass surface mount PIN diode for our study. The circuit element values for the selected PIN diode are obtained from the data sheet of the manufacturer which is shown in Figure 2.2 [Ref. 8].

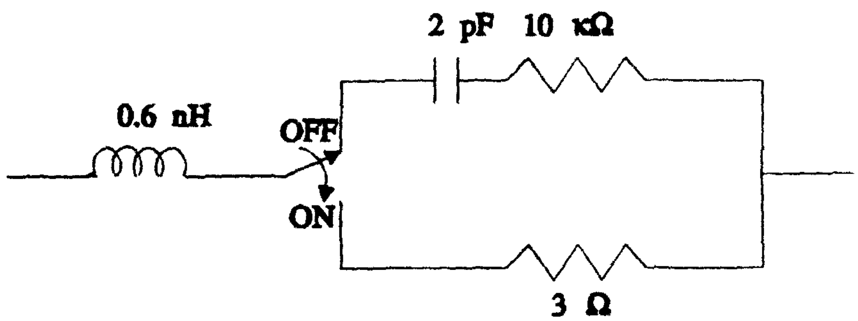


Figure 2.1 PIN Diode Equivalent Circuit

B. A 1.5 METER WIRE ANTENNA LOADED WITH PIN DIODES

The first scheme consists of a 1.5 meter antenna loaded with PIN diodes along its length. The diodes will be selectively switched ON or OFF to control the electrical length of the antenna which, in turn, controls the input impedance. Two different loading techniques are considered.

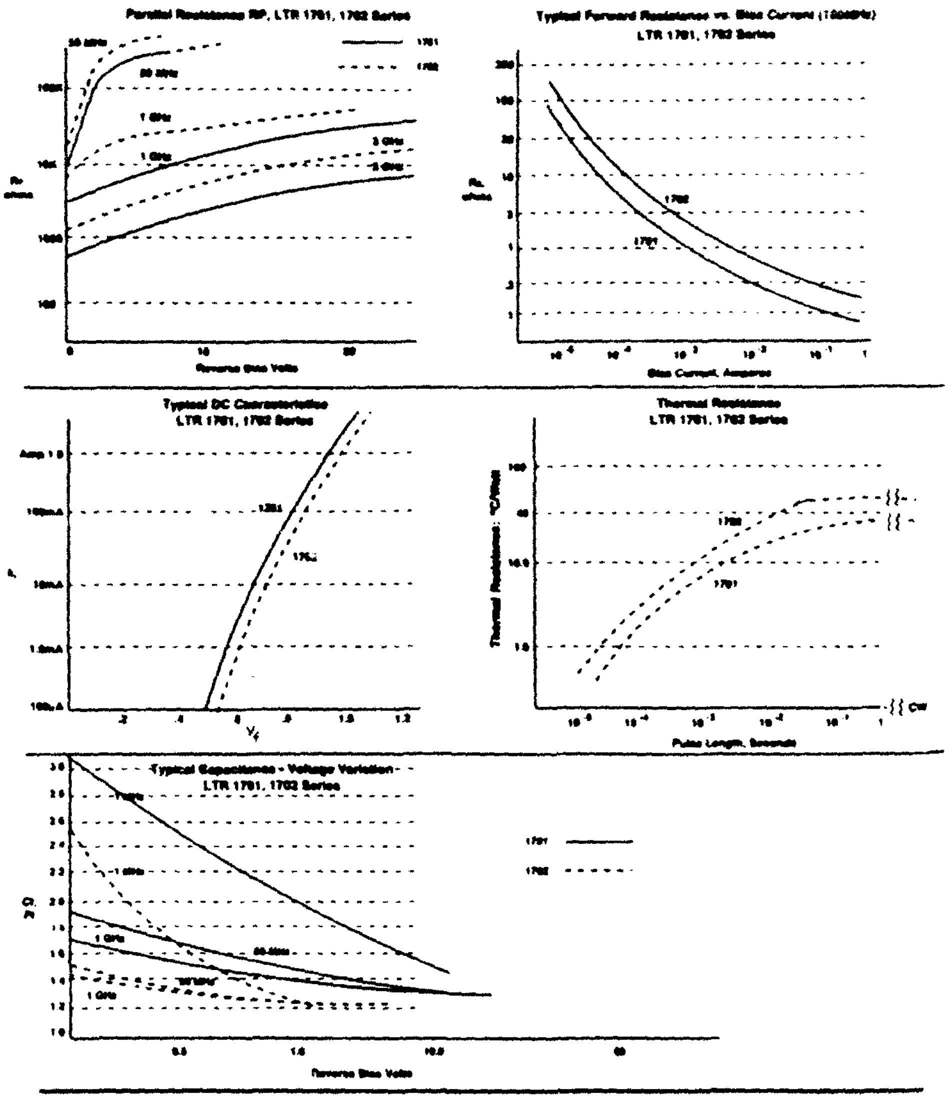


Figure 2.2 Specification Curves of the Selected PIN Diode (From Reference [8])

1. The First Type of Loading

Figure 2.3 illustrates the monopole antenna loaded with four PIN diodes and their exact locations along the antenna. The placement of the diodes for this type of loading is determined by the requirement that the antenna have the same electrical length at certain spot frequencies over 30-90 MHz. The electrical length of the monopole at 30 MHz is 0.15λ, where λ is the free space wavelength. To maintain the same electrical length at 45 MHz, the first diode will be placed at a distance of 1.0 m from the base and switched OFF at 45 MHz. Table 1 shows the exact location of each diode and the corresponding frequency at which it is switched OFF. The details of the calculation are described in the next chapter.

The impedance seen at the feed point as a result of using non-ideal diodes will be examined first. We have used the WIRE program [Ref. 4] to generate this data. Table 2 lists the antenna input impedance seen at the feed point. For the sake of comparison, the input impedance without the use of diodes is also shown. It is seen that the variations in the input impedance of the antenna are significantly reduced due to loading. The input impedance is not flat because of the non-ideal characteristics of the diodes and due to mutual coupling with the wires in the switched off sections. A matching network that reduces the frequency variations of the impedance will be designed in the next chapter.

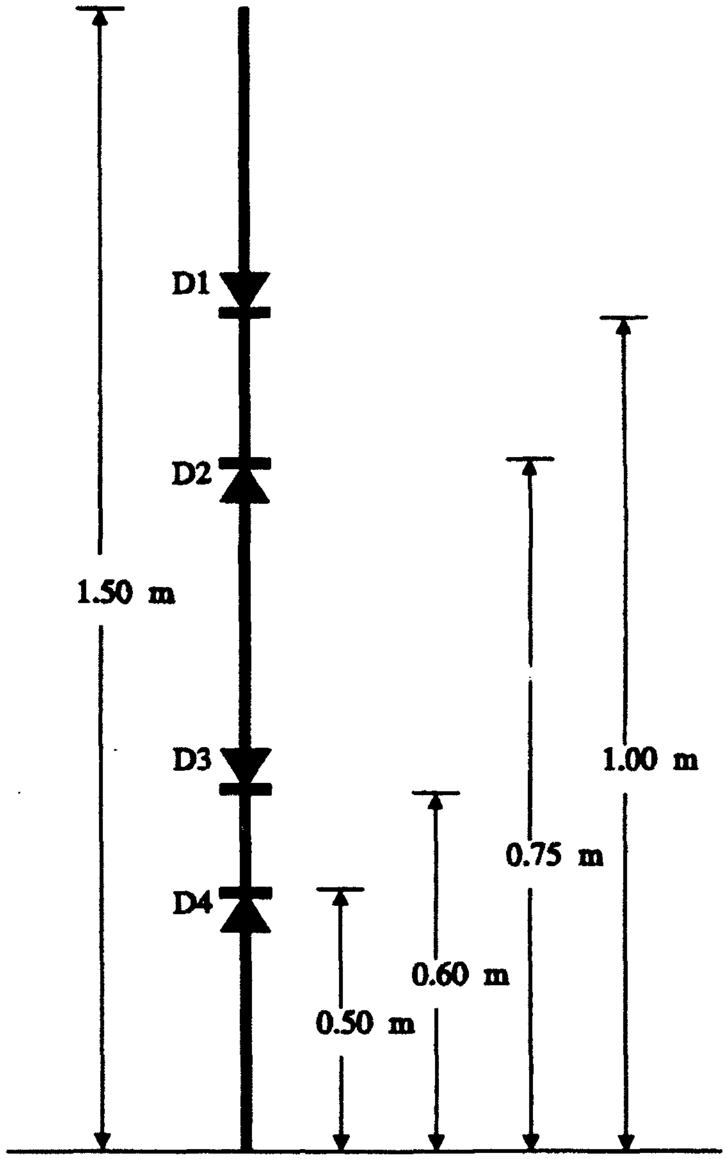


Figure 2.3 The First 1.5 m Monopole Wire Antenna Loaded with PIN Diodes

TABLE 1 THE DIODE LOCATIONS ON THE ANTENNA

Diodes	Location (Meters)	Switching Frequency (MHz)
D1	1.00	45
D2	0.75	60
D3	0.60	75
D4	0.50	90

TABLE 2. ANTENNA INPUT IMPEDANCE

Frequency (MHz)	Input Impedance (Ω)	
	Unloaded	Loaded with Diodes
30	9.797-j194.3	13.59-j192.6
35	14.45-j131.8	18.76-j131.1
40	20.08-j77.58	25.87-j77.70
45	29.56-j27.44	19.65-j172.6
50	41.87+j21.50	22.33-j134.5
55	49.66+j71.72	26.04-j100.4
60	86.27+j125.4	17.28-j158.2
65	127.8+j184.3	19.26-j131.1
70	195.9+j248.0	21.78-j106.2
75	311.7+j306.7	15.62-j149.7
80	504.4+j316.9	17.17-j129.0
85	744.4+j162.6	19.03-j109.6
90	798.9-j188.0	14.90-j137.6

2. The Second Type of Loading

We considered a second monopole antenna with a different set of diode locations. Figure 2.4 illustrates the second monopole antenna loaded with PIN diodes together with their exact locations along the antenna. The placement of the diodes in this case is based on making the antenna length resonant at some spot frequencies. The first resonant frequency of the antenna occurs around 50 MHz where its electrical length is approximately 0.25λ. To make the antenna length resonant at 60 MHz, the first diode is placed at a distance of 1.25 m from the base and switched OFF at 60 MHz. Other diodes are placed in a similar fashion. Table 3 shows the exact location of each diode with the corresponding switching frequency. Because the electrical length of the antenna is resonant only at some spot frequencies, its impedance will have some variations at the other frequencies. Table 4 lists the antenna input impedance at the feed point. A matching network that reduces these impedance variations will be presented in Chapter IV. This second type of loading will be used to compare with the first type of loading in terms of the system's complexity and overall efficiency.

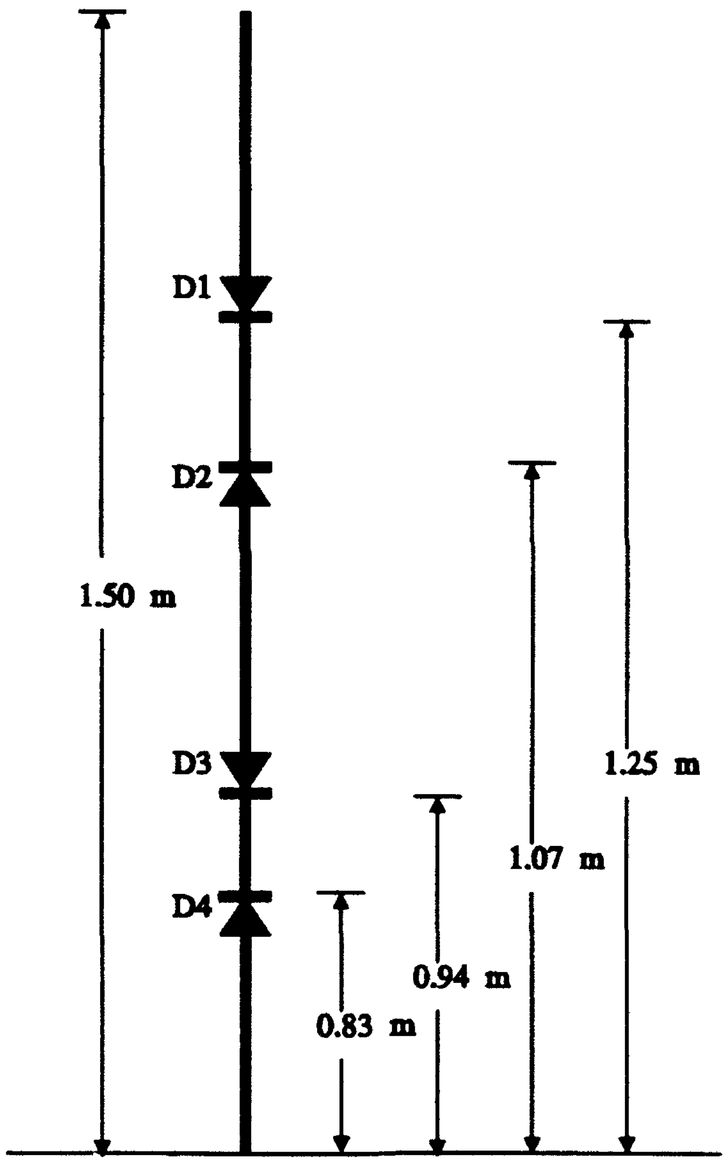


Figure 2.4 The Second 1.5 m Monopole Wire Antenna Loaded with PIN Diodes

TABLE 3 THE DIODE LOCATIONS ON THE ANTENNA

Diodes	Location (Meters)	Switching Frequency (MHz)
D1	1.250	60
D2	1.070	70
D3	0.940	80
D4	0.833	90

TABLE 4 ANTENNA INPUT IMPEDANCE

Frequency (MHz)	Input Impedance (Ω)
30	11.34-j192.6
35	16.27-j131.1
40	23.06-j77.61
45	32.56-j28.00
50	46.11+j20.67
55	66.03+j70.80
60	53.26+j26.54
65	70.87+j66.79
70	52.10+j26.44
75	66.72+j59.82
80	48.63+j19.23
85	60.20+j46.86
90	50.32+j25.66

C. AN UNLOADED 1.5 METER WIRE ANTENNA

The final scheme to be considered is an unloaded 1.5 meter monopole with a complex matching network as shown in Figure 2.5. Input impedance will be generated over ten sub-bands within 30-90 MHz. Tuning networks will be designed for each sub-band. PIN diodes will be used to connect the matching networks and the possibility of network switching will be explored. The overall response of the network with the parallel connections will be studied in detail in Chapter V.

D. THE BODE-FANO CRITERION

One of the fundamental problems in the design of communication systems is transferring maximum power from a generator to a load. Maximum power transfer can only be achieved if the impedance presented to the generator is equal to the source resistance. In the case of the unloaded monopole antenna, the input impedance fluctuates rapidly with frequency. A matching network is needed to match the antenna input impedance to the generator resistance. The Bode-Fano criterion sets an upper limit to the achievable bandwidth of a complex load. Figure 2.6 illustrates a equivalent circuit for the problem.

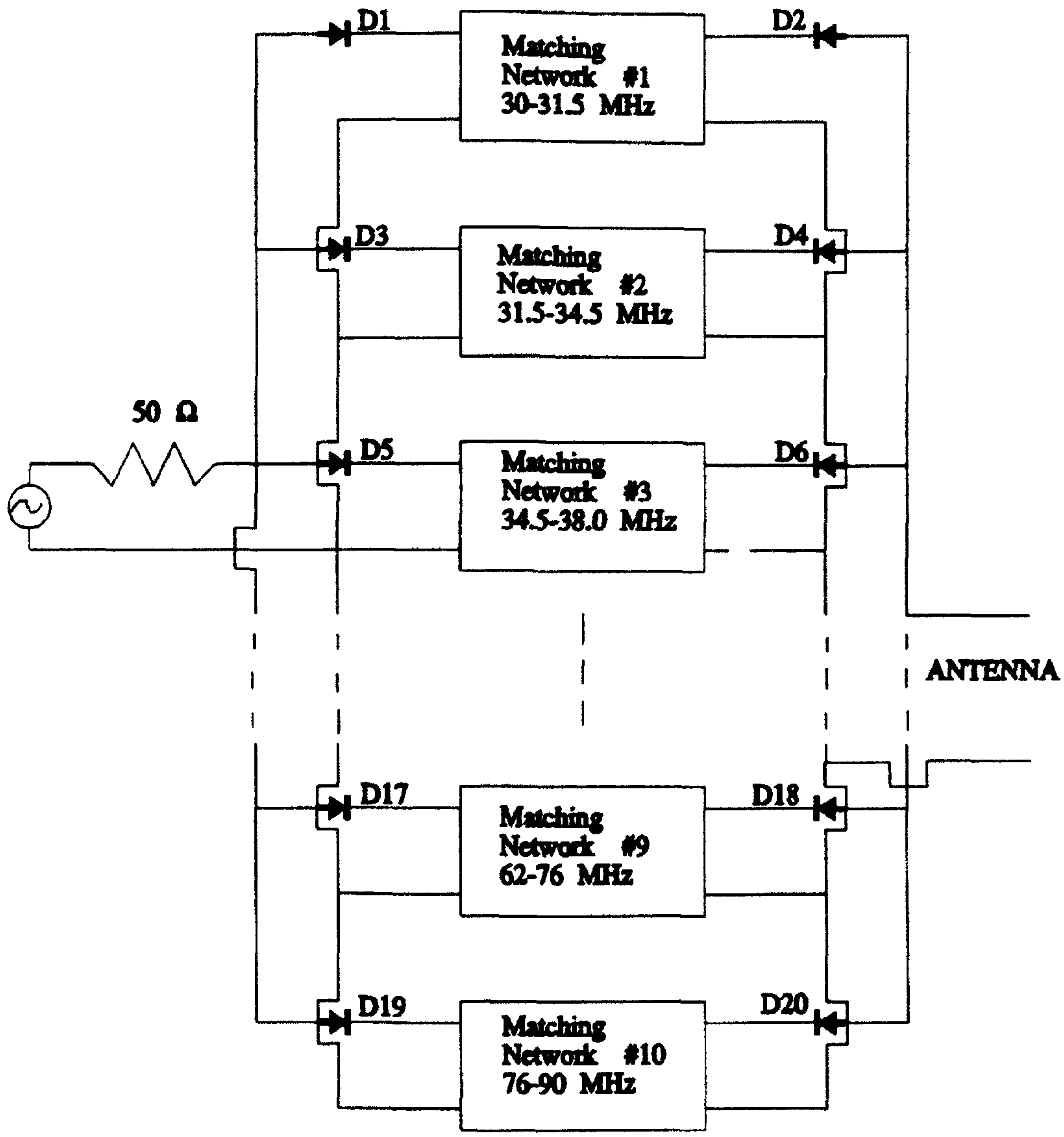


Figure 2.5 The Parallel Connection of the Matching Networks

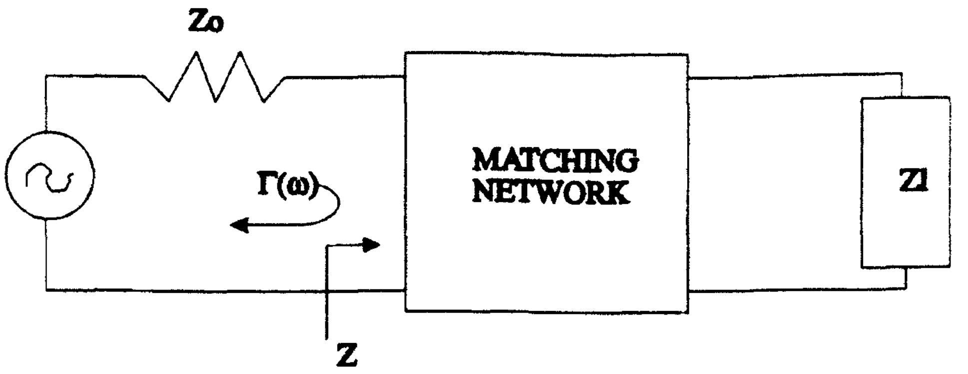


Figure 2.6 Matching Network for an Arbitrary Load Impedance

For a match to be achieved, the maximum tolerance on the match as well as the minimum bandwidth need to be considered. Bode and Fano [Ref. 9] have studied limitations on the achievable bandwidth for a given load and established that there is an upper limit to this bandwidth for a given maximum tolerance (VSWR).

The Transducer Power Gain (TPG), defined as the ratio of the load power P_L to the maximum power P_o that can be delivered by the generator as shown in Figure 2.5, is expressed as

$$TPG=\frac{P_l}{P_o}=1-|\Gamma|^2, \qquad (2.1)$$

where Γ is the reflection coefficient defined by

$$\Gamma=\frac{Z-Z_o}{Z+Z_o}, \qquad (2.2)$$

Z is the impedance presented to the generator, and Z_o is the source resistance. Therefore, the power rejected by the load is

$$|\Gamma|^2 = 1 - \frac{P_l}{P_o}. \tag{2.3}$$

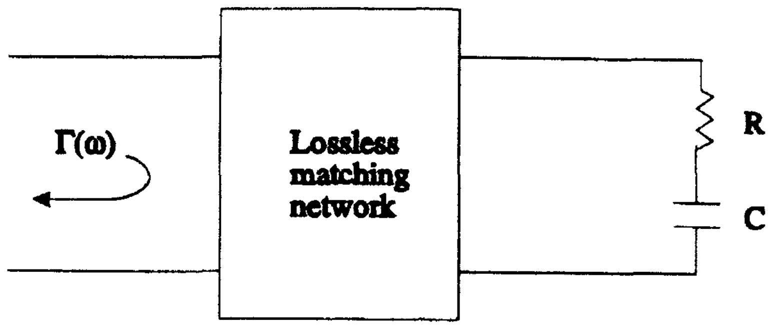
If the generator were connected to the matching network by means of a transmission line whose characteristic impedance is equal to the source resistance, the voltage standing-wave ratio (VSWR) on the line would be given by [Ref. 9]

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}. \tag{2.4}$$

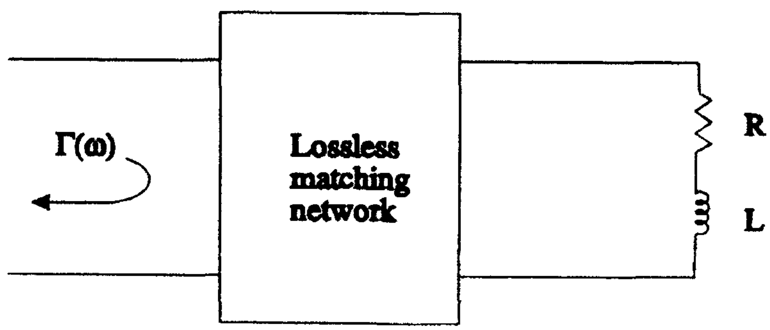
The Bode-Fano criterion essentially gives a theoretical limit on the minimum reflection coefficient magnitude that can be obtained with an arbitrary matching network [Ref. 10]. The minimum magnitude of reflection coefficient will determine the best VSWR for matching. Figure 2.6 illustrates lossless networks used to match a series R-C and a series R-L load impedances.

The Bode-Fano criterion states that

$$\int_0^\infty \ln\frac{1}{|\Gamma(\omega)|}\, d\omega \le \pi \omega_o^2 RC \tag{2.5}$$



(a)



(b)

Figure 2.6 (a) Series R-C (b) Series R-L

$$\int_0^{\infty} \ln \frac{1}{|\Gamma(\omega)|} d\omega \leq \frac{\pi R}{L} \tag{2.6}$$

where $\Gamma(\omega)$ is the reflection coefficient seen looking into the arbitrary lossless matching network [Ref. 10] and ω_o is a center frequency. The derivation of this result is given in [9]. If the reflection coefficient is to be maintained less than a specified maximum Γ_m over a band width $\Delta\omega$, equations (2.5) and (2.6) require that

$$\int_0^{\infty} \ln \frac{1}{|\Gamma|} d\omega \leq \int_{\Delta\omega} \ln \frac{1}{\Gamma_m} = \Delta\omega \ln \frac{1}{\Gamma_m} \leq \pi \omega_o^2 RC \tag{2.7}$$

$$\int_0^{\infty} \ln \frac{1}{|\Gamma|} d\omega \leq \int_{\Delta\omega} \ln \frac{1}{\Gamma_m} = \Delta\omega \ln \frac{1}{\Gamma_m} \leq \frac{\pi R}{L}. \tag{2.8}$$

It can be concluded that a broad bandwidth (large $\Delta\omega$) can only be achieved at the expense of high reflection coefficient Γ_m in the passband. Therefore a perfect match can only obtained at a finite number of frequencies [Ref. 10]. Two other cases, a parallel RC and a parallel RL may also be considered using the Bode-Fano limit. However, the input impedance of an electrically small antenna is in the form of series RC configuration. As an example, at a frequency of 30 MHz the 1.5 m long unloaded monopole antenna has an input impedance of 9.8-j194.3 ohms (see Table 2). This impedance may be thought of as being produced by a capacitor of value 27.3 pF in series with a resistor of 9.8 ohms. According to equation 2.7, the maximum bandwidth over which a VSWR less than 2:1 ratio can be maintained is 4.3 MHz. In practice, the bandwidth achievable is less than this theoretical maximum. Thus, there is a fundamental limit to the achievable bandwidth of an electrically small antenna with low input resistance and relatively high $Q = 1/(\omega_o RC)$. This is the rationale for dividing the frequency band into a number of sub-bands and designing matching networks for each narrow band.

III. MONOPOLE LOADED WITH PIN DIODES-I

As discussed in the previous chapter, two techniques of loading the antenna are considered in this research. In this chapter, we study the first loading technique. In this case the placement of the diodes on the antenna is determined by the requirement that the antenna have the same electrical length at some spot frequencies. The second loading technique is considered in the next chapter. First, the parameters of the diode will be described. Then the antenna input impedance, radiation patterns and efficiency will be discussed. Finally, the results obtained from MATCHNET and TOUCHSTONE will be discussed.

A. PIN DIODE STATES, IMPEDANCE AND LOCATIONS

1. Diode States

The locations of the diodes on the monopole were determined by the requirement that the electrical length of the antenna be approximately the same over the frequency band of 30 to 90 MHz. The monopole is designed to have the same electrical length of 0.15λ at 30, 45, 60, 75 and 90 MHz. The ON and OFF states of the diodes depend entirely on the operating frequencies. Table 5 illustrates the states of each diode with respect to the operating frequency.

2. Diode Impedance

The parameters of the diodes have been discussed in the previous chapter. Table 6 illustrates the impedance of the PIN diodes in their ON and OFF states with respect to the frequency. All PIN diodes were assumed to be identical.

3. Actual Diode Locations

The monopole was modeled by the WIRE program using 50 segments. The WIRE program divides the 1.5 m antenna into segments and assigns pulse number to each one of the segments. Loads can only be placed at the junction between two segments. Because of this the actual location of the diodes may differ slightly from the required location. The required locations of the diodes are shown in Table 1 of Chapter II. Table 7 shows the locations of the diodes and the pulse numbers as generated by the WIRE program.

TABLE 5 THE DIODES STATES

Frequency (MHZ)	Diode #4 (D4)	Diode #3 (D3)	Diode #2 (D2)	Diode #1 (D1)
30	ON	ON	ON	ON
35	ON	ON	ON	ON
40	ON	ON	ON	ON
45	ON	ON	ON	OFF
50	ON	ON	ON	OFF
55	ON	ON	ON	OFF
60	ON	ON	OFF	OFF
65	ON	ON	OFF	OFF
70	ON	ON	OFF	OFF
75	ON	OFF	OFF	OFF
80	ON	OFF	OFF	OFF
85	ON	OFF	OFF	OFF
90	OFF	OFF	OFF	OFF

TABLE 6 DIODE IMPEDANCE DURING THE ON AND OFF STATES

	OFF STATE	ON STATE
Frequency (MHz)	D1=D2=D3=D4 (kΩ)	D1=D2=D3=D4 (Ω)
30	10-j2.653	3+j0.1131
35	10-j2.274	3+j0.1319
40	10-j1.989	3+j0.1510
45	10-j1.768	3+j0.1696
50	10-j1.591	3+j0.1885
55	10-j1.447	3+j0.2073
60	10-j1.326	3+j0.2262
65	10-j1.224	3+j0.2450
70	10-j1.137	3+j0.2639
75	10-j1.061	3+j0.2830
80	10-j0.994	3+j0.3016
85	10-j0.936	3+j0.3204
90	10-j0.884	3+j0.3401

TABLE 7 DIODE LOCATIONS IN THE WIRE PROGRAM

Diodes	Pulse No.	Actual Distance (m)	Required Distance (m)
D1	34	0.99	1.00
D2	26	0.75	0.75
D3	21	0.60	0.60
D4	18	0.51	0.50

B. THE ANTENNA INPUT IMPEDANCE

Once all the necessary information has been entered into the WIRE program, it computes the input impedance, current distribution and radiation pattern of the antenna. The input impedance of the antenna is shown in Table 2 of Chapter II. The input impedance of the antenna is capacitive over the entire bandwidth because the electrical length was maintained relatively constant around 0.15λ.

C. ELEVATION PLANE RADIATION PATTERNS

The radiation patterns were also obtained from the WIRE program. The output data files from the WIRE program were exported into Matlab for plotting and adding pertinent information. Figure 3.1 illustrates the radiation patterns over a perfect ground plane within the 30 to 90 MHz frequency band. At 30 MHz the antenna has slightly larger 3 dB beamwidth than at other frequencies. From 45 to 90 MHz, the radiation patterns are approximately the same as can be seen from Figure 3.1. Overall we see that the radiation pattern is more or less constant over the entire band.

