DEVELOPMENT OF A CONTINUOUS PHASE SHIFTER FOR A MICROWAVE PHASED ARRAY HYPERThERMIA SYSTEM

BY

RONALD DEAN BOESCH

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DEDICATION

I dedicate this work to Margaret Garcia, my confidante, fiancée, and partner in life.
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CHAPTER 1
INTRODUCTION

Hyperthermia, the elevation of tissue temperature above 37°C, has long been recognized as a cancer treatment. Early translations of Ramajama (200 B.C.), Hippocrates (400 B.C.), and Galen (200 A.D.) record the use of red hot irons in the treatment of nonulcerating cancer. During the Renaissance, spontaneous tumor regression was noted to accompany illnesses involving infectious fevers. More recently, interest has focused on the mechanisms of the healing effect and its ramifications for treatment. Cancerous tissue is more thermosensitive than normal tissue [Giovanella, 1983]. However, the tumor response to heat alone does not justify hyperthermia as a solitary treatment. Hyperthermia, in conjunction with traditional therapies, results in a higher tumor response than when the individual therapies are given alone [Watmough, 1986]. This result justifies the use of thermoradiotherapy and thermochemotherapy.

There are a number of methods used for producing hyperthermia. The whole body temperature may be elevated through systemic hyperthermia, or only the tumor region may be heated, through local hyperthermia. For systemic hyperthermia therapy, patients have been covered with molten wax or fitted with water circulating suits [Hahn, 1982]. For systemic hyperthermia the temperature must be less than 40.8°C. In local hyperthermia, the tumor may be selectively heated to a higher temperature than that used in systemic hyperthermia. The therapeutic local hyperthermia tem-
perature range is 42 - 45°C for treatment times of 30 to 180 minutes. The tumor region may be heated in two ways, interstitially or noninvasively.

With the interstitial method, an antenna is inserted into the tumor region. The electromagnetic energy emitted by the antenna is absorbed by the tissue, providing very localized tumor heating. This method is useful with radiotherapy because the antenna can also be used as a container for x-ray emitting radioisotopes.

With the noninvasive method, an applicator on the outside of the body directs energy inward. To reduce excessive surface heating, an array of radiators is used as opposed to a single element. The array distributes the same power as a single element over a larger area reducing the local surface power density. Figure 1 (Figures and Tables appear at the end of the text) demonstrates this situation. The radiated energy may be electromagnetic (EM) or ultrasonic. Each modality has advantages and limitations which determine what types of tumor sites can be successfully treated.

A microwave system for depositing 915 MHz electromagnetic radiation in a tumor was outlined by Benson [1985] using an array configuration described by Gee et al. [1984]. This array has the capability to focus EM energy to a localized region that can be electronically scanned. A modified system based on Benson's design was shown in Fig. 2. A single source is divided equally into the individual channels for each radiator. The signal goes through a phase shifter and amplifier to control the phase and
amplitude of the energy. Dual directional couplers allow energy sampling so the phase and amplitude of each element are available for feedback control. The control signals are adjusted so that the relative phase from an element to a receiver at the tumor site is the same for elements. This insures constructive interference and, therefore, focus of energy at the tumor site.

Control of the focus is then critically dependent on the phase control of each channel that is provided by electronic phase shifters. The electronic phase shifting can be accomplished using the variable transmission properties of ferrites or the variable reactances of diodes. Generally, ferrites are not useful for frequencies below 3 GHz, whereas diode phase shifters are useful up to 20 GHz [Whicker, 1974].

Diode phase shifters can be digital or analog. Figure 3 shows the varieties of digital phase shifters [Garver, 1976]. The switched path type phase shifter (Fig. 3A) switches between varying lengths of transmission paths using PIN diodes. The transmission type phase shifter (Fig. 3B) changes phase by switching between loadings on the transmission line. The reflection type phase shifter (Fig. 3C) switches the effective length of a short circuited transmission line. Each of the digital phase shifters shown in Fig. 3 results in a single phase shift bit. Many bits are required to achieve phase resolution. For example, 4 bits are required for 22.5 degree resolution. The resolution of a phase shifter, however, could be increased with fewer components using an analog phase shifter.

Analog phase shifters have been developed based on several
different concepts. Representative examples are shown in Fig. 4. The vector device (Fig. 4A) generates variable amplitude complex vectors that, when combined, generate variable phase vectors [Kumar, 1981]. The frequency locked device (Fig. 4B) is based on the phase change that occurs when one oscillator of a locked pair is frequency shifted [Rubin, 1972]. The dual gate FET device (Fig. 4C) relies on the variable transmission phase through an FET amplifier when one gate is variably resonant [Tsironis, 1980]. A reflective type analog phase shifter, the simplest analog shifter, is realized in the hybrid coupler phase shifter (Fig. 4D). The hybrid coupler phase shifter uses the variable resonant loads on a quadrature hybrid coupler to control phase [White, 1974]. The variable resonant load uses the changing capacitance of a reverse bias varactor diode to change phase. The input power to these devices is limited (100 mW [Garver, 1976], 1 W [White, 1982]) to prevent nonlinear operation due to excursion from the varactor bias point. These devices also have an insertion loss which varies with phase that must be minimized [Garver, 1969; Henoch, 1971].

Given the extensive literature on phase shifting devices, one could use many of these designs for changing phase in a microwave hyperthermia system. However, commercially available phase shifters are very expensive and are usually designed for a specific purpose. They are relatively broadband and low power with a linear phase-voltage relationship. The hyperthermia system does not require a wide bandwidth of operation or the linear phase-voltage response. It is reasonable to expect that a simple,
inexpensive phase shifter could be designed for this purpose. Design constraints for a phase shifter for use in a 915 MHz hyperthermia system are shown in Table 1. For the amplifiers investigated, an input of 250 mW should be sufficient to achieve 50 W output power. Hence, the phase shifter should handle 250 mW input power. A minimal number of components should be used, as one phase shifter is needed for each channel. The 915 MHz phase shifter should have a ±10 MHz bandwidth to allow for the oscillator drift. The amplitude variation with bias should be minimized to uncouple the amplitude and phase controls. The amount of phase variation necessary from a phase shifter is dependent upon the geometry of the antenna array applicator and its relation to the desired heating region. The array applicator considered is a seven element hexagonal array with antenna feeds spaced eight-tenths a wavelength apart [Benson, 1985]. The intent is to heat at a maximum depth on the order of one wavelength. The applicator and heating region are shown in Fig. 5. From the figure, the maximum path length difference for centered heating is 100 degrees between waves from the center element and any other element. The figure shows the geometry for constructive interference during off center heating. The path length difference in this case is 180 degrees. Given these two cases, a phase shifter with 180 degree phase variation is necessary. The goal of this research was to design a simple, inexpensive, narrowband, 180 degree continuous phase shifter with minimum amplitude variation that is able to operate in a phased array hyperthermia system where it would receive 250 mW of input power.
CHAPTER 2

THEORY

The theory of operation of the reflective type phase shifter shown in Fig. 4D will be considered. This type can incorporate a circulator or a 3 dB hybrid coupler. After studying the operation of each device, emphasis will center upon the 3 dB hybrid coupler, a reciprocal device, because it is smaller than the ferrite needed for a circulator, less expensive than the ferrite, and requires no matching network. The hybrid coupler load will then be considered. Analysis will begin on the varactor and then on its series or parallel combination with an inductor in an attempt to achieve greater phase variation. The analysis will conclude with an accurate representation of the phase shifter, including the parasitic loss of the load.

To begin, a simple phase shifter involves a load attached to one port of a circulator. The circulator is a three port device providing one-way sequential power transmission between ports, as shown in Fig. 6A. The energy entering one port exits from the adjacent counterclockwise port. The scattering matrix of this device [Gandhi, 1981] is

$$[S] = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \quad (2.1)$$

From the scattering matrix, an input, A, (inputs, denoted A, and outputs, denoted B, of scattering matrices have the dimension of square root of power) at port 1 appears as an output of port 3.
If a load is attached to port 3, the output of port 3 is reflected. Port 3 now has an input of $\text{Re}^{j\theta}A$ where $R$ is the magnitude and $\theta$ is the phase of the complex reflection coefficient, $\Gamma$, of the load. The input to port 3, $\text{Re}^{j\theta}A$, is transmitted without reflection to a properly terminated port 2. The result then, is to have the input signal at port 1, $A$, transmitted to port 2 with an amplitude and phase determined by the reflection coefficient of a load attached to port 3. If the reflection coefficient has a variable phase, then $S_{21}$ is variable in phase and the phase shifter is realized.

The phase shifter using a circulator is not a reciprocal device. That is, the phase shifting property for $S_{21}$ does not hold for $S_{12}$. An input at port 2 will appear as an output at port 1 with no phase changes due to the load on port 3. A phase shifter using a 3 dB quadrature hybrid coupler is a reciprocal device, as will be shown.

A 3 dB quadrature hybrid coupler is a four port device as shown in Fig. 5b. The scattering matrix for this device is [Helszajn, 1978]

\[
[S] = \frac{1}{\sqrt{2}} \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & j & 1 & 0 \\
j & 0 & 0 & 1 \\
\end{bmatrix} \quad . 
\tag{2.2}
\]

Essentially, the input power to either port 1 or 2 is split equally between ports 3 and 4 with a quadrature phase relationship. The same happens to power directed to either port 3 or 4. For phase shifting, a signal, $A$, is applied to port 1; port 2 is
terminated in 50 ohms, and ports 3 and 4 are terminated with loads giving reflection coefficients \( \Gamma_3 \) and \( \Gamma_4 \), respectively. For these conditions, the input signal matrix is

\[
\begin{bmatrix}
A_1 & 0 \\
\Gamma_3 A_1 / \sqrt{2} \\
j\Gamma_4 A_1 / \sqrt{2}
\end{bmatrix} .
\tag{2.3}
\]

Using the input matrix, the output, \( B \), of port 2 is

\[
B_2 = \frac{[j\Gamma_3 A_1 + j\Gamma_4 A_1]}{2} .
\tag{2.4}
\]

Using the scattered wave, the output power is obtained as

\[
P_{\text{out}} = \frac{B_2 B_2^*}{2}
= \frac{[\Gamma_3 \Gamma_3^* + \Gamma_4 \Gamma_4^* + \Gamma_3 \Gamma_4^* + \Gamma_4 \Gamma_3^*]A_1^2}{8} .
\tag{2.5}
\]

Assuming \( \Gamma_3 = \Gamma_4 = \text{Re}^j\theta \) then

\[
P_{\text{out}} = \frac{R^2 A_1^2}{2} .
\tag{2.6}
\]

With these same assumptions, the outgoing wave is, using (2.4),

\[
B_2 = jRA_1 e^{j\theta} .
\tag{2.7}
\]
The output relations (2.6) and (2.7) show two facts. One, for identical loads on ports 3 and 4 with $R = 1$, all the power is transmitted from port 1 to 2. Two, the phase relation of the transmitted wave is dependent upon the phase of the reflection coefficients of ports 3 and 4. Hence, changing the phase of the reflection coefficient changes the transmission phase through the coupler, and a phase shifter is realized.

Reciprocal operation is verified by injecting a signal into port 2 and calculating the output signal of port 1. The input matrix is

\[
\begin{pmatrix}
0 \\
A_2 \\
\text{j}\Gamma_3 A_2 / \sqrt{2} \\
\text{j}\Gamma_4 A_2 / \sqrt{2}
\end{pmatrix}.
\]

Using this input matrix, the output, $B$, of port 1 is

\[
B_1 = \frac{(\text{j}\Gamma_3 A_2 + \text{j}\Gamma_4 A_2)}{2}.
\]

As above, assuming identical loads of the form

\[
\Gamma_3 = \Gamma_4 = \text{Re}^\text{j}\theta
\]

the transmitted signal is

\[
\text{j}RA_2 e^\text{j}\theta
\]

with output power

\[
P_{\text{out}} = \frac{B_1 B_1^*}{2} = \frac{R^2 A_2^2}{2}.
\]
Comparing, the transmission from port 1 to 2 is the same as that from port 2 to 1. This phase shifter behaves reciprocally as anticipated, and our design will focus on this hybrid coupler type.

The above case assumed both loads were identical. In general, the magnitude and phase of the loads may differ. The resulting expressions are then very complicated. A more manageable case is considered, that with loads of identical magnitude and different phase.

The reflection coefficients are then

\[ \Gamma_3 = \text{Re} \quad j^\theta_3, \quad \Gamma_4 = \text{Re} \quad j^\theta_4. \]  

\[ (2.13a,b) \]

The output signal at port 2 due to an input signal in port 1 is

\[ B_2 = \frac{\text{Re} \quad j^\theta_3 A_1 + \text{Re} \quad j^\theta_4 A_1}{2} \]

\[ = \frac{\text{RA}_1}{2} \quad j^\theta_3 + j^\theta_4 \]

\[ = j^\text{RA}_1 \quad \left[ \cos \theta_3 + j \sin \theta_4 + \cos \theta_4 + j \sin \theta_4 \right] \]

\[ = j^\text{RA}_1 \quad \left[ \cos \left( \frac{\theta_3 + \theta_4}{2} \right) \cos \left( \frac{\theta_3 - \theta_4}{2} \right) + 2 j \sin \left( \frac{\theta_3 + \theta_4}{2} \right) \cos \left( \frac{\theta_3 - \theta_4}{2} \right) \right] \]

\[ = j^\text{RA}_1 \quad \cos \left( \frac{\theta_3 - \theta_4}{2} \right) \quad e^{j \left( \frac{\theta_3 + \theta_4}{2} \right)} \].  

\[ (2.14) \]
The power in this signal is given by

\[ P_{\text{out}} = \frac{B_2 B_2^*}{2} = \frac{R^2 A_1^2}{2} \cos^2\left(\frac{\theta_3 - \theta_4}{2}\right). \]  \hspace{1cm} (2.15)

So, for loads differing only in phase, the transmission phase is the average phase of the reflection coefficients and the power amplitude is governed by a cosine function operating on the phase difference. If a 1 dB loss is acceptable, the phase of the loads may differ by as much as 54 degrees. If this is a constant phase difference, the loss is constant. However, variable loss may occur if the phase difference varies. As above, a 54 degree phase difference variation results in a 1 dB amplitude variation. Variable loss variation may also occur if the equal magnitude of the reflection coefficients vary. Replacing \( R \) with \( R + R \) in Eq. (2.15) shows that a 1 dB loss variation can occur if both magnitudes vary together by 10% (assuming \( R = 1 \)). Also note that transmission loss occurs when the magnitude of the reflection coefficient is not unity due to power absorption in the load.