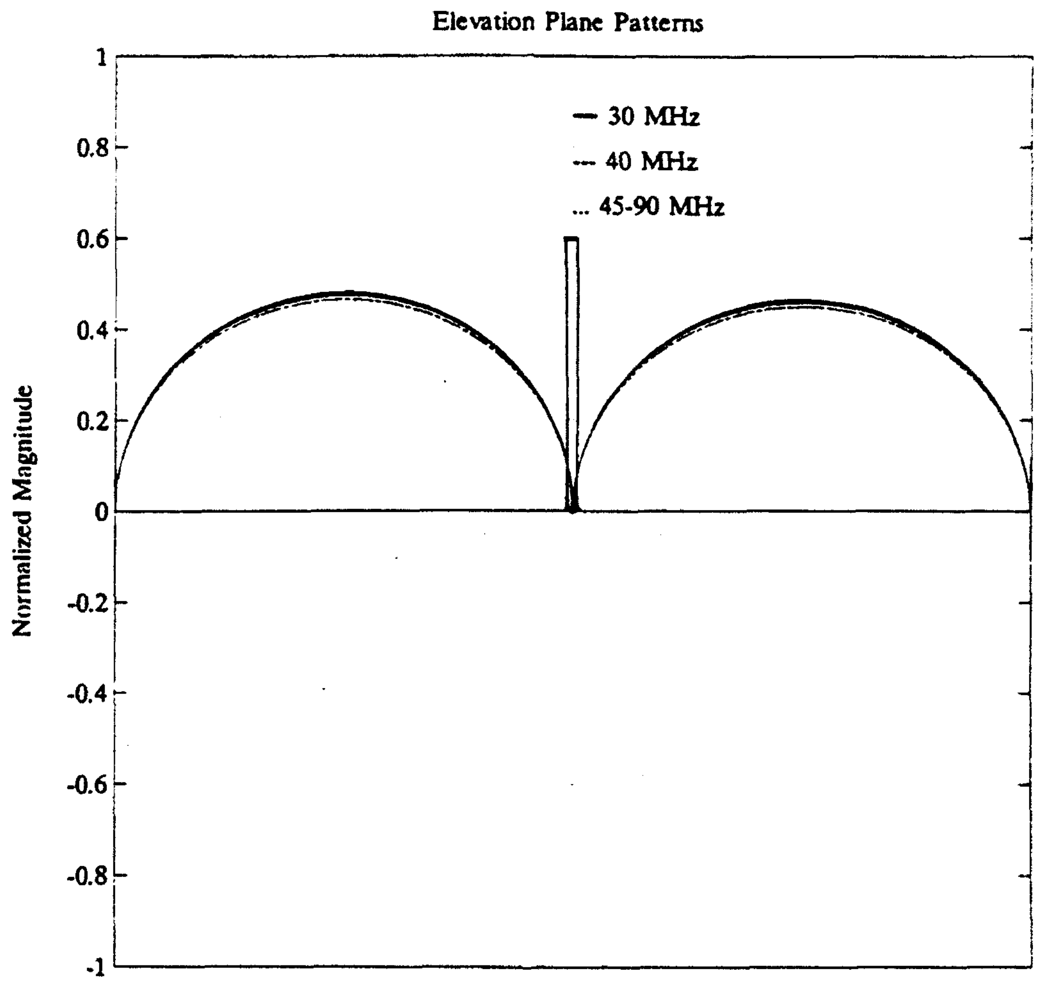


Figure 3.1 The Antenna Radiation Pattern

D. THE ANTENNA EFFICIENCY

The efficiency of the loaded antenna can be determined from the current distribution on the antenna. The unloaded antenna can be regarded as a lossless antenna. Assuming that the base metal for the antenna is aluminum, its total loss resistance R_{loss} can be calculated using [Ref. 11]

$$R_{loss}=\frac{h}{a}\sqrt{\frac{f}{2\sigma}} \qquad (3.1)$$

where

h = height of the antenna

a = radius of the antenna

f = frequency in MHz

σ = conductivity in S/m ($3.57\mathrm{x}10^{7}$ S/m for Al).

At a frequency of 30 MHz the 1.5 m high, 0.5 cm radius monopole will have a loss resistance R_{loss} of 0.2 ohms. The radiation resistance of the same monopole at 30 MHz is 9.8 ohms. Thus, the radiation efficiency of the unloaded monopole is 98% at 30 MHz. Therefore, the unloaded monopole can be considered lossless, and the losses on the loaded monopole attributed entirely to loading by the PIN diodes. The efficiency η_a of the loaded monopole can be obtained by the expression

$$\eta_a=(1-\frac{P_l}{P_{in}})*100 \qquad (3.2)$$

where

$$P_l = \frac{1}{2} \sum_{i=1}^{4} Re(Z_D) \, |I_D|^2 \qquad (3.3)$$

$$P_{in} = \frac{1}{2} Re(Z_{in}) \, |I_{in}|^2 \qquad (3.4)$$

and

P_l = power loss due to loaded diodes

Z_D = diode impedance

I_D = current through diode

P_{in} = input power to the antenna

I_{in} = input current to the antenna

Z_{in} = antenna input impedance.

The current distribution on the antenna can be obtained from the WIRE program. Table 8 shows the magnitude of the current through the diodes and input power to the antenna for a 1 volt input voltage. Figure 3.2 shows the antenna efficiency as a function of frequency. The reduced efficiency relative to the unloaded antenna is due to the insertion loss of the diodes.

TABLE 8 DIODE CURRENT MAGNITUDE AND INPUT POWER

Freq. (MHz)	D_1 (mA)	D_2 (mA)	D_3 (mA)	D_4 (mA)	P_{in} (mW)
30	2.030	2.830	3.290	3.560	0.180
35	3.200	4.410	5.090	5.480	0.535
40	5.670	7.720	8.840	9.44	1.929
45	0.160	1.770	2.630	3.110	0.326
50	0.196	2.370	3.510	4.140	0.600
55	0.251	3.310	4.870	5.720	1.211
60	0.035	0.154	1.650	2.410	0.341
65	0.041	0.179	2.060	3.010	0.548
70	0.050	0.214	2.640	3.840	0.926
75	0.016	0.036	0.148	1.384	0.345
80	0.018	0.040	0.167	1.654	0.507
85	0.022	0.046	0.192	2.000	0.768
90	0.012	0.017	0.039	0.145	0.389

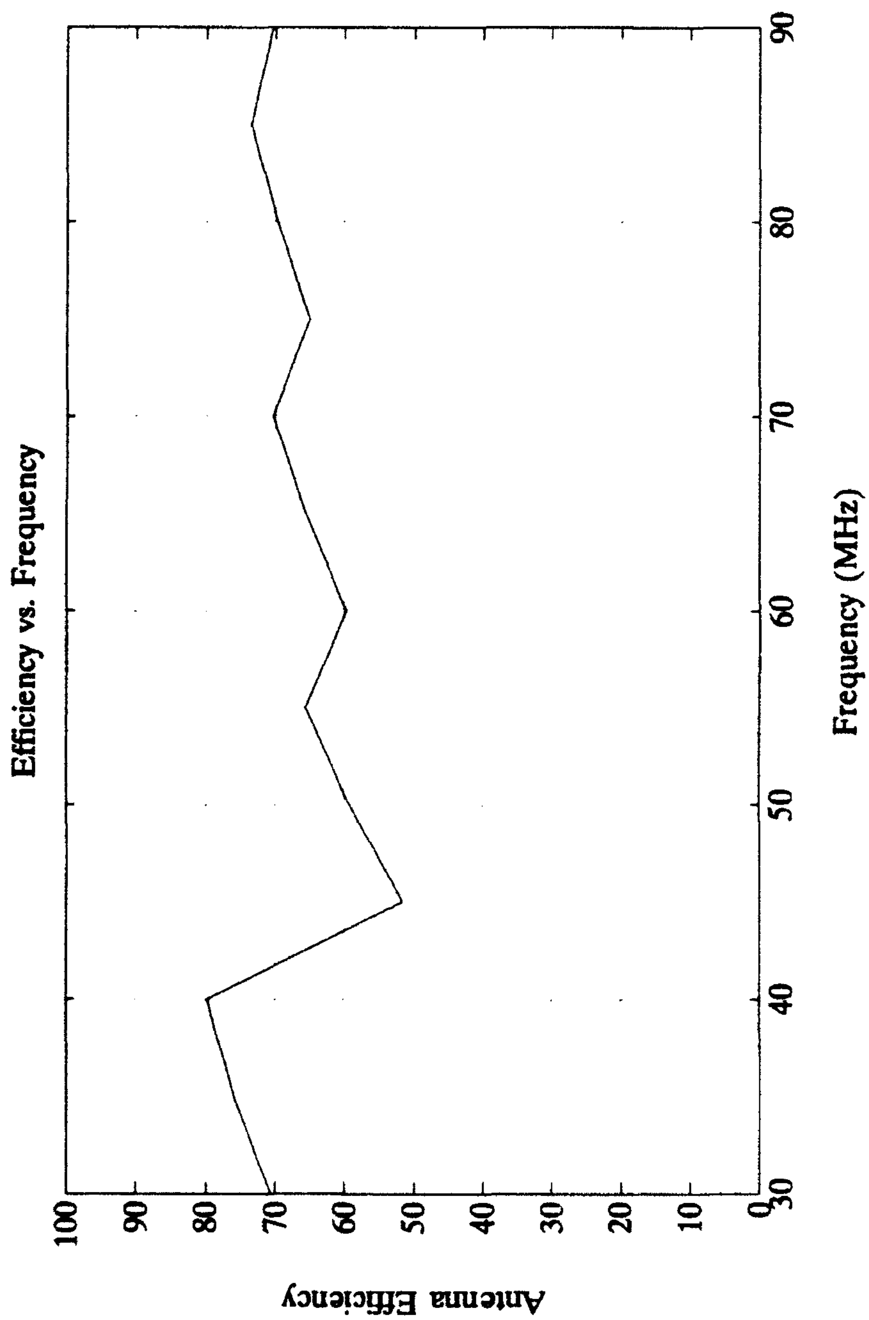


Figure 3.2 The Antenna Efficiency

E. MATCHING NETWORK FOR THE ANTENNA

For the monopole loaded with diodes we designed a single matching network from 30 to 90 MHz. A VSWR of 2:1 or less was required which implies that the reflection coefficient, Γ, be less than 1/3. We may apply the Bode-Fano criterion to see if it is possible to obtain this match over the entire band. The impedance characteristics of the antenna are shown in Table 2. We treat the antenna approximately as a series RC network, with the R and C values corresponding to the impedance at the geometric mean frequency of about 50 MHz. Using $\Delta f = 90-30 = 60$ MHz, $f_o = 50$ MHz, $1/(\omega_o C) = 134.5$ ohms and $\Gamma_m = 1/3$, we see that the resistance needs to be at least 56.4 ohms. The real part of the antenna input impedance is only 22 ohms. Hence, 40 ohms is added in series with the antenna to ensure that the VSWR will be less than 2:1. This, however, increases the transmission loss.

The matching network is a 2-port device inserted between the generator and the antenna plus the 40 ohms series resistance. The generator is connected to port number 1, and the antenna is connected to port number 2. The reflection coefficient seen looking into port 1 when all other ports are terminated in matched loads is the scattering parameter S_{11}. S_{21} is the transmission coefficient from port 1 to 2, when all other ports are terminated in matched loads [Ref. 10].

First a matching network was synthesized and optimized using the program MATCHNET, then the synthesized matching network was simulated and further optimized by TOUCHSTONE. Both lossless and lossy inductors were considered in the simulation.

1. MATCHNET Results

Table 9 illustrates the output circuit file from MATCHNET. A lowpass response and six degrees were chosen for this matching network. The number of the elements in the output file depends on the degree chosen. The output file gives the values and the configuration of the circuit. This result will be used to create TOUCHSTONE circuit files.

TABLE 9 OUTPUT CIRCUIT FILE FOR THE FIRST SUB-BAND

The Lumped Element Design	
From The Generator To The Load	
Series Inductor	4.500E-007 H
Shunt Inductor	2.300E-007 H
Series Capacitor	8.060E-011 F
Shunt Capacitor	9.400E-011 F
Series Capacitor	1.200E-009 F
Shunt Inductor	1.400E-007 H
-Lossless Capacitors -Lossless Inductors	

2. TOUCHSTONE Results

A circuit file for TOUCHSTONE was constructed using the result from MATCHNET. TOUCHSTONE also requires an input file of the antenna reflection coefficient. The antenna reflection coefficient referenced to 50 ohms is

$$S_{11}=\frac{Z_a-50}{Z_a+50}, \tag{3.5}$$

where Z_a is the input impedance of the antenna. A TOUCHSTONE circuit file, input file, and output file for this case are listed in Appendix D. After optimization, the final element values in the TOUCHSTONE circuit file turned out to be significantly different from the values listed in Table 9.

Figure 3.3 shows the final response of the antenna with matching network. We see that $|S_{11}|$ is well below -10 dB which means that the VSWR in the passband is 2:1 or better. A relatively constant $|S_{21}|$ is seen over the entire frequency band. The reduction in $|S_{21}|$ is due to the added series resistance. Figure 3.4 shows a schematic of the matching network.

The responses of Figure 3.3 are based on lossless inductors and capacitors. Lossy inductors with a Q of 75 were also used in a simulation, but the responses in this case were the same as in the lossless inductor case. Thus, lossy inductors did not affect the output responses shown in Figure 3.3. The circuit and output files are listed in Appendix D.

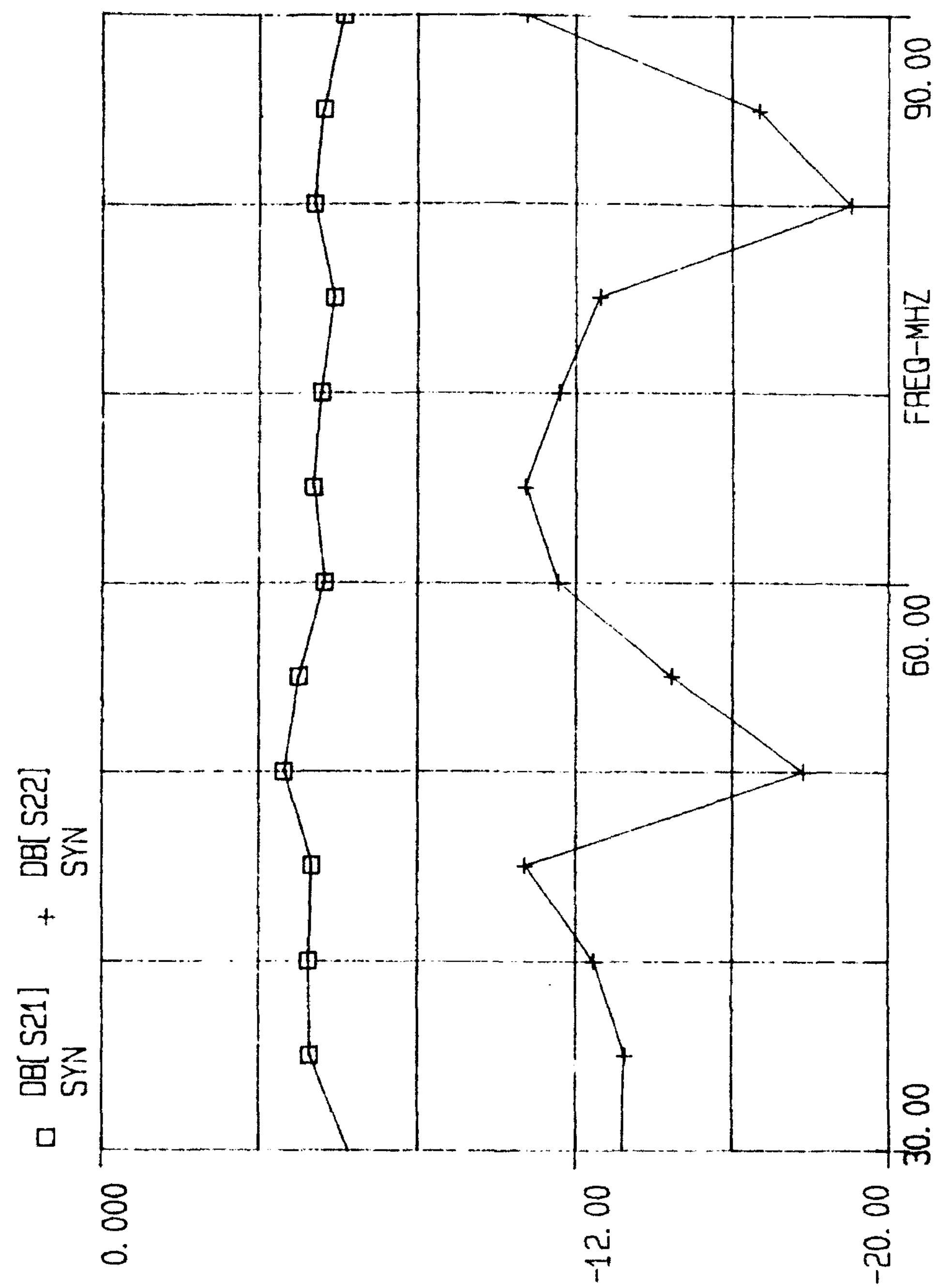


Figure 3.3 The Simulation Response

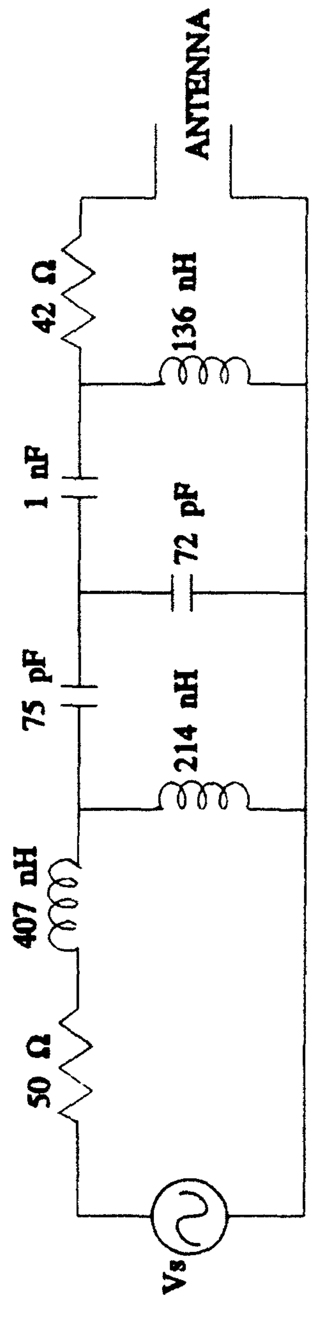


Figure 3.4 The Matching Network

The magnitude of S_{21} squared is the power transferred from the generator to the antenna. Thus, the maximum available power transferred to the load is between 24% to 34%, but the overall transfer of power to radiated fields will be lower because the antenna itself is not lossless.

F. OVERALL EFFICIENCY

To obtain the loss in power transferred from the source to free space we look at the overall efficiency $\eta_a|S_{21}|^2$. Figure 3.5 illustrates the overall efficiency of the system. The efficiency varies between 17% and 24%. Compared to a resistively loaded monopole antenna of [Ref. 1] where the overall efficiency varied between 6% at the lower frequency to 28% at the high frequency. The present design is better because the overall efficiency remains relatively constant over the entire band. Further discussion and comparisons will be made in the subsequent chapter.

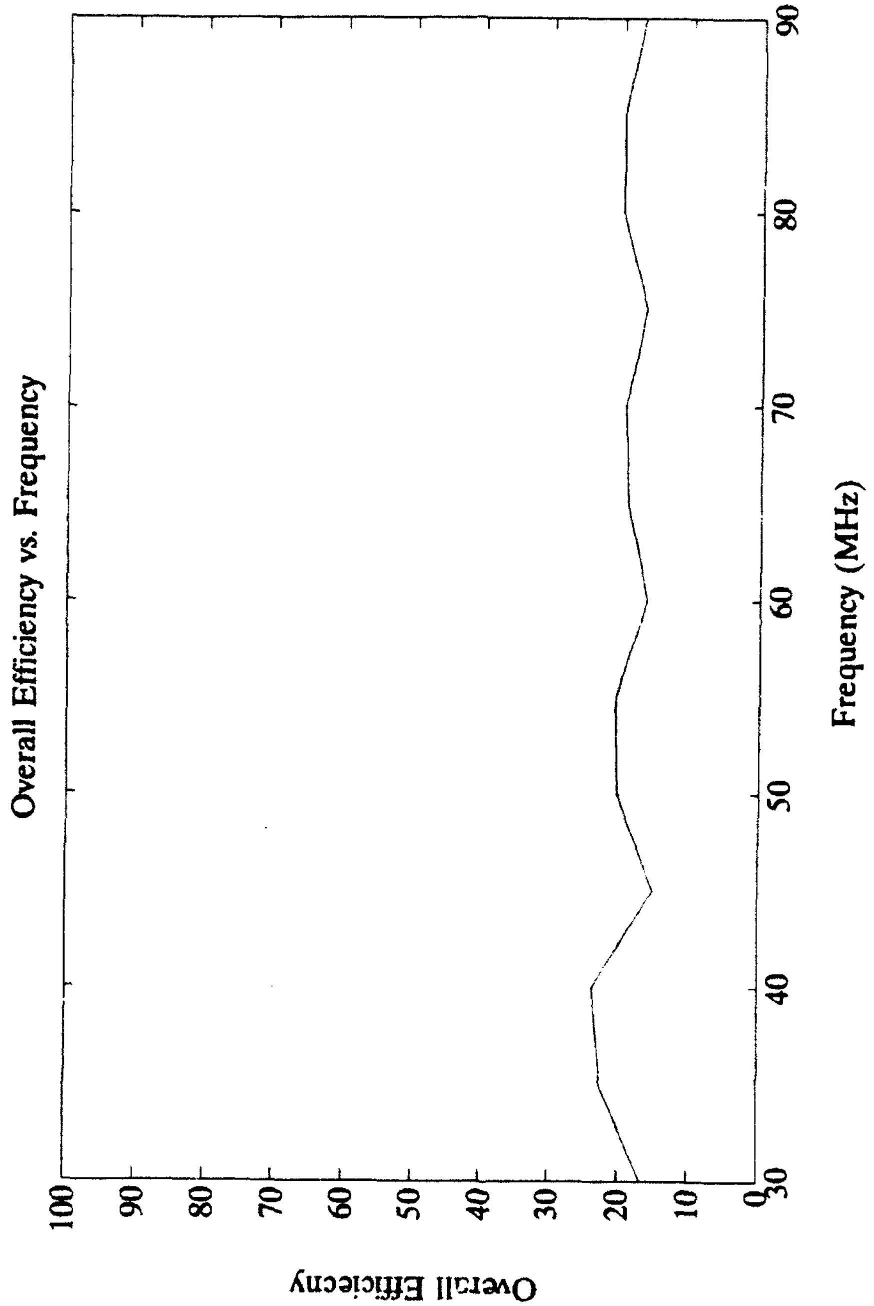


Figure 3.5 The Overall Power Efficiency

IV. MONOPOLE LOADED WITH PIN DIODES-II

The input reactance of the antenna using the first loading technique was capacitive over the entire frequency band. It is difficult to design a low-loss matching network for a highly capacitive load. Consequently S_{21} was reduced in the first loading technique. In an attempt to improve on the efficiency of the first loading technique, we tried other locations for placing the diode. The locations in this case are determined by making the antenna resonant at selected spot frequencies. Recall that the first resonance occurs when the monopole length is around 0.25λ. The present choice should therefore result in higher efficiency particularly at the higher frequencies. In contrast, the electrical length was maintained at 0.15λ in the previous chapter. Figure 2.2 shows the locations of the diodes on the antenna.

The procedures for obtaining the pattern and VSWR are similar to those discussed in the previous chapter. The diode states, impedances, and locations will be discussed first. The antenna input impedance and its elevation plane radiation patterns will be discussed next. Since the monopole is loaded with diodes, it cannot be considered lossless; therefore, the antenna efficiency will be discussed separately. Finally, the design of MATCHNET and the results from TOUCHSTONE will be presented.

A. PIN DIODE STATES AND LOCATIONS

1. Diode States

Table 10 illustrates the state of each diode with respect to the operating frequency.

TABLE 10 THE DIODES STATES

Frequency (MHZ)	Diode #4 (D4)	Diode #3 (D3)	Diode #2 (D2)	Diode #1 (D1)
30	ON	ON	ON	ON
35	ON	ON	ON	ON
40	ON	ON	ON	ON
45	ON	ON	ON	ON
50	ON	ON	ON	ON
55	ON	ON	ON	ON
60	ON	ON	ON	OFF
65	ON	ON	ON	OFF
70	ON	ON	OFF	OFF
75	ON	ON	OFF	OFF
80	ON	OFF	OFF	OFF
85	ON	OFF	OFF	OFF
90	OFF	OFF	OFF	OFF

2. Diode Locations

Table 11 illustrates the locations of the diodes with respect to pulse numbers in the WIRE program.

TABLE 11 THE DIODE LOCATIONS IN THE WIRE PROGRAM

Diodes	Pulse No.	Actual Location (m)	Required Location (m)
D4	29	0.840	0.833
D3	32	0.930	0.940
D2	37	1.080	1.070
D1	43	1.260	1.250

B. THE ANTENNA INPUT IMPEDANCE

The input impedance, current distribution, and radiation pattern of the antenna were obtained by using the WIRE program as discussed in the previous chapter. The input impedance of the antenna is shown in Table 4. The antenna is highly capacitive at the lower end of the bandwidth, and becomes inductive beyond the first resonant frequency of 50 MHZ. Even here the high capacitance and low resistance at the lower end of the band poses problems in the design of the matching network.

C. ELEVATION PLANE RADIATION PATTERNS

The radiation patterns for the present case were also obtained from the WIRE program. Figure 4.1 illustrates the elevation plane over perfect ground plane for different frequencies. The 3 dB beamwidth at 30 MHz is slightly wider than the others. The radiation patterns remain roughly the same from 50 to 90 MHz.

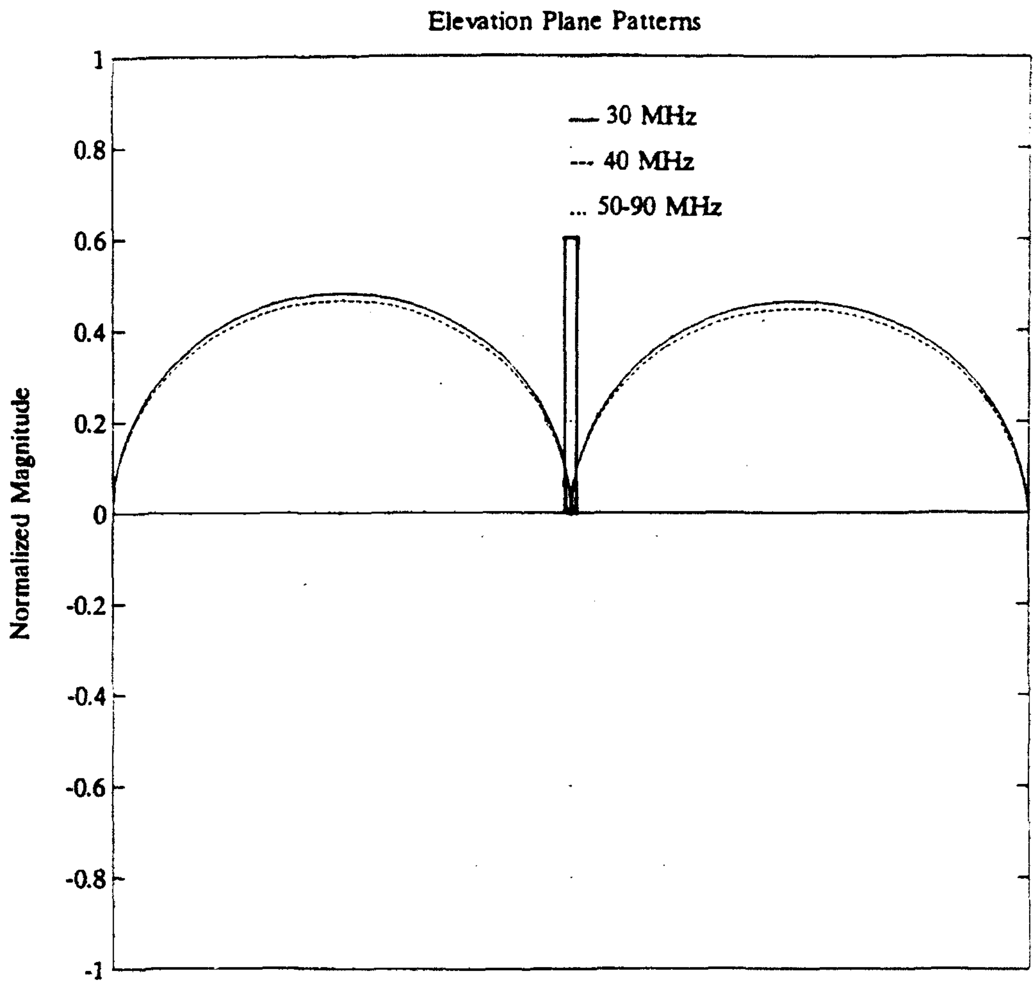


Figure 4.1 The Antenna Radiation Pattern

D. THE ANTENNA RADIATION EFFICIENCY

The efficiency of the antenna was deter…ined by equations 3.2, 3.3 and 3.4. Table 12 shows the magnitude of the current and input power to the antenna for a unit voltage applied at the feed.

Figure 4.2 illustrates the antenna efficiency versus the frequency. Due to losses in the PIN diodes, the loaded monopole has a non-ideal efficiency between 85.0% and 92.0%. Compared to the previous case shown in Figure 3.2, we see that this antenna has a higher efficiency. This is due to the longer electrical length.