Since phase differences result in the total power not being transmitted, it is instructive to consider the power reflected back to the input port. The reflected signal at port 1 is
\[ B_1 = \frac{\frac{\imath \theta^3}{\text{Re} A_1 + \imath x \text{Re} A_1}}{2} \]
\[ = \frac{A_1 R}{2} \left[ e^{\imath \theta^3} - e^{\imath \theta^4} \right] \]
\[ = \frac{A_1 R}{2} \left[ \cos \theta^3 + \imath \sin \theta^3 - \cos \theta^4 - \imath \sin \theta^4 \right] \]
\[ = \frac{A_1 R}{2} \left[ -2 \sin \left(\frac{\theta^3 + \theta^4}{2}\right) \sin \left(\frac{\theta^3 - \theta^4}{2}\right) + 2 \imath \sin \left(\frac{\theta^3 - \theta^4}{2}\right) \cos \left(\frac{\theta^3 + \theta^4}{2}\right) \right] \]
\[ = \imath A_1 R \left[ \sin \left(\frac{\theta^3 - \theta^4}{2}\right) \left[ \sin \left(\frac{\theta^3 + \theta^4}{2}\right) + \cos \left(\frac{\theta^3 + \theta^4}{2}\right) \right] \right] \]
\[ = \imath A_1 R \sin \left(\frac{\theta^3 - \theta^4}{2}\right) e^{\frac{\imath (\theta^3 + \theta^4)}{2}} \] (2.16)

The power in this signal is given by
\[ P_{\text{out}} = \frac{B_1 B_1^*}{2} = \frac{A^2 R^2}{2} \sin^2 \left(\frac{\theta^3 - \theta^4}{2}\right) \] (2.17)

Several important points are apparent in this result. If the reflection coefficients of the loads are identical in phase and amplitude, no power is reflected to the input port. For loads differing only in the phase of their reflection coefficients, the power returned to the input is related by the sine operating on the phase difference. The 54 degree phase difference examined above results in a reflected power of -7 dB. Nonidentical loads should not be sought since they only have detrimental effects on the returned and transmitted powers.
Several characteristics are desired for the loads on ports 3 and 4. First, a load with a reflection coefficient of unity magnitude is desired. For nonunity loads, power is absorbed by the load and less is transmitted. Still, none is reflected back to the input if the phases are equal. Any reactive load satisfies the unity magnitude criterion. Second, the load should have an electronically variable phase to provide electronic phase shifting. A varactor diode can be used to provide this behavior because its junction capacitance depends on its reverse bias voltage. The characteristics of a varactor diode will now be examined, and then its use as a variable load will be considered.

A model for a packaged varactor is shown in Fig. 7. The junction capacitance, $C_j$, varies, as stated above, with reverse bias. The capacitance voltage relation [Helszajn, 1978] is

$$C_j(v) = C_{\text{min}}(\frac{\phi + V_b}{\phi + v})^\gamma,$$  \hspace{1cm} (2.18)

where $\phi$ is the contact potential, $V_b$ is the reverse breakdown voltage, $C_{\text{min}}$ is the junction capacitance at the breakdown voltage, and $\gamma$ is a function of the impurity profile with value $1/2$ for abrupt junctions. A measure of the capacitance variability is the capacitor tuning ratio which is generally the capacitance at 0 volts divided by the capacitance at the breakdown voltage. Also varying with reverse bias is $R_j$, the junction resistance. The relation for the reciprocal of the resistance, $G$, [Shurmer, 1971] is
\[ G(v) = \frac{e^{v/kT}}{I_0 e^{v/kT}} , \]  

where \( v \) is the reverse bias, \( I_0 \) is the reverse leakage current, and \( kT/e \) is the contact potential. The other quantities in the model, \( C_p \) and \( I_p \), are due to packaging and are constant with respect to bias voltage.

The varying parameters of the model, \( C_j \) and \( R_j \), give rise to a quality factor for the junction which varies with bias voltage. Since quality factor is defined as the ratio of the average energy stored per cycle to the average energy dissipated per cycle, the variable relation is

\[ Q_s = \frac{G(v)}{\omega C(v)} . \]

This quality factor has two implications. First, the reflection coefficient of the varactor cannot have a magnitude of unity because of the presence of a dissipative element. However, the higher the quality factor, the closer to unity is the reflection coefficient magnitude. Second, since \( Q_s \) varies with bias voltage, the reflection coefficient magnitude varies with bias voltage.

After focusing on the characteristics of a varactor diode, we will consider the varactor as a variable load. For a simplified initial analysis, the varactor will be modeled solely by its junction capacitance. The reflection coefficient is then
\[
\Gamma = \frac{1/j\omega C(v) - Z_0}{1/j\omega C(v) + Z_0} = \frac{(1 - jZ_0\omega C(v))^2}{1 + (Z_0\omega C(v))^2}.
\] (2.21)

The expression for the magnitude is one as expected due to the exclusion of dissipative elements in the simplified model. The phase of the reflection coefficient is given as

\[
\text{ang}(\Gamma) = 2\tan^{-1}(-Z_0\omega C(v)).
\] (2.22)

The argument of the inverse tangent function is always negative. For a very small capacitance, the angle can approach 0 degrees. For a very large capacitance, the angle can approach -180 degrees. Hence, the phase can only be varied to a maximum of 180 degrees. This maximum is only achieved when the capacitance variation is very large. Thus, the goal of 180 degree phase variation cannot be realistically achieved by this simple load.

Sufficient phase variation may be simply achieved with the addition of an inductor. The addition of the inductor allows for positive phase angles because an inductor has positive reactance. Conversely, the varactor only allowed negative phase angles because a capacitor has negative reactance. An inductor and varactor together create a greater potential for phase variation. The inductor and varactor may be combined in series or parallel. Both cases will be considered. First consider the series combi-
nation of reactive elements. The voltage reflection coefficient is

\[ r = \frac{j\omega L + 1/j\omega C(v) - Z_0}{j\omega L + 1/j\omega C(v) + Z_0} \]

\[ = \frac{-(-Z_0 + j(\omega L - 1/\omega C(v)))^2}{(\omega L - 1/\omega C(v))^2 + Z_0^2} \]  

(2.23)

The angle of the reflection coefficient is then

\[ \text{ang}(r) = 2\tan^{-1}\left(\frac{\omega L - 1/\omega C(v)}{-Z_0}\right) - 180 \]  

(2.24)

This function provides the greater phase variability around series resonance \((\omega = 1/L:C(v))\). With properly chosen reactance values operating around series resonance, a 180 degree phase shift is accessible.

Now consider the parallel combination of an inductor and varactor. Assuming the ideal model for the varactor, solely the junction capacitance, the impedance of the parallel combination is

\[ Z_L = \frac{j\omega L/j\omega C(v)}{j\omega L + 1/j\omega C(v)} \]

\[ = \frac{j\omega L}{1 - \omega^2 LC(v)} \]  

(2.25)
Using this impedance, the reflection coefficient is

\[
\Gamma = \frac{j(\omega L/(1 - \omega^2 LC)) - Z_0}{j(\omega L/(1 - \omega^2 LC)) + Z_0}.
\]  

(2.26)

The magnitude of this is one by inspection as expected because there are no dissipative elements. The phase of the reflection coefficient is

\[
\text{ang}(\Gamma) = 2\tan^{-1}\left(\frac{\omega L}{Z_0(\omega^2 LC - 1)}\right) - 180°.
\]  

(2.27)

At parallel resonance, the denominator of the argument of the inverse tangent function is zero, giving a total angle of 0 degrees. The largest impedance variation is available around this parallel resonance. The greatest phase variation is also obtainable at that operating point. The maximum variation in phase is, then, obtainable around resonance, be it parallel or series resonance.

The parallel and series resonant loads presented thus far model the varactor by solely its junction capacitance. More realistically, these loads should incorporate a resistance to account for the finite quality factors of the reactive elements. The resonant loads will now be reconsidered with the addition of the resistive element.

First consider the series load with a series resistance accounting for the finite quality factor. The reflection coefficient is then
\[ \Gamma = \frac{j\omega L + 1/j\omega C(v) + R - Z_0}{j\omega L + 1/j\omega C(v) + R + Z_0}. \] (2.28)

Certainly, the magnitude of the reflection coefficient is not one. At series resonance the magnitude is
\[ |\Gamma| = \frac{|R - Z_0|}{|R + Z_0|}. \] (2.29)

In regions where the reflection coefficient is dominated by reactance, the magnitude approaches one. Hence, the reflection coefficient has variable amplitude. For small \( R \) and high series \( Q \), the intrinsic transmission line impedance, \( Z_0 \), dominates and the phase response is similar to Eq. (2.24).

Now consider the parallel load with a parallel resistance accounting for the finite quality factor. The resulting impedance is
\[ Z_L = \frac{j R \omega L / (1 - \omega^2 LC)}{j \omega L / (1 - \omega^2 LC) + R}. \] (2.30)

At parallel resonance, only \( R \) is apparent and the reflection coefficient is
\[ \Gamma = \frac{R - Z_0}{R + Z_0}. \] (2.31)

For high parallel \( Q \), \( R \) is large compared to the intrinsic transmission line impedance and the reflection coefficient magnitude
approaches one. Certainly, as the load is changed, the magnitude of $\Gamma$ is changed.

The magnitude of $\Gamma$ changed with varactor bias voltage in both the series and parallel resonant loads. This occurred only when a constant resistance was used in the model, accounting for the finite $Q$. Actually, the resistance is not constant (Eq. (2.19)) and the packaged varactor is more complicated than just the model of the junction resistance and capacitance. To most closely predict the behavior of these loads over bias voltage, the more complete model of Fig. 7 will be used in the computer simulation.
CHAPTER 3
DESIGN

Consider now the design of the phase shifter circuit. The implementation involves examination of the circuit technology used, consideration of the resonant load, and physical construction of the phase shifter.

The technology chosen for circuit construction is microstrip circuitry because of the ease of fabrication and the availability of design equations. The essential features will be summarized here [Edwards, 1984]. The geometry of microstrip is shown in Fig. 8. The figure shows the field lines dividing between the substrate and free space. The transmission line would be expected to have an effective permittivity, \( \varepsilon_{eff} \), that is a weighted function of the permittivities of the substrate and free space. This function depends on the geometry (i.e., width and height) of the transmission line as does the characteristic transmission line impedance, \( Z_0 \). The relations are given below in the form most useful for design, those assuming that the substrate permittivity and desired characteristic impedance are known. They are

\[
w = \frac{e^{H'}}{h} \left( \frac{1 - \varepsilon_r}{4\varepsilon_r} \right)^{-1} \quad \text{if } Z_0 > \{44 - 2\varepsilon_r \text{ ohms}\} \quad (3.1)
\]

and

\[
\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \left( 1 - \frac{1}{\varepsilon_r + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{\varepsilon_r \pi} \right) \left( \ln \frac{4}{2} \right) \quad \text{if } \frac{w}{h} < 1.3 \quad (3.2)
\]

where, for both expressions,
\[ H' = \frac{Z_0}{119.9} \sqrt{\frac{2(\varepsilon_r+1)}{\varepsilon_r+1}} + \frac{1}{2} \frac{\varepsilon_r^{-1}}{\varepsilon_r+1} (\ln \frac{\varepsilon_r}{\varepsilon_r-1} + \ln \frac{\pi}{\varepsilon_r}) \]  \quad (3.3)

Given these relations, microstrip transmission lines of desired impedance may be laid down with their electrical lengths known.

The microstrip transmission lines are used to realize series or parallel inductances as distributed microstrip elements. The inductances are realized as cascaded steps in microstripline or parallel shotted stubs, respectively [Vendelin, 1982]. As a further consideration, the inductance value may have to be altered for tuning the load to achieve the desired performance. The parallel inductance value is easier to vary than the series inductance value because it involves moving a short (which may also be a distributed entity as will be shown later) as opposed to cutting microstripline to alter the cascaded steps required for series inductance. For this reason, the parallel resonant load was chosen for implementation.

The component values for the parallel resonant load must be determined. The optimum inductor varactor combination can be picked with respect to several criteria. Phase linearity with respect to voltage is an important criterion for phase modulators. It is not a constraint for a phased array phase shifter. Broadband response is another criterion generally sought in phase shifters. However, this is not a constraint for the hyperthermia system with a single frequency source. On the other hand, constant insertion loss with respect to voltage is an important criterion relevant to the hyperthermia system.
The driving force, then, in choosing the resonant load is to obtain 180 degrees of continuous phase variation with a minimal amount of amplitude variation. The resonant load has two degrees of freedom, the inductance and variable capacitance. With these, the two constraints of phase and loss may be achieved. The load is optimized with an interactive program to insure a full understanding of load trends. The program is given a value for the 4 volt varactor capacitance. It finds the value of inductance that will achieve 180 degrees of phase variation. The maximum loss variation is then recorded. Varactor 4 volt capacitance sizes are available in the same steps as resistors (any varactor capacitance quoted here refers to 4 volt value unless otherwise noted). The available varactor values are tried until the minimum loss variation is found which allows 180 degrees of phase variation. Once the optimum load is found, attention turns to circuit realization.

The realization of the phase shifter is shown in Fig. 9. The functions of the elements are described as follows. The 3 dB hybrid coupler is shown with four transmission lines to its ports. The input and output ports have blocking capacitors, (Republic Electronics Corporation), to block DC voltages. (Manufacturers' addresses are provided in Appendix E.) The reflection ports are loaded identically. The first element from the hybrid coupler port is the varactor, Alpha Industries. This varactor is mounted in a pill type package, which is inserted through the substrate as one side and must be connected to the ground plane. It operates from 0 - 30 volts. The distributed
inductor is realized by the next length of transmission line which is shorted with a variable capacitor (Johanson Mfg. Corp.), through to the ground plane. The next section is a shorted quarter wavelength transmission line which allows the varactor bias voltage to be applied without loading the circuit.

The decoupling is realized because the impedance of a shorted quarter wave line is

\[ Z = jZ_0 \tan\left(\frac{\lambda}{\pi} \right) = jZ_0 \tan \frac{\pi}{2} = jZ_0^\infty = \text{open circuit} \quad (3.4) \]

The shorting is done using a chip capacitor (Republic Electronics Corporation). The bias voltage is applied using a BNC connector, whereas the microwave signal is available through SMA connectors.

Further consideration reveals how the distributed resonant inductance value is varied. The distributed variable inductance is realized by a variable capacitance as shown by the Smith chart of Fig. 10. The total length of the transmission line is fixed. Point A, the capacitor position and point C, the distributed inductance position, are fixed on the circuit but not on the Smith chart. Point B, the ideal short position, is fixed on the Smith chart. The Smith chart position of the capacitor, A, depends on the capacitance value and can move with changing capacitance. Since the arc length from A to C on the Smith chart is fixed, moving A moves C. With C moving, and B the ideal short position fixed on the Smith chart, the distance from B to C, \( l_{BC} \), is variable. This length gives the value of the distributed inductance through the relation
\[ j \omega L = j Z_0 \tan \beta_{1BC} \quad . \] (3.5)

Thus, the inductance value is controlled by the capacitance value.
CHAPTER 4
METHODS

The methods outlined here involve the testing of a quadrature hybrid coupler and the testing of the phase shifter. The hybrid coupler testing was used to verify its action as part of a phase shifter with a simple load, an open circuit. The phase shifter testing had three purposes. The first was to verify the accuracy of the theoretical model used to describe the phase shifter. If accurate, the model can be used to select the optimum values of inductor and varactor. The second function was to show that the optimum load does indeed provide the lowest loss variation for 180 degrees of phase shift. To do this, loads had to be built with higher and lower varactor values that would not perform as well. The third function of the testing was to observe the power limits and frequency limits of the optimum device.

The first test was designed to verify the theory of the 3 dB quadrature hybrid coupler as an element in a phase shifter. Line stretchers provided variable open circuits as loads for the coupler. The test set up is shown in Fig. 11. The procedure was to put a 3 dB quadrature hybrid in a test jig to which the line stretchers could be attached. Using the HP 8505 Network Analyzer, the transmission phase of $S_{21}$ and $S_{12}$ through the hybrid was measured as the sliding line stretcher on ports 3 and 4 were moved.
The next test was to measure the phase shifter. However, the key parameters needed to analyze phase shifter operation could be obtained by carefully studying the reflection properties of the load. This equivalence results because for identical loads, the transmission through the phase shifter is directly dependent on the reflection coefficients of the loads. Hence, studying the behavior of the phase shifting load yields much the same information as studying the transmission through the phase shifter. In addition, building a load is less work than building a whole phase shifter. (It is solely one reflecting branch of the shifter shown in Fig. 9.) Therefore, loads were used for testing where possible.

The test set up for a load is shown in Fig. 12. The bias for the varactor was supplied by the HP 6215A Power Supply. The bias was monitored by a Data Supply 2480R Digital Multimeter. As the reflection coefficient of the phase shifting load was desired, $S_{11}$ was measured using the HP 8507 Network Analyzer. The tuning capacitor (distributed inductance) was varied until the phase difference from 0 to 30 volts was 180 degrees. Then the magnitude and phase of $S_{11}$ were recorded at increments of reverse bias from 0 to 30 volts. The data was entered into the HP 9817 Computer where it could be stored, plotted, and analyzed.

After measuring loads in this way to verify its operation the procedure was automated for measurement of either the load or the phase shifter as shown in Fig. 13. The HP 9817 computer controlled the equipment. The TERM3V and TERM4 programs were written to tune and measure the phase shifting load and phase
shifter, respectively. A listing of these programs is included in Appendix D. The varactor bias was supplied and monitored by the Tektronix PS 5010 Power Supply and DM 5010 Multimeter, respectively. The programs used error correcting routines to measure the device S-parameters with the HP 8507 Network Analyzer. The programs read the data from the voltmeter and network analyzer so they could be stored, plotted, and analyzed.

The automated measurements were used to collect most of the required data. The testing requirements fulfilled by these measurements were the verification of the phase shifter model, verification that the optimum load had been found, and determination of the device frequency response. However, these automated measurements could not investigate the power limits of the device, as the HP 8507 has an input power limit of 1 mW.

The test set up for the higher power measurements is shown in Fig. 14. The MCL RF Power Generator Model 15222 with Model 6050 RF plug in was used as a power source. A 10 dB coupler was used as a pad to allow higher power source operation where it was more stable. The energy into and out of the phase shifter was sampled by 30 dB couplers. The sampled energy was routed to two measuring devices. The HP 438A Power Meter with HP 8481A Power Sensors were used to measure the absolute input power or the input-output power ratio. This gave the transmission loss. The HP 8405A Vector Voltmeter was used to monitor output transmission phase with respect to the input phase. The varactor bias voltage is applied with the HP 6215H Power Supply and monitored with the Fluke 8600A Digital Multimeter. An 11.3 kohm resistor was placed
in series with the varactor bias so the varactor through current could be monitored with an HP 3466A Digital Multimeter. The current was monitored to prevent burning out the varactor diodes. This high power measurement measured phase shifter performance at 250 mW, the desired operating power, and measured how much power the phase shifter could tolerate. With this measurement, the testing was complete.
CHAPTER 5
RESULTS

Using the methods described in Chapter 4, a series of experiments was performed to test the operation of the quadrature hybrid phase shifters. These experiments measured the hybrid coupler to verify its operation as a phase shifter element. They also carefully analyzed loads and phase shifters of varying varactor values to verify the theoretical model and to find the optimum load with regard to loss variation. The results from the procedure to verify operation of the 3 dB hybrid coupler are shown in Table 2. The transmission phase through the device was changed when the lengths of the line stretchers were varied. A 1.3 cm change in length gave a 19 degree change in the electrical length. The transmission phase through the device was found to be the average of that due to each reflecting port. These results are summarized in measurements 1, 2, and 3 in the table. Measurement 1 was obtained with both line stretchers at the minimum length (transmission phase 164 degrees) while measurement 2 was made with both line stretchers at the maximum length (transmission phase 145 degrees). For measurement 3 one line stretcher was at the minimum length while the other was at the maximum length. The record transmission phase was 154 degrees, which is the average of the two previous results. Measurements 3 and 4 show that the device is reciprocal. Interchanging the loads on the reflection ports in these measurements did not change the transmission phase. These results verify the operation of a 3 dB
hybrid coupler in a phase shifter when the loads on ports 3 and 4 have reflection coefficients differing only in phase.

Next, the interactive program MDLHFPTR (see Appendix C) was used to choose the optimum inductor varactor load combination. By considering a range of varactor values, the optimum value was found to be 3.9 pF. The phase and amplitude responses of the 3.9 pF simulation as a function of varactor bias voltage are shown in Figs. 15 and 16, respectively.

With the predicted optimum load known, microstrip loads were constructed using varactors with values in a range above and below the optimum. Figures 17 - 24 show the phase and amplitude responses of phase shifting loads with varactor values of 10 pF, 5.6 pF, 3.9 pF, and 3.3 pF. The phase and amplitude variations of these loads are summarized in Table 3, where the 3.9 pF load is indeed shown to be optimum.

In order to compare the predictions, the model used in the simulation with the experimental measurements, the results are plotted on the same axes in Figs. 25 - 32. Since the relative changes in phase and amplitude are the important criteria, the average phase and amplitude were subtracted to enhance direct comparison. This action is justified because the hybrid coupler and circuitry have an arbitrary but constant phase and loss that are not incorporated into the model. In addition, the entire circuit has a composite quality factor that is dependent upon construction. Therefore, the estimated quality factor of the transmission lines and components was adjusted slightly to achieve the best fit of the data and the simulations.
Two complete hybrid coupler phase shifters were built using 3.9 pF and 5.6 pF varactors. Their phase and amplitude responses are shown in Figs. 33 - 36. These responses are similar to those of the 3.9 pF and 5.6 pF loads. The 3.9 pF phase shifter was studied further because it was the predicted and found to be the optimum phase shifter. The additional parameters studied were return loss and the phase and amplitude variation as a function of frequency and input power. The return loss of this phase shifter (> 18 dB) is shown in Fig. 37. Table 4 summarizes the phase and amplitude variation of the 3.9 pF phase shifter at frequencies within a 10% bandwidth of 915 MHz. As shown, the phase and amplitude sensitivities near the operating frequency are 0.3 degree/MHz and 0.009 dB/MHz, respectively. Table 5 summarizes the performance at power levels from 50 mW to 1 W.
CHAPTER 6
DISCUSSION

This discussion will provide a comparison of the theoretical model with the constructed loads and phase shifters. Furthermore, it will compare the continuous phase shifter developed in this thesis with other continuous phase shifters described in the literature.

First, a comparison of the results of loads and phase shifters of the same inductor-varactor combination shows that each provides the same response. The phase and amplitude responses of the 3.9 pF varactor from the phase shifting load in Figs. 21 and 22 and the phase shifter of Figs. 33 and 34 are replotted in Figs. 38 and 39 for direct comparison. The responses, though close, are not identical. Two factors may be responsible. First, the varactor manufacturer gives a ±10% tolerance on the 4 volt varactor capacitance. Thus, the varactor in the load and the phase shifter are possibly of different values. This changes the required inductance that obtains 180 degrees phase variation resulting in a different combination. Second, both devices were constructed by hand and their construction was not identical, which would give rise to slightly different composite quality factors, Q. Different quality factors will, as will be shown, result in altered response curves. Given these physical differences between two devices, the load and the phase shifter behave similarly and provide comparable phase shifting information.
The next comparison, between the load and the circuit simulation, shows the simulation is an accurate representation. The simulation uses the model of the varactor shown earlier in Fig. 7 with a modification suggested by the manufacturer [Alpha Industries, 1985]. The modification is an inductance placed in series with the composite structure of Fig. 7. With this model in the simulation, the simulation is plotted on the same axis as the measurements in Figs. 25 to 32. The model agrees quite closely with the measurements. Though not exactly alike, the character of the curves is extremely similar. In addition to similar curve character, the simulation and the measurements both indicate the same optimal inductor-varactor combination for 180 degrees phase variability. Both point to the combination involving a 3.9 pF varactor. From Table 4, it is evident that the 3.3 pF varactor could not achieve 180 degree phase variation, and the 5.6 pF varactor exhibited more loss variation than the 3.9 pF circuit. Thus, the simulation of the phase shifter appears to be valid for generating characteristic phase shifter responses and for finding the optimum varactor-inductor combination.

The optimum combination was further tested to investigate performance with respect to frequency and power level. At frequencies higher than 915 MHz the loss variation goes down as does the phase variation (< 180 degrees). At frequencies lower than 915 MHz the maximum phase variation increases (> 180 degrees) as does the loss variation. The result is that, at 915 MHz, just the necessary 180 degree phase variation is achieved with its associated loss variation.
An increase in power level results in both an increase in phase and loss variation. Since more phase variation is present than required, the increased loss variation is decreased by retuning the circuit to have just the required 180 degree phase shift. The tuning capacitor was screwed in fully, generating more inductance, to give 187 degree phase variation and 2.69 dB of loss variation at an input power level of 250 mW. This test not only indicates that higher power requirements require greater loss variation but that the circuit should be tuned at the anticipated operational power level.

The importance of having closely tracking loads in a phase shifter was discussed in Chapter 2. To investigate this, the hybrid coupler of the 5.6 pF phase shifter was replaced with transmission lines so each load could be individually observed. The phase and amplitude of their reflection coefficients are plotted on the same axes for direct comparison in Figs. 40 and 41. The phase variation is less than 180 degrees because the phase shifter was returned during a higher power measurement. As in the comparison of the 3.9 pF load and phase shifter, the responses are similar but not identical. This is due in part to the 10% varactor tolerance cited earlier and also to slight differences in construction. In practice then, identical loads will not be realized and additional transmission loss results.

Further investigation of the simulation indicates trends with respect to the phase desired and the quality factor achieved. Table 6 shows that as more phase variation is required, more loss variation will have to be accepted. A gen-
eral characteristic of this effect is that the optimum loss curve for any desired phase variation is a curve with the loss at 0 volts and 30 volts close in value. Simulations relating the change in loss variation with respect to Q are shown in Fig. 42. They indicate that not only does the absolute loss decreases with increasing Q, but the curve character also changes. Figure 43 shows that phase variation is not significantly affected by changes in Q.

With the phase shifter fairly well characterized by experiment and simulation, it would be instructive to compare this realization with others in the literature. One variety generates complex vectors whose amplitudes are varied before recombination to yield a constant magnitude vector of desired phase [Hwang, 1984; Kumar, 1981; Johnson, 1981]. As a representative, the Kumar circuit (Fig. 4) can be seen to be a much more complicated circuit. Each of the FET amplifiers has independent control to generate the proper vector. Theoretically, the device should have no amplitude variation, but it exhibited ± 3 dB amplitude variation due to power combiner characteristics.

Another variety of phase shifter is based on the change in phase shift that occurs when the resonant frequency of an oscillator is changed, but the frequency of oscillation is constrained by injection (frequency) locking the oscillator to a stable frequency source [Cohen, 1984; Rubin, 1972]. The control is applied through a varactor tuned Gunn oscillator. Once built, Cohen [1984] achieved 160 mW of power for 160 degree continuous active phase shifting. The necessity of building two oscillators
makes this circuit more complex than the hybrid coupler design studied here.

Yet another phase shifter realization uses dual gate metal-semiconductor junction field effect transistors (MESFETs) where the signal is amplified through one gate while the transmission phase is controlled by a resonant circuit on the second gate utilizing the variable gate capacitance [Tsironis, 1980; 1981; Pengelly, 1981]. The Tsironis circuit (Fig. 4) achieved 90 degree phase variation with 1.8 dB amplitude variation. Amplitude variation was compensated for with an automatic gain control (AGC) dual gate FET amplifier following the phase shifter. Pengelly [1981] states that the magnitude of the phase shift depends strongly on the input matching network and in any case is limited in range.

The most widely reported realization is the reflection type phase shifter [Niehenke, 1985; Boire, 1985; Dawson, 1984; Hopper, 1979; Modelski, 1979; Ulriksson, 1979; Rippy, 1975; Henoch, 1971; Garver, 1969]. This type has many variations of varactor resonant loads and is, of course, the realization of this thesis. The literature devices operated at maximum power levels of 10 to 100 mW. Dawson [1984] noted phase shift variation with signal level. This gives additional support to the phase variation with power level shown in Table 5. All of the reported devices have exhibited the amplitude variation with bias. Garver [1969] and Henoch [1971] have addressed this problem. Garver [1969] uses a properly chosen resistance in parallel with his resonant circuit to equalize the loss variation. The
resistance depends on the highest and lowest values of the resonant load resistance. Garver [1969] achieved 0.56 dB variation at a 100 mW power level. Henoch [1971] uses a quarter wave transformer to equalize the loss variation. The transformer is designed for the most opposed resistance states of the resonant load. Henoch [1971] achieved 1.3 dB amplitude variation at an unspecified power level. These methods of loss equalization do so at the expense of higher absolute loss.

The reflective type phase shifter for the hyperthermia system is different from the ones in the literature in several ways. The power levels of the previously reported devices are limited by concerns of linear operation [White, 1974] which is not a constraint for the hyperthermia system device. The method of minimization of loss variation is also different. The amplitude variation for the hyperthermia phase shifter is minimized by proper resonant load choice. The devices in the literature are not afforded this flexibility because their resonant elements are picked with regard to linear phase-voltage constraints. The phase shifter constructed here is then a higher power, simple device that meets different needs than those of the continuous phase shifters in the literature.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The goals of this project were to design and construct a simple phase shifter suitable for operation in a 915 MHz phased array microwave hyperthermia system. The suitability is determined with regard to phase, loss, frequency, and power variation. The necessary phase shift of 180 degrees was achieved with the minimum loss variation (0.51 dB). The device has the required \( \pm 10 \) MHz bandwidth with no significant performance decrease. The loss variation increases with input power level and at the 250 mW level is 2.7 dB. Within the design constraints, then, a phase shifter has been developed which is suitable for operation in a phased array microwave hyperthermia system.

Avenues for further investigation may now be suggested. Certainly, the size of the phase shifter may be reduced by using a higher dielectric constant substrate. The fixed size of the discrete elements complicates this reduction. The blocking and quarter wave shorting capacitors could be turned on their sides to accommodate the thinner transmission lines. Smaller packages for the varactor and screw turn capacitor might be sought. However, the discontinuity of these elements with the transmission line can be tuned out with the screw turn capacitor. This element might be placed to the outside of the transmission line to avoid cutting it. In addition to size reduction, a metal case should enclose the phase shifter to confine radiation. Edwards [1984] has outlined shielding provisions. The shielding lowers
both the characteristic impedance and the effective microstrip permittivity. Hence, the transmission lines would have to be narrowed and the distributed elements lengthened. Further decrease in loss variation, if necessary, might be achieved with the addition of elements suggested by Garver [1969] or Henoch [1971]. Dawson et al. [1984] has suggested a method to reduce phase shift variation with power level at the expense of more varactors. Finally, if more phase shift were necessary because of a change in applicator configuration, several channels for achieving 360 degree phase variation are available. The obvious configuration is two of the devices designed in this project. Another method would be to cascade an analog 180 degree phase shifter with a digital 180 degree phase shift [Boire, 1985]. A final method would be to realize more complex loads on the 3 dB hybrid coupler as suggested by the loads of Henoch [1971] or Garver [1969]. Except for size reduction and shielding, the above suggestions are only included in the event that future constraints might justify the added complexities of the circuits.
TABLE 1

Continuous Phase Shifter Design Criteria

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Power</td>
<td>250 mW</td>
</tr>
<tr>
<td>Frequency</td>
<td>915 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>± 10 MHz</td>
</tr>
<tr>
<td>Phase Variation</td>
<td>180 degrees</td>
</tr>
<tr>
<td>Amplitude Variation</td>
<td>Minimize</td>
</tr>
<tr>
<td>Measurement</td>
<td>Line stretcher length on 0 Degree Port (cm)</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>7.32</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8.64</td>
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<td>3</td>
<td>8.64</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.32</td>
</tr>
<tr>
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</table>

* Measurement set up as shown in Fig. 11.