TABLE 12 DIODE CURRENT MAGNITUDE AND INPUT POWER

Freq. (MHz)	D4 (mA)	D3 (mA)	D2 (mA)	D1 (mA)	Pin (mW)
30	2.537	2.238	1.720	1.061	0.152
35	3.979	3.523	2.721	1.685	0.466
40	7.064	6.278	4.874	3.032	1.759
45	14.70	13.12	10.24	6.403	8.828
50	14.00	12.56	9.867	6.198	9.029
55	8.340	7.519	5.948	3.456	3.522
60	9.969	8.266	5.093	0.413	7.520
65	6.863	5.701	3.529	0.266	3.736
70	7.428	5.100	0.402	0.092	7.632
75	5.388	3.706	0.274	0.062	4.154
80	4.214	0.429	0.099	0.042	8.891
85	3.167	0.304	0.070	0.030	5.172
90	0.367	0.100	0.044	0.026	7.866

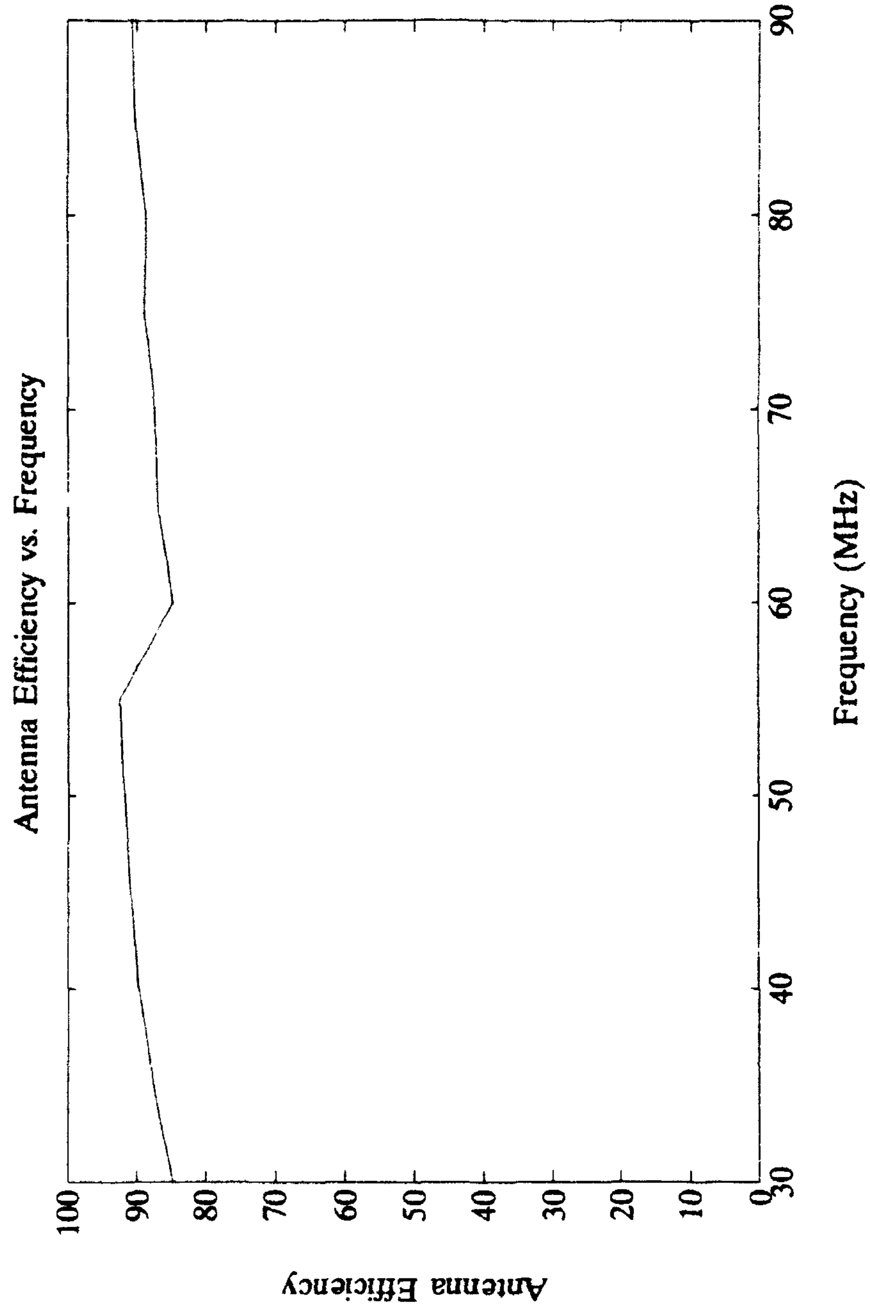


Figure 4.2 Antenna Efficiency

E. THE RESULTS FROM MATCHNET AND TOUCHSTONE

We attempted to design a single matching network for the antenna shown in Figure 2.2. However, due to a high Q $(=1/(\omega oRC))$ at the lower end of the frequency band, the reflection coefficient, Γ, was too high for the network to be useful. In order to design matching networks with an acceptable VSWR we considered dividing the frequency range into two smaller bands; the first from 30-45 MHz, and a second from 45-90 MHz. To determine whether acceptable matching networks could be designed over these sub-bands, we apply the Bode-Fano criterion. For example in the first sub-band, Δf is 15 MHz, the geometric mean frequency fo is around 35 MHz and the imaginary part of the input impedance of the antenna from Table 4 is -131.1 Ω. In order to achieve a VSWR $\leq$ 2.0, the real part of this complex load should be greater than 20 ohms. The real part of the antenna input impedance however is 16.27 ohms. Hence we need to add at least 4 ohms in series with the antenna to achieve a VSWR $\leq$ 2.0.

The approaches to synthesizing, optimizing, and simulating the matching networks are the same as those discussed in Chapter III. First, matching networks were synthesized and optimized by using MATCHNET. Next, the synthesized matching networks were simulated and further optimized by TOUCHSTONE to obtain the optimum responses. When the optimum responses for each sub-bands are achieved, the circuits were connected in parallel via PIN diodes, and further optimized to account for coupling effects and PIN diodes losses.

1. MATCHNET Results

Table 13 and 14 show the input data files for the two sub-bands. Table 13 indicates that the real part of the input impedance at 30 MHz is quite low. In order to achieve a minimum reflection coefficient, a 30 ohms resistance was added to the real part of the antenna in the first sub-band. The added resistance will minimize Γ at the expense of S21. No resistance is necessary for the second sub-band. Table 15 and 16 illustrate output circuit files from MATCHNET corresponding to the input files in Table 13 and 14. The output files give the values of the elements and the configuration of the circuit. The results from the output files were used to create TOUCHSTONE circuit files for simulation and optimization.

TABLE 13 MATCHNET INPUT FILE FOR THE FIRST SUB-BAND

R 50 Z A			
Frequency (Hz)	Real Part Impedance (Ω)	Imaginary Part Imped. (Ω)	Desired Mag. of S21
3.0e7	11.34	-192.6	0.98
3.5e7	16.27	-131.1	0.98
4.0e7	23.06	-77.61	0.98
4.5e7	32.26	-28.00	0.98

TABLE 14 MATCHNET INPUT FILE FOR THE SECOND SUB-BAND

R 50 Z A			
Frequency (Hz)	Real Part Imped. (Ω)	Imaginary Part Imped. (Ω)	Desired Mag. of S21
4.5e7	32.56	-28.00	0.98
5.0e7	46.11	20.67	0.98
6.0e7	53.26	26.54	0.98
7.0e7	52.10	26.44	0.98
8.0e7	48.63	19.23	0.98
9.0e7	50.32	25.66	0.98

TABLE 15 OUTPUT CIRCUIT FILE FOR THE FIRST SUB-BAND

The Lumped Element Design	
Series Capacitor	5.000E-011 F
Shunt Inductor	1.600E-006 F
Series Inductor	6.150E-007 H
Shunt Inductor	1.400E-007 H
Shunt Capacitor	1.410E-010 F
Series Inductor	5.000E-007 H
-Lossless Capacitors -Lossless Inductors	

TABLE 16 OUTPUT CIRCUIT FILE FOR THE SECOND SUB-BAND

The Lumped Element Design	
Shunt Inductor	8.500E-007 H
Series Capacitor	1.598E-009 F
-Lossless Capacitors -Lossless Inductors	

2. TOUCHSTONE Results

The circuit files for TOUCHSTONE were constructed using the results from MATCHNET. TOUCHSTONE also needs the antenna impedance data in the form of scattering parameters as discussed in Appendix C and Chapter III. The circuit output and input files of TOUCHSTONE are listed in Appendix E. First, each sub-band was simulated and optimized individually. After the optimum responses were achieved, the circuits were connected in parallel by means of PIN diodes and further optimization was performed.

a. *Idividual Responses*

Figure 4.3 shows the response of the individual network in the first sub-band. S11 is well below -10 dB implying that the VSWR in the passband is better than 2:1. Only a small portion of maximum available power, about 9% according to Figure 4.3, is reflected. However the power transferred from the generator to the load, $|S21|^2$, is only between 20% to 42%. This is due to losses in the matching network. The overall radiation efficiency will be even lower because of losses on the antenna.

No resistance was added to the second sub-band because the real part of the complex load meets the Bode-Fano criterion. It is also easier to design a matching network for this case because of the lower Q of the antenna. Figure 4.4 illustrates the response of the matching network for the second sub-band. The value of $|S21|^2$ for this band is between 90% to 95%.

The two circuits were connected in parallel using PIN diodes as switches. A final simulation and optimization was performed to account for the coupling effects and PIN diodes losses. The two circuits are listed in Appendix E.

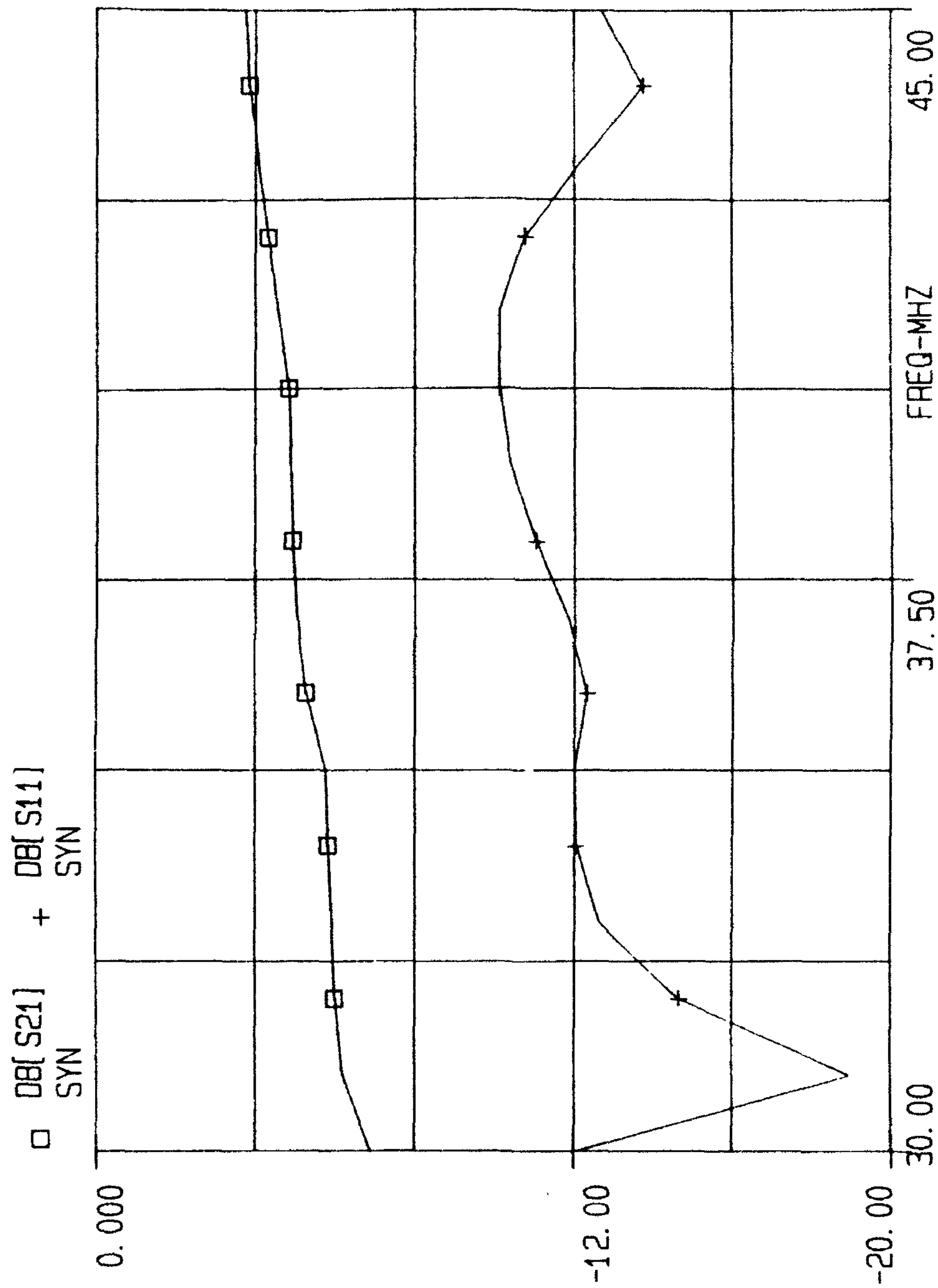


Figure 4.3 Output Response of the First Sub-band (30-45 MHz)

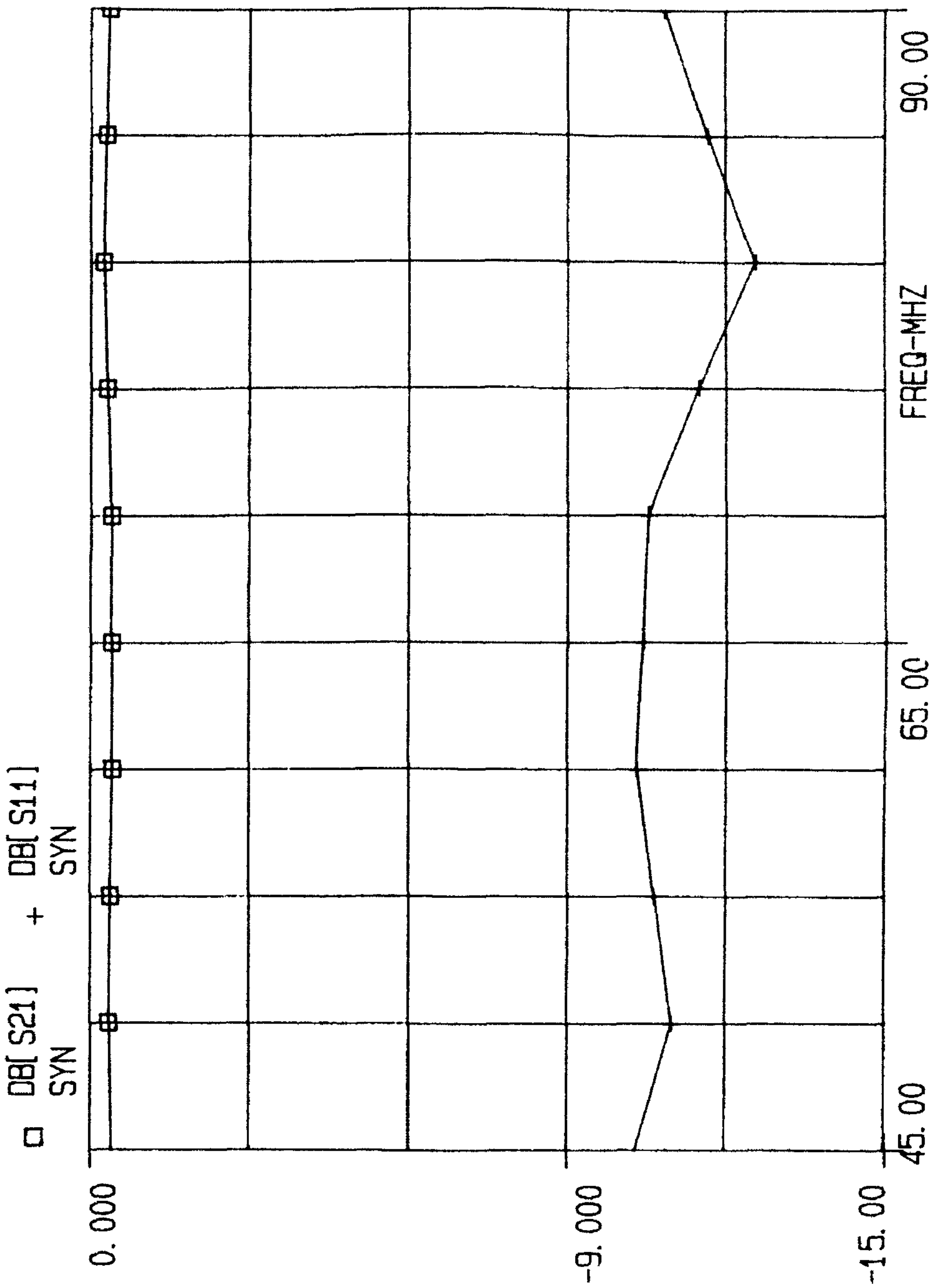


Figure 4.4 The Output Response of the Second Sub-band (45-90 MHz)

b. *Parallel Connection Responses*

The added resistance is now part of the matching network. The values of the elements and the added resistance were varied slightly in the parallel connection after optimization. Further optimization was done for each sub-band to account for the coupling effects and PIN diode resistance. The final values for all the elements are in TOUCHSTONE circuit files in Appendix E. The parallel connection used the same input files as the individual network.

Figure 4.5 illustrates the response in the first sub-band of the parallel connection after optimization. The S21 response is basically the same as in Figure 4.3. However, the S11 response changed slightly, but is still well below -10 dB. Initially, 30 Ω was added to the circuit to counteract the high reflection coefficient at the lower end of the frequency band. After optimization in the individual circuit, the added resistance was changed from 30 Ω to 40 Ω to achieve optimum response. The 40 Ω resistance in the individual circuit changed to 27 Ω after optimization in the parallel circuit connection. The forward biased resistance of the PIN diodes is 3 Ω when switched ON as shown in Table 9. Therefore, the final value for the added resistance was optimized to 27 Ω as predicted by Bode-Fano criterion. The presence of the diodes did not affect the responses significantly.

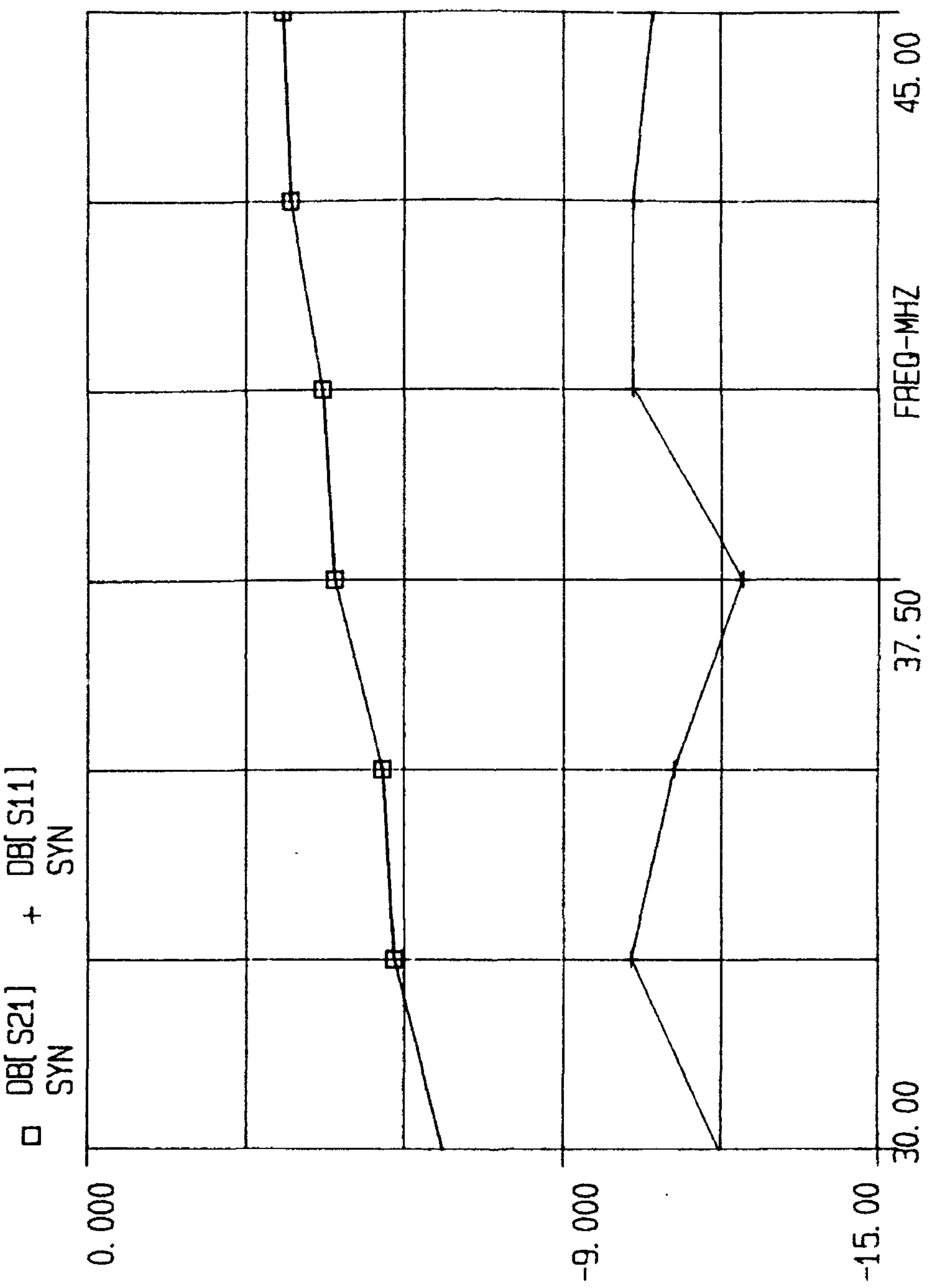


Figure 4.5 Overall Response in the First Sub-band

Figure 4.6 illustrates the response in the second sub-band for the parallel connection. The response of S21 changed by about 0.5 dB from the individual response. The effect is due to the two PIN diodes which introduce 6 Ω into the matching network when they are switched ON. Further optimization was done to compensate for the losses of the diodes. However, the power transfer efficiency ($|S21|^2$) remained between 78% to 84%. Compared with that of the individual response, there is a drop of about 11%. $|S11|$ remains well below -11 dB. The presence of the diodes has a more pronounced effect on $|S21|$.

Figure 4.7 illustrates the integrated matching network of the system. The PIN diodes are connected between the generator and matching networks and between the matching networks and antenna. Diodes D1 and D2 are switched ON and D3 and D4 are switched OFF between 30 and 45 MHz. The roles of D1, D2 and D3, D4 are reversed for 45-90 MHz.

Lossy inductors with a Q of 75 were used to replace the lossless inductors in the integrated matching network to investigate the effects on the responses. The responses remained basically the same as shown in Figure 4.5 and 4.6. Therefore, the output plots are not shown, but the TOUCHSTONE circuit and output files are listed in Appendix E.

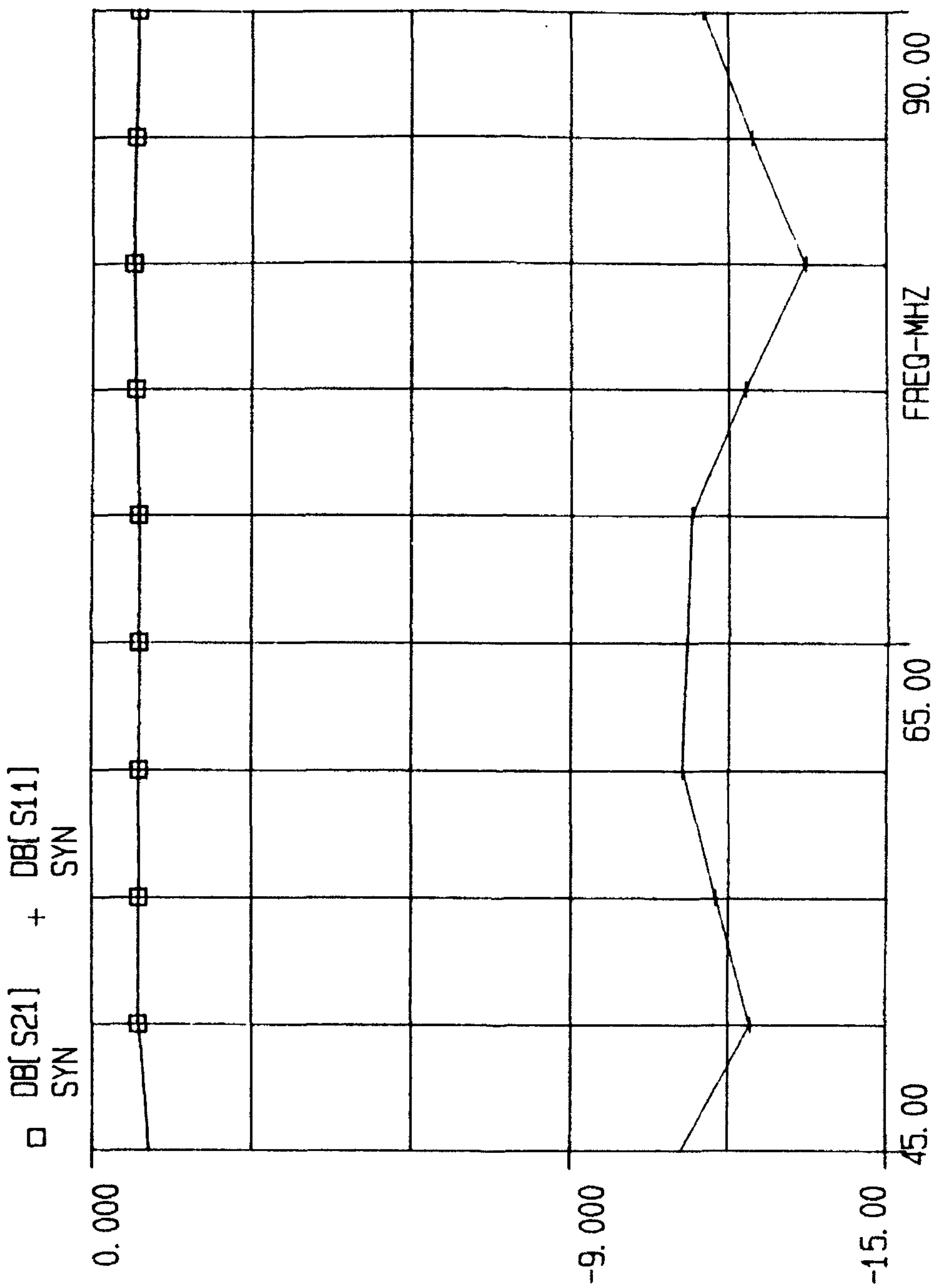


Figure 4.6 Overall Response in the Second Sub-band

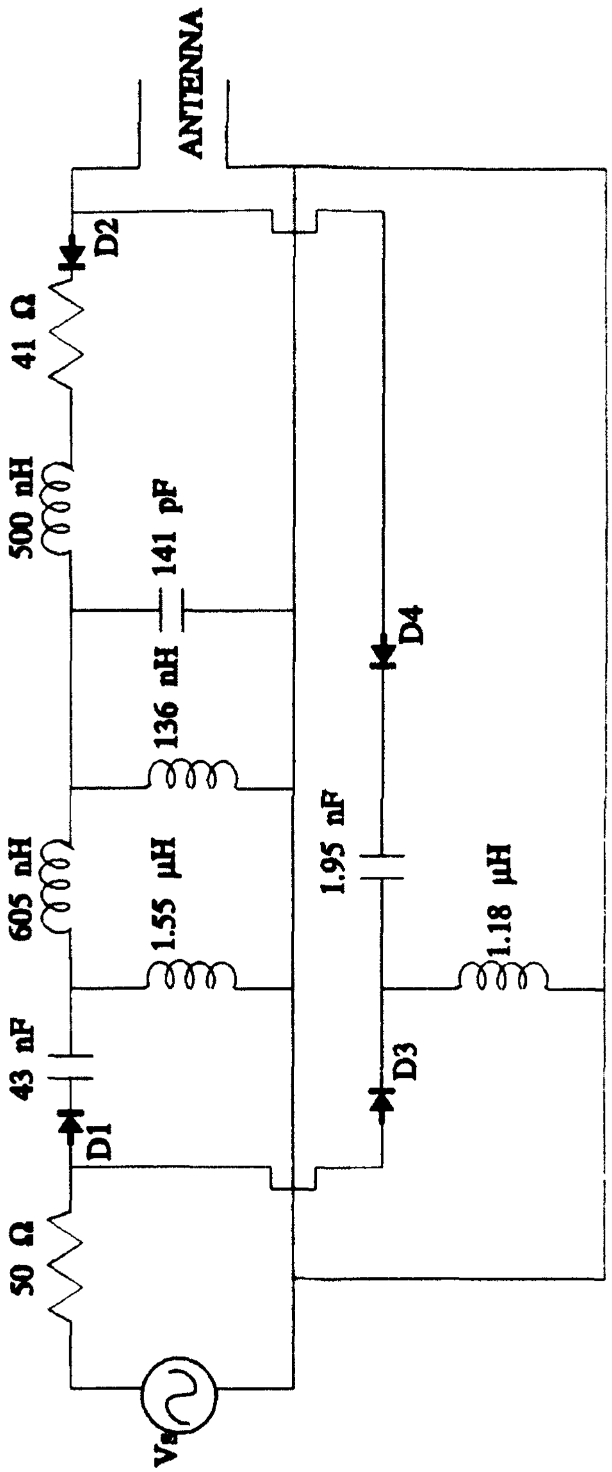


Figure 4.7 Integrated Matching Network for the Antenna of Fig. 2.2

F. THE OVERALL POWER EFFICIENCY

To obtain the overall power efficiency of the antenna and matching network, the power transfer efficiency in both sub-bands were multiplied by the antenna efficiency shown in Figure 4.2. Figure 4.8 illustrates the overall power efficiency. Low efficiency is still prevalent in the lower end of the frequency band, but improves as the frequency increases. The efficiency varies between 18% at low frequency to 75% at high frequency. Compared to the first loading technique, this method shows quite an improvement in the overall power efficiency, particularly at the higher end. In addition, the antenna and matching network are still relatively simple.