** This phase measurement is sporadic because it was close to the 180 degree phase transition on the screen.
**TABLE 3**

Comparison of Theoretical and Measured Load Characteristics for Various Varactors

<table>
<thead>
<tr>
<th>Varactor in Load (pF)</th>
<th>Measured Phase Variation (Degrees)</th>
<th>Measured Loss Variation (dB)</th>
<th>Model Phase Variation (Degrees)</th>
<th>Model Loss Variation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>182*</td>
<td>2.4</td>
<td>180.4</td>
<td>2.36</td>
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<tr>
<td>5.6</td>
<td>180.6</td>
<td>0.81</td>
<td>180.3</td>
<td>0.78</td>
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<tr>
<td>3.9</td>
<td>177.9</td>
<td>0.72</td>
<td>180.3</td>
<td>0.68</td>
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<tr>
<td>3.3</td>
<td>173.5</td>
<td>1.02</td>
<td>171.4</td>
<td>1.11</td>
</tr>
</tbody>
</table>

* This was the manual measurement (Fig. 12) as opposed to the other done with the automated measurement (Fig. 13).
**TABLE 4**

Measurement of Phase Shifter (3.9 pF varactor) Operation within a 10% Bandwidth

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Phase Variation (Degrees)</th>
<th>Loss Variation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>865</td>
<td>187.0</td>
<td>1.01</td>
</tr>
<tr>
<td>875</td>
<td>187.0</td>
<td>0.89</td>
</tr>
<tr>
<td>885</td>
<td>186.0</td>
<td>0.77</td>
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<tr>
<td>895</td>
<td>185.0</td>
<td>0.69</td>
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<tr>
<td>905</td>
<td>184.0</td>
<td>0.60</td>
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<tr>
<td>915</td>
<td>181.0</td>
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<tr>
<td>925</td>
<td>178.0</td>
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<td>935</td>
<td>174.0</td>
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<tr>
<td>945</td>
<td>171.9</td>
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<tr>
<td>955</td>
<td>167.9</td>
<td>0.29</td>
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<tr>
<td>965</td>
<td>163.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>
TABLE 5

Operating Characteristics of Phase Shifter with a 3.9 pF Varactor at Higher Power Levels

<table>
<thead>
<tr>
<th>Actual Power* (mW)</th>
<th>Phase Variation (Degrees)</th>
<th>Transmission Power Variation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>217</td>
<td>1.35</td>
</tr>
<tr>
<td>51</td>
<td>224</td>
<td>1.78</td>
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<td>239</td>
<td>5.23</td>
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<tr>
<td>1050</td>
<td>241</td>
<td>5.83</td>
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</table>

After retuning to minimize power variation

<p>| | | |</p>
<table>
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<tbody>
<tr>
<td>530</td>
<td>190</td>
<td>3.44</td>
</tr>
<tr>
<td>270</td>
<td>187</td>
<td>2.69</td>
</tr>
</tbody>
</table>

* Actual power calculated from measurement using 31.2 dB coupling factor.
TABLE 6

Model Predictions for Minimum Loss Variation* in Hybrid Coupler Phase Shifter Design

<table>
<thead>
<tr>
<th>Phase Variation (Degrees)</th>
<th>Loss Variation (dB)</th>
<th>Varactor Capacitance (4 volt, pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.68</td>
<td>3.9</td>
</tr>
<tr>
<td>200</td>
<td>1.00</td>
<td>4.4</td>
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<tr>
<td>230</td>
<td>1.64</td>
<td>6.4</td>
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<td>270</td>
<td>2.97</td>
<td>10.0</td>
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<tr>
<td>315</td>
<td>6.81</td>
<td>22.0</td>
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</tbody>
</table>

* The minimum loss variation for a specified phase variation is found by inputting varactor values into the model until the minimum loss variation is achieved. This process could be automated using nonlinear optimization techniques.


<table>
<thead>
<tr>
<th>Substrate</th>
<th>Frequency Measured (MHz)</th>
<th>Cavity Mode</th>
<th>Relative Dielectric Constant (Calculated)</th>
<th>Manufacturer specification</th>
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<tr>
<td>Kepro PR-4</td>
<td>495</td>
<td>1,1</td>
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<td></td>
<td>696</td>
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<td>857</td>
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<td>937</td>
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<td>988</td>
<td>2,2</td>
<td>4.35</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td><strong>4.354 ± 0.0196</strong></td>
<td><strong>4.8 @ 1 MHz</strong></td>
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<tr>
<td>3MCC250GX</td>
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<td>1,1</td>
<td>2.53</td>
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<td></td>
<td>605</td>
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<td></td>
<td>851</td>
<td>2,2</td>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1019</td>
<td>3,2</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1048</td>
<td>1,3</td>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1061</td>
<td>4,1</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>2.51 ± 0.058</strong></td>
<td><strong>2.45 ± 0.04 @ 10 GHz</strong></td>
</tr>
</tbody>
</table>

*This measurement shows that the method gives a dielectric constant 0.8 - 4% too high.*
A. Single Element

B. Array of Elements

Figure 1. Field concentration for single element and focused array of elements.
Figure 2. Block diagram of 915 MHz phased array hyperthermia system.
A. Switched Path Phase Shifter

\[ \Delta \phi = 2\pi \Delta \ell / \lambda \]

B. Transmission Phase Shifter

\[ \Delta \phi = 2 \tan^{-1} \left( \frac{B_n}{1 - B_n^2} \right) \]

C. Reflection Phase Shifter

\[ \Delta \phi = 2\pi \Delta \ell / \lambda \]

Figure 3. Three common digital phase shifter designs [Garver, 1976].
**A. Vector Phase Shifter [Kumar, 1981]**

**B. Frequency Lock Phase Shifter [Cohen, 1984]**

**C. Dual Gate FET Phase Shifter [Tsironis, 1981]**

**D. Hybrid Coupler Phase Shifter**

Figure 4. Four different types of analog phase shifter designs.
Figure 5. Geometry of applicator and heated region used to determine necessary phase shift.
Figure 6. Central elements of reflective type analog phase shifter.
Figure 7. Circuit model of packaged varactor diode.
A. Microstrip Transmission Line

B. Electric and Magnetic Field Lines Near Microstrip

Figure 8. General geometry of microstrip line.
Figure 9. Schematic and circuit realization of hybrid coupler phase shifter.
A - Capacitor Position
B - Ideal Short Position
C - Distributed Inductor Position

Figure 10. Smith chart showing the translation of capacitance to distributed inductance.
Figure 11. Test setup for hybrid coupler with line stretchers.
Figure 12. Manual measurement of load.
Figure 13. Automated measurement for load or phase shifter.
Figure 14. High power measurement of phase shifter.
Figure 15. Phase response of 3.9 pF load model.
Figure 16. Amplitude response of 3.9 pF load model.
Figure 17. Measured amplitude response of 10 pF load.
Figure 18. Measured phase response of 10 pF load.
Figure 19. Measured amplitude response of 5.6 pF load.
Figure 20. Measured phase response of 5.6 pF load.
Figure 21. Measured amplitude response of 3.9 pF load.
Figure 22. Measured phase response of 3.9 pF load.
Figure 23. Measure amplitude response of 3.3 pF load.
Figure 24. Measured phase response of 3.3 pF load.
Figure 25. Comparison of simulation (Q = 21), A, and measurement, B, of phase response of 10 pF load.
Figure 26. Comparison of simulation (Q - 21), A, and measurement, B, of phase response of 10 pF load.
Figure 27. Comparison of simulation (Q = 41), A, and measurement, B, of amplitude response of 5.6 pF load.
Figure 28. Comparison of simulation ($Q = 41$), A, and measurement, B, of phase response of 5.6 pF load.
Figure 29. Comparison of simulation ($Q = 41$), A, and measurement, B, of amplitude response of 3.9 pF load.
Figure 30. Comparison of simulation (Q = 41), A, and measurement, B, of phase response of 3.9 pF load.
Figure 31. Comparison of simulation (Q = 41), A, and measurement, B, of amplitude response of 3.3 pF load.
Figure 32. Comparison of simulation (Q = 41), A, and measurement, B, of phase response of 3.3 pF load.
Figure 33. Amplitude response of 3.9 pF phase shifter.
Figure 34. Phase response of 3.9 pF phase shifter.
Figure 35. Amplitude response of 5.6 pF phase shifter.
Figure 36. Phase response of 5.6 pF phase shifter.
Figure 37. Return loss of 3.9 pF phase shifter.
Figure 38. Comparison of amplitude response of 3.9 pF load, A, and 3.9 pF phase shifter, B.
Figure 39. Comparison of phase response of 3.9 pf load, A, and 3.9 pf phase shifter, B.
Figure 40. Comparison of phase response of 0 degree port load, A, and 90 degree port load, B, in 5.6 pF phase shifter.
Figure 41. Comparison of amplitude response of 0 degree port load, A, and 90 degree port load, B, in 5.6 pf phase shifter.
Figure 42. Comparison of amplitude response of 3.9 pF simulation for (A) $Q = 31$, (B) $Q = 41$, and (C) $Q = 51$. 
Figure 43: Comparison of phase response of 3.9 pF simulation for (A) \( Q = 31 \), (B) \( Q = 41 \), and (C) \( Q = 51 \).
APPENDIX A

DETERMINATION OF RELATIVE PERMITTIVITY

The method of determining the relative permittivity is based on the relation between the resonant frequency of a cavity and its permittivity. The method is a modification of the method using one coupling hole [Edwards, 1984]. A double-sided copper clad substrate has copper tape soldered around the edges to totally enclose the substrate with metal. Two holes are drilled close to the edges of diametrically opposed corners. These holes are used for input and output couplings with male SMA connectors and are drilled close to the edges for light cavity coupling. The connector sheath is soldered to one side of the cavity with the center conductor soldered to the other. The transmission coefficient of the coupling holes is measured to find the transmission peaks where the cavity is resonant. These resonant frequencies are given by

\[ f_{n,m} = \frac{c}{2\pi/\varepsilon_r \sqrt{\frac{n^2}{a} + \frac{m^2}{b}}} \]  \[ 1/2 \]  \hspace{1cm} (A.1)

where \( c \) is the speed of light, \( \varepsilon_r \) is the relative permittivity, \( a \) is the cavity length, \( b \) is the cavity width and \( m \) and \( n \) are the mode numbers. Inverting this formula to find the relative permittivity gives

\[ \varepsilon_r = \frac{c^2}{4f_{n,m}^2} \left[ \frac{n^2}{a} + \frac{m^2}{b} \right] \]  \hspace{1cm} (A.2)
The only ambiguity is to decide what mode a frequency represents. Estimates of the permittivity are used in a program matching frequencies with their mode (see Appendix B). Once the modes are known, formula (A.2) is used to determine the permittivity. Results of the method are shown in Table 7. A known and unknown dielectric are measured and, as can be seen, the method is fairly accurate, giving an estimate that is 1 - 4% too high.
APPENDIX B

LISTING OF CAVITY

10 ! This program will calculate the resonant frequencies of a
20 ! cavity given the dimension: of the cavity. In addition it
30 ! identifies each frequency with the particular mode it represents.
40 ! Transcribed to HP from Cyber on July 1, 1986
50 ! Stored as CAVITY by Ron Boesch
60 ! Frq. is an array containing the mode frequencies
70 ! Mu is the free space permeability
80 ! Relperm is the relative permittivity
90 ! Freperm is the free space permittivity
100 ! L is the length of the cavity
110 ! W is the width of the cavity
120 ! Index is an array that helps get the frequencies in mode order
130 OPTION BASE 1
140 DIM Frq(7,7), Bfrq(49), Indx(49), Aindx(49), Bindx(49)
150 Mu=PI*4.8E-7
160 Freperm=8.854E-12
170 INPUT "WHAT IS THE RELATIVE PERMITTIVITY?", Relperm
180 INPUT "WHAT IS THE LENGTH(inches, longest dimension)?", L
190 INPUT "WHAT IS THE LENGTH(inches, shortest dimension)?", W
200 PRINTER IS 701
210 PRINT "LENGTH(inches)", L
220 PRINT "WIDTH(inches)", W
230 PRINT "RELATIVE PERMITTIVITY", Relperm
240 PRINT
250 L=L*(2.54/100)
260 W=W*(2.54/100)
270 Konst=1/(2*PI*(Mu*Relperm*Freperm)^.5)
280 N=1
290 ***
300 'Calculating resonant frequencies of I,J modes
310 ***
320 FOR I=1 TO 7
330 FOR J=1 TO 7
340 Frq(I,J)=Konst*{(PI*(I-1)/L)^2+(PI*(J-1)/W)^2)^.5
350 Bfrq(N)=Frq(I,J)
360 Aindx(N)=I-1
370 Bindx(N)=J-1
380 Indx(N)=N
390 N=N+1
400 NEXT J
410 NEXT I
420 PRINT "LENGTH WIDTH FREQUENCY"
430 PRINT "MODE MODE "
440 N=49
450 ***
460 'Using a indexed sort to order modes by increasing frequency
470 ***
480 While: IF N=0 THEN GOTO Printer
490 FOR I=1 TO N-1
500 IF Bfrq(Indx(I))>Bfrq(Indx(I+1)) THEN
510 TEMP=Indx(I+1)
520 Indx(I+1)=Indx(I)
530 Indx(I)=Temp
540 END IF
550 NEXT I
560 N=N-1
570 GOTO While
580 ***
590 'Printing resonant frequencies omitting frequencies that
600 'correspond to 0 in either L or W as constant values are
610 'not realistic
620 '***
630 Printer: FOR I=1 TO 49
640 'IF Aindx(Indx(I))=0 OR Bindx(Indx(I))=0 THEN GOTO 660
650 PRINT Aindx(Indx(I)),Bindx(Indx(I)),Bfreq(Indx(I))
660 NEXT I
670 PRINTER IS CRT
680 DISP "DONE"
690 WAIT 3
700 DISP "    "
710 END
APPENDIX C

LISTING OF MDL_SHFTR

! This program is used as an interactive optimizer to find the optimum
! varactor-inductance combination to get a minimum loss variation for a
! 180 degree phase variation. The simulation uses a five element varactor
! model with package capacitance (Cpack) of 18 pF, junction inductance
! (Lj) of .4 nH and package inductance (Lp) of .05 nH. The loss of the
! varactor is modeled by a Q that varies with bias (modeled by a quadratic
! fit of manufacturer's data). The 4 volt Q is also a function of the 4
! volt capacitance and is chosen according to manufacturer's specifica-
! tions (Alpha Industries). The program prompts for the total 4 volt
! capacitance (given by manufacturer) and different values are tried
! until the minimum loss variation is achieved. The inductance chosen
! to resonate is modeled with a constant Q which represents the Q of all
! the elements needed to realize the composite inductance (tuning cap,
! transmission line loss, etc.).

STORED AS MDL_SHFTR

July 3, 1986 by Ron Boesch

OPTION BASE 1

DIM X(200), Y(200)

DIM X#(50), Y#(50), D#(50)

PRINTER IS CRT

Begin:

INPUT "What is the Capacitance at 4 V (including package capacitance)", C4

Z=50

Qpar=30.887

Omega=2*PI*9.15E+8

Cpack=1.8E-13

Lp=5.6E-11

Lj=4.4E-10

Ca=(1/(Omega*C4)+Omega*Lp)*Omega)^(-1)

Cb=Ca-Cpack

Cj4=((1/(Omega*Cb)+Omega*Lj)*Omega)^(-1)

Cj0=Cj4*((1+(4/.8))^.47)

Q915=(50/915)*1600

Qstart=Q915*(12/16)

Q4=(13/12)*Qstart

Starts: 'FINDING APPROPRIATE Q FOR C4

IF C4<3.31E-11 THEN Q4=(14/12)*Qstart

IF C4<2.21E-11 THEN Q4=(16/12)*Qstart

IF C4<1.81E-11 THEN Q4=(18/12)*Qstart

IF C4<1.51E-11 THEN Q4=(20/12)*Qstart

IF C4<1.21E-11 THEN Q4=(22/12)*Qstart

IF C4<1.01E-11 THEN Q4=(24/12)*Qstart

IF C4<8.21E-12 THEN Q4=(26/12)*Qstart

IF C4<6.81E-12 THEN Q4=(28/12)*Qstart

IF C4<5.61E-12 THEN Q4=(30/12)*Qstart

IF C4<4.71E-12 THEN Q4=(32/12)*Qstart

IF C4<3.91E-12 THEN Q4=(34/12)*Qstart

IF C4<3.31E-12 THEN Q4=(36/12)*Qstart

IF C4<2.71E-12 THEN Q4=(38/12)*Qstart

IF C4<2.21E-12 THEN Q4=(40/12)*Qstart

L=1/(Omega^-2*Cj0)

CALL R_pmodel(Cj0,0,L,Cpack,Lp,Lj, Omega,Q4, Cmin, Rmin)

CALL R_pmodel(Cj0,30,L,Cpack,Lp,Lj, Omega,Q4, Cmed, Rmax)

Cmed=(Cmin+Cmax)/2

Lres=L

Lfract=.2*L

L=L-Lfract

PRINTER IS 701
PRINT "FINDING LARGER INDUCTANCE THAT PROVIDES 180 SHIFT"
PRINTERS IS CRT

FOR I=0 TO 30 STEP 30
CALL R_pmodel(Cj0,I,L,Cpack,Lp,Lj,Omega,Q4,Cp,Rp)
K1=1-((Omega^2)*L*Copt)
K2=Omegas*L*(Rp^2)*K1
K3=(Omegas*L)^2+(Rp*K1)^2
K4=(Omegas*L)^2*Rp-Z*K3
K5=(Omegas*L)^2*Rp+Z*K3
Anglo=ATN(K2/K4)
IF K2<0 AND K4<0 THEN Anglo=Anglo-PI
IF K4>0 AND K2>0 THEN Anglo=Anglo-PI
Ang2o=ATN(K2/K5)
IF K2<0 AND K5<0 THEN Ang2o=Ang2o-PI
IF K2>0 AND K5>0 THEN Ang2o=Ang2o-PI
Ango=Anglo-Ang2o
Angdego=(Ango+360)/(2*PI)
Angdego=Angdego MOD 360
IF ABS(Angdego)>180 THEN Angdego=Angdego-360*SGN(Angdego)
IF I=0 THEN Anglow=Angdego
IF I=30 THEN Angdif=Anglow-Angdego
NEXT I
PRINTERS IS 701
IF ABS(Angdif)<190 THEN PRINT Angdif
IF ABS(Angdif)<200 THEN Lfract=04*Lres
IF ABS(Angdif)<185 THEN Lfract=01*Lres
IF ABS(Angdif)<180.5 THEN GOTO Start
PRINT "Q IS ASSUMED QUADRATIC, CHOSEN FOR 4 VOLT CAPACITANCE"
PRINT "PHASE SPAN=",Angdif
PRINT "INDUCTANCE=",L
PRINT "PACKAGE L=",Lj
PRINT "PACKAGE C=",Cpack
PRINT "Q(4)=",Q4
PRINT "CT(4)=",C4
CALL R_pmodel(Cj0,4,L,Cpack,Lp,Lj,Omaga,Q4,Cp,Rp)
PRINT "C4(Resonant)=",Cp
PRINT "MEDIAN C=",Cmed
PRINT "CMA(X(Res.))=",Cmin
PRINT "CMI(N(Res.))=",Cmax
PRINT "C(0)/C(50)=",Cmin/Cmax
PRINTERS IS CRT
PRINT "Same: INPUT "Type 1 for MAG(db) plot, 2 for PHASE plot",Flag2
W=1
Magdbmax=0
Magdbmin=-100
IF Flag2=1 THEN Label$="Mag(db)"
IF Flag2=2 THEN Label$="Phase"
X$="Varactor Bias (Volts)"
IF Flag2=1 THEN Y$="Return Loss (db)"
IF Flag2=2 THEN Y$="Phase (Degrees)"
FOR I=0 TO 30 STEP .5
X(W)=I
CALL R_pmodel(Cj0,I,L,Cpack,Lp,Lj,Omaga,Q4,Cp,Rp)
K1=1-((Omaga^2)*L*Cp)
K2=Omegas*L*(Rp^2)*K1
K3=(Omegas*L)^2+(Rp*K1)^2
K4=(Omegas*L)^2*Rp-Z*K3
K5=(Omegas*L)^2*Rp+Z*K3
IF Flag2=2 THEN GOTO Angle_gen
1200 Mag=(K2^2+K4^2)/(K2^2+K5^2)
1210 Magdb=10*LOG (Mag)
1220 IF Magdbmax>Magdb THEN Magdbmax=Magdb
1230 IF Magdbmin<Magdb THEN Magdbmin=Magdb
1240 Y(W)=Magdb
1250 GOTO Loop
1260 Angle_gen: ! This section to generate phase
1270 Angl=ATN(K2/K4)
1280 IF K2<0 AND K4<0 THEN Ang1=Ang1-PI
1290 IF K4<0 AND K2>0 THEN Ang1=Ang1-PI
1300 Ang2=ATN(K2/K5)
1310 IF K2<0 AND K5<0 THEN Ang2=Ang2-PI
1320 IF K2>0 AND K5<0 THEN Ang2=Ang2-PI
1330 Ang=Ang1-Ang2
1340 Angdeg=(Ang*360)/(2*PI)
1350 Angdeg=Angdeg MOD 360
1360 IF ABS(Angdeg)>180 THEN Angdeg=Angdeg-360*SGN(Angdeg)
1370 Y(W)=Angdeg
1380 Loop: !
1390 W=W+1
1400 NEXT I
1410 PRINTER IS 701
1420 IF Flag=1 THEN PRINT "Maximum return loss", Magdbmax
1430 IF Flag=1 THEN PRINT "Minimum return loss", Magdbmin
1440 IF Flag=1 THEN PRINT "Return loss difference", Magdbmax-Magdbmin," dB"
1450 PRINTER IS CRT
1460 Numb=W-1
1470 ! INPUT "What is the x-axis label (<50)?", X$
1480 ! INPUT "What is the Y-AXIS label (<50)?", Y$
1490 ! INPUT "What is the graph title (<50)?", D$
1500 Catch: INPUT "Enter 1 for screen plot, 2 for paper plot.", Flag
1510 IF Flag=1 THEN GOTO Past
1520 IF Flag=2 THEN GOTO Past
1530 GOTO Catch ! If 1 or 2 not received, ask again
1540 Past: ! default line
1550 DISP "Hit continue(f2) when done with this graph"
1560 WAIT 1
1570 CALL Plotit(X(*), Y(*), Numb, X$, Y$, D$, Flag)
1580 INPUT "Would you like to make another plot of the same data (Y/N)?", Ans$
1590 IF Ans$="y" OR Ans$="Y" THEN GOTO Catch
1600 INPUT "Would you like to store this simulation to disk (Y/N)?", Ans$
1610 IF Ans$="N" OR Ans$="n" THEN GOTO Quest2
1620 Total=Numb
1630 Co1=2
1640 INPUT "What is the FILNAME?", Fname$
1650 CREATE BDAT Fname$, 2*Total+10, 8
1660 DISP "Saving simulation to disk."
1670 ASSIGN @Path1 TO Fname$
1680 OUTPUT @Path1, I; Total
1690 OUTPUT @Path1, 2; Col
1700 W=1
1710 FOR I=3 TO Col*Total+3 STEP Col
1720 OUTPUT @Path1, I; X(W)
1730 OUTPUT @Path1, I+1; Y(W)
1740 W=W+1
1750 NEXT I
1760 ASSIGN @Path1 TO *
1770 Quest2: !
1780 INPUT "Would you like to make another plot with same parameters (Y/N)?", Ans$
1790 IF Ans$="y" OR Ans$="Y" THEN GOTO
INPUT "Would you like to recalculate with new capacitance (Y/N)", Ans$
1810 IF Ans$="Y" OR Ans$="Y" THEN GOTO Begin
1820 DISP "DONE"
1830 WAIT 1
1840 DISP ""
1850 END
1860 SUB Cdiv(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
1870 SUBEND .
1880 '**********************************************************************
1890 : PLOTTING SUBROUTINE
1900 '**********************************************************************
1910 SUB Plotit(Valx(*),Valy(*),Numbf,Xtitle,Ytitle,Dev$,Flag)
1920 C$=CHR$+(255)&"k"
1930 Vxmin=1,E+49
1940 Vymin=1,E+49
1950 Vymax=-1,E+49
1960 Vxmax=-1,E+49
1970 FOR J=1 TO Numbf
1980 IF Valx(J)<Vxmin THEN Vxmin=Valx(J) !Look into the file to
1990 IF Valx(J)>Vxmax THEN Vxmax=Valx(J) !find the minimum and
2000 IF Valy(J)<Vymin THEN Vymin=Valy(J) !maximum values to be
2010 IF Valy(J)>Vymax THEN Vymax=Valy(J) !plotted
2020 NEXT J
2030 X1=Vxmin
2040 X2=Vxmax
2050 Y1=Vymin
2060 Y2=Vymax
2070 OUTPUT KBD;"!;"
2080 Startx=X1 !Set X graph limits to the
2090 Stopx=X2 !min and max found
2100 Starty=Y1-(Y2-Y1)/10 !Set Y graph limits to the min
2110 Stopy=Y2+(Y2-Y1)/10 !and max plus .1*(the span)
2120 Step=(Stopx-Startx)/10 !Offset of X from starting point
2130 Step=(Stopy-Starty)/8 ! Provide exit
2140 ON KBD GOTO Exit ! Clear screen for graph
2150 OUTPUT 2 USING ";#,K";C$ ! Initialize various graphics parameters.
2160 GINIT ! Use the internal screen
2170 IF Flag=1 THEN PLOTTER IS 3,"INTERNAL" ! Turn on the graphics screen
2180 IF Flag=2 THEN PLOTTER IS 705,"HPB1"
2190 GRAPHICS ON ! Reference point: center of top of label
2200 LONG 6 ! Determine how many SDUs wide the screen is
2210 X_gdu_max=100*MAD(MAX(1,RATIO))
2220 Y_gdu_max=100*MAD(MAX(1,1/RATIO))
2230 FOR I=-.3 TO .3 STEP .1 ! Offset of X from starting point
2240 MOVE X_gdu_max/2+I,Y_gdu_max Move to about middle of top of screen
2250 LABEL USING ";#,K";Dev$ ! Write title of plot
2260 NEXT I ! Next position for title
2270 DEG ! Angular mode is degrees (used in LDIR)
2280 LDIR 90 ! Specify vertical labels
2290 CSIZE 3.5 ! Specify characters
2300 MOVE 0,Y_gdu_max/2 ! Move to center of left edge of screen
2310 LABEL USING ";#,K";Ytitle ! Write Y-axis label
2320 LONG 4 ! Reference point: center of bottom of label
2330 LDIR 0 ! Horizontal labels again
2340 MOVE X_gdu_max/2,.07*Y_gdu_max X: center of screen; Y: above key labels
2350 LABEL USING ";#,K";Xtitle ! Write X-axis label
2360 VIEWPORT .1*X_gdu_max,.98*X_gdu_max,15*Y_gdu_max,.9*Y_gdu_max
2370 WINDOW 0,100,16,18 ! Define subset of screen area
2380 AXES 1,0.05,0.18,5,5,3 ! Anisotropic scaling: left/right/bottom/top
2390 AXES 1,0.05,0.18,5,5,3 ! Draw axes intersecting at lower left
AXES 1,05,100,18,5,5,3
IF Flag=2 THEN 2420
LINE TYPE 3
GRID 10,25,0,16,1,1
LINE TYPE 1
CLIP OFF
CSIZE 2.6,6
LONG .
FOR I=0 TO 100 STEP 10
MOVE I,15.99
Fqw=Stepx/10*I+Startx
IF ABS(Fqw)>1000 THEN LABEL USING ",5D.D";Fqw
IF ABS(Fqw)>10 AND ABS(Fqw)<1000 THEN LABEL USING ",4D.D";Fqw
IF ABS(Fqw)>10 AND ABS(Fqw)<100 THEN LABEL USING ",3D.2D";Fqw
NEXT I
LONG B
FOR I=16 TO 10 STEP .25
VALU=Stepy/25*(16-I)+Starty
MOVE -.5,I
IF ABS(Valu)>10 THEN LABEL USING ",4D.D";Valu
IF ABS(Valu)<10 THEN LABEL USING ",2D.2D";Valu
NEXT I
PENUP
LABEL statement leaves the pen down
PEN 2
LINE TYPE 1
FOR I=1 TO Numbf
Fry=16+.25/Stepy*(Valy(I)-Starty)
Frx=10/Stepx*(Valx(I)-Startx)
PLOT Frx,Fry
NEXT I
PEN 0
PAUSE
OUTPUT KBD;"!;"
Exit; GRAPHICS OFF
OUTPUT 2 USING ",K";C$
GINIT
GCLEAR
SUBEND
!******************************************************************
! MODEL FOR THE VARACTOR
! L-C-R \ /L-C-R
! -L-<--<-- converted to <-<--
! \--C--> \--R--
!******************************************************************
SUB Rp(model(Cj0,Vb,Lres,Cpack,Lpak,Lj,Omeg,Q4,Cp,Rp))
!Lj=4.10
!Lpak=5.11
Qpar=43.887
Q=(.4+(1.3*Vb)+(.002*(Vb^2)))*Q4
Cpv=(Cj0/((1+(Vb/.8))^-.47))
Zpv=(1/(Omeg*Cpv))-(Omeg*Lj)
!Constant Q due to board and Scap
!Quadratic Q vs. V dependence
!Junction capacitance
!Including effect of Lj
Cpvb=(1/(Zpv*Omega))
Ct=Cpvb+Cpack
Zres=(1/(Ct*Omega))-(Omega*Lpaket)
Cres=(1/(Zres*Omega))
Rres=(Q*(Ct^2))/(Cpvb*Omega*(Cres^2))
Rinduct=Qpar*Omega*Lres
Rp=(Rres*Rinduct)/(Rres+Rinduct)
Cp=Cres.
PRINT IS CRT
PRINT Vb,Cpv,Cpvy,Cp
PRINT IS 701
SUBEND
APPENDIX

LISTING OF AUTOMATED MEASUREMENT PROGRAMS

1. TERM 4

This program is designed to automate the testing of the phase
shifter. It is a modified version of a 3 term error model,
TERM3, written to error correct for reflection measurements.
Since transmission needs to be measured, TERM3 is modified
to error correct the transmission terms. The transmission
is corrected using half of an 8 term error model. (Hence it is a
4 term error model.) The reflections are measured as S22 on the
test set and the transmissions are measured as S12 on the test
set.