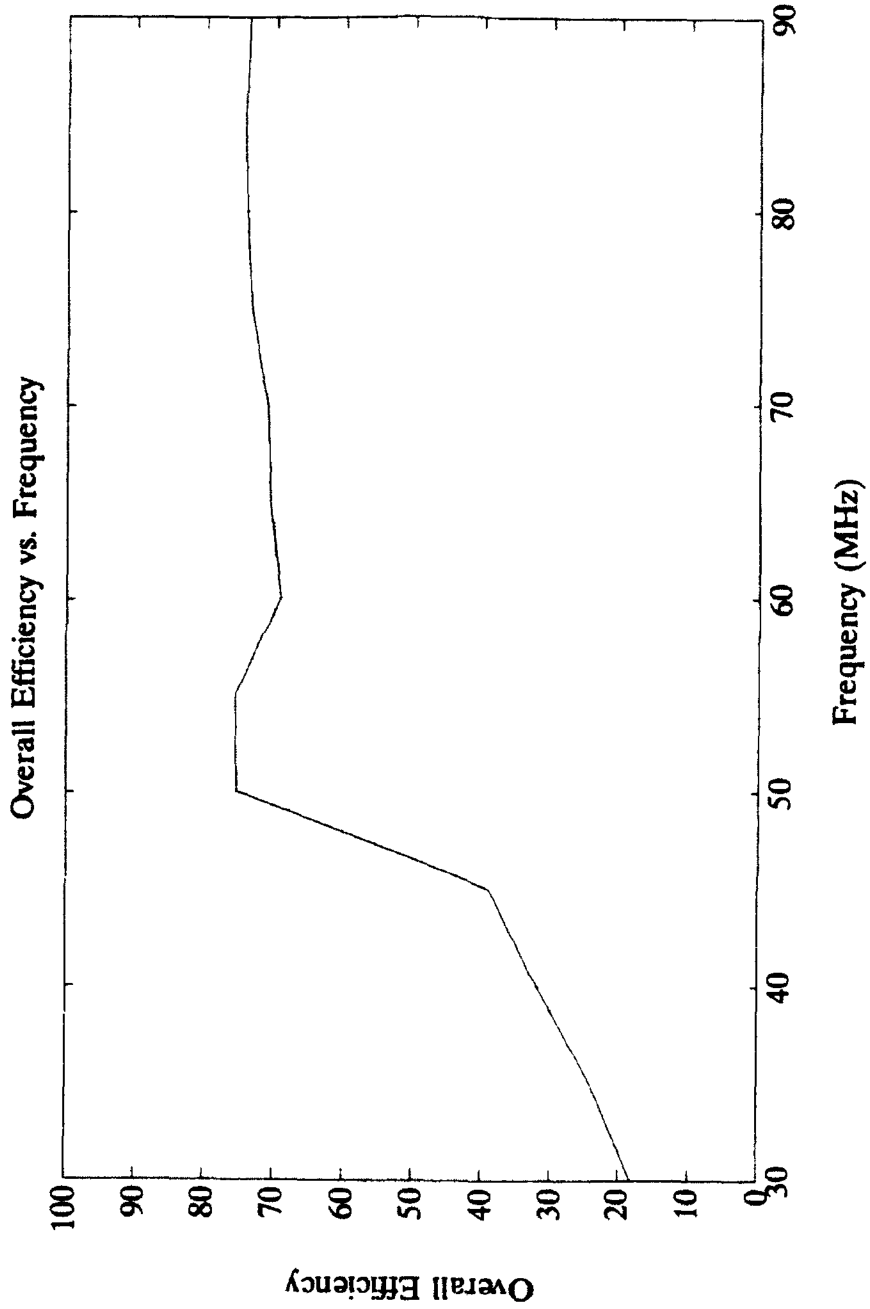


Figure 4.8 The Overall Power Efficiency

V. THE UNLOADED 1.5 METER MONOPOLE ANTENNA

In this chapter an unloaded monopole of length 1.5 m is analyzed. Since it is impossible to design a single matching network for the antenna with an acceptable VSWR over the entire band of 30-90 MHz, matching networks are designed for narrower bands and then connected using PIN diodes. The PIN diode states will be switched as a function of frequency to provide coverage over the entire band. Note that this scheme works in situations where the instantaneous bandwidth required is small and the carrier frequency is scanned over a wide band such as in frequency hopping. Note that even though a tuning network provides a good match in its own sub-band, there is no guarantee that its performance will be acceptable when several of these are connected as in the proposed scheme. However, in the last chapter we have demonstrated that additional optimization yields matching networks that perform well in an integrated scheme. In Section A we present the impedance characteristics of an unloaded antenna. In Section B we present the design of the matching networks.

The matching networks are first simulated and optimized individually, then they are connected in parallel using PIN diodes for final simulation and optimization. Finally, the inductors are made slightly lossy and their effect on the overall response is studied.

A. THE ANTENNA PARAMETERS

The antenna is the same as in the loaded monopole case (1.5 m in height and 0.5 cm in radius), except that it is unloaded. As discussed in Chapter III, if the base metal used for the monopole is aluminum, it can be assumed lossless. The frequency is partitioned into a number of bands as discussed before. For a percentage bandwidth P, the upper and lower frequencies of each sub-band are related as

$$f_u = \frac{100+P}{100-P} f_l \tag{5.1}$$

where f_u and f_l are the upper and lower frequencies of each band, respectively. We chose the bandwidth to be approximately five percent for the first eight sub-bands and ten percent for the remaining two sub-bands. The antenna input impedance was obtained from the WIRE program and is given in Appendix F. The impedance is highly capacitive at the lower end of the frequency band as expected.

B. THE DESIGN OF MATCHING NETWORKS

In each case we apply the Bode-Fano criterion and add the appropriate values of resistance needed to achieve a low input VSWR. Series resistance is needed at the lower end where the antenna impedance is dominated by a capacitive reactance.

Table 17 shows the input data file for the first sub-band. We added 10 ohms in series with the antenna in accordance with the Bode-Fano criterion. The same procedures can be followed to build the remaining nine data files. For more information about the construction of data files, the reader may refer to Appendix B and [5]. The matching networks resulting from MATCHNET for each sub-band are shown in Figures 5.1 (a) through 5.1 (j). The output data file resulting from the matching network synthesis which contains the values of the elements and the network configuration, is also given in Table 18.

TABLE 17 INPUT DATA FILE FOR THE FIRST SUB-BAND

R 50 Z A			
Frequency (Hz)	Real Part Imped. (ohms)	Imaginary Part Imped. (ohms)	Desired Magnitude of S_{21}
3.00e7	19.797	-194.3	0.98
3.05e7	20.200	-187.5	0.98
3.10e7	20.620	-180.9	0.98
3.15e7	21.050	-174.3	0.98

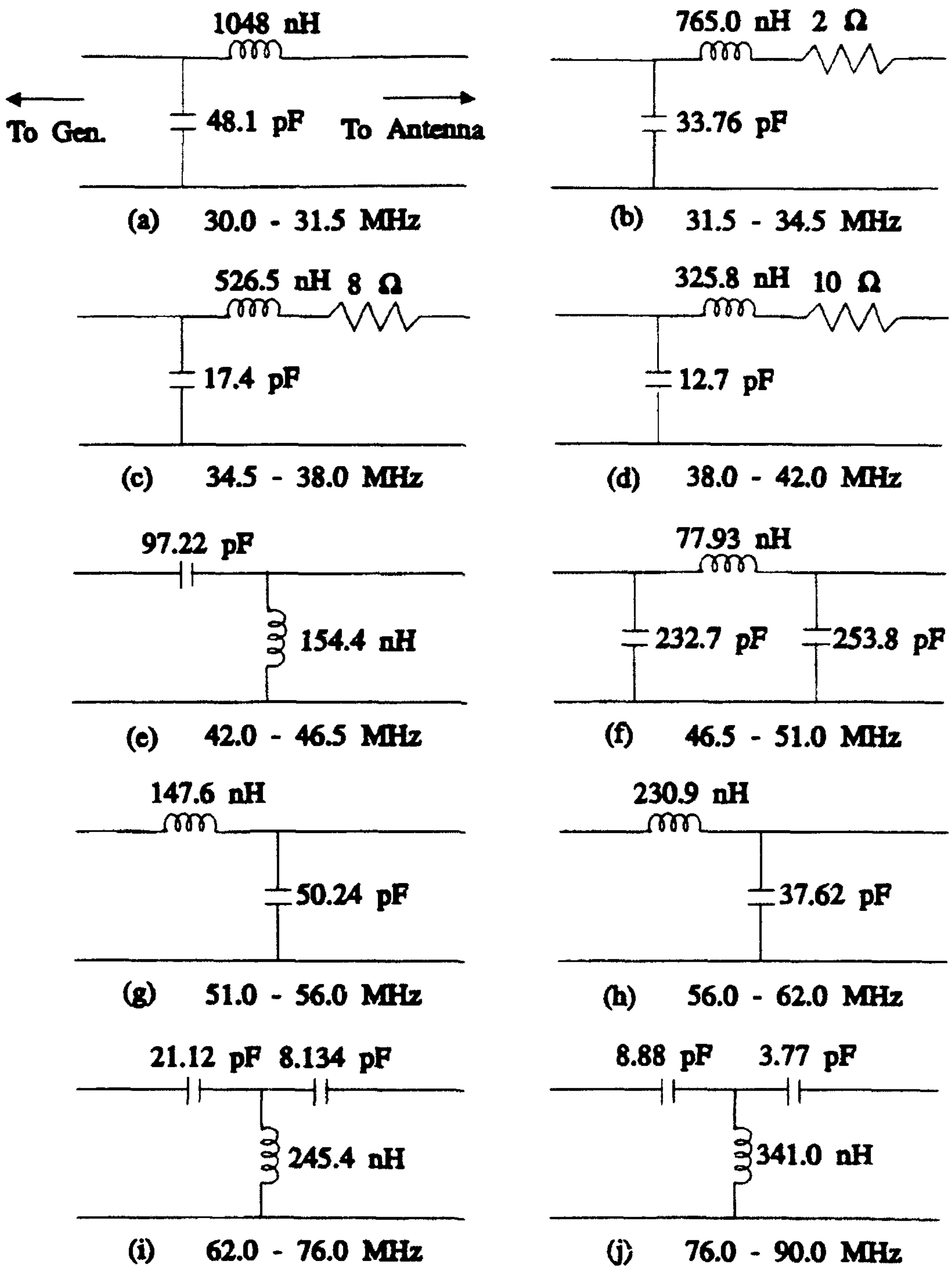


Figure 5.1 Individual Matching Networks

TABLE 18 OUTPUT DATA FILE FOR THE FIRST SUB-BAND

The Lumped Element Design	
Shunt Capacitor	7.500E-011 F
Series Inductor	1.060E-006 H
-Lossless Capacitors -Lossless Inductors	

C. SIMULATION RESULTS OF THE INDIVIDUAL RESPONSES

The circuit files for TOUCHSTONE are constructed using the results from the output data files of MATCHNET. The circuit file for the first sub-band is shown in Appendix G. After optimization, the element values in each sub-band changed from those given in Figure 5.1. The input data for the circuit files are the scattering parameters of the antenna as defined in equation (3.5).

The added 10 Ω resistance for the first through fourth sub-bands is now part of the matching networks. Figure 5.2 through Figure 5.11 are the optimum individual responses from simulation after optimization. The circuit file, input file, and output file given in Appendix G are for the first sub-band only. However, the same procedures can be followed to obtain the files for the remaining nine sub-bands. The values of the elements in each matching network were tuned to give optimum response, and the final values are also given in Appendix G. As expected, the element values changed. The response of S_{11}

for all ten bands is less than -10 dB or better implying a VSWR less than 2:1.

The response of S_{21} in the first four sub-bands is quite low as illustrated in Figure 5.2 to 5.5. The low response of S_{21} is caused by the added resistance. The maximum available power transferred to the antenna is equal to the $|S_{21}|^2$. Therefore, the networks absorb as much as 60% of the maximum available power in the first four sub-bands.

For the upper frequencies, the response is shown in Figure 5.6 to 5.11. It is seen that as much as 98% of the maximum available power is delivered to the antenna at the higher frequencies.