STORRED AS TERM4

Written May 14, 1986 by Ronald D. Boesch

*****************************

OPTION BASE 1

DIM Dirm(221), Dirp(221), Openm(221), Openp(221), Esfm(221), Esfp(221)
DIM Erfm(221), Erfp(221)
DIM Dutm(221), Dutp(221), Shortm(221), Shortp(221)
DIM Fq(221), S11g(100), S11p(100), S21g(100), S21p(100), Volt(100)
DIM Tdut(100), Tdtp(100), Rdut(100), Rdtp(100)
DIM Esfr(221), Esfi(221), Erfi(221), Erfr(221), Dirr(221), Diri(221)
DIM Tmr(221), Tmi(221), Tmn(221), Tmp(221)
DIM X$[501], Y$[501], D$[501]

ABORT 7
LOCAL 7

Source=719.4
Processor=716
Test_set=720
Power_supply=722
Voltmeter=708

INPUT "Do you want to manually measure for 180 degree only (Y/N)?", Ans$
IF Ans$="N" OR Ans$="n" THEN GOTO Auto
DISP "Turn on powersupply, HP505, and then hit CONT (f2)"
PAUSE
DISP "Hand calibrate 505 then hit CONT (f2)"
PRINTER 1S CRT

PRINT "*****CALIBRATION SEQUENCE*****"
PRINT "Set start and stop frequencies, set marker at 915 MHz"
PRINT "***Reflection, S22"
PRINT "  Connect Reverse Short"
PRINT "  Channel 1: MKR,B/R,POLAR MAG,ZRO (hold until display zero)"
PRINT "  Electrical Length: B, CLR if REL lighted"
PRINT "  LENGTH and VERNIER B for smallest cluster,ZRO."
PRINT "  Channel 1: POLAR PHASE,ZRO (hold until display zero),"
PRINT "  REF, REF OFFSET so display reads +180 degrees"
PRINT "  ZRO, MKR."
PRINT "***Transmission, S12"
PRINT "  Connect Through"
PRINT "  Channel 1: A/R,POLAR MAG,POLAR FULL 1."
PRINT "  MKR,ZRO (hold until display zero),"
PRINT "  Electrical Length: A, CLR if REL lighted"
PRINT "  LENGTH and VERNIER A for smallest cluster,ZRO."
PRINT "  Channel 1: POLAR PHASE,ZRO (hold until display zero)"
PRINT "  DLY,ZRO (hold until display zero)."
PAUSE
PRINT USING "25/"
OUTPUT Powersupply:"VPOS 0;IPOS .3;FSOUT ON"
OUTPUT Voltmeter:"DCV; MODE TRIG"
!
! "********Manual" OPERATION FOR TUNING TO 180 DEGREES OF SHIFT************
!
Manual: OUTPUT Powersupply:"VPOS 0"
WAIT .2
OUTPUT Voltmeter:"DT TRIG"
ENTER Voltmeter;Vlt
DISP "Record transmission phase at 0 V then CONT"
PAUSE
OUTPUT Powersupply:"VPOS 30"
WAIT .2
OUTPUT Voltmeter:"DT TRIG"
ENTER Voltmeter;Vlt
DISP "Record transmission phase at 30 V then CONT"
PAUSE
INPUT "Is the manual measurement done (Y/N)?",Ans$
IF Ans$="N" OR Ans$="N" THEN GOTO Manual
OUTPUT Powersupply:"VPOS 0"
WAIT .2
OUTPUT Voltmeter:"DT TRIG"
ENTER Voltmeter;Vlt
! 
! "*****AUTOMATED MEASUREMENT OF DEVICE AFTER TUNING*********

Auto: "Automated measurement section
OUTPUT Test_set:"2"
OUTPUT Source:"06V99I1R3M3W471FB0E"
OUTPUT Processor:"COBIC1D2C2D2E"
IMAGE "FA",K"E"
BEEP
INPUT "ENTER START FREQUENCY(in Mhz,G.E. 600 Mhz)",Fstart
Fstart=Fstart*1.E+6
BEEP
INPUT "ENTER STOP FREQUENCY(in Mhz,L.E. 1200 Mhz)",Fstop
Fstop=Fstop*1.E+6
BEEP
INPUT "ENTER STEP FREQUENCY(in Mhz)",Fstep
Fstep=Fstep*1.E+6
BEEP
Numb=INT((Fstop-Fstart)/Fstep)+1
PRINT USING "25/"
PRINT " ******* CALIBRATION *******"
PRINT USING "10/
OUTPUT Processor:"C1I5M2S2C2I5M3S2E"
IMAGE "FA",K,"E"
BEEP
DISP "CONNECT 50 OHM LOAD (PORT 2) THEN HIT CONTINUE."
PAUSE
CALL Collect(Dirm(*),Dirp(*),Fstart,Fstop,Fstep,Fq(*))
IF Dirm(1)>-32 THEN
DISP "Load reflected G.E. -32 dB, Program Stopped"
Flgstp=1
END IF
IF Flgstp=1 THEN STOP
DISP "CONNECT SHORT (PORT 2) THEN HIT continue."
PAUSE
CALL Collect(Shortm(*), Shortp(*), Fstart, Fstop, Fstep, Fq(*))
DISP "CONNECT OPEN (PORT 2) THEN HIT continue."
PAUSE
CALL Collect(Openm(*), Openp(*), Fstart, Fstop, Fstep, Fq(*))
OUTPUT Processor:C114C214E
DISP "CONNECT THROUGH THEN HIT continue."
PAUSE
CALL Collect(Tmm(*), Tmp(*), Fstart, Fstop, Fstep, Fq(*))
PRINT USING "20/
DISP "Calculating intermediate calibration results"
FOR I=1 TO Numb
CALL Db_mag(Dirm(I), Dirmt) ! CONVERT dB READINGS TO MAGNITUDE
CALL Db_mag(Shortm(I), Shortmt)
CALL Db_mag(Openm(I), Openmt)
CALL Db_mag(Tmm(I), Tmmt)
CALL P_r(DIRM(I), Dirp(I), Dirr(I), Diri(I)) ! CONVERT POLAR MAGNITUDE AND PHASE
CALL P_r(Shortm(I), Shortp(I), Shortr, Shorti) ! TO RECTANGULAR
CALL P_r(Openm(I), Openp(I), Openr, Openi)
CALL P_r(Tmm(I), Tmp(I), Tmr(I), Tmi(I))
Esfrnum=Openr+Shortr-2*Dirr(I) ! CALCULATE THE ERROR TERMS
Esfimun=Openi+Shorti-2*Diri(I) ! AND THE CORRECTED VALUES
Esfrden=Openr+Shortr ! rnum= REAL PART OF NUMERATOR
Esfiden=Openi+Shorti ! iiden= IMAGINARY PART OF DENOMINATOR, ETC.
CALL Cddiv(Esfrnum, Esfinum, Esfren, Esfden, Esfri(I), Esfi(I))
Erfmr=Dirr(I)-Shortr
Erfmi=Diri(I)-Shorti
Erfnum=2*Openr-2*Dirr(I)
Erfmen=2*Openi-2*Diri(I)
Erfden=Openr+Shortr
Erfden=Openi+Shorti
CALL Cddiv(Erfrnum, Erfinum, Erfden, Erfden, Em, Ei)
CALL Cmul(Em, Ei, Erfmr, Erfmi, Erfri(I), Erfi(I))
NEXT I ! END OF ERROR TERM GATHERING AND COMPUTATION

!*****DEVICE TRANSMISSION AND REFLECTION MEASUREMENT*****
Fques: INPUT "FREQUENCY OF DEVICE MEASUREMENT(MHZ)" , Fmeas
INPUT "What is the title if this is to be plotted(<50)" , D$
Fmeas=Fmeas*1.E+6
Num=INT((Fstop-Fstart)/Fstep)+1
Fmeasi=-1
FOR I=1 TO Num
IF Fq(I)=Fmeas THEN Fmeasi=I
NEXT I
IF Fmeasi=-1 THEN
DISP "Frequency out of range (or not integral multiple)"
WAIT 1.5
GOTO Fques
DISP ""
END IF
CALL Measdut(Fmeas, Tdudt(*), Tdup(*), Rdudt(*), Rdutp(*), Volt(*))
K=Fmeasi
DISP "Performing error correction on measured data."
! i
! !**ERROR CORRECTION OF DEVICE MEASUREMENT**************
FOR I=1 TO 61
CALL Db_mag(Rdudt(I), Rdutm)
CALL P_r(Rdutm,Rdtp(I),Rdtr,Rduti)
Sarnum=Rdutr-Dirt(K)
Sainum=Rduti-Diri(K)
CALL Cmult(Sarnum,Sainum,Esfr(K),Esfi(K),Ctemr,Ctemi)
Sarden=Ctemr+Erfr(K)
Saiden=Ctemi+Erfi(K)
CALL Cdiv(Sarnum,Sainum,Sarden,Saiden,Sar,Sai)
CALL R_p(Sar,Sai,Sam,Sap)
CALL Mag_db(Sam,Sadb)
S1ig(I)=Sadb
S1ip(I)=Sap
CALL Cmult(Esfr(K),Esfi(K),Sar,Sai,Ctmpn,Ctmpi)
Ctmpn=1-Ctmpn
CALL Db_mag(Tdutd(I),Tdutm)
CALL P_r(Tdutm,Tdutp(I),Tdutr,Tduti)
CALL Cmult(Tdutr,Tduti,Ctmpn,Ctmpi,Tnumr,Tnuml)
CALL Cdiv(Tnumr,Tnuml,Tmr(K),Tmi(K),Trnsr,Trnsi)
CALL R_p(Trnsr,Trnsi,Trnsdb)
CALL Mag_db(Trnsr,Trnsdb)
S21g(I)=Trnsdb
S21p(I)=Trnsp
NEXT I
!

! ******************PLOTTING OF MEASUREMENT***************
!
X$="Varactor Bias (Volts)"
INPUT "Would you like to make a plot(Y/N)?",Ans$
IF Ans$="N" OR Ans$="N" THEN GOTO Save
Reques: INPUT "SCREENPLOT(1) or PAPERPLOT(2)",Flag
IF Flag=1 THEN GOTO Pass
IF Flag=2 THEN GOTO Pass
GOTO Reques
Pass: INPUT "Transmission(1) or Reflection(2) plot",Flag3
IF Flag3=1 THEN GOTO Transmit
INPUT "Mag(1) or Phase(2) plot",Flag4
IF Flag4=1 THEN GOTO Magplot1
Y$="Reflected Phase (Degrees)"
CALL Plotit(Volt(*),S1ig(*),61,X$,Y$,D$,Flag)
GOTO Ques
Magplot1: Y$="Reflected Return (dB)"
CALL Plotit(Volt(*),S1ig(*),61,X$,Y$,D$,Flag)
GOTO Ques
Transmit: INPUT "Mag(1) or Phase(2) plot",Flag4
IF Flag4=1 THEN GOTO Magplot2
Y$="Transmission Phase (Degrees)"
CALL Plotit(Volt(*),S21g(*),61,X$,Y$,D$,Flag)
GOTO Ques
Magplot2: Y$="Transmission Loss"
CALL Plotit(Volt(*),S21g(*),61,X$,Y$,D$,Flag)
Ques: INPUT "Would you like to plot something else?(Y/N)?",Ans$
IF Ans$="Y" OR Ans$="y" THEN GOTO Reques
!

! ******************SAVING AND PRINTING OF DATA*************
!
Save!: Storage of data has yet to be done
INPUT "Do you want a hard copy of the data(Y/N)?",Ans$
IF Ans$="N" OR Ans$="N" THEN GOTO Save2
DISP "Make sure printer is on to get hard copy"
FOR I=1 TO 61
PRINT USING "&X,DDDD.DDD";Volt(I),S21g(I),S21p(I),S11g(I),S11p(I)
NEXT I

Sav2: INPUT "Do you want to save data to disk (Y/N)?", Ans$
IF Ans$="N" OR Ans$="n" THEN GOTO Terminate
Total=61
Col=5
INPUT "What is the name of the DATA FILE", FileName$
CREATE BDAT FileName$,5*Total+10,8
DISP "Saving data to disk"
ASSIGN @Path1 TO FileName$
OUTPUT @Path1,1;Total
OUTPUT @Path1,2;Col
W=1
FOR I=3 TO Col*Total+3 STEP Col
OUTPUT @Path1,1;Volt(W)
OUTPUT @Path1,1+1;S21g(W)
OUTPUT @Path1,1+2;S21p(W)
OUTPUT @Path1,1+3;S11g(W)
OUTPUT @Path1,1+4;S11p(W)
W=W+1
NEXT I
ASSIGN @Path1 TO *
Terminate:
INPUT "would you like to make another measurement (Y/N)?", Ans$
IF Ans$="Y" OR Ans$="y" THEN GOTO Fques
DISP "done"
WAIT .5
DISP " "
END

!********************************************************************
SUBROUTINES ********************************************************************

!********************************************************************
POLAR TO RECTANGULAR CONVERSION

!********************************************************************
SUB P_r(Pv1,Pv2,Pv3,Pv4)

DEG
PV3=Pv1*COS(Pv2)
PV4=Pv1*SIN(Pv2)
SUBEND

!********************************************************************
RECTANGULAR TO POLAR CONVERSION

!********************************************************************
SUB R_p(Pv1,Pv2,Pv3,Pv4)