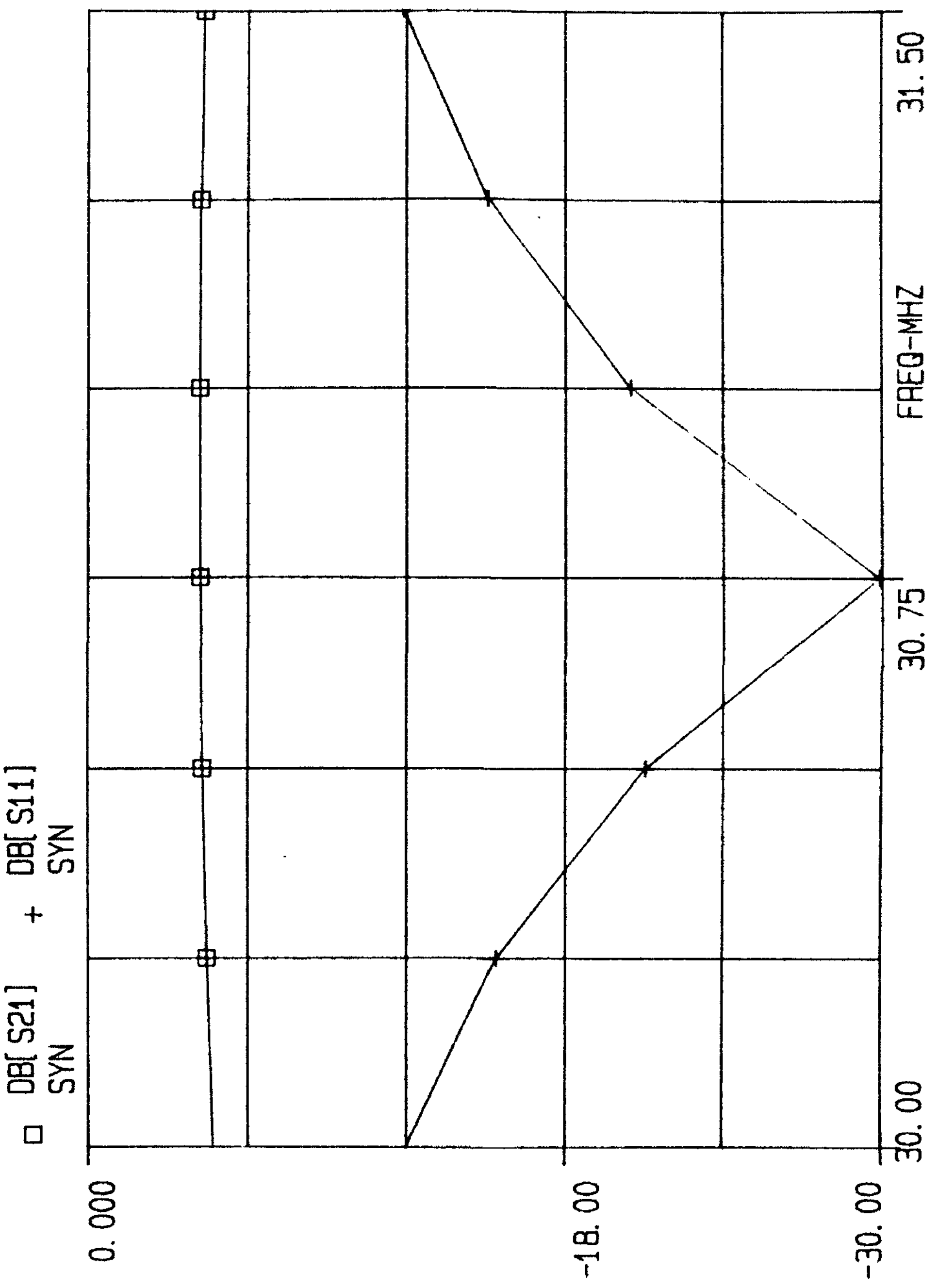


Figure 5.2 Individual Response in the First Sub-band

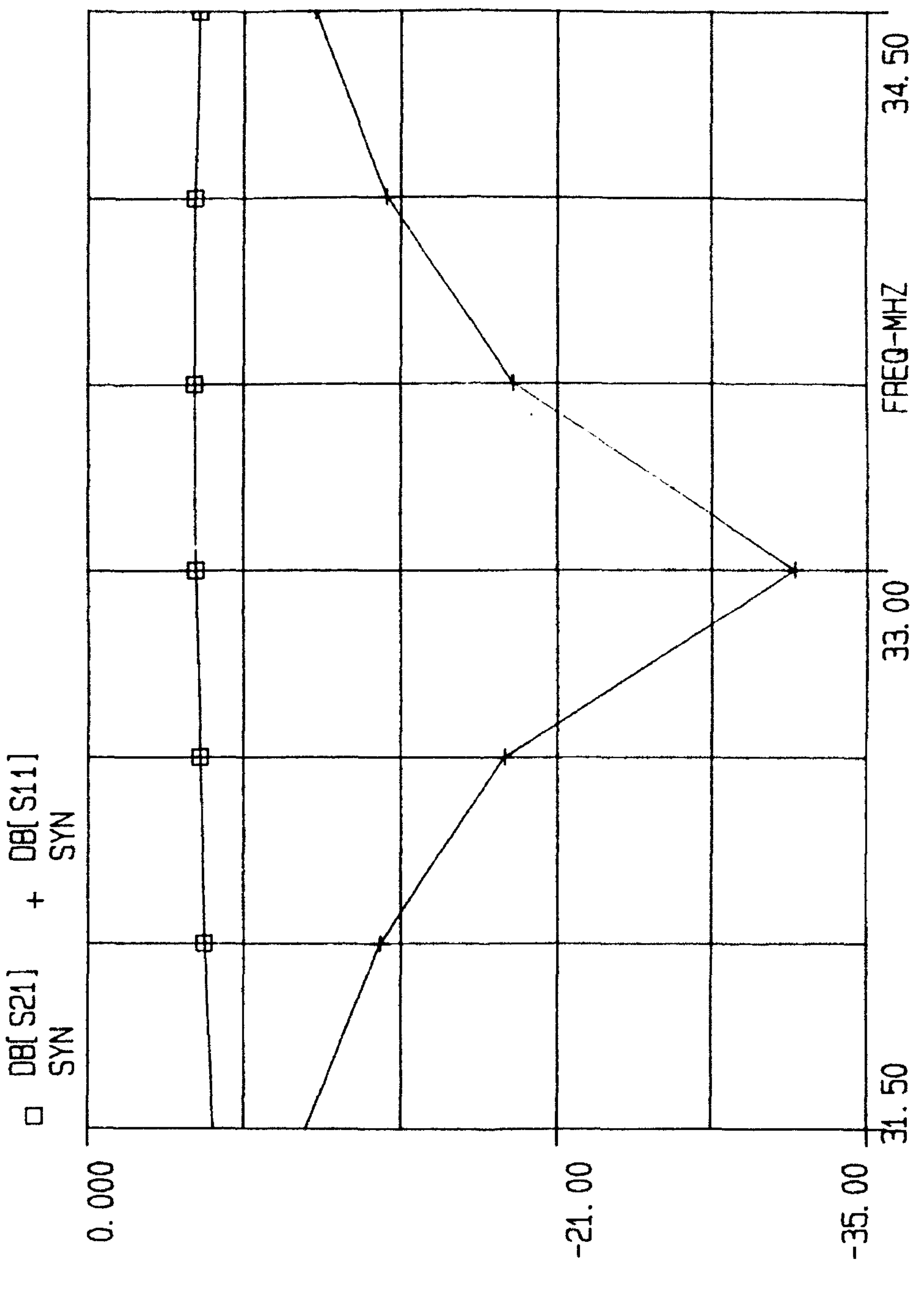


Figure 5.3 Individual Response in the Second Sub-band

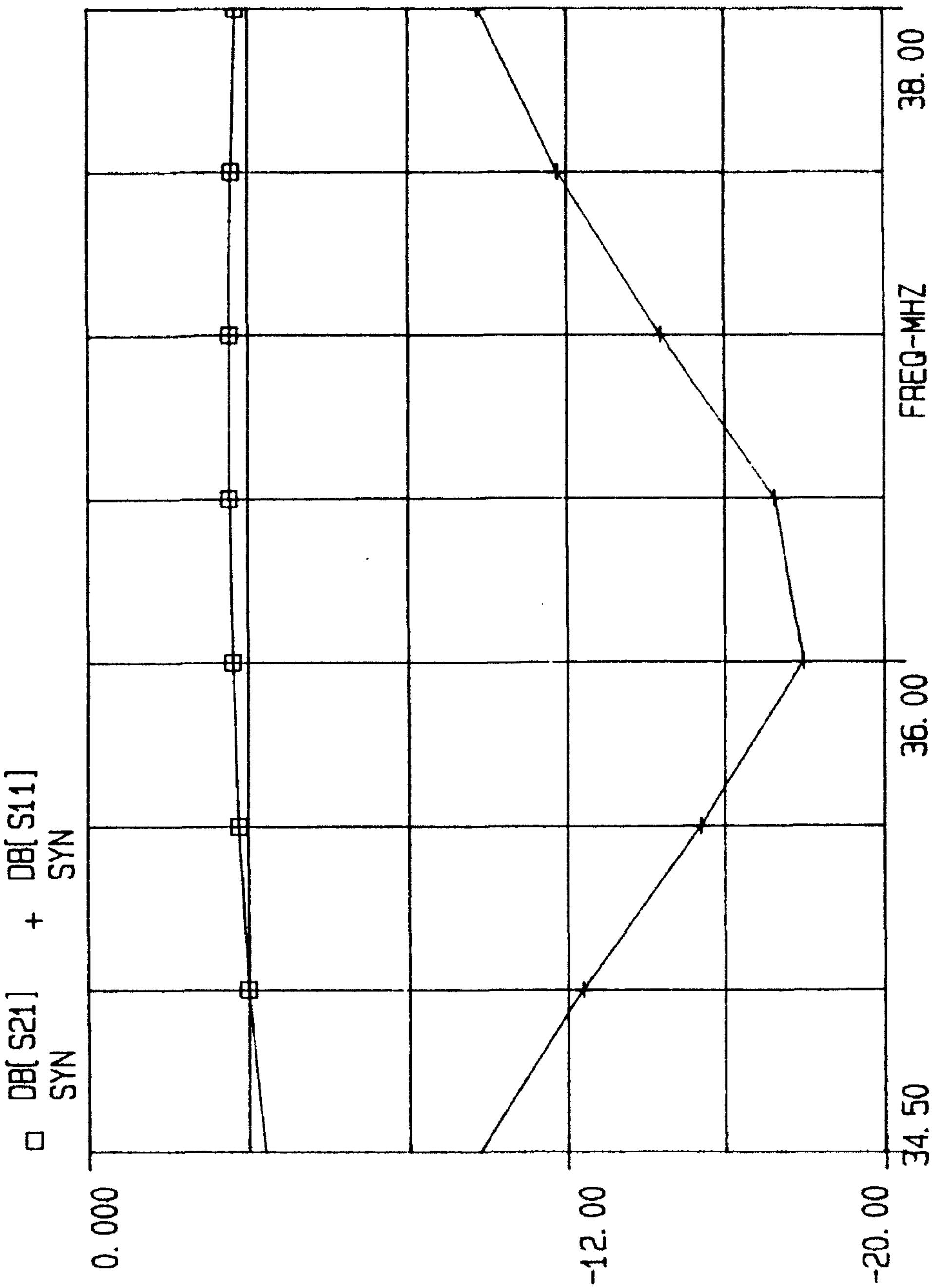


Figure 5.4 Individual Response in the Third Sub-band

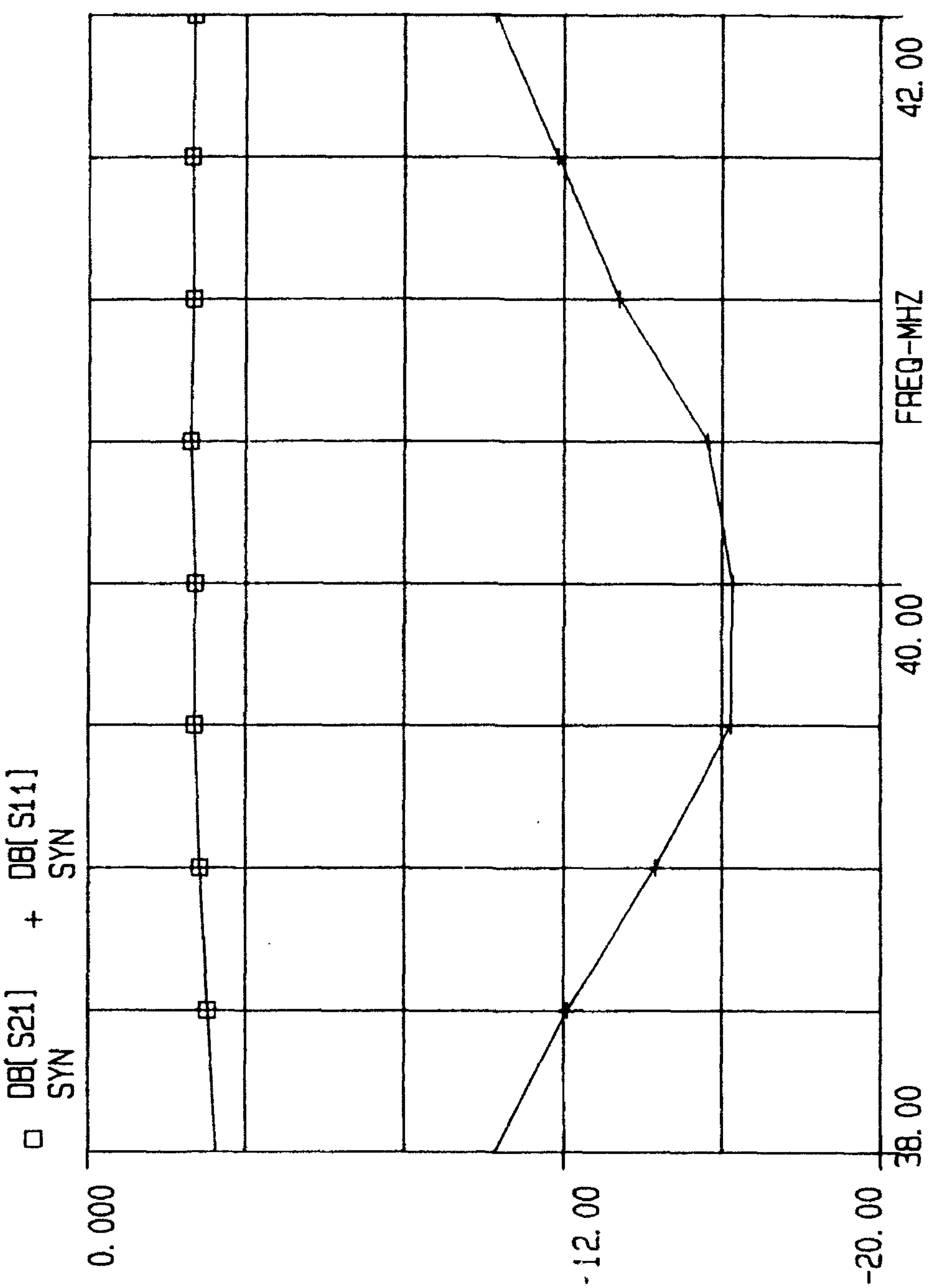


Figure 5.5 Individual Response in the Fourth Sub-band

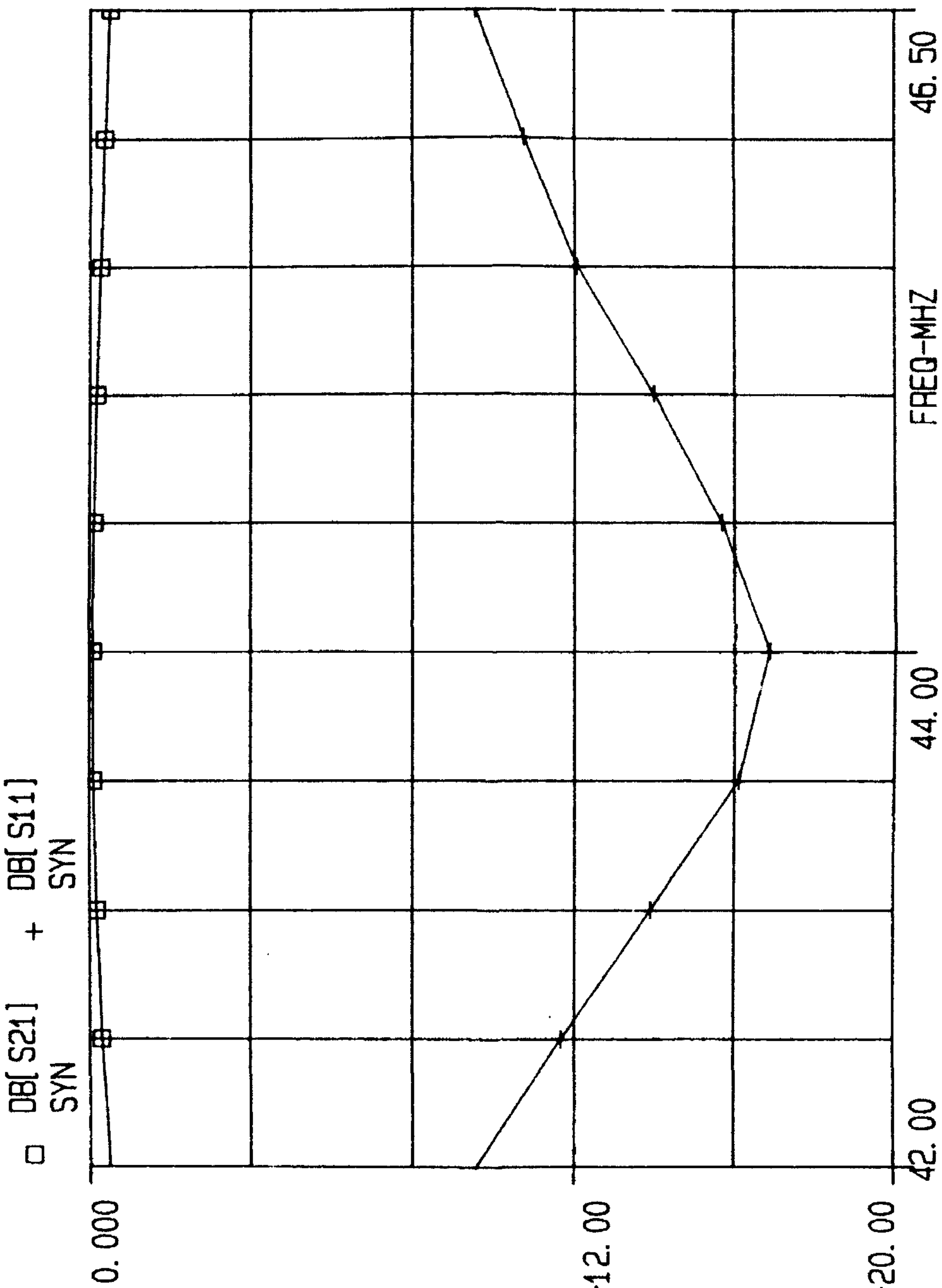


Figure 5.6 Individual Response in the Fifth Sub-band

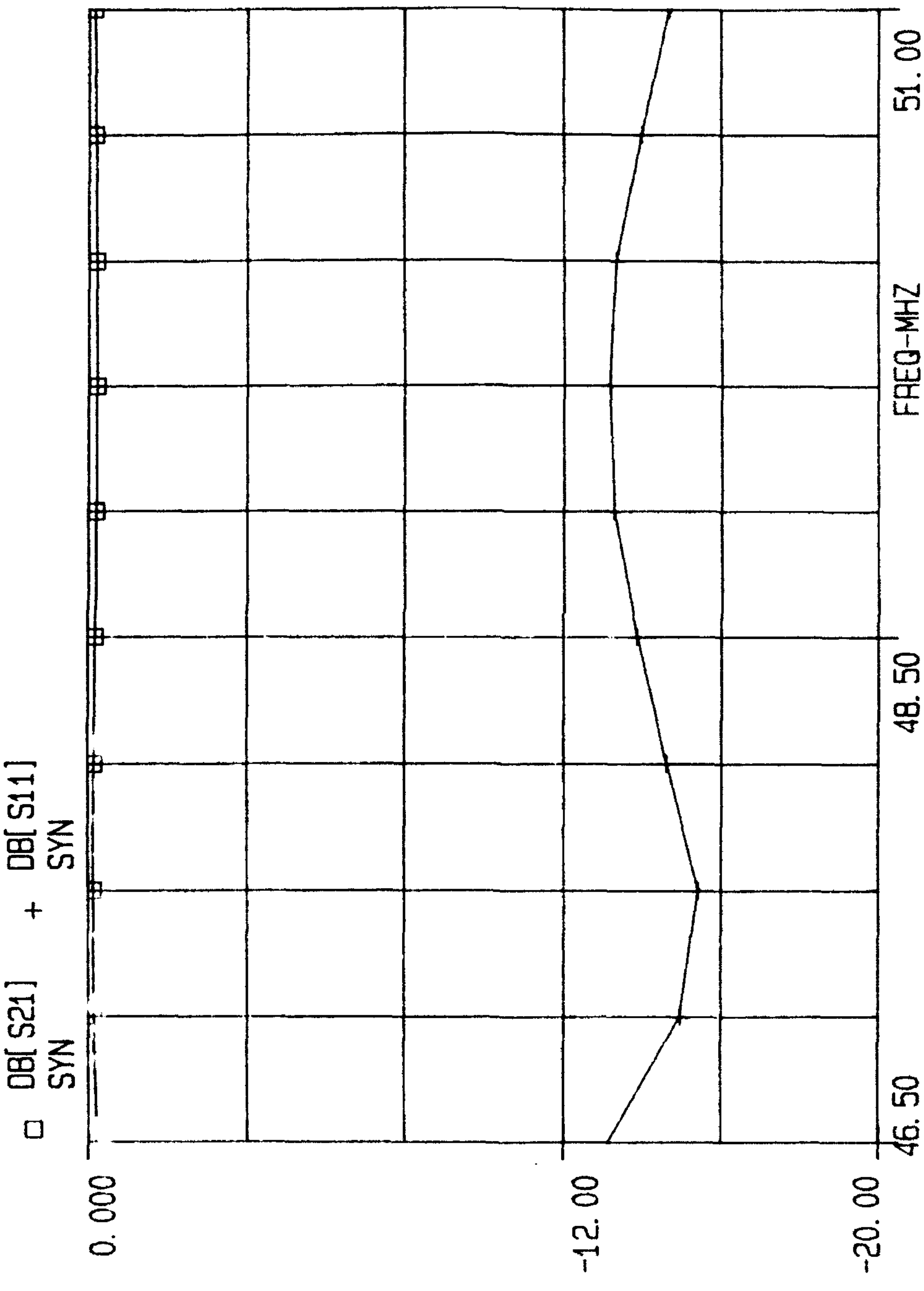


Figure 5.7 Individual Response in the Sixth Sub-band

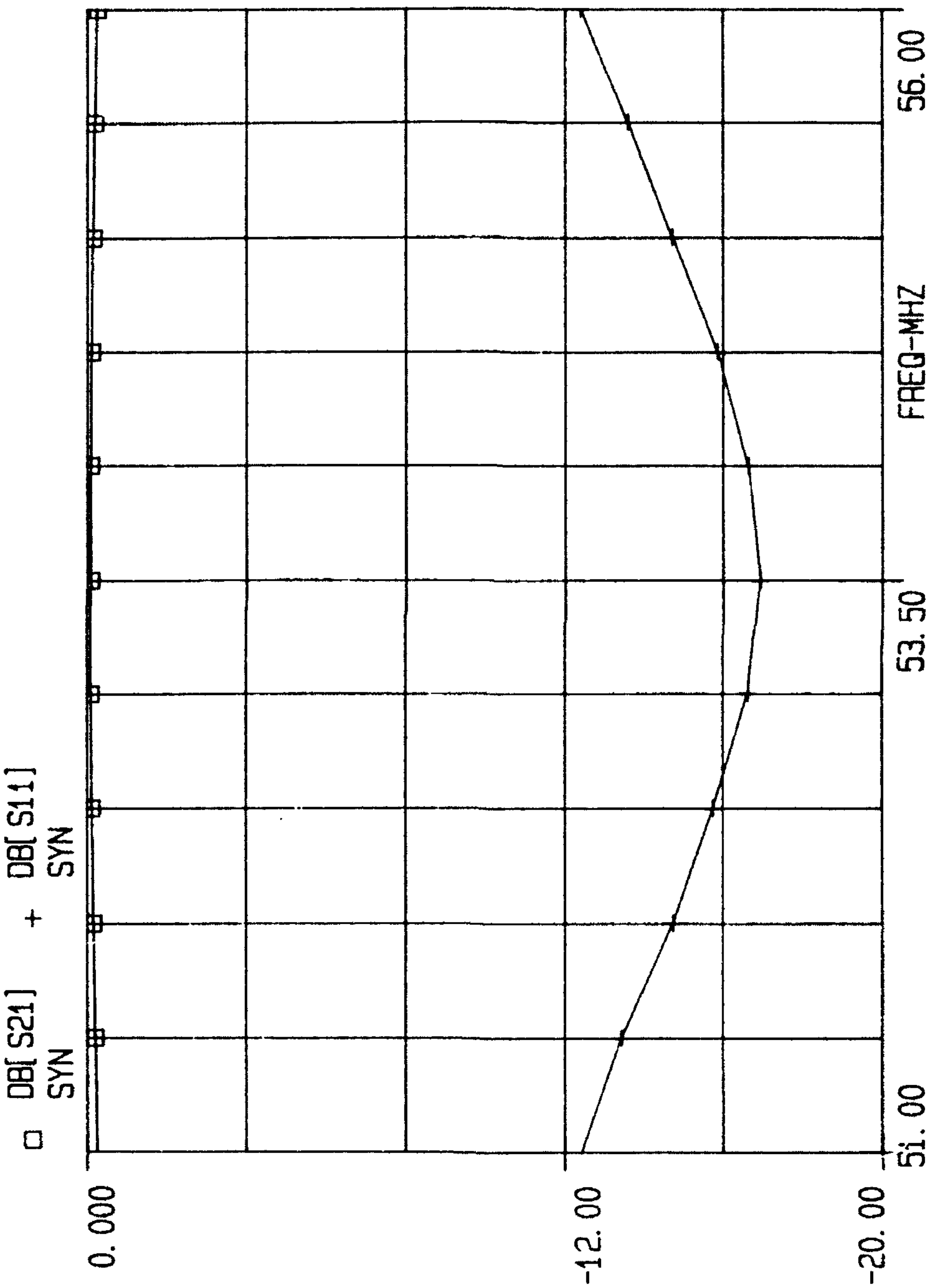


Figure 5.8 Individual Response in the Seventh Sub-band

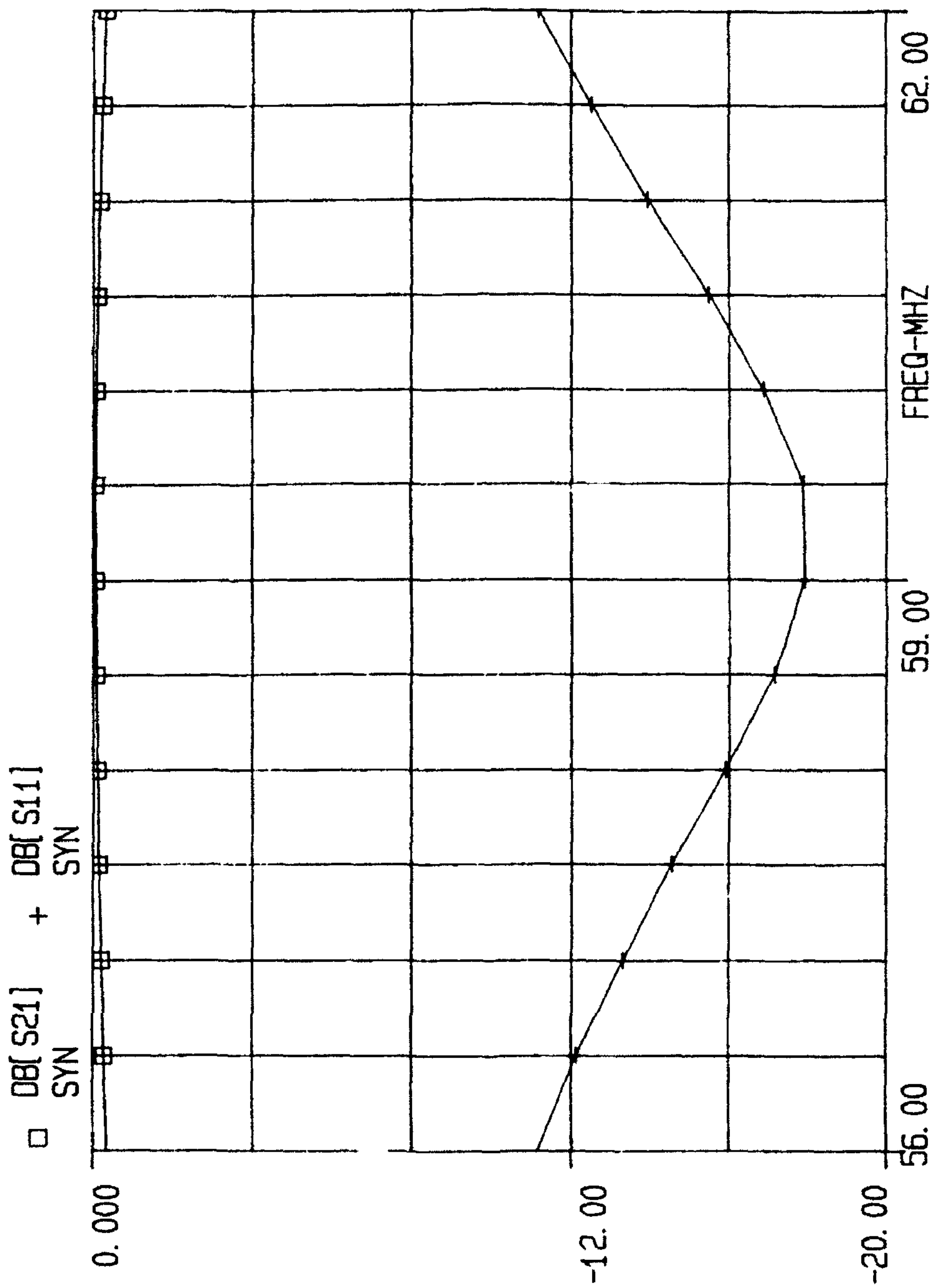


Figure 5.9 Individual Response in the Eighth Sub-band

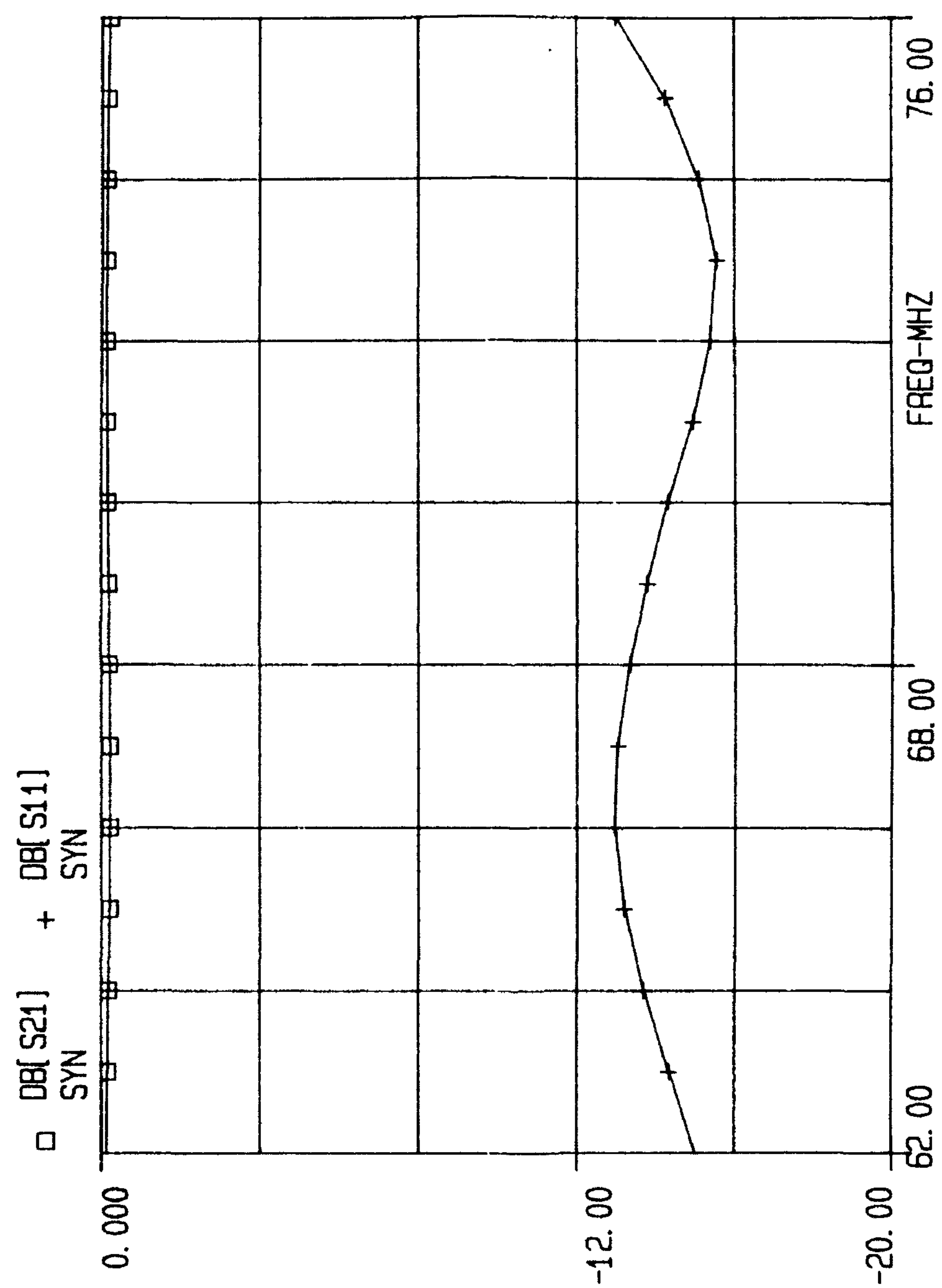


Figure 5.10 Individual Response in the Ninth Sub-band

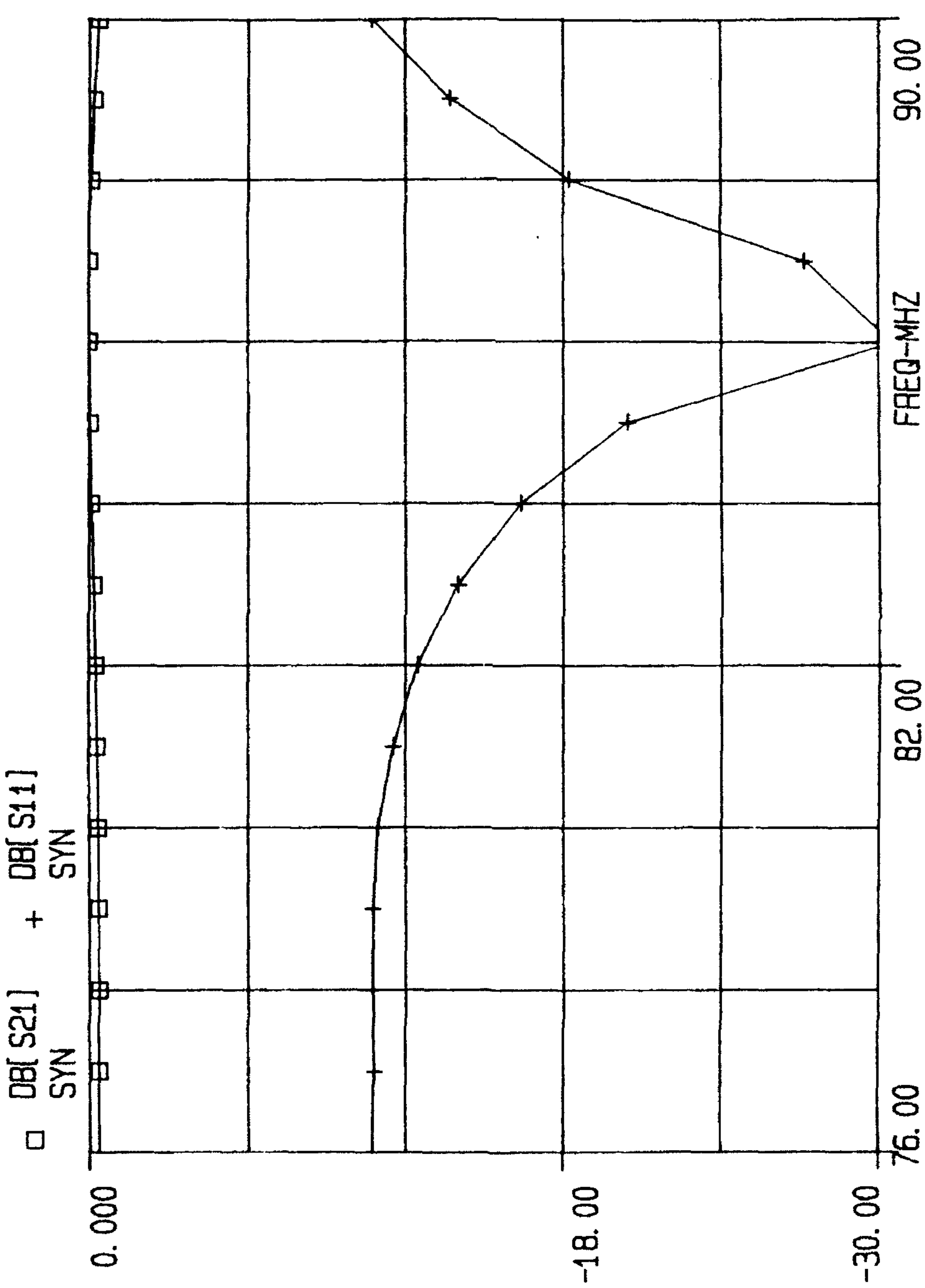


Figure 5.11 Individual Response in the Tenth Sub-band

D. PARALLEL CONNECTION SIMULATION RESULTS

The individually optimized and simulated matching networks discussed in the previous section were connected together in parallel via PIN diodes for switching. Two diodes were used for each of the matching networks. When the diodes are switched ON, the network is active. When they are switched OFF, ideally, the network for the particular sub-band should be totally isolated from the others. However, since the diodes are non-ideal, coupling can take place between various networks. To account for coupling effects and the presence of the diode forward biased impedance, the integrated matching network was further optimized for each one of the sub-bands. Once the optimum responses were achieved for each one of the sub-bands, the simulations were performed.

The selected diodes all have a 3 Ω forward biased resistance, and will therefore introduce an additional 6 Ω to each matching network. Hence, more available power will be absorbed by the network in addition to the coupling losses. The losses will be significant at the lower end of the frequency band because the individual responses were already low.

Figure 5.12 to 5.21 illustrate the responses for each sub-band after the integration and optimization. As expected, the losses are significant at the lower, albeit the VSWR is less than 2:1. An additional 3 dB loss was introduced in the first four sub-bands, and approximately 1 to 1.5 dB loss was introduced to the others due to the parallel connection. These losses were due to the presence of forward biased resistance of the diode and the coupling effects. Since the antenna itself is assumed to be lossless, the overall power efficiency is found to be between 20% and 78% for this particular scheme. The efficiency decreases by about 20% from its isolated response, but the system has the capability of being electronically switched. The circuit and output data files are given in Appendix H. The final integrated matching network configuration is shown in Figure 5.22. Figure 5.23 shows the element values of the final matching networks of Figure 5.22.

The overall response of the system shown in Fig. 5.22 is illustrated in Figure 5.24. Figure 5.25 illustrates the overall efficiency of the system. The efficiency varies between 20% and 78%. Compared to the loaded antennas considered in the previous chapters where the overall efficiencies varied between 17% and 18% for the first loading technique and 18% and 83% for the second loading technique, the present design has a better overall efficiency than the first loading technique and somewhat comparable to the second. However, the matching network of the system is far more complex.

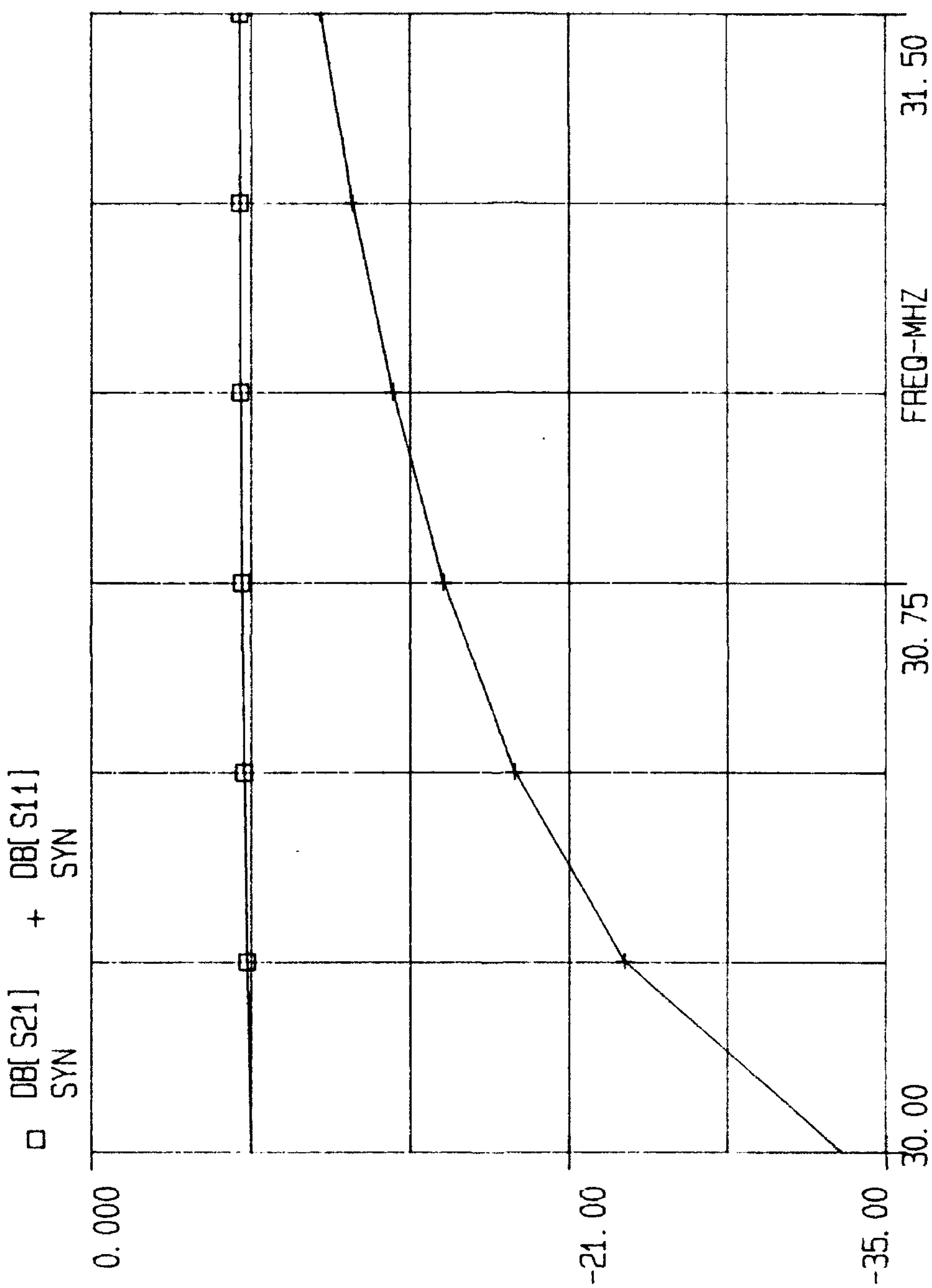


Figure 5.12 The Parallel Connection Response of the First Sub-band

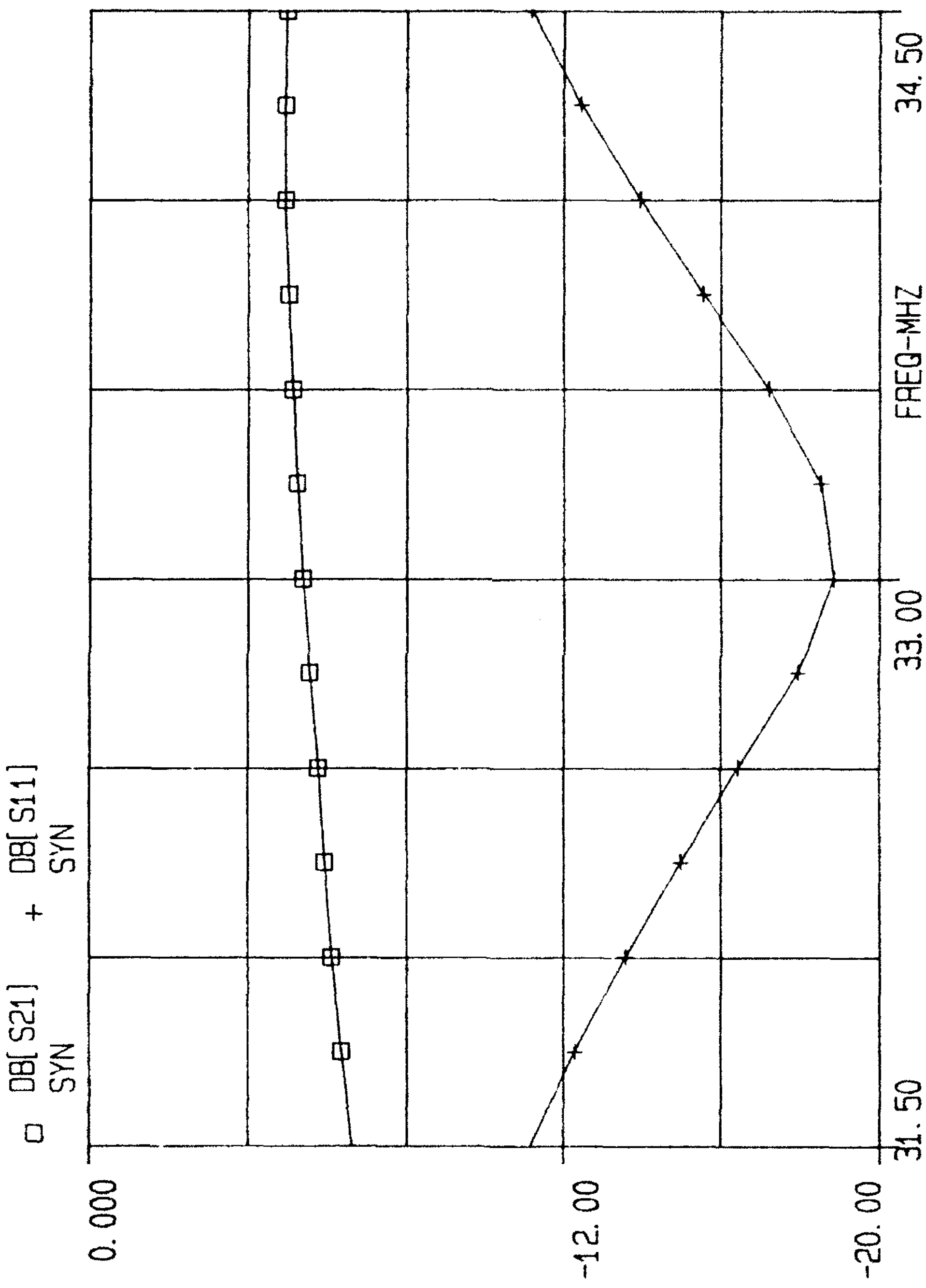


Figure 5.13 The Parallel Connection Response of the Second Sub-band

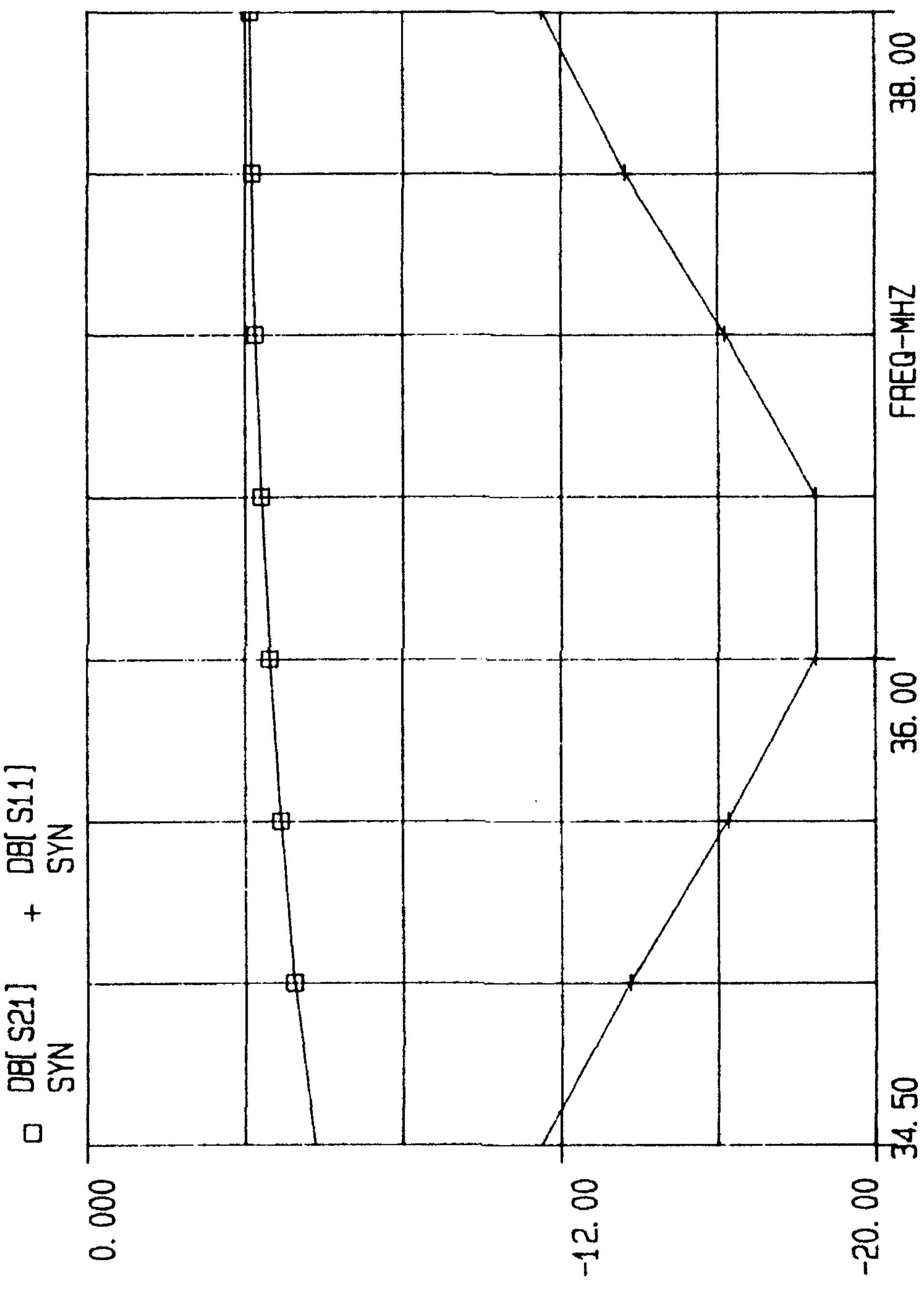


Figure 5.14 The Parallel Connection Response of the Third Sub-band

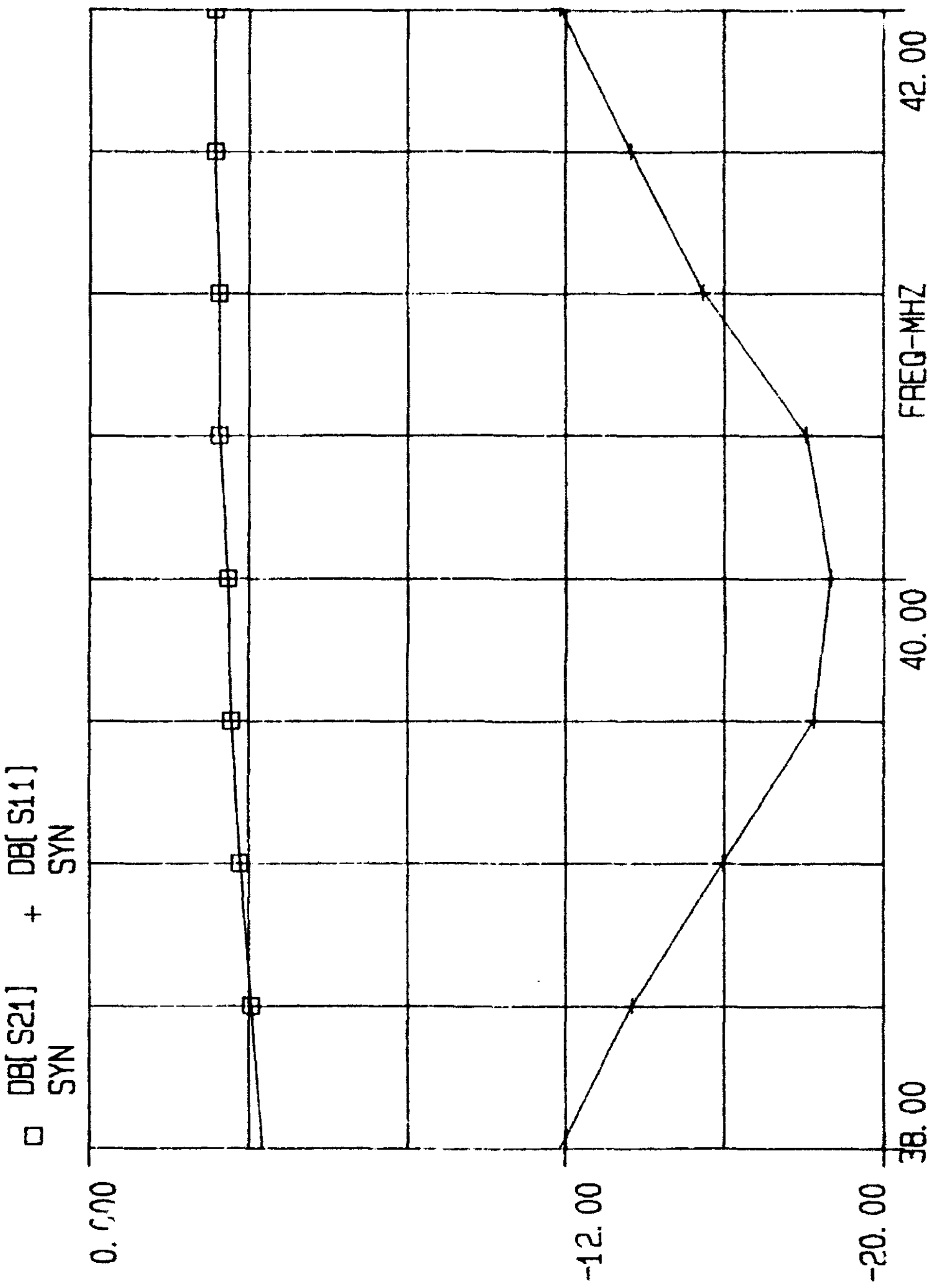


Figure 5.15 The Parallel Connection Response of the Fourth Sub-band

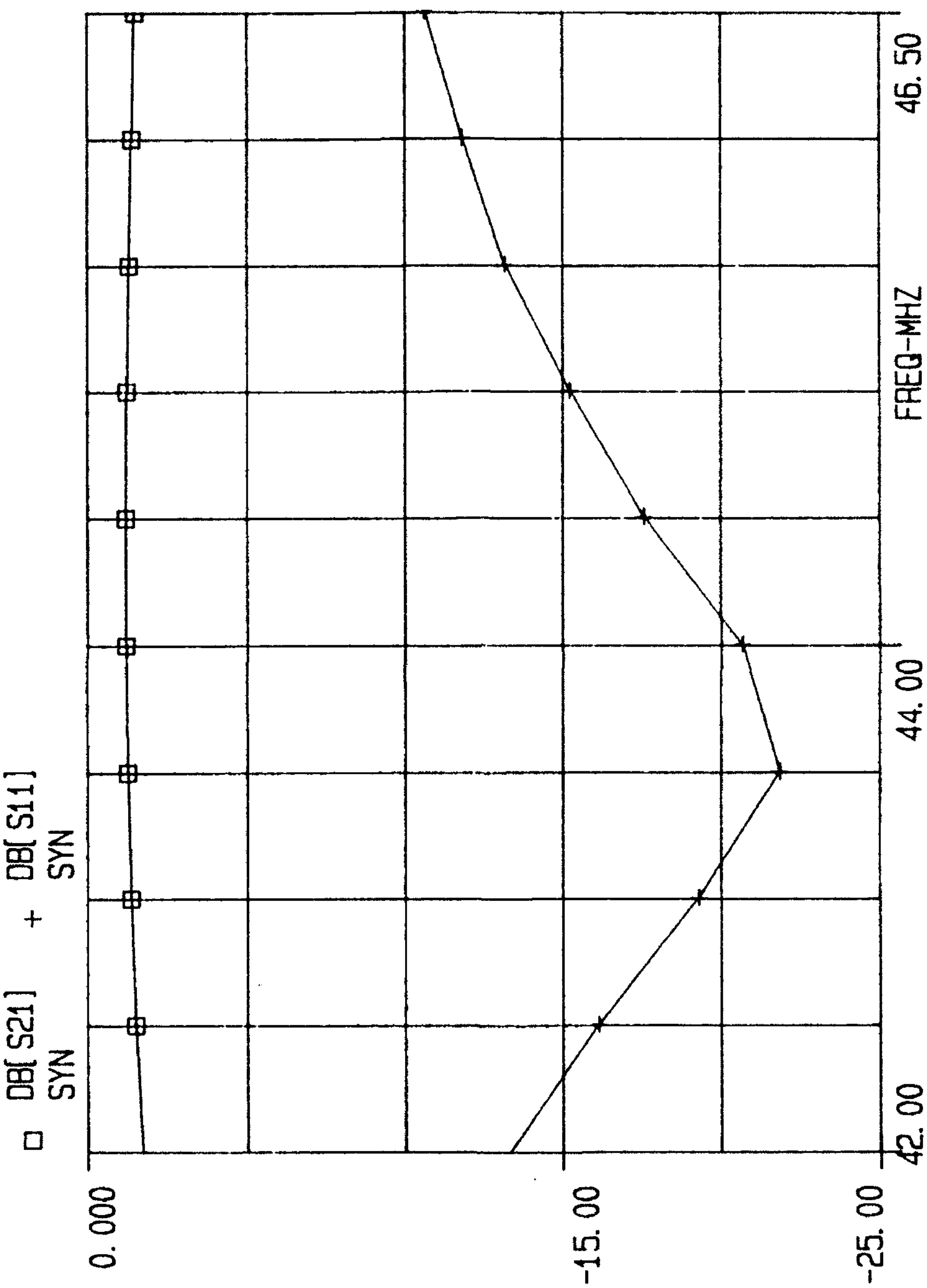


Figure 5.16 The Parallel Connection Response of the Fifth Sub-band

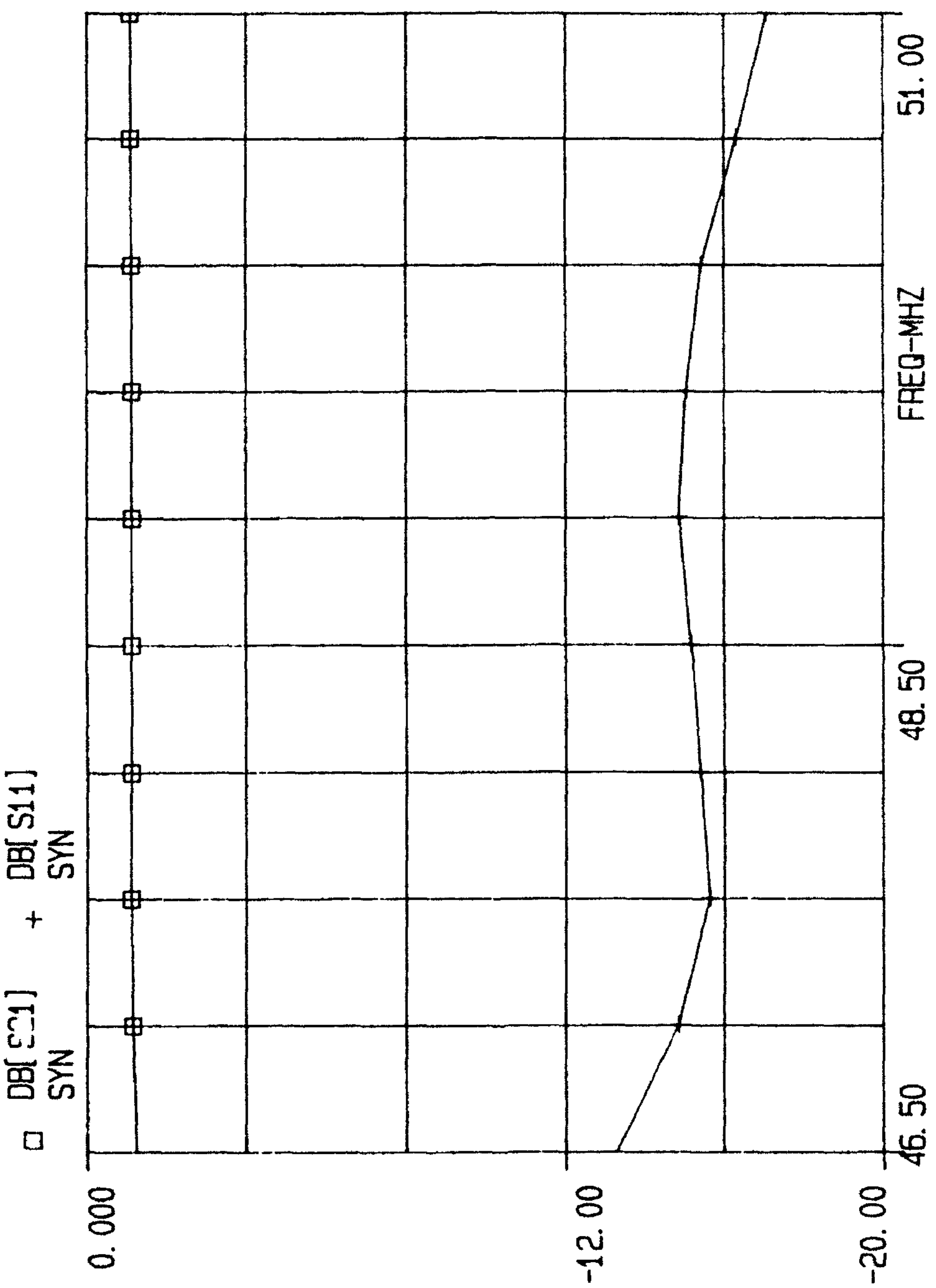


Figure 5.17 The Parallel Connection Response of the Sixth Sub-band

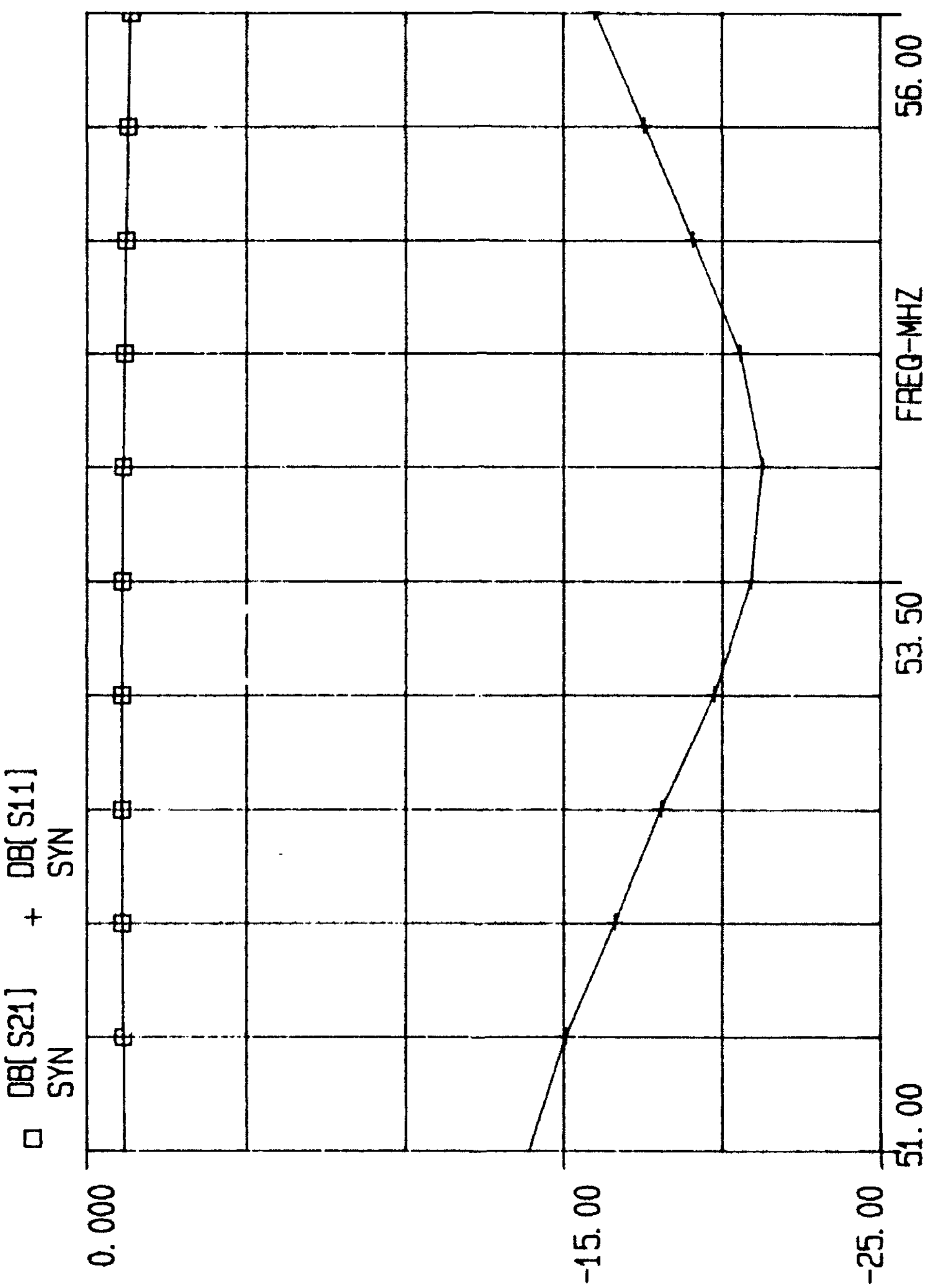


Figure 5.18 The Parallel Connection Response of the Seventh Sub-band

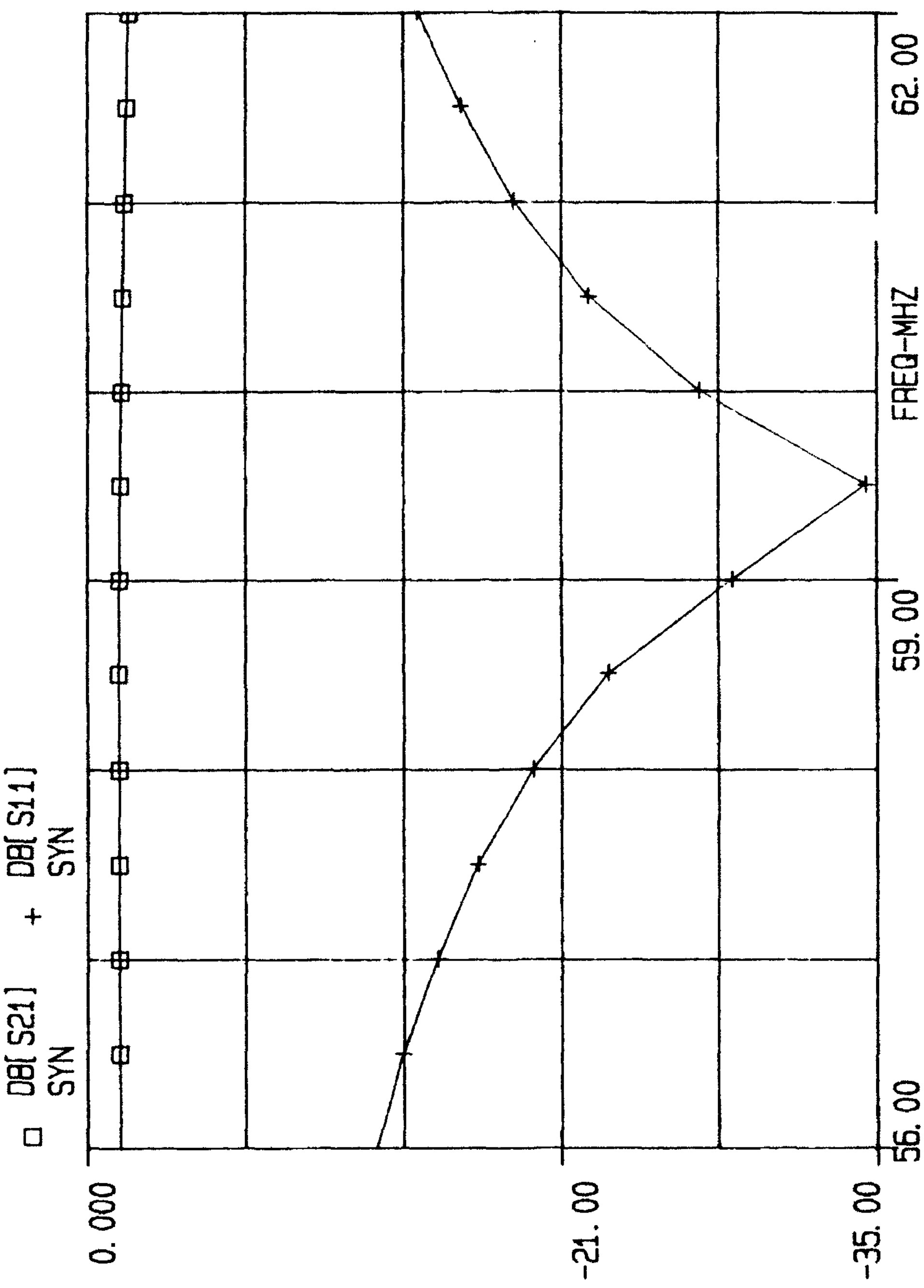


Figure 5.19 The Parallel Connection Response of the Eighth Sub-band

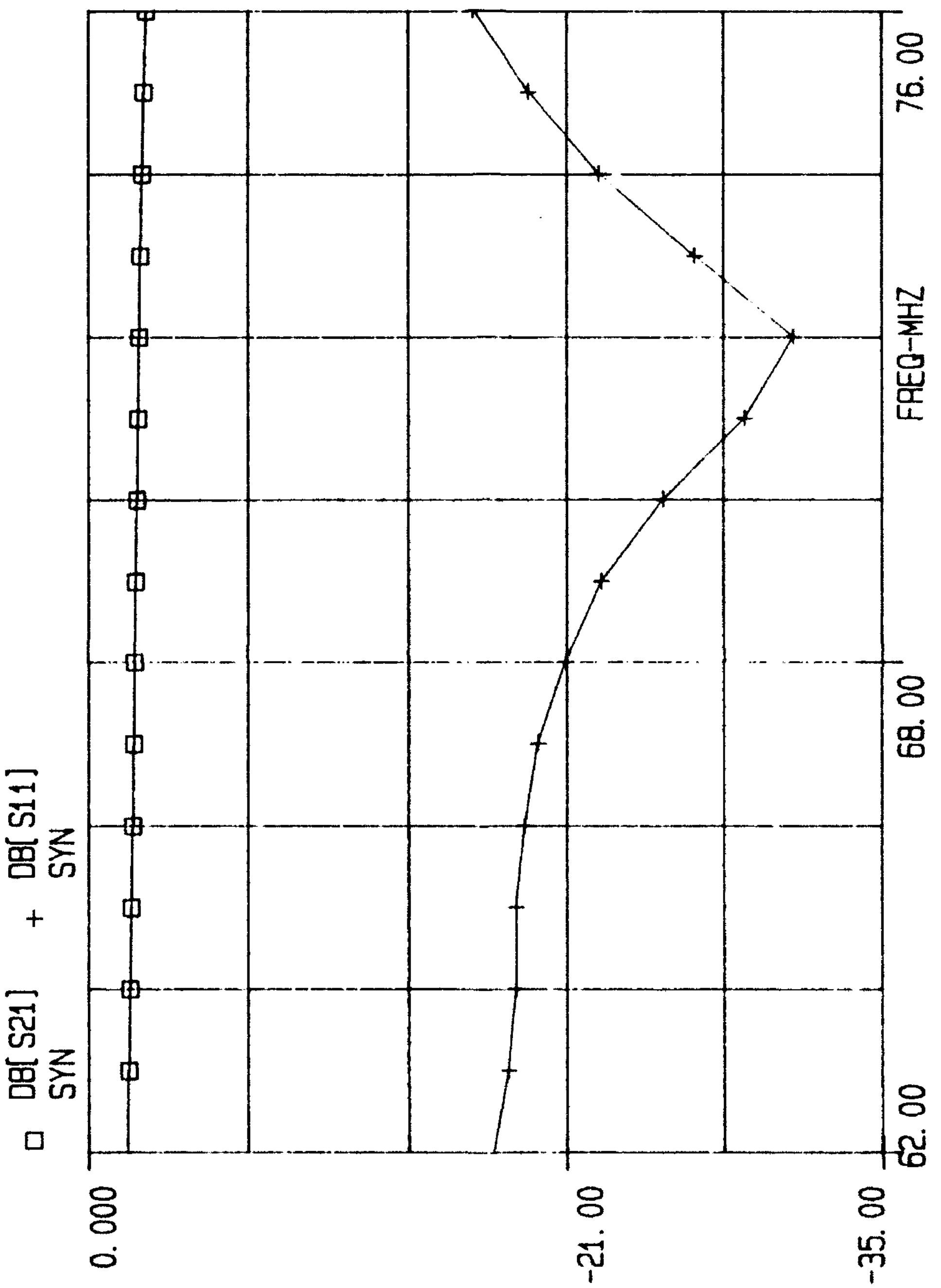


Figure 5.20 The Parallel Connection Response of the Ninth Sub-baı.d

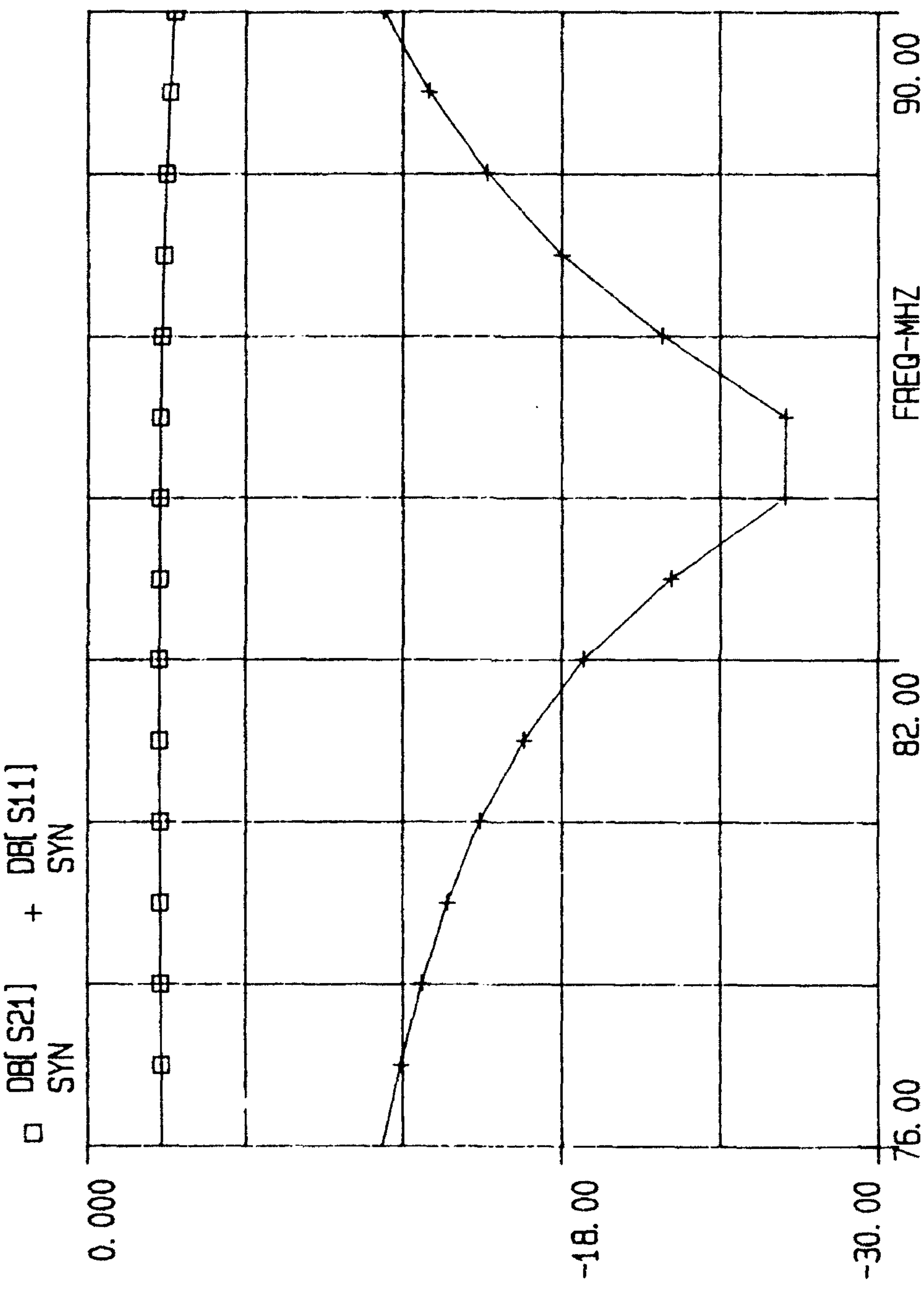


Figure 5.21 The Parallel Connection Response of the Tenth Sub-band

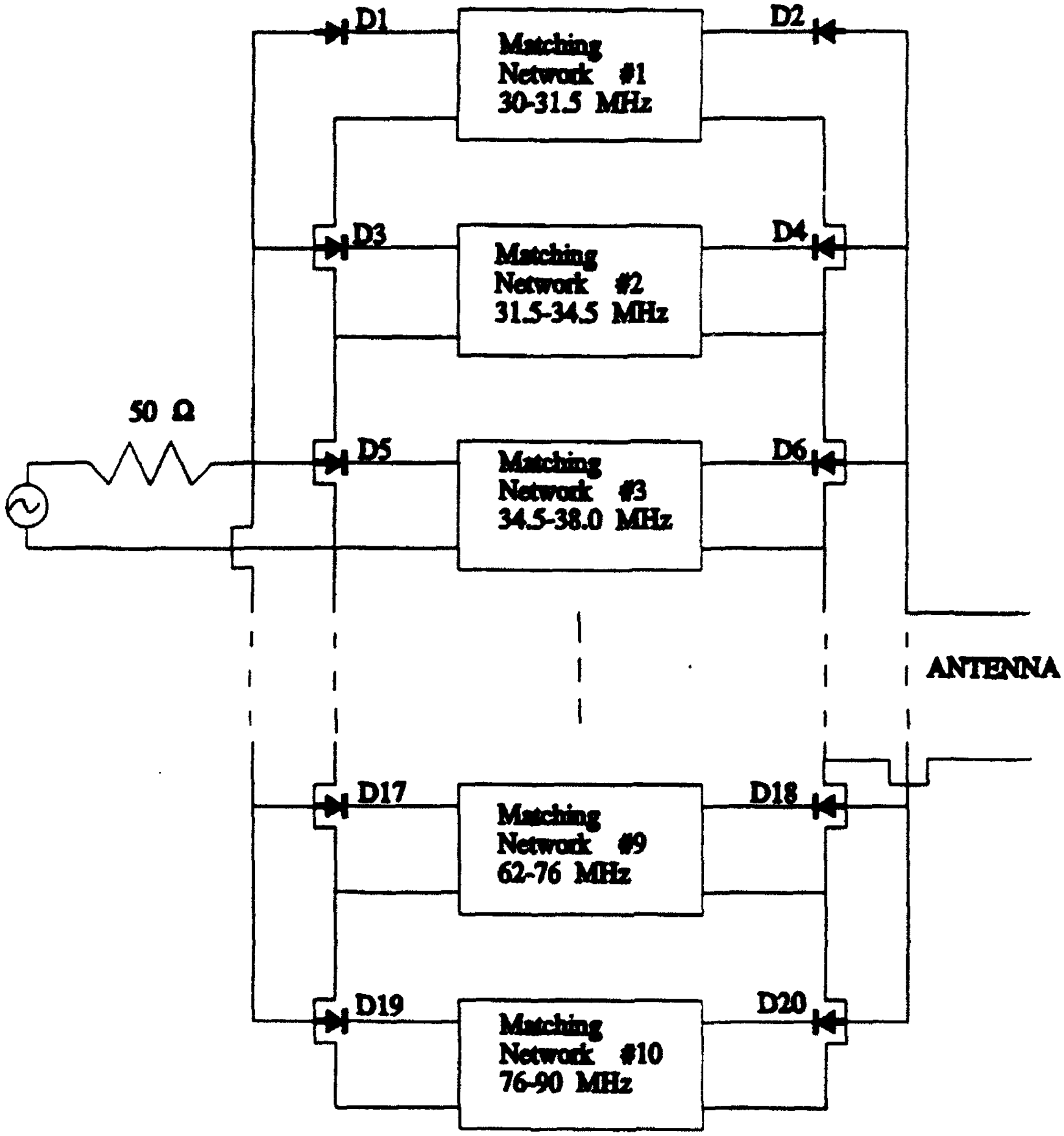


Figure 5.22 The Final Integrated Matching Network

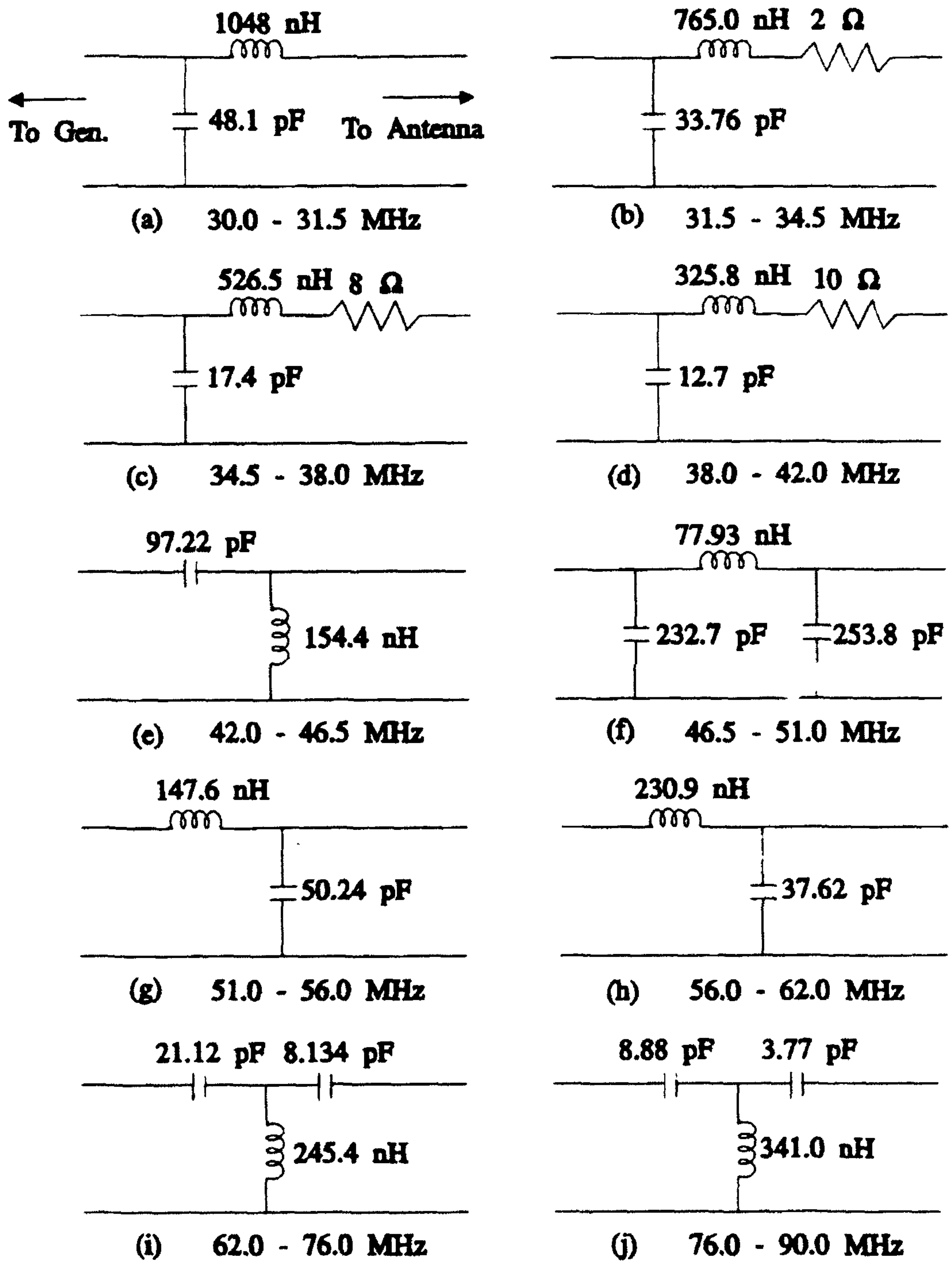


Figure 5.23 Final Matching Networks

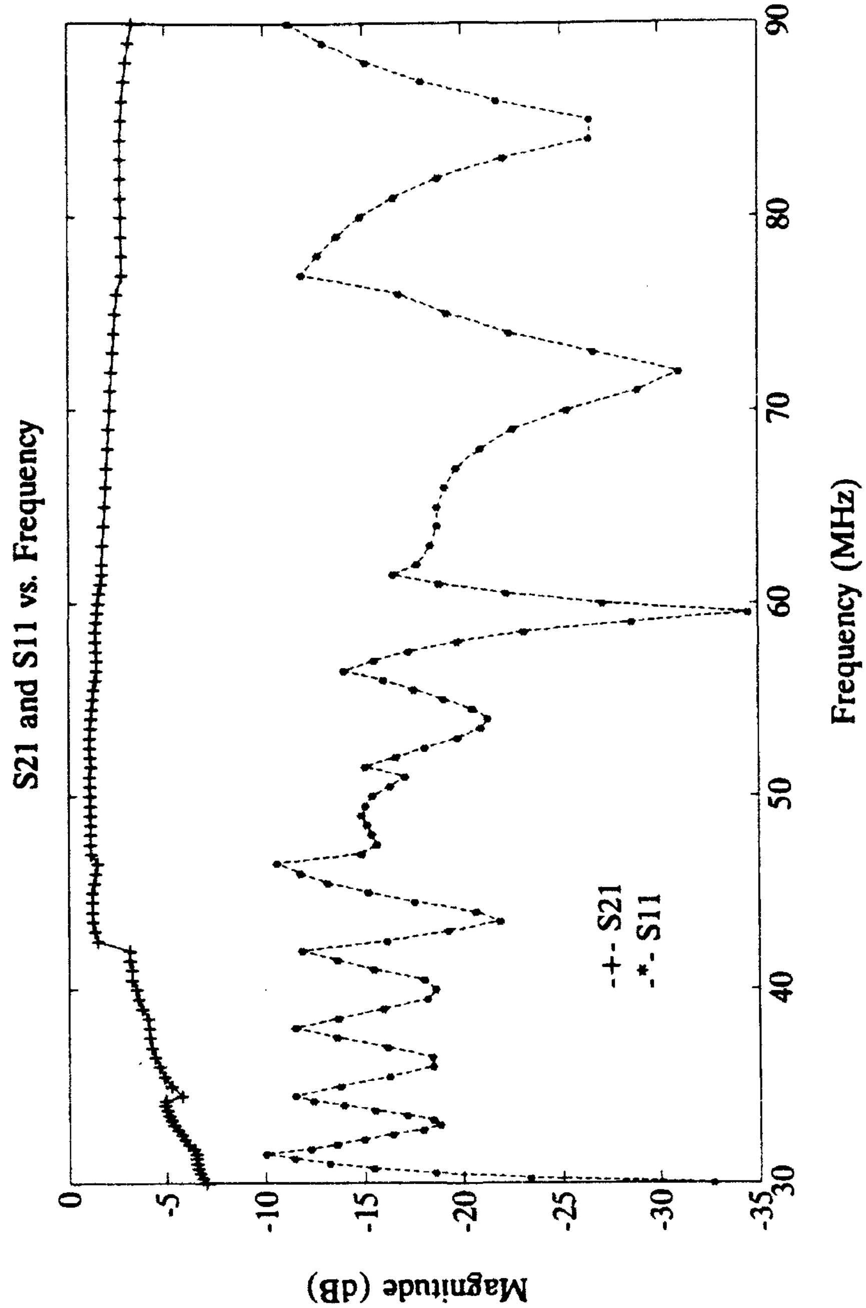


Figure 5.24 Overall Parallel connection Response

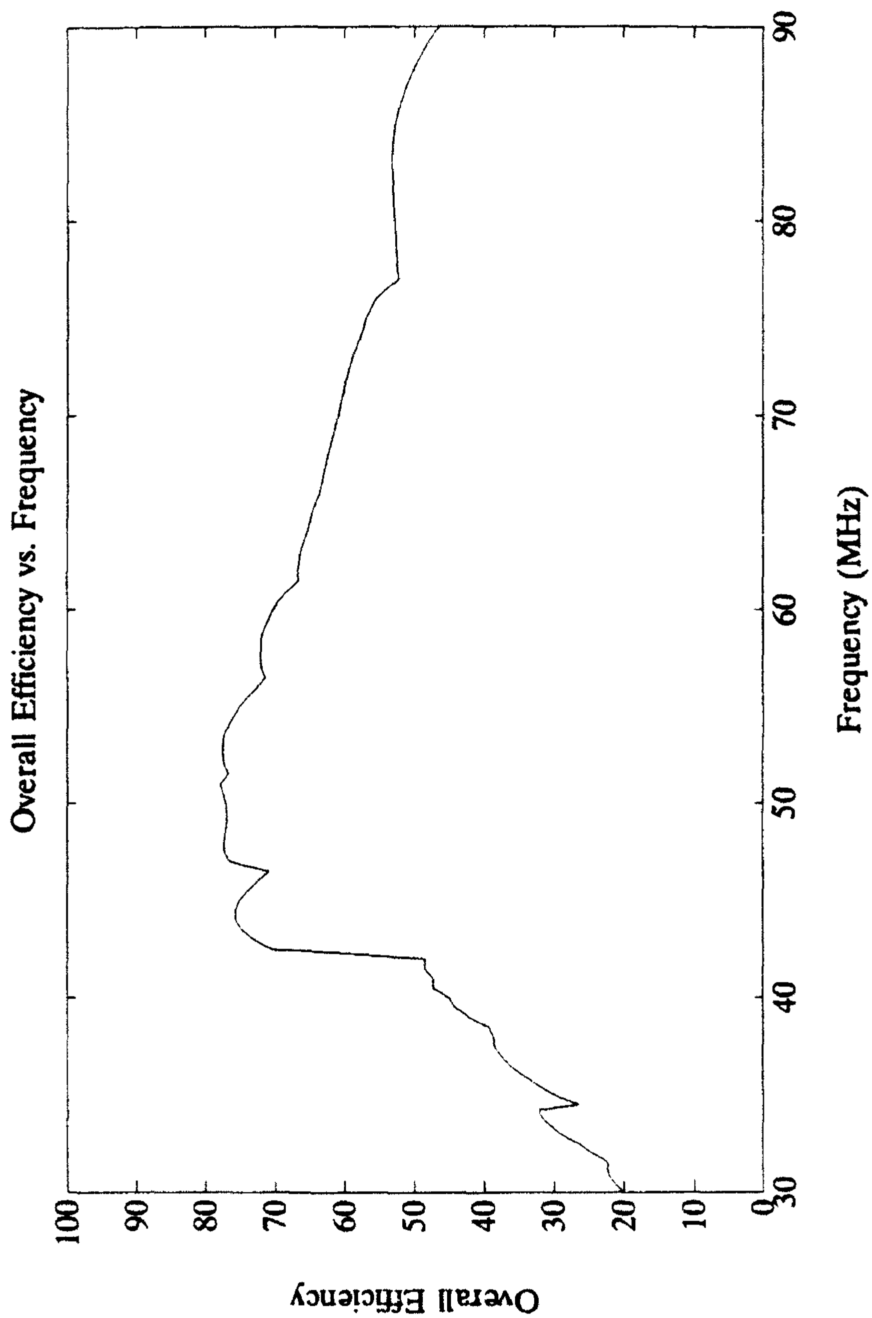


Figure 5.25 Overall Efficiency of The System

E. PARALLEL CONNECTION WITH LOSSY INDUCTORS

Up to this point, The design and discussion of the matching networks up to this point were based on lossless inductor and capacitors. Both MATCHNET and TOUCHSTONE have the capability to synthesize and simulate lossless and lossy inductor and capacitors as discussed in Appendices A and B.

A lossy inductor with a Q of 75, was used to replace the lossless inductor in the integrated matching network to investigate the effects on the responses. The responses remained essentially the same as in the lossless case; therefore, the output plots are not shown. The circuit files and output data files are listed in Appendix H.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Two schemes were studied in this research. In the first scheme, a 1.5 m monopole antenna was loaded with PIN diodes which are switched electronically to vary the electrical length. Two variations of the diode locations were considered for the first scheme. In the second scheme, an unloaded monopole was considered and matching networks were designed over a number of sub-bands. The networks were then connected in parallel and electronically switched to cover the entire band.

In the first loading technique of the first scheme, the electrical length of the antenna was maintained constant at selected frequencies. The antenna input impedance was highly capacitive over the entire frequency band. The antenna had a radiation efficiency between 55 to 80%. The loss was due entirely to the loaded PIN diodes which introduce some insertion loss. To minimize the reflection coefficient, the Bode-Fano criterion was applied and a 40 Ω resistor was added in series to the antenna. A single matching network was then synthesized, optimized and simulated. The maximum available power transferred to the load was between 24 to 34%. By multiplying the power transfer efficiency with the antenna radiation efficiency, the overall efficiency was found to be between 17 and 24%.

In the second loading technique, the diode locations on the antenna were determined by making the antenna resonant at some spot frequencies. The loaded antenna had a radiation efficiency between 85 and 93%. Even with the loads, the input impedance of the antenna remained highly capacitive at the low end of the frequency band. To realize an acceptable design, the Bode-Fano criterion was applied and the frequency band was divided into two bands: 30 to 45 MHz and 45 to 90 MHz. Matching networks were designed for each band. Optimization was performed on each matching network until the optimum response was obtained. Then the matching networks were connected in parallel with diodes to form an integrated electronically switchable matching network. The power transfer efficiency was between 20 and 83%, and the overall efficiency was found to be between 19 to 74%. In the latter case, the system remained fairly simple: a loaded monopole and a simple integrated matching network.

The design of the matching network for an unloaded antenna of the second scheme is far more difficult. The frequency band was first divided into ten sub-bands. Matching networks were designed for each sub-band. The matching networks for each sub-band were simulated and optimized separately, then they were connected in parallel with diodes to form an integrated matching network that can be switched.

The Bode-Fano criterion was also applied to the first four sub-bands in this scheme. Significant losses occurred at the lower end of the frequency band. The losses were caused mainly by the resistance added to the matching networks to reduce the reflection coefficient. The forward bias resistance of the diode and coupling effects also contribute to the loss. The power transfer efficiency was between 20 and 78%. Since the unloaded antenna is considered lossless, the overall power efficiency is the same as the power transfer efficiency.

Both schemes achieved the required VSWR performance. For the loaded monopole having the same electrical length at some spot frequencies, the system has an overall efficiency between 17 and 24% with a single matching network. For the loaded monopole designed to have the same resonant length at some spot frequencies, the matching network consists of two 2-port networks connected in parallel yielding an overall efficiency between 18 and 83%. For the unloaded monopole, the matching network consists of ten 2-port networks connected in parallel and the system has an overall efficiency between 20 and 78%.

B. RECOMMENDATIONS

Comparing the three results, it appears that the loaded monopole antenna that maintains a resonant length at some spot frequencies offers a possible solution to the problem. It results in a simple integrated matching network and significant large overall power efficiency, particularly at the higher frequencies.

APPENDIX A

WIRE PROGRAM

The WIRE program was written by Dr. William Davis at Virginia Polytechnic Institute and State University. It evaluates the current density distribution, radiation pattern, total power, etc. for wire type antennas. The test antenna geometry is input into the program by breaking it up into one or more straight wire sections. The program uses the moment method with triangular basis functions to represent the current distribution on the wire as shown in Figure A.1 [Ref. 4].

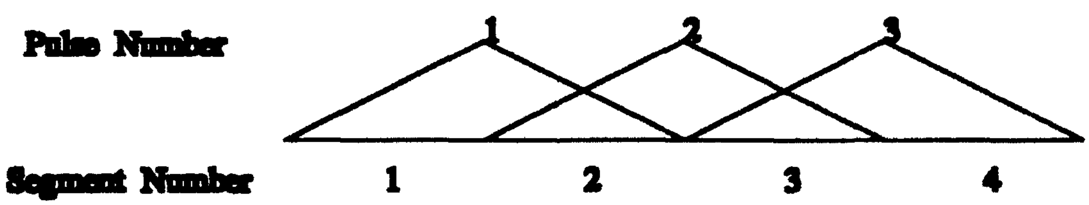


Figure A.1 Triangular Basis Function

SCREEN #1 ENTERING THE GEOMETRY OF THE TEST ANTENNA

The program has the capability of accepting the input geometry of the test antenna by reading from a data file with

.dta extension or through screen interactively. The maximum number of wires the program can accept is 160.

SCREEN #2 ANTENNA CONFIGURATION

First, this screen allows the user to specify the number of segments the wire is to be broken up into. As illustrated in Figure A.1, the number of triangular basis functions used is one less than the number of segments chosen. The more segments chosen, the longer the run time of the program.

Second, the user enters the first end point coordinates (X, Y, Z) in meters and specifies whether this end of the wire is connected to another wire in the antenna geometry or to ground plane. Then, the user will repeat the same procedure for the second endpoint.

Third, user enters the radius of this wire in meters. Finally, the program provides the user with the opportunity to change any or all of the above information. The default parameters for the radiation pattern plot assumes that the antenna is placed in the XZ plane (Y=0).

SCREEN #3 ANTENNA GEOMETRY

This screen illustrates the end points coordinates of the segments. The coordinates shown are the centers of the basis functions; therefore, the starting and ending coordinates of the overall wire are not listed. This geometry should be used to determine the pulse number at which the loads and the excitations should be placed.

SCREEN #4 FREQUENCY

This screen allows user to input the test frequency in MHz and the test environment; either free space or an infinite, perfectly conducting ground plane. The wavelength will be automatically computed.

SCREEN #5 LOADS

The WIRE program is capable of handling loads up to one less than the number of segments. This screen allows user to enter the number of lumped loads along the antenna length. If no loads are being placed on the antenna this number is set to zero.

SCREEN #6 LOAD INFORMATION

If the test antenna has loads, this screen allows the user to specify the load impedance and its locations on the test antenna. The user will specify the pulse number, the resistance and the reactance of the load. The impedance is entered in ohms.

SCREEN #7 SOURCE MENU

This screen allows user to specify whether the test antenna is receiving or transmitting the signal.

SCREEN #8 EXCITATIONS

This screen allow user to specify the number of antenna excitations.

ANTENNA MENU

When the above information have been entered, the program will give the user the Antenna Menu which contains the following options:

Input Geometry	- G
Change Environment	- E
Change Loads	- L
Files (Output)	- F
Define Excitations	- X
Solve for Currents	- C
Display Pattern	- P
QUIT	- Q

For more information about each of the above options, refer to Using The Wire Program [Ref. 12]. The reference will explain how to obtain input impedance, current distribution, radiation pattern, etc. of the test antenna and also gives a good example of how to enter the geometry of the antenna.

APPENDIX B

MATCHNET: MICROWAVE MATCHING NETWORK SYNTHESIS

A. BACKGROUND

MATCHNET was written by Dr. Stephen E. Sussman-Fort of the State University of New York. It is a program for the automated synthesis of broadband matching networks of low-pass, high-pass, and bandpass (lumped and distributed) with arbitrary gain-shape between complex sources and loads .

The synthesis method used in MATCHNET is known as the real-frequency technique proposed by Carlin and Komiak [Ref. 13]. The real-frequency technique requires only a simple numerical description of the source and load as necessary data for the synthesis. The design process can proceed automatically once the source and load have been described.

MATCHNET is fairly simple to use. The first step is to construct a data file containing tabulation of the passband frequencies. The second step is to specify a numerical description of the source and load as either complex impedances, admittances, or reflection coefficients at each frequency point. The third step is to specify the gain required of the network at each frequency point.

MATCHNET can synthesize matching networks between a real source to a complex load and a complex source to a complex load and accepts two forms of input data files. The following three examples will demonstrate the two cases.