DEG
PV3=SQRT(Pv1^2+Pv2^2)
PV4=90*(SIGN(Pv2)+(Pv2=0))
2990 IF Pv1=0 THEN 3010
3000 $v4=ATN((PV2/(PV1+1,E-49)))+PV4*(1-6GN(PV1))
3010 SUBEND
3020 !
3030 !   **********************************************************************
3040 !   COMPLEX MULTIPLICATION
3050 !   **********************************************************************
3060 !
3070 SUB Cmult(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
3080 Cmult:
3090 $v5=Pv1*Pv3-Pv2*Pv4
3100 $v6=Pv1*Pv4+Pv2*Pv3
3110 SUBEND
3120
3130 !   **********************************************************************
3140 !   COMPLEX DIVISION
3150 !   **********************************************************************
3160 !
3170 SUB Cdiv(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
3180 Cdiv:
3190 $v7=Pv3*Pv3+Pv4*Pv4
3200 $v5=(pv1*pv3+p v2*pv4)/(Pv7+1,E-49)
3210 $v6=(pv2*pv3-pv1*pv4)/(Pv7+1,E-49)
3220 SUBEND
3230
3240 !   **********************************************************************
3250 !   PLOTTING SUBROUTINE
3260 !   **********************************************************************
3270 SUB Plotit(Valx(*),Valy(*),Numbf,Xtitle,Ytitle,Dev#,Flag)
3280 C#=CHR$(255)&"K"
3290 Vxmin=1,E+49
3300 Vymin=1,E+49
3310 Vymax=-1,E+49
3320 Vxmax=-1,E+49
3330 FOR J=1 TO Numbf
3340 IF Valx(J)<Vxmin THEN Vxmin=Valx(J)
3350 IF Valx(J)>Vxmax THEN Vxmax=Valx(J)
3360 IF Valy(J)<Vymin THEN Vymin=Valy(J)
3370 IF Valy(J)>Vymax THEN Vymax=Valy(J)
3380 NEXT J
3390 X1=Vxmin
3400 X2=Vxmax
3410 Y1=Vymin
3420 V2=Vymax
3430 OUTPUT KBD;"I;"
3440 Startx=X1
3450 Stopx=X2
3460 Starty=Y1-(Y2-Y1)/10
3470 Stopy=Y2+(Y2-Y1)/10
3480 Step=(Startx-Starty)/10
3490 Stepy=(Stopy-Starty)/8
3500 ON KBD GOTO Exit ! Provide exit
3510 OUTPUT 2 USING ";,K;",C$ ! Clear screen for graph
3520 GINIT ! Initialize various graphics parameters.
3530 IF Flag=1 THEN PLOTTER IS 3,"INTERNAL" ! Use the internal screen
3540 IF Flag=2 THEN PLOTTER IS 705,"HPGL"
3550 GRAPHICS ON ! Turn on the graphics screen
3560 LORG 6 ! Reference point: center of top of label
3570 X_gdu_max=100*MAX(1,RATIO) ! Determine how many GDUs wide the screen is
3580 Y_gdu_max=100*MAX(1,1/RATIO) ! Determine how many GDUs high the screen is
3590 FOR I=-.3 TO .3 STEP .1  OFFSET of X from starting point
3600 MOVE X_gdu_max/2+I,Y_gdu_max! Move to about middle of top of screen
3610 LABEL USING "#,K";Dev$  WRITE title of plot
3620 NEXT I  NEXT position for title
3630 DEG  Angular mode in degrees (used in LDIR)
3640 LDIR 90  Specify vertical labels
3650 CSIZE 3.5  Specify smaller characters
3660 MOVE 0,Y_gdu_max/2  Move to center of left edge of screen
3670 LABEL USING "#,K";Ytitl$  Write Y-axis label
3680 LONG 4  Reference point: center of bottom of label
3690 LDIR 0  Horizontal labels again
3700 MOVE X_gdu_max/2,.07*Y_gdu_max! X: center of screen; Y: above key labels
3710 LABEL USING "#,K";Xtitl$  Write X-axis label
3720 VIEWPORT .1*X_gdu_max,.98*X_gdu_max,.15*Y_gdu_max,.9*Y_gdu_max  Define subset of screen area
3730 WINDOW 0,100,16,18  Anisotropic scaling: left/right/bottom/top
3740 AXES 1,.05,0,16,5,5,5,3  Draw axes intersecting at lower left
3750 AXES 1,.05,100,18,5,5,3  Draw axes intersecting at upper right
3760 IF Flag=2 THEN 3780
3770 LINE TYPE 3
3780 GRID 10,.25,0,16,1,1  Draw grid with no minor ticks
3790 LINE TYPE 1
3800 CLIP OFF  So labels can be outside VIEWPORT limits
3810 CSIZE 2.6,.6  Smaller chars for axis labelling
3820 LONG 6  Ref. pt: Top center  
3830 FOR I=0 TO 100 STEP 10  Every 10 units  
3840 MOVE I,.15,.99  A smidgeon below X-axis  
3850 Fqw=Stepx/10*I+Startx  Label X-axis
3860 IF ABS(Fqw)>1000 THEN LABEL USING "#,5D.D";Fqw  Compact; no CR/LF
3870 IF ABS(Fqw)>100 AND ABS(Fqw)<1000 THEN LABEL USING "#,4D.D";Fqw  Compact; no CR/LF
3880 IF ABS(Fqw)>10 AND ABS(Fqw)<100 THEN LABEL USING "#,3D.2D";Fqw  Compact; no CR/LF
3890 IF ABS(Fqw)>1 AND ABS(Fqw)<10 THEN LABEL USING "#,2D.3D";Fqw
3900 IF ABS(Fqw)<1 THEN LABEL USING "#,D.3D";Fqw
3910 NEXT I  et sequens  
3920 LONG 8  Ref. pt: Right center  
3930 FOR I=16 TO 10 STEP .25  Every quarter  
3940 Valu=Stepy/25*(I-16)+Starty  Label Y-axis
3950 MOVE -,5,I  Smidgeon left of Y-axis  
3960 IF ABS(Valu)>10 THEN LABEL USING "#,4D.D";Valu  DD.D; no CR/LF
3970 IF ABS(Valu)<10 AND ABS(Valu)>1 THEN LABEL USING "#,2D.2D";Valu
3980 IF ABS(Valu)<1 THEN LABEL USING "#,D.3D";Valu
3990 NEXT I  et sequens  
4000 PENUP  LABEL statement leaves the pen down
4010 PEN 2
4020 LINE TYPE 1
4030 FOR I=1 TO Numbf  Points to be plotted...
4040 Fry=16+.25/Stepy*(Valy(I)-Starty)
4050 Frx=10/Stepx*(Valx(I)-Startx)
4060 PLOT Fry,Frx  Get a data point and plot it against X
4070 NEXT I  et cetera
4080 PEN 0
4090 LINE TYPE 1
4100 PAUSE
4120 OUTPUT KBD;"!;"  !
4130 Exit: GRAPHICS OFF
OUTPUT 2 USING "#,K";C$

GINIT
GCLEAR

; finis

DECIBEL TO MAGNITUDE CONVERSION

SUB Db_mag(Valdb,Valmg)
Valmg=10^(Valdb/20)
SUBEND

MAGNITUDE TO DECIBEL CONVERSION

SUB Mag_db(Valmg,Valdb)
Valdb=20*LGT(Valmg)
SUBEND

DATA GATHERING ROUTINE FOR STANDARDS

SUB Collect(Mag(*),Phase(*),Fstart,Fstop,Fstep,Fq(*))
Processor=716
IMAGE "FA","K","E"

Source=719  ! ******* 719.4 CHANGED TO 719
Num=INT((Fstop-Fstart)/Fstep)+1

Freq=Fstart+Fstep

OUTPUT Source USING 4420;Freq  ! RATHER THAN WAITING AN UNUSUAL

AMOUNT OF TIME (SEE LINE 2552) FOR THE FIRST DATA POINT

THE FREQUENCY SOURCE MAY BE STEPPED BEFORE ANY DATA IS TAKEN

WAIT .3
ENTER Processor;Garbage1,Garbage2
WAIT .3
FOR I=1 TO Num
Freq=Freq+Fstep
Fq(I)=Freq

OUTPUT Source USING 4420;Freq

; READING ON THE FIRST MEASUREMENT THE FIRST TIME

THIS SUBPROGRAM IS CALLED - WAIT 7 IS SUFFICIENT

SOMETIMES, WAIT 11 WAS USED AND FOUND TO BE OK

ABOUT 50% OF THE TIME - WAIT 15 DIDN'T FAIL IN

ANY OF MY TRIALS.

WAIT .3
IF I<>1 THEN GOTO Grab
WAIT 15

Grab: ENTER Processor;Mag(I),Phase(I)
NEXT I
BEEP
SUBEND

Routine For Measuring Device at
Single Frequency From 0 to 30 Volts

!
SUB Measdat(Freq, Transm(*), Transp(*), Reflm(*), Reflp(*), Volt(*))

DISP "Turn on 8505, DVM, Powersupply then CONT"

PAUSE

Processor=716 ! Processor address
Source=719 ! Source address
Powersupply=722 ! Powersupply address
Voltmeter=708 ! Voltmeter address
Test_set=720 ! Test set address

OUTPUT Powersupply; "VPOS 0; IPOS .3; FSOUT ON"
OUTPUT Voltmeter; "DCV ; MODE TRIG"
OUTPUT Test_set; "2"
OUTPUT Processor; "C1152SSE"
WAIT 2

Key: IMAGE "FA", K, "E"
Offset=.05*Freq
Freq=Freq-Offset
OUTPUT Source USING Key; Freq
WAIT .3
DISP "CONNECT DEVICE THEN CONTINUE(f2)"
PAUSE

OUTPUT Source USING Key; Freq
ENTER Processor; Garbage1, Garbage2

DISP "Measuring test device transmission with swept voltage"
FOR I=1 TO 61
V=(I-1)/2
OUTPUT Powersupply; "VPOS"; V
WAIT .25
OUTPUT Voltmeter; "DT TRIG"
WAIT .25
ENTER Voltmeter; Volt(I)
ENTER Processor; Transm(I), Transp(I)
NEXT I

OUTPUT Processor; "C11552C2ISSE" ! Switch to reflection terms
ENTER Processor; Garbage1, Garbage2
DISP "Measuring test device reflection with swept voltage"
FOR I=1 TO 61
V=(I-1)/2
OUTPUT Powersupply; "VPOS"; V
WAIT .25
OUTPUT Voltmeter; "DT TRIG"
WAIT .25
ENTER Voltmeter; Volt(I)
ENTER Processor; Reflm(I), Reflp(I)
NEXT I

OUTPUT Powersupply; "VPOS 0"
OUTPUT Processor; "C114552C2I4E" ! Switch back to transmission terms
BEEP
SUBEND
2. TERM 3V

! This program is designed to automate the testing of the phase
! shifter. It is a modified version of a 3 term error model,
! TERM3, written to error correct for reflection measurements.
! Since transmission needs to be measured, TERM3 is modified
! to error correct the transmission terms. The transmission
! is corrected using half of a 8 term error model. (Hence it is a
! 4 term error model) The reflections are measured as S22 on the
! test set and the transmissions are measured as S12 on the test
! set.

MODIFICATION: This program measures the phase shifting load.
That is, only the reflection coefficient.

STORED AS TERM3V

Written July 11, 1986 by Ronald D. Boesch

OPTION BASE 1
DIM Dirm(221),Dirp(221),Openm(221),Openp(221),Esfm(221),Esfp(221)
DIM Erfm(221),Erfp(221)
DIM Dutm(221),Dutp(221),Shortm(221),Shortp(221)
DIM Fq(221),Sl1g(100),Sl1p(100),Voll(100)
DIM Rdutd(100),Rdutp(100)
DIM Esfr(221),Esfi(221),Erfi(221),Erfr(221),Dirr(221),Diri(221)
DIM X$[50],Y$[50],D$[50]
ABORT 7
LOCAL 7
REMOTE 7
Source=719.4
Processor=716
Test_set=720
Powersupply=722
Volmeter=708

INPUT "Do you want to manually measure for 180 degree only (Y/N)?", Ans$
IF Ans$="N" OR Ans$="n" THEN GOTO Auto
DISP "Turn on powersupply, HP8505, and then hit CONT (f2)"
PAUSE
DISP "Hand calibrate 8505 then hit CONT (f2)"
PRINTER IS CRT