B. MATCHING A REAL SOURCE TO A COMPLEX LOAD

This first example will illustrate how to match a real source to a complex load. A network is to be designed to match S_{11}, input reflection coefficient of a GaAs FET chip, as a complex load, to a 50 ohm source across the frequency band, 8 to 12 GHz. The matching network must provide the indicated gain-slope S_{21} magnitude response between the real source and the complex load. The data entry in the file is entirely free-format; blank lines are allowed anywhere; comment lines are denoted by the single apostrophe being the first non-blank character on the line. Furthermore, comments may be appended to the end of any data line. MATCHNET also will inform the user of most data file errors. Thus the data file for this example could be:

```
'Matching GaAs FET for Maximum Unilateral Gain
'Real 50 ohm source.  S-parameter load, 50 ohm reference
'Absolute value for S21.

R    50    S    50    A

'Frequency (Hz)      load             S21

6.00E9          0.780        -089      0.578
6.50E9          0.765        -096      0.619
7.00E9          0.750        -103      0.659
7.50E9          0.740        -110      0.703
8.00E9          0.730        -117      0.746
8.50E9          0.715        -124      0.806
9.00E9          0.700        -131      0.865
9.50E9          0.685        -138      0.933
10.00E9         0.670        -144      1.000
```

This second example is to illustrate the other form of input data file. A network is to be designed to match to complex input impedance of a monopole antenna to a 50 ohm source across the frequency band, 45 to 90 MHz.

```
R    50    Z    A
'Frequency (Hz)      load           S21

45.0E9     32.56          -28.00     0.98
50.0E9     46.11          +20.67     0.98
55.0E9     66.03          +70.80     0.98
60.0E9     53.26          +26.54     0.98
65.0E9     70.87          +66.79     0.98
70.0E9     52.10          +26.44     0.98
75.0E9     66.72          +59.82     0.98
80.0E9     48.63          +19.23     0.98
85.0E9     60.20          +46.86     0.98
90.0E9     50.32          +25.66     0.98
```

The first line of the data files provide the following information: 'R' indicates real-source with 50 ohm being the value of the source resistance. The third block is denoted by an 'S' when the reflection coefficient S_{11} of the load is being input. In the case of specifying the impedance data of the load, the letter 'Z' is used. The letter 'A' indicates the absolute magnitude of S_{21}. The output files of both examples will be shown in program execution.

C. MATCHING A COMPLEX SOURCE TO A COMPLEX LOAD

This example will illustrate how to construct a data file for matching a complex source to a complex load. The format of the data file is slightly different from the first example.

'Matching between a pair of GaAs FETs.
'S_{22} of the first chip as source with 50 reference.
' S_{11} of the second chip as load with 50 ohm reference.
'Absolute value for S_{21}.

C S 50 S 50 A

'Frequency (Hz)	Source		load		S_{21}
8.000E9	0.735	-42	0.775	-107	0.732
8.500E9	0.737	-44	0.762	-113	0.770
9.000E9	0.740	-47	0.750	-118	0.809
9.500E9	0.745	-49	0.740	-123	0.842
10.00E9	0.750	-52	0.730	-128	0.875
10.25E9	0.751	-53	0.710	130	0.895
10.50E9	0.752	-55	0.720	-132	0.909
11.00E9	0.755	-58	0.710	-136	0.943
11.50E9	0.760	-60	0.702	-140	0.971
12.00E9	0.765	-62	0.695	-145	1.000

The first line of the data file provides the following information: 'C' indicates complex-source; 'S' indicates its scattering parameter, S_{22} followed by the corresponding reference resistance; the second 'S' indicates the scattering parameter, S_{11}, of the complex load followed by a corresponding reference resistance; and finally, 'A' indicates the absolute magnitude of the desired gain of S_{21}. The impedance form of the input data file in this case is similar to the second example of the first case. The first line will read C S 50 Z A, which means that the complex load is input in the form of impedance and everything else is the same as explained above.

D. EXECUTING MATCHNET

The program can be executed by typing DES followed by hitting the ENTER key at the DOS prompt. Assume the corrected input data file has been constructed, if a synthesis is desired, the user, in response to program queries, (1) choose the desired topology, (2) specifies the data file name, and (3) selects the desired network degree. The program then goes through a sequence of steps to arrive at a preliminary design. This initial design is optimized by the program to arrive at a final matching network the response accuracy of which is verified by a network analysis. The user can control the flow of the program, interrupting it whenever desired to examine the screen.

E. EXAMPLE

This example illustrates the result of the first input data file. Options Selected in MATCHNET Data Input:

- Desired degree of matching network: ------------ 3
- Low-Pass (L), Bandpass (LP+BP), High-Pass (HP), or Bandpass (HP+BP):--- LP
- Lossless lumped elements.
- Characteristic impedance of: TRL, SST: ---- 120 ohms; OST: ----- 25 ohms
- Defaults used for all other options.
- Program stops resistance excursion optimization after 6 iterations.

Final Lumped Elements Design	Final Distributed Element Design
Max. Response Error <= 0.18 dB	Max. Response Error <= 0.16 dB
after 98 iterations	after 56 iterations
----------------------------	----------------------------
(From source to load)	(From source to load)
Series Inductor: 1.194E-010 H	RTL:120 .ohms,1.82 deg at 8.0 GHz
Shunt Capacitor: 5.052E-013 F	OST:25.0 ohms, 29.83 deg at 8.0 GHz
Series Inductor: 5.992E-010 H	TRL: 120 ohms, 14.46 deg at 8.0 GHz
-Lossless Capacitors	-Distributed elements always
-Lossless Inductors	-lossless with MATCHNET.

Similar steps can be taken to synthesize matching networks for the other two examples. Depending on the degree of matching networks and topologies chosen the output data files will differ. For more information about MATCHNET, the reader may consult MATCHNET User's Manual [Ref. 5].

APPENDIX C

THE EESOF'S TOUCHSTONE

A. BACKGROUND

Touchstone is one of the most advanced software for RF/microwave computer-aided engineering (CAE). It was designed by microwave engineers at EEsof, Inc.,. TOUCHSTONE's extraordinary power comes from nodal description and random optimization. An example of TOUCHSTONE's versatility is the ability it gives the user to interchange computed S-parameters between files. Its flexibility is shown by the way the user can easily define plotting grids and direct specific measurements of multiple networks to these plots. It features a full screen editor and an interactive tuner. TOUCHSTONE's graphics allow the user to print any file or window on the chosen printer, and the user can print any plot on any recommended plotters. Therefore, an attempt to explain all its capabilities and features would be a major task by itself. Thus, only those capabilities and features used in aiding this research will be discussed. Anyone who is interested in learning more about TOUCHSTONE should consult the TOUCHSTONE User's Manual [Ref. 6].

B. INPUT DATA FILE

The matching networks were synthesized using MATCHNET as discussed in Appendix B. TOUCHSTONE allows the user to optimize and simulate the synthesized matching networks, but it requires input data and circuit files.

First, input data file of the complex load needs to be constructed. The input data is the reflection coefficient, S_{11}, of the complex load. Consistency between the units of the input files and the circuit files must be maintained. For example, if the frequency is expressed in MHz in the circuit files, it must also be expressed in MHz in the input files. The S-parameter of the input data files can be documented in any way the user wishes. Comments used for documentation follow the exclamation mark, !, can be the only entry on a line or can follow the data on any line. An example of the input data file is shown below. The first line after the delimiter contains the following information: Frequency is in MHz; S indicates the S-parameter of the complex load; MA indicates that the magnitude and angle of the S11 of the complex load and R indicates the reference measurement followed by corresponding resistance. For different forms of input S-parameter, refer to the TOUCHSTONE User's Manual [Ref. 6].

```
! FILE NAME: SUBBAND #1 30-31.5 MHZ
! USER:  THIEM, KEEM B.
! DATE:  17 DECEMBER 1992
# MHZ S MA R 50
! SCATTERING PARAMETERS:
! FREQ    /S11/     <S11
30.0    .976    -28.80
30.5    .973    -29.78
31.0    .970    -30.81
31.5    .967    -31.90
```

C. CIRCUIT FILE

Knowing the configuration of the matching network between the real source and complex load, a TOUCHSTONE circuit can be easily constructed. The circuit file for the above input data file is shown below:

```
!==============================================================
!                     FREQUENCY : 30.00000 to 31.50000 MHz
!    INPUT FILE  : b:\sbn1.slp
!    OUTPUT TERM : R = 50.00000 Ohms
!
!==============================================================

DIM
   FREQ MHZ     ! Frequency is in MHz.
   RES  OH      ! Resistance is in ohms.
   IND  NH      ! Inductor is in nano Henries.
   CAP  PF      ! Capacitor is in pico-Farads.
   LNG  MIL     ! Length is in mili inches.
   ANG  DEG     ! Angle is in degrees.

VAR
!  C\94.34695
!  L\1.137e+03
!  R\7.42810

!This block is used for optimization.  C is the symbol for a
!capacitor.  L is the symbol for an inductor and R for a
!resistor.  The back slash followed by the initial value of
!the element indicates that the element is unconstrained and
!allows to change in any direction during the optimization
!process and the exclamation marks are removed.
```

```
CKT
   CAP      1    0   C = 84.94891
   IND      1    2   L = 1.082e+03
   RES      2    3   R = 17.50990
DEF2P       1    3   SYN

!The location of the element in the circuit block is specified
!by the node number.  During the optimization process, the
!equal sign is replaced by \, so the changes of the element
!can be tracked by the variables listed in the VAR block.
!DEF2P is defining a two port network.



   S1PA     1    0   b:\sbn1.s1p
DEF1P       1        R2

!DEF1P is defining a one port device.  In this case, the one
!port device is the refection coefficient of the test
!antenna.

   RES      1    0   R = 50.00000
DEF1P       1        R1

!This 50 ohm is the source impedance.

OUT
   SYN  DB[S21]   GR1
   SYN  MAG[S21]
   SYN  DB[S11]   GR1
   SYN  MAG[S11]

!This is the output block.  The user specifies the type of
!plots he or she desires.  In this example, the magnitudes of
!S21 and S11 in dB will be plotted versus frequency in linear
!scale.

FREQ
   SWEEP    30.00000  31.50000  0.250000

!This is linear frequency sweeping with an increment of
!0.25.

GRID
   RANGE    30.00000  31.50000  0.250000
   GR1      0.000000  -30.0000  6.000000

! Range specifies the x-axis.
! GR1 specifies the y-axis.
```

```
TERM
   SYN      R1  R2
OPT
!   SYN  DB[S21]>-2.0
!   SYN  DB[S11]<-15
```

! This block lists the terminations.

!This block is needed only during the optimization process. !The user specifies which responses he or she wishes to !optimize. Again, the exclamation marks are removed during the !optimization process. This example illustrates that the user !wishes to have the response of S21 to be greater than -2.0 dB !and the response of S11 to be less than -14.0 dB.

The TOUCHSTONE circuit file is used to describe a circuit and specify measurements. The circuit file is divided into the following blocks:

DIM (Dimensions) Used to override the default dimensions.

VAR (Variables) Used to define variables that can be used in the circuit description. This block must precede the CKT block since the VAR block will set up variables that are subsequently used in the CKT block.

EQN (Equations) Used to provide up to 25 equations and up to 50 variables using the equations.

CKT* (Circuit) Used to define the circuit topology, elements, and user-defined networks. The CKT block must precede the OUT, TERM, PROC, and OPT blocks since the networks defined in the CKT block are subsequently used in the OUT, TERM, PROC, and OPT blocks

TERM	(Terminations) Used to define external terminations that are different than 50 ohms; also used to change the normalization impedance.
PROC	(Processor) Used to perform calculations on the S-parameters of two different networks, to arrive at S-parameters for a new network. Used networks defined in the CKT block.
OUT*	(Output) Used to describe the output or measurements of interest for the previously defined networks. Contains networks defined in the CKT block or the PROC block.
FREQ*	(Frequency) Used to set up the simulation frequencies.
GRID	(Grid) Used to define the rectangular plotting grids.
OPT	(Optimization) Used to define the error function to be minimized by the optimizer.
TOL	(Tolerance) Used to specify S-parameter tolerance for Monte Carlo Analysis.

TOUCHSTONE processes a circuit file when the user sweeps the frequencies, tunes the circuit, and optimizes the circuit. All processing is done based on the user's instructions in the circuit file. Not all of the above blocks are required in all the circuit files, but the asterisk blocks are required in all circuit files. The collection of blocks describes the user's circuit file designs and determines what measurements will be taken and how the results will be displayed.

One of the most important feature in TOUCHSTONE used in aiding this research is the optimizer. The optimizer was used to obtain the desired responses of S21 and S11 of the matching network.

The first step in optimization is to specify all the variables in the VAR block for the elements in the CKT block that wish to be optimized. The initial values of all the variables must be specified after the back slash. The back slash is used for the unconstrained element values. If the constrained element values are desired, the # sign is used. For example, if resistance is equal to 50 ohms, the user wishes to have the value of the resistance constrained between 40 and 80 ohms, the proper syntax is R # 50 40 80. This syntax will allow the resistance to vary between 40 and 80 ohms with starting value of 50 ohms. The same hold true for both capacitor and inductor. Further, if there is more than one capacitor or inductor in the circuit, the variables are specified by C1, C2 or L1, L2 and so on and followed by the constrained or the unconstrained syntax.

Assumed that the values of the element are unconstrained, the second step is to change all the equal signs in the CKT block to back slashes followed by the initial values of the element.

Finally, under the OPT block the user has to specify what needs to be optimized. The above circuit file is a good example. The user wishes to optimize the responses of S21 and S11. For more information about TOUCHSTONE, the reader should consult the TOUCHSTONE User's Manual [Ref. 6].

APPENDIX D

TOUCHSTONE FILES FOR THE FIRST LOADING TECHNIQUE

A. TOUCHSTONE FILES

1. Input File

```
# MHZ S MA R 50
!FREQ   /S11/   <S11
30      0.966   -28.98
35      0.910   -41.08
45      0.942   -31.95
50      0.899   -39.89
60      0.940   -34.72
65      0.908   -41.04
75      0.940   -36.60
80      0.915   -41.78
90      0.933   -39.56
```

2. The Circuit File for Lossless Inductor Case

```
! =================Wed Feb 17 11:54:04 1993=================
!                      LUMPED CHEBYSHEV BANDPASS NETWORK
!                     FREQUENCY : 30.00000 to 90.00000 MHz
!    INPUT FILE   : b:\tet.slp
!    OUTPUT TERM  : R = 50.00000 Ohms
 ============================================================
DIM
   FREQ MHZ
   RES  OH
   IND  NH
   CAP  PF
   LNG  MIL
   ANG  DEG

VAR
!  R\23.54875
!  L1\510.76941
!  L2\144.42105
!  L3\111.75767
!  C1\72.88605
!  C2\97.03240
!  C3\1.157e+03
```

```
CKT
   RES      1   2  R = 41.74455
   IND      2   3  L = 407.40540
   IND      3   0  L = 213.77481
   CAP      3   4  C = 74.48090
   CAP      4   0  C = 71.46120
   CAP      4   5  C = 1.008e+03
   IND      5   0  L = 136.28874
DEF2P       1   5 SYN


   S1PA     1   0  b:\test.s1p
DEF1P       1      R1

   RES      1   0  R = 50.00000
DEF1P       1      R2

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S22]  GR1
   SYN  MAG[S22]

FREQ
   SWEEP   30.00000  90.00000  5

GRID
   RANGE    30.00000  90.00000  10.00000
   GR1      0.000000  -20.0000  4.000000

TERM
   SYN     R1  R2
OPT

!  SYN DB[S21]>-3
!  SYN DB[S22]<-14
```

3. The Output File of The Lossless Inductors Case

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S22] SYN	MAG[S22] SYN
30.0000	-6.273	0.486	-13.198	0.219
35.0000	-5.282	0.544	-13.268	0.217
40.0000	-5.252	0.546	-12.476	0.238
45.0000	-5.353	0.540	-10.735	0.291
50.0000	-4.644	0.586	-17.845	0.128
55.0000	-5.027	0.561	-14.447	0.190
60.0000	-5.662	0.521	-11.574	0.264
65.0000	-5.383	0.538	-10.748	0.290

70.0000	-5.579	0.526	-11.602	0.263
75.0000	-5.908	0.507	-12.625	0.234
80.0000	-5.399	0.537	-19.067	0.111
85.0000	-5.635	0.523	-16.692	0.146
90.0000	-6.158	0.492	-10.787	0.289

4. The Circuit File of The Lossy Inductors Case

```
!================Wed Feb 17 11:54:04 1993=================
!
!                        LUMPED CHEBYSHEV BANDPASS NETWORK
!                       FREQUENCY : 30.00000 to 90.00000 MHz
!    INPUT FILE  : b:\tet.s1p
!    OUTPUT TERM : R = 50.00000 Ohms
!
===========================================================

DIM
   FREQ MHZ
   RES  OH
   IND  NH
   CAP  PF
   LNG  MIL
   ANG  DEG
VAR
!  R\23.54875
!  L1\510.76941
!  L2\144.42105
!  L3\111.75767
!  C1\72.88605
!  C2\97.03240
!  C3\1.157e+03

CKT
   RES     1   2   R = 41.74455
   IND     2   3   L = 407.40540   Q = 75 F = 30.00 MOD = 3
   IND     3   0   L = 213 77481   Q = 75 F = 30.00 MOD = 3
   CAP     3   4   C = 74.48090
   CAP     4   0   C = 71.46120
   CAP     4   5   C = 1.008e+03
   IND     5   0   L = 136.28874   Q = 75 F = 30.00 MOD = 3
DEF2P      1   5  SYN

   S1PA    1   0   b:\test.s1p
DEF1P      1       R1

   RES     1   0   R = 50.00000
DEF1P      1       R2

OUT
   SYN  DB[S21]  GR1
```

```
   SYN  MAG[S21]
   SYN  DB[S22]  GR1
   SYN  MAG[S22]

FREQ
   SWEEP   30.00000  90.00000  5

GRID
   RANGE    30.00000  90.00000  10.00000
   GR1      0.000000  -20.0000  4.000000

TERM
   SYN      R1  R2
OPT

!  SYN DB[S21]>-3
!  SYN DB[S22]<-14
```

5. The Ouput File for The Lossy Inductors Case

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S22] SYN	MAG[S22] SYN
30.0000	-6.273	0.486	-13.198	0.219
35.0000	-5.282	0.544	-13.268	0.217
40.0000	-5.252	0.546	-12.476	0.238
45.0000	-5.353	0.540	-10.735	0.291
50.0000	-4.644	0.586	-17.845	0.128
55.0000	-5.027	0.561	-14.447	0.190
60.0000	-5.662	0.521	-11.574	0.264
65.0000	-5.383	0.538	-10.748	0.290
70.0000	-5.579	0.526	-11.602	0.263
75.0000	-5.908	0.507	-12.625	0.234
80.0000	-5.399	0.537	-19.067	0.111
85.0000	-5.635	0.523	-16.692	0.146
90.0000	-6.158	0.492	-10.787	0.289

APPENDIX E

TOUCHSTONE FILES FOR THE SECOND LOADING TECHNIQUE

A. TOUCHSTONE INPUT, CIRCUIT AND OUTPUT FILES FOR LOSSLESS INDUCTORS

1. First Subband

```
! FILE NAME: D1T.S1P (30-45 MHz)
! USER: THIEM, KEEM B.
! DATE: 2 FEBRUARY 1993
# MHZ S MA R 50
! SCATTERING PARAMETERS:
! FREQ      /S11/      <S11
30          .972      -29.01
35          .923      -41.24
40          .771      -62.41
45          .378      -103.2
```

2. Second Subband

```
! FILE NAME: D2T.S1P (45-90 MHz)
! USER: THIEM, KEEM B.
! DATE: 2 FREBRUARY 1993
# MHZ S MA R 50
! SCATTERING PARAMETERS:
! FREQ      /S11/      <S11
45          .378      -103.2
50          .214       88.50
60          .250       68.581
70          .250       70.94
80          .192       83.04
90          .25        74.94
```

3. Individual First Subband Circuit File

```
! ===================Mon Feb 01 21:36:11 1993==============
!   INDIVIDUAL RESPONSE CIRCUIT FILE FOR THE FIRST SUBBAND
    !                       LUMPED CHEBYSHEV BANDPASS NETWORK
    !                    FREQUENCY : 30.00000 to 45.00000 MHZ
!    INPUT FILE   : B:\D1T.S1P
!    OUTPUT TERM  : R = 50.00000 Ohms
===========================================================
```

```
DIM
   FREQ MHZ
   RES  OH
   IND  NH
   CAP  PF
   LNG  MIL
   ANG  DEG
VAR
!  C\11.23042
!  L1\4.105e+03
!  L2\1.559e+03
!  L3\93.40764
!  L4\324.20563
!  C2\92.71099
!  R\47.37385

CKT
   CAP  1  2  C = 43.07811
   IND  2  0  L = 1547.0000
   IND  2  3  L = 604.91559
   PLC  3  0  L = 136.34697  C = 140.98766
   IND  3  4  L = 499.77933
   RES  4  5  R = 40.72760
DEF2P      1    5  SYN

   S1PA    1    0  B:\D1t.S1P
DEF1P      1       R2

   RES     1    0  R = 50.00000
DEF1P      1       R1

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
  SWEEP   30.00000  45.00000  1.000000

GRID
   RANGE    30.00000  45.00000  2.500000
   GR1      0.000000  -15.0000  3.000000

TERM
   SYN     R1  R2

OPT
!     SYN DB[S21]>-2.0
!     SYN DB[S11]<-15
```

4. Individual Second Subband Circuit file

```
! =====================Mon Feb 02 16.00:11 1993============
!   INDIVIDUAL RESPONSE CIRCUIT FILE FOR THE SECOND SUBBAND
!                LUMPED CHEBYSHEV BANDPASS NETWORK
!                FREQUENCY : 45.00000 to 90.00000 MHz
! =========================================================


DIM
   FREQ MHZ
   RES  OH
   IND  NH
   CAP  PF
   LNG  MIL
   ANG  DEG
VAR


CKT
  IND  1  0  L = 850.00000
  CAP  1  2  C = 1598.0000
DEF2P      1    2  SYN

   RES      1    0  R = 50.0000
DEF1P      1       R1

   S1PA     1    0  B:\D2t.S1P
DEF1P      1       R2

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
  SWEEP   45.00000  90.00000  5.000000

GRID
   RANGE    45.00000  90.00000  5.000000
   GR1      0.000000  -15.0000  3.000000

TERM
   SYN     R1  R2
```

5. The Parallel Connection Circuit File

```
!THIS PROGRAM WILL SIMULATE THE MATCHING NETWORK THAT WAS
!OBTAINED FROM MATCHNET, A MATCHING NETWORK SYNTHESIZER
!     P     R     O     G     R     A     M     .
! USER: THIEM, KEEM B.
! DATE: 30 JANUARY 1993
! CIRCUIT: NETOWRK2.CKT
! 30 TO 45 MHz

DIM
  FREQ MHZ
  RES OH
  IND NH
  CAP PF
  LNG MIL
  TIME PS
  COND /OH
  ANG DEG

VAR
! L1\1.659e+03
! L2\584.11731
! L3\136.28328
! L4\460.68747
! C1\42.54408
! C2\153.95158
! R\32.16720

EQN

CKT
   SRLC   1  2  R = 10000.00 L = 0.60000 C = 2.0000
DEF2P     1  2  OFF
   SRL    1  2  R = 3.000000 L = 0.60000
DEF2P     1  2  ON
   ON     1  2  !D1
   CAP    2  3  C = 43.28508
   IND    3  0  L = 1.708e+03
   IND    3  4  L = 570.67963
   PLC    4  0  L = 129.26649 C = 151.07663
   IND    4  5  L = 493.59613
   RES    5  6  R = 27.69878
   ON     6  7  !D2
   OFF    1  8  !D3
   IND    8  0  L = 1183.0000
   CAP    8  9  C = 1954.0000
   OFF    9  7  !D4
DEF2P     1  7   SYN

     RES   1  0  R = 50
DEF1P      1     Z1
```

```
    S1PA 1   0  B:\D1T.S1P
DEF1P      1      Z2

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
  SWEEP  30   45  2.5

GRID
  RANGE  30  45  2.5
  GR1    0  -15  3

TERM
SYN      Z1  Z2
OPT
!  SYN  DB[S21]>-2.000
!  SYN  DB[S11]<-15.00
```

The circuit file can be obtained by turning off D1 and D2 and on D3 and D4.

B. THE FOLLOWINGS ARE TOUCHSTONE OUTPUT FILES

1. Individual First Subband Output File

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S11] SYN	MAG[S11] SYN
30.0000	-6.923	0.451	-11.955	0.252
31.0000	-6.206	0.489	-18.971	0.113
32.0000	-6.016	0.500	-14.621	0.186
33.0000	-5.932	0.505	-12.600	0.234
34.0000	-5.855	0.510	-12.036	0.250
35.0000	-5.788	0.514	-11.994	0.251
36.0000	-5.291	0.544	-12.320	0.242
37.0000	-5.058	0.559	-11.827	0.256
38.0000	-4.956	0.565	-11.038	0.281
39.0000	-4.909	0.568	-10.405	0.302
40.0000	-4.865	0.571	-10.135	0.311
41.0000	-4.585	0.590	-10.116	0.312
42.0000	-4.334	0.607	-10.772	0.289
43.0000	-4.077	0.625	-12.185	0.246
44.0000	-3.853	0.642	-13.758	0.205
45.0000	-3.764	0.648	-12.658	0.233

2. Parallel Connection First Subband Output File

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S11] SYN	MAG[S11] SYN
30.0000	-6.726	0.461	-11.972	0.252
32.5000	-5.814	0.512	-10.298	0.306
35.0000	-5.603	0.525	-11.124	0.278
37.5000	-4.687	0.583	-12.405	0.240
40.0000	-4.465	0.598	-10.339	0.304
42.5000	-3.835	0.643	-10.346	0.304
45.0000	-3.688	0.654	-10.733	0.291

The output files for the second subband for both individual and parallel responses are not shown because they have the same format.

C. TOUCHSTONE CIRCUIT AND OUTPUT FILES FOR LOSSY INDUCTORS

1. Circuit File for The First Subband

```
!THIS PROGRAM WILL SIMULATE THE MATCHING NETWORK THAT WAS
!OBTAINED FROM MATCHNET, A MATCHING NETWORK SYNTHESIZER
!PROGRAM.
! USER: THIEM, KEEM B.
! DATE: 30 JANUARY 1993
! CIRCUIT: NETOWRK2.CKT
! 30 TO 45 MHz

DIM
  FREQ MHZ
  RES OH
  IND NH
  CAP PF
  LNG MIL
  TIME PS
  COND /OH
  ANG DEG

VAR
! L1\1.659e+03
! L2\584.11731
! L3\136.28328
! L4\460.68747
! C1\42.54408
```

```
! C2\153.95158
! R\32.16720

EQN

CKT
   SRLC   1  2  R = 10000.00 L = 0.60000 C = 2.0000
DEF2P     1  2  OFF
   SRL    1  2  R = 3.000000 L = 0.60000
DEF2P     1  2  ON
   ON     1  2  !D1
   CAP    2  3  C = 43.28508
   IND    3  0  L = 1.708e+03  Q = 75  F = 30.00  MOD = 3
   IND    3  4  L = 570.67963  Q = 75  F = 30.00  MOD = 3
   IND    4  0  L = 129.26649  Q = 75  F = 30.00  MOD = 3
   CAP    4  0  C = 151.07663
   IND    4  5  L = 493.59613  Q = 75  F = 30.00  MOD = 3
   RES    5  6  R = 27.69878
   ON     6  7  !D2
   OFF    1  8  !D3
   IND    8  0  L = 1183.0000  Q = 75  F = 30.00  MOD = 3
   CAP    8  9  C = 1954.0000
   OFF    9  7  !D4
DEF2P     1  7   SYN

     RES  1  0  R = 50
DEF1P     1     Z1

     S1PA 1  0  B:\D1T.S1P
DEF1P     1     Z2

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
  SWEEP  30   45  2.5

GRID
  RANGE  30  45  2.5
  GR1    0  -15  3

TERM
SYN     Z1  Z2
OPT
!  SYN  DB[S21]>-2.000
!  SYN  DB[S11]<-15.00
```

2. The Output File for The First Subband

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S11] SYN	MAG[S11] SYN
30.0000	-6.726	0.461	-11.972	0.252
32.5000	-5.814	0.512	-10.298	0.306
35.0000	-5.603	0.525	-11.124	0.278
37.5000	-4.687	0.583	-12.405	0.240
40.0000	-4.465	0.598	-10.339	0.304
42.5000	-3.835	0.643	-10.346	0.304
45.0000	-3.688	0.654	-10.733	0.291

The output file for the second subband in this case is not shown because it has the same format as the above output file. The circuit file of the second subband can be obtained by turning D3 and D4 on and D1 and D2 off.

APPENDIX F

UNLOADED ANTENNA INPUT IMPEDANCE

Frequecy (MHz)	Real Part	Imaginary Part
30.0	9.797	-194.3
30.5	10.20	-187.5
31.0	10.62	-180.9
32.0	11.49	-174.3
32.5	11.95	-161.7
33.0	12.42	-155.5
33.5	12.90	-149.4
34.0	13.40	-143.4
34.5	13.92	-137.6
35.0	14.45	-131.8
35.5	15.00	-126.1
36.0	15.57	-120.4
36.5	16.15	-114.9
37.0	16.76	-109.4
37.5	17.38	-103.9
38.0	18.02	-98.54
38.5	18.68	-93.22
39.0	19.37	-87.95
39.5	20.07	-82.72
40.0	20.08	-77.54
40.5	21.55	-72.40
41.0	22.33	-67.30
41.5	23.13	-62.23
42.0	23.96	-57.19
42.5	24.82	-52.18
43.0	25.70	-47.19
43.5	26.62	-42.23
44.0	27.57	-37.28
44.5	28.54	-32.35
45.0	29.56	-27.44
45.5	30.60	-22.53
46.0	31.69	-17.64
46.5	32.81	-12.75
47.0	33.97	-7.866
47.5	35.17	-2.982
48.0	36.42	1.903
48.5	37.71	6.791
49.0	39.05	11.69

50.0	41.87	21.50
51.0	44.91	31.37
52.0	48.18	41.31
53.0	51.72	51.33
54.0	55.53	61.47
55.0	59.66	71.72
56.0	64.13	82.11
57.0	68.99	92.67
58.0	74.26	103.40
59.0	80.01	114.30
60.0	86.27	125.40
61.0	93.12	136.70
62.0	100.60	148.30
63.0	108.80	160.10
64.0	117.90	172.10
65.0	127.80	184.30
66.0	138.80	196.80
67.0	150.90	209.40
68.0	164.40	222.20
69.0	179.30	235.10
70.0	195.90	248.00
71.0	214.30	260.80
72.0	234.90	273.40
73.0	257.80	285.40
74.0	283.30	296.60
75.0	311.70	306.70
76.0	343.40	315.20
77.0	378.40	321.30
78.0	416.90	324.30
79.0	459.00	323.20
80.0	504.40	316.90
81.0	552.60	304.00
82.0	602.50	283.20
83.0	652.70	253.20
84.0	700.90	213.10
85.0	744.40	162.60
86.0	780.20	102.10
87.0	805.40	33.64
88.0	817.50	-40.07
89.0	815.20	-115.3
90.0	798.90	-188.0

APPENDIX G

TOUCHSTONE CIRCUIT, INPUT AND OUTPUT FILES FOR INDIVIDUAL RESPONSES

A. THE CIRCUIT FILE OF THE FIRST SUBBAND

```
!===========================================================
!
!                   FREQUENCY : 30.00000 to 31.50000 MHz
!    INPUT FILE   : b:\sbn1.s1p
!    OUTPUT TERM  : R = 50.00000 Ohms
!
!===========================================================

DIM
   FREQ MHZ
   RES  OH
   IND  NH
   CAP  PF
   LNG  MIL
   ANG  DEG

VAR
!  C\94.34695
!  L\1.137e+03
!  R\7.42810

CKT
   CAP      1   0   C = 84.94891
   IND      1   2   L = 1.082e+03
   RES      2   3   R = 17.50990
DEF2P       1   3   SYN

   S1PA     1   0   b:\sbn1.s1p
DEF1P       1       R2

   RES      1   0   R = 50.00000
DEF1P       1       R1

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]
```

```
FREQ
   SWEEP     30.00000  31.50000  0.250000

GRID
   RANGE     30.00000  31.50000  0.250000
   GR1       0.000000  -30.0000  6.000000

TERM
   SYN      R1  R2

OPT

!    SYN  DB[S21]>-2.0
!    SYN  DB[S11]<-15
```

B. THE INPUT FILE FOR THE FIRST SUBBAND

```
! FILE NAME: SUBBAND #1 30-31.5 MHZ

! USER:  THIEM, KEEM B.
! DATE:  2 FEBRUARY 1993

# MHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ     /S11/     <S11
30.0     .976     -28.80
30.5     .973     -29.78
31.0     .970     -30.81
31.5     .967     -31.90
```

C. THE OUTPUT FILE FOR THE FIRST SUBBAND

```
         FREQ-MHZ  DB[S21] MAG[S21]  DB[S11] MAG[S11]
                     SYN      SYN      SYN      SYN

      30.0000   -4.740    0.579  -11.918    0.254
      30.2500   -4.503    0.595  -15.313    0.172
      30.5000   -4.339    0.607  -20.938    0.090
      30.7500   -4.251    0.613  -29.959    0.032
      31.0000   -4.234    0.614  -20.588    0.093
      31.2500   -4.291    0.610  -15.127    0.175
      31.5000   -4.408    0.602  -11.921    0.255
```

APPENDIX H

TOUCHSTONE CIRCUIT AND OUTPUT DATA FILES FOR PARALLEL CONNECTION RESPONSE WITH LOSSLESS AND LOSSY INDUCTORS

A. LOSSLESS INDUCTORS

1. The Circuit for The First Subband

```
!=============WED 3 FEBRUARY 1993 MATCHNET RESULTS=========
!
!                          FREQUENCY : 30.00000 to 90.000000 MHz
!    INPUT TERM  :  R = 50.00000 Ohms
!    OUTPUT FILE :  b:\sbn1.slp
!                                     NETWORK1.CKT
!===========================================================

DIM
   FREQ MHZ
   IND  NH
   CAP  PF
   RES  OH
   LNG  MIL
   ANG  DEG

VAR
!  C\151.94962
!  L\465.60162
!  R\13.70525


CKT

   SRLC  1    2  R = 10000.00 L = 0.600000 C = 2.00000
DEF2P    1    2  OFF

   SRL   1    2  R = 3.000000 L = 0.600000
DEF2P    1    2  ON

   ON    1    2
   CAP   2    0  C = 48.09608
   IND   2    3  L = 1052.000
   RES   3    4  R = 0.006650
   ON    4    5
```

```
    OFF   1    6
    CAP   6    0  C = 33.76012
    IND   6    7  L = 765.0523
    RES   7    8  R = 1.562790
    OFF   8    5
    OFF   1    9
    CAP   9    0  C = 17.38480
    IND   9    10 L = 526.5190
    RES   10   11 R = 8.000000
    OFF   11   5
    OFF   1    12
    CAP   12   0  C = 12.65326
    IND   12   13 L = 325.8341
    RES   13   14 R = 10.00000
    OFF   14   5
    OFF   1    15
    CAP   15   16 C = 97.21679
    IND   16   0  L = 154.4312
    OFF   16   5
    OFF   1    17
    CAP   17   0  C = 232.7000
    IND   17   18 L = 77.93000
    CAP   18   0  C = 253.8000
    OFF   18   5
    OFF   1    19
    IND   19   20 L = 147.6000
    CAP   20   0  C = 50.24000
    OFF   20   5
    OFF   1    21
    IND   21   22 L = 230.9000
    CAP   22   0  C = 37.62000
    OFF   22   5
    OFF   1    23
    CAP   23   24 C = 21.12000
    IND   24   0  L = 245.4000
    CAP   24   25 C = 8.134000
    OFF   25   5
    OFF   1    26
    CAP   26   27 C = 8.880000
    IND   27   0  L = 341.0079
    CAP   27   28 C = 3.772320
    OFF   28   5
DEF2P       1    5   SYN

    RES     1    0   R = 50.00000
DEF1P       1        R1

    S1PA    1    0   b:\sbn1.s1p
DEF1P       1        R2

OUT
    SYN  DB[S21]  GR1
```

```
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
   SWEEP    30.00000  31.50000  0.250000

GRID
   RANGE    30.00000  31.50000  0.250000
   GR1      0.000000  -35.0000  7.000000

TERM
   SYN   R1  R2

OPT

!  SYN DB[S21]>-2.00
!  SYN DB[S11]<-15.0
```

2. The Output File for The First Subband

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S11] SYN	MAG[S11] SYN
30.0000	-7.011	0.446	-32.659	0.023
30.2500	-6.829	0.456	-23.345	0.068
30.5000	-6.688	0.463	-18.585	0.118
30.7500	-6.588	0.468	-15.464	0.169
31.0000	-6.526	0.472	-13.228	0.218
31.2500	-6.504	0.473	-11.453	0.268
31.5000	-6.515	0.472	-10.046	0.315

B. LOSSY INDUCTORS

1. The Circuit File for The First Subband

```
!===========WED 3 FEBRUARY 1993 MATCHNET RESULTS============
!
!                      FREQUENCY : 30.00000 to 90.000000 MHz
!    INPUT TERM  :  R = 50.00000 Ohms
!    OUTPUT FILE :  b:\sbn1.slp
!                                NETWORK1.CKT
!=============================================================

DIM
   FREQ MHZ
   IND  NH
   CAP  PF
```

```
    RES   OH
    LNG   MIL
    ANG   DEG

CKT

    SRLC   1    2   R = 10000.00 L = 0.600000 C = 2.00000
DEF2P      1    2   OFF

    SRL    1    2   R = 3.000000 L = 0.600000
DEF2P      1    2   ON

    ON     1    2
    CAP    2    0   C = 48.09608
    IND    2    3   L = 1048.000 Q = 75 F = 30.00 MOD = 3
    RES    3    4   R = 0.006650
    ON     4    5
    OFF    1    6
    CAP    6    0   C = 33.76012
    IND    6    7   L = 765.0523 Q = 75 F = 31.50 MOD = 3
    RES    7    8   R = 1.562790
    OFF    8    5
    OFF    1    9
    CAP    9    0   C = 17.38400
    IND    9    10  L = 526.5196 Q = 75 F = 34.50 MOD = 3
    RES    10   11  R = 8.000000
    OFF    11   5
    OFF    1    12
    CAP    12   0   C = 12.65326
    IND    12   13  L = 325.8341 Q = 75 F = 38.00 MOD = 3
    RES    13   14  R = 10.00000
    OFF    14   5
    OFF    1    15
    CAP    15   16  C = 97.21679
    IND    16   0   L = 154.4312 Q = 75 F = 42.00 MOD = 3
    OFF    16   5
    OFF    1    17
    CAP    17   0   C = 232.7000
    IND    17   18  L = 77.93000 Q = 75 F = 46.50 MOD = 3
    CAP    18   0   C = 253.8000
    OFF    18   5
    OFF    1    19
    IND    19   20  L = 147.6000 Q = 75 F = 51.00 MOD = 3
    CAP    20   0   C = 50.24000
    OFF    20   5
    OFF    1    21
    IND    21   22  L = 230.9000 Q = 75 F = 56.00 MOD = 3
    CAP    22   0   C = 37.62000
    OFF    22   5
    OFF    1    23
    CAP    23   24  C = 21.12000
    IND    24   0   L = 245.4000 Q = 75 F = 62.00 MOD = 3
```

```
   CAP    24   25 C = 8.134000
   OFF    25   5
   OFF    1    26
   CAP    26   27 C = 8.880000
   IND    27   0  L = 341.0079 Q = 75 F = 76.00 MOD = 3
   CAP    27   28 C = 3.772320
   OFF    28   5
DEF2P        1    5   SYN

   RES       1    0   R = 50.00000
DEF1P        1        R1

   S1PA      1    0   b:\sbn1.s1p
DEF1P        1        R2

OUT
   SYN  DB[S21]  GR1
   SYN  MAG[S21]
   SYN  DB[S11]  GR1
   SYN  MAG[S11]

FREQ
   SWEEP    30.00000  31.50000  0.250000

GRID
   RANGE    30.00000  31.50000  0.250000
   GR1      0.000000  -35.0000  7.000000

TERM
   SYN   R1  R2
```

2. The Output File for The First Subband

FREQ-MHZ	DB[S21] SYN	MAG[S21] SYN	DB[S11] SYN	MAG[S11] SYN
30.0000	-7.019	0.446	-34.335	0.019
30.2500	-6.832	0.455	-24.547	0.059
30.5000	-6.685	0.463	-19.285	0.109
30.7500	-6.580	0.469	-15.948	0.159
31.0000	-6.513	0.472	-13.596	0.209
31.2500	-6.486	0.474	-11.746	0.259
31.5000	-6.491	0.474	-10.286	0.306

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