PRINT "******CALIBRATION SEQUENCE*******"
PRINT "Set start and stop frequencies, set marker at 915 MHz"
PRINT "***Reflection, S22"
PRINT "Connect Reverse Short"
PRINT "Channel 1: MKR,B/R,POLAR MAG,ZRO (hold until display zero)"
PRINT "Electrical Length: B,CLR if REL lighted"
PRINT "LENGTH and VERNIER B for smallest cluster,ZRO."
PRINT "Channel 1: POLAR PHASE,ZRO (hold until display zero),"
PRINT "REF, REF OFFSET so display reads +180 degrees"
PRINT "ZRO, MKR."
PRINT "***Transmission, S12"
PRINT "Connect Through"
PRINT "Channel 1: A/R,POLAR MAG,POLAR FULL 1,"
PRINT "MKR,ZRO (hold until display zero),"
600 PRINT USING "25/
610 OUTPUT Powersupply;"VPOS 0;IPOS .3;FSDUT ON"
620 OUTPUT Voltmeter;"DCV; MODE TRIG"
630 !
640 !
650 !********"Manual" OPERATION FOR TUNING TO 180 DEGREES OF SHIFT************
660 !
670 Manual: OUTPUT Powersupply;"VPOS 0"
680 WAIT .2
690 OUTPUT Voltmeter;"DT TRIG"
700 ENTER Voltmeter;Vlt
710 DISP "Record transmission phase at 0 V then CONT"
720 PAUSE
730 OUTPUT Powersupply;"VPOS 30"
740 WAIT .2
750 OUTPUT Voltmeter;"DT TRIG"
760 ENTER Voltmeter;Vlt
770 DISP "Record transmission phase at 30 V then CONT"
780 PAUSE
790 INPUT "Is the manual measurement done (Y/N)?",Ans$
800 IF Ans$$="n" OR Ans$$="N" THEN GOTO Manual
810 OUTPUT Powersupply;"VPOS 0"
820 WAIT .2
830 OUTPUT Voltmeter;"DT TRIG"
840 ENTER Voltmeter;Vlt
850 !
860 !
870 !********AUTOMATED MEASUREMENT OF DEVICE AFTER TUNING************
880 !
890 Auto: !Automated measurement section
900 OUTPUT Test_set;"2"
910 OUTPUT Source;"06V99IR3M3W4T1FB0E"
920 OUTPUT Processor;"C0B1C1D2C2D2E"
930 IMAGE "FA",K,"E"
940 BEEP
950 INPUT "ENTER START FREQUENCY(in Mhz,G.E. 600 Mhz)",Fstart
960 Fstart=Fstart*1.E+6
970 BEEP
980 INPUT "ENTER STOP FREQUENCY(in Mhz,L.E. 1200 Mhz)",Fstop
990 Fstop=Fstop*1.E+6
1000 BEEP
1010 INPUT "ENTER STEP FREQUENCY(in Mhz)",Fstep
1020 Fstep=Fstep*1.E+6
1030 BEEP
1040 Num=int((Fstop-Fstart)/Fstep)+1
1050 PRINT USING "25/
1060 PRINT " ******* CALIBRATION *******"
1070 PRINT USING "10/
1080 OUTPUT Processor;"C115M2S2C2I5M3S2E"
1090 IMAGE "FA",K,"E"
1100 BEEP
1110 DISP "CONNECT 50 OHM LOAD (PORT 2) THEN HIT CONTINUE."
1120 PAUSE
1130 CALL Collect(Dirm(*),Dirp(*),Fstart,Fstop,Fstep,Fq(*))
1140 IF Dirm(1)>-32 THEN
1150 DISP "Load reflected G.E. -32 dB, Program Stopped"
1160 Flgstep=1
1170 END IF
1180 IF Flgstep=1 THEN STOP
1190 DISP "CONNECT SHORT (PORT 2) THEN HIT continue."
PAUSE
1210 CALL Collect(Shortm(*), Shortp(*), Fstart, Fstop, Fstep, Fq(*))
1220 DISP "CONNECT OPEN (PORT 2) THEN HIT continue."
1230 PAUSE
1240 CALL Collect(Openm(*), Openp(*), Fstart, Fstop, Fstep, Fq(*))
1250 PRINT USING "20/"
1260 DISP "Calculating intermediate calibration results"
1270 FOR I=1 TO Numb
1280 CALL Dm_mag(Dirm(I), Dirr(I), I) ! CONVERT dB READINGS TO MAGNITUDE
1290 CALL Dm_mag(Shortm(I), Shortr(I))
1300 CALL Dm_mag(Openm(I), Openr(I))
1310 CALL P_r(Dirm(I), Dirr(I), I) ! CONVERT POLAR MAGNITUDE AND PHASE
1320 CALL P_r(Shortm(I), Shortr(I), Shortl(I)) ! TO RECTANGULAR
1330 CALL P_r(Openm(I), Openr(I), Openl(I), I)
1340 Esfrnum=Openr+Shortr-2*Dirr(I) ! CALCULATE THE ERROR TERMS
1350 Esfrnum=Openr+Shortr-2*Dirr(I) ! AND THE CORRECTED VALUES
1360 Esfrden=Openr-Shortr
1370 Esfrden=Openr-Shortr ! rnum= REAL PART OF NUMERATOR
1380 CALL Cdiv(Esfrnum, Esfrnum, Esfrden, Esfrden, Esfr(I), Esfr(I))
1390 Erfm=Dirr(I)-Shortr
1400 Erfm=Dirr(I)-Shortr
1410 Erfm=Dirr(I)-Shortr
1420 Erfm=Dirr(I)-Shortr
1430 Erfm=Dirr(I)-Shortr
1440 Erfm=Dirr(I)-Shortr
1450 CALL Cdiv(Erfm, Erfm, Erfm, Erfm, Erfm, Em, Ei)
1460 CALL Cmult(Em, Ei, Erfm, Erfm, Erfm, Erfm(I), Erfm(I))
1470 NEXT I ! END OF ERROR TERM GATHERING AND COMPUTATION
1480 !
1490 !
1500 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
1510 !
1520 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
1530 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
1540 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
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1670 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
1680 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
1690 !**********DEVICE TRANSMISSION AND REFLECTION MEASUREMENT******
Saiden=Ctemi+Erfl(K)
CALL Cdiv(Sarnum,Sainum,Sarden,Saiden,Sar,Sai)
CALL R_p(Sar,Sai,Sam,Sap)
CALL Mag_db(Sam,Sadb)
S11g(I)=Sadb
S11p(I)=Sap
NEXT I
!
!
! *************** PLOTTING OF MEASUREMENT ******************
!
X$="Varactor Bias (Volts)"
INPUT "Would you like to make a plot (Y/N)?",Ans$
IF Ans$="n" OR Ans$="N" THEN GOTO Save
Reques: INPUT "SCREENPLOT(1) or PAPERPLOT(2)",Flag
IF Flag=1 THEN GOTO Pass
IF Flag=2 THEN GOTO Pass
GOTO Reques
Pass: Flag3=2
IF Flag3=1 THEN GOTO Transmit
INPUT "Mag(1) or Phase(2) plot",Flag4
IF Flag4=1 THEN GOTO Magplot1
Y$="Reflected Phase (Degrees)"
CALL Plotit(Volt(*),S11p(*),61,X$,$Y$,D$,Flag)
GOTO Ques
Magplot1: Y$="Reflected Return (dB)"
CALL Plotit(Volt(*),S11g(*),61,X$,$Y$,D$,Flag)
GOTO Ques
Transmit: INPUT "Mag(1) or Phase(2) plot",Flag4
IF Flag4=1 THEN GOTO Magplot2
Y$="Transmission Phase (Degrees)"
CALL Plotit(Volt(*),S21p(*),61,X$,$Y$,D$,Flag)
GOTO Ques
Magplot2: Y$="Transmission Loss"
CALL Plotit(Volt(*),S21g(*),61,X$,$Y$,D$,Flag)
Ques: INPUT "Would you like to plot something else? (Y/N)" ,Ans$
IF Ans$="Y" OR Ans$="y" THEN GOTO Reques
!
!
! ********************** SAVING AND PRINTING OF DATA **************
!
Sav$: "Storage of data has yet to be done"
INPUT "Do you want a hard copy of the data (Y/N)?",Ans$
IF Ans$="n" OR Ans$="N" THEN GOTO Sav2
DISP "Make sure printer is on to get hard copy"
PRINTER IS 701
PRINT D$
PRINT ""
PRINT " "
PRINT "Voltage Reflection"
PRINT " Bias Magnitude Phase "
FOR I=1 TO 61
PRINT USING "6X,DDDD.DDD";Volt(I),S11g(I),S11p(I)
NEXT I
PRINTER IS CRT
Sav2: INPUT "Do you want to save data to disk (Y/N)?",Ans$
IF Ans$="N" OR Ans$="n" THEN GOTO Terminate
Total=61
Col=3
INPUT "What is the name of the DATA FILE",FileName$
2400 CREATE BDAT Fname$,3*Total+10,8
2410 DISP "Saving data to disk"
2420 ASSIGN @Path1 TO Fname$
2430 OUTPUT @Path1,1;Total
2440 OUTPUT @Path1,2;Col
2450 W=1
2460 FOR I=3 TO Col*Total+3 STEP Col
2470 OUTPUT @Path1,I;Volt(W)
2480 OUTPUT @Path1,I+1;S11g(W)
2490 OUTPUT @Path1,I+2;S11p(W)
2500 W=W+1
2510 NEXT I
2520 ASSIGN @Path1 TO *
2530 Terminate: !
2540 INPUT "would you like to make another measurement(Y/N)?",Ans$
2550 IF Ans$="Y" OR Ans$="Y" THEN 8070 Fques
2560 DISP "done"
2570 WAIT -.5
2580 DISP "",""
2590 END
2600 !
2610 !
2620 !******************************************************************** SUBROUTINES ********************************************************************
2630 !
2640 !
2650 !******************************************************************** POLAR TO RECTANGULAR CONVERSION ********************************************************************
2660 !
2670 !******************************************************************** RECTANGULAR TO POLAR CONVERSION ********************************************************************
2680 !
2690 SUB P_r(Pv1,Pv2,Pv3,Pv4)
2700 DEG
2710 Pv3=Pv1*COS(Pv2)
2720 Pv4=Pv1*SIN(Pv2)
2730 SUBEND
2740 !
2750 !******************************************************************** COMPLEX MULTIPLICATION ********************************************************************
2760 !
2770 !
2780 SUB Cmult(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
2790 Cmult: !
2800 Pv5=Pv1*Pv3-Pv2*Pv4
2810 Pv6=Pv1*Pv4+Pv2*Pv3
2820 SUBEND
2830 !
2840 !******************************************************************** COMPLEX DIVISION ********************************************************************
2850 !
2860 !
3000    SUB Cdiv(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
3010    Cdiv:
3020    Pv7=Pv3*Pv3+Pv4*Pv4
3030    .PV5=(Pv1*Pv3+Pv2*Pv4)/(Pv7+1.E-49)
3040    Pv6=(Pv2*Pv3-Pv1*Pv4)/(Pv7+1.E-49)
3050    SUBEND
3060    !
3070    !******************************************************************************
3080    !  PLOTTING SUBROUTINE
3090    !******************************************************************************
3100    SUB Plotit(Valx(*),Valy(*),Numbf,Xtitl$,Ytitl$,Dev$,Flag)
3110    C$=CHR$(255)&"k"
3120    Vxmin=1.E+49
3130    Vymin=1.E+49
3140    Vymax=-1.E+49
3150    Vxmax=-1.E+49
3160    FOR J=1 TO Numbf
3170    IF Valx(J)<Vxmin THEN Vxmin=Valx(J)
3180    IF Valx(J)>Vxmax THEN Vxmax=Valx(J)
3190    IF Valy(J)<Vymin THEN Vymin=Valy(J)
3200    IF Valy(J)>Vymax THEN Vymax=Valy(J)
3210    NEXT J
3220    X1=Vxmin
3230    X2=Vxmax
3240    Y1=Vymin
3250    Y2=Vymax
3260    OUTPUT KBD;"i;"
3270    Startx=X1
3280    Starty=Y1-(Y2-Y1)/10
3290    Stopy=Y2+(Y2-Y1)/10
3300    Stepx=(Startx-Starty)/8
3310    Step= operated on KBD Exit
3320    OUTPUT 2 USING ":,",C$   ! Clear screen for graph
3330    GINIT   ! Initialize various graphics parameters.
3340    IF Flag=1 THEN PLOTTER IS 3,"INTERNAL"   ! Use the internal screen
3350    IF Flag=2 THEN PLOTTER IS 705,"HPGL"
3360    GRAPHICS ON   ! Turn on the graphics screen
3370    LORG 6   ! Reference point: center of top of label
3380    X_gdu_max=100*MAX(1,RATIO)   ! Determine how many GDUs wide the screen is
3390    Y_gdu_max=100*MAX(1,RATIO)   ! Determine how many GDUs high the screen is
3400    FOR I=-.3 TO .3 STEP .1   ! Offset of X from starting point
3410    MOVE X_gdu_max/2+I,Y_gdu_max/2   ! Move to about middle of top of screen
3420    LABEL USING ":,",Dev$   ! Write title of plot
3430    NEXT I   ! Next position for title
3440   (deg)   ! Angular mode is degrees (used in LDIR)
3450    LDIR 90   ! Specify vertical labels
3460    CSIZE 3.5   ! Specify smaller characters
3470    MOVE 0,Y_gdu_max/2   ! Move to center of left edge of screen
3480    LABEL USING ":,",Ytitl$   ! Write Y-axis label
3490    LORG 4   ! Reference point: center of bottom of label
3500    LDIR 0   ! Horizontal labels again
3510    MOVE X_gdu_max/2,.07*Y_gdu_max   ! X: center of screen; Y: above key labels
3520    LABEL USING ":,",Xtitl$   ! Write X-axis label
3530    VIEWPORT .1*X_gdu_max,.98*X_gdu_max,.1*Y_gdu_max,.9*Y_gdu_max   ! Define subset of screen area
3540    WINDOW 0,100,16,18   ! Anisotropic scaling: left/right/bottom/top
3550    AXES 1,.05,0,16,5,5,3   ! Draw axes intersecting at lower left
3560    AXES 1,.05,100,18,5,5,3   ! Draw axes intersecting at upper right
IF Flag=2 THEN 3610
LINE TYPE 3
GRID 10,.25,0,16,1,1  ! Draw grid with no minor ticks
LINE TYPE 1
CLIP OFF  ! So labels can be outside VIEWPORT limits
CSIZE 2.6,.6  ! Smaller chars for axis labelling
LORG 1,15.99  ! Ref. pt: Top center \ / 
FOR I=0 TO 100 STEP 10  ! Every 10 units \ / 
MOVE I,15.99  ! A smidgeon below X-axis \ > Label X-axis
Fqw=Stepx/10*I+Startx
IF ABS(Fqw) > = 100 THEN LABEL USING ",#5D.D";Fqw  ! Compact; no CR/LF 
/ 
IF ABS(Fqw) > = 100 AND ABS(Fqw) < 1000 THEN LABEL USING ",#4D.D";Fqw  ! Compact; no CR/LF 
/ 
IF ABS(Fqw) > 10 AND ABS(Fqw) < 10 THEN LABEL USING ",#3D.2D";Fqw  ! Compact; no CR/LF 
/ 
IF ABS(Fqw) < 1 THEN LABEL USING ",#,3D.3D";Fqw 
NEXT I  ! et sequens 
/ 
LORG 8  ! Ref. pt: Right center \ / 
FOR I=16 TO 18 STEP .25  ! Every quarter \ / 
Valu=Stepy/.25*(I-16)+Starty
MOVE -.5,I  ! Smidgeon left of Y-axis \ > Label Y-axis
IF ABS(Valu) > = 10 THEN LABEL USING ",#4D.4D";Valu  ! DD; no CR/LF 
/ 
IF ABS(Valu) < 10 AND ABS(Valu) > 1 THEN LABEL USING ",#,2D.2D";Valu 
NEXT I  ! et sequens 
/ 
PENUP  ! LABEL statement leaves the pen down
PEN 2
LINE TYPE 1
FOR I=1 TO Numbf  ! Points to be plotted...
Fr=x=16+.25*Stepy*(Valy(I)-Starty)
Fry=x/10*Stepx*(Valx(I)-Startx)
PLT Fry,Frx
GET a data point and plot it against X 
/ et cetera
NEXT I
PEN 0
LINE TYPE 1
PAUSE
OUTPUT KBD:"!;" 
Exit: GRAPHICS OFF
OUTPUT 2 USING ",#K";C$
GINIT
GCLEAR  ! finis
SUBEND
SUBEND
SUB Db_mag(Valdb,Valmg)
Valmg=10^(Valdb/20)
SUBEND
SUBEND
SUBEND
SUB Mag_db(Valmg,Valdb)
Valdb=20+LGT(Valmg)
SUBEND

! ************************************************************
! DATA GATHERING ROUTINE FOR STANDARDS
! ************************************************************

SUB Collect(Mag(*),Phase(*),Fstart,Fstop,Fstep,Fq(*))
Processor=716
IMAGE "FA",K,"E"
Source=719  ! ********* 719.4 CHANGED TO 719
Num=INT((Fstop-Fstart)/Fstep)+1
Freq=Fstart+Fstep
OUTPUT Source USING 4250;Freq  ! RATHER THAN WAITING AN UNUSUAL
! AMOUNT OF TIME (SEE LINE 2552) FOR THE FIRST DATA POINT
! THE FREQUENCY SOURCE MAY BE STEPED BEFORE ANY DATA IS TAKEN
WAIT .3
ENTER Processor;Garbage1,Garbage2
WAIT .3
FOR I=1 TO Num  
Freq=Freq+Fstep
Fq(I)=Freq
OUTPUT Source USING 4250;Freq
! READING ON THE FIRST MEASUREMENT THE FIRST TIME
! THIS SUBPROGRAM IS CALLED - WAIT 7 IS SUFFICIENT
! SOMETIMES, WAIT 11 WAS USED AND FOUND TO BE OK
! ABOUT 50% OF THE TIME - WAIT 15 DIDN'T FAIL IN
! ANY OF MY TRIALS.
WAIT .3
IF I<>1 THEN GOTO Grab
WAIT 15
Grab: ENTER Processor;Mag(I),Phase(I)
NEXT I
BEEP
SUBEND

! ************************************************************
! Routine For Measuring Device at
! Single Frequency From 0 to 30 Volts
! ************************************************************

SUB Measure(Freq,Reflm(*),Reflp(*),Volt(*))
DISP "Turn on 9505,DVM,Powersupply then CONT"
PAUSE
Processor=716  !Processor address
Source=719  !Source address
Powersupply=722  !Powersupply address
Voltmeter=708  !Voltmeter address
Test_set=720  !Test set address
OUTPUT Powersupply;"VPOS O;IPOS .3;FSOUT ON"
OUTPUT Voltmeter;"DCV ;MODE TRIG"
OUTPUT Test_set;"2"
WAIT 2
Key: IMAGE "FA",K,"E"
Offset=.03*Freq
Freq=Freq-Offset
OUTPUT Source USING Key;Freq
WAIT .3
DISP "CONNECT DEVICE THEN CONTINUE(2)"
PAUSE
Freq=Freq+Offset
OUTPUT Source USING Key;Freq
OUTPUT Processor;"C1ISSSC215E" ;Switch to reflection terms
ENTER Processor;Garbage1,Garbage2
DISP "Measuring test device reflection with swept voltage"
FOR I=1 TO 61
   V=(I-1)/2
OUTPUT Powersupply;"VPOS";V
WAIT .25
OUTPUT Voltmeter;"DT TRIG"
WAIT .25
ENTER Voltmeter;Volt(I)
ENTER Processor;Reflm(I),Reflp(I)
NEXT I
OUTPUT Powersupply;"VPOS 0"
BEEP
SUBEND
REFERENCES


