# DEVELOPMENT OF A CONTINUOUS PHASE SHIFTER FOR A MICROWAVE PHASED ARRAY HYPERTHERMIA SYSTEM

BY

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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$^{o}$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 sytemic hyperthermia the temperature must be less than 40.8$^{o}$C. In local hyperthermia, the tumor may be selectively heated to a higher temperature than that used in systemic hyperthermia. The therapeutic local hyperthermia temperature range is 42 - 45$^{o}$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

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

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 $Re^{j\theta}A$ where R is the magnitude and $\theta$ is the phase of the complex reflection coefficient, $\Gamma$, of the load. The input to port 3, $Re^{j\theta}A$, 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]

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

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

$$\begin{vmatrix} A_1 \\ 0 \\ \Gamma_3 A_1/\sqrt{2} \\ j\Gamma_4 A_1/\sqrt{2} \end{vmatrix} \quad . \tag{2.3}$$

Using the input matrix, the output, B, of port 2 is

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

Using the scattered wave, the output power is obtained as

$$P_{out} = \frac{B_2 B_2^*}{2}$$

$$= \frac{[\Gamma_3\Gamma_3^* + \Gamma_4\Gamma_4^* + \Gamma_3\Gamma_4^* + \Gamma_4\Gamma_3^*]A_1^2}{8} \quad . \tag{2.5}$$

Assuming $\Gamma_3 = \Gamma_4 = Re^{j\theta}$ then

$$P_{out} = \frac{R^2 A_1^2}{2} \quad . \tag{2.6}$$

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

$$B_2 = jRA_1\, e^{j\theta} \quad . \tag{2.7}$$

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

$$\begin{vmatrix} 0 \\ A_2 \\ j\Gamma_3 A_2/\sqrt{2} \\ \Gamma_4 A_2/\sqrt{2} \end{vmatrix} \quad . \tag{2.8}$$

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

$$B_1 = \frac{(j\Gamma_3 A_2 + j\Gamma_4 A_2)}{2} \quad . \tag{2.9}$$

As above, assuming identical loads of the form

$$\Gamma_3 = \Gamma_4 = Re^{j\theta} \tag{2.10}$$

the transmitted signal is

$$jRA_2\, e^{j\theta} \tag{2.11}$$

with output power

$$P_{out} = \frac{B_1 B_1{}^*}{2} = \frac{R^2 A_2{}^2}{2} \quad . \tag{2.12}$$

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

$$\Gamma_3 = Re^{j\theta_3}, \; \Gamma_4 = Re^{j\theta_4} \quad . \tag{2.13a,b}$$

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

$$B_2 = \frac{[jRe^{j\theta_3} A_1 + jRe^{j\theta_4} A_1]}{2}$$

$$= j\frac{RA_1}{2} [e^{j\theta_3} + e^{j\theta_4}]$$

$$= j\frac{RA_1}{2} [\cos\theta_3 + j\sin\theta_4 + \cos\theta_4 + j\sin\theta_4]$$

$$= j\frac{RA_1}{2} [2\cos(\frac{\theta_3+\theta_4}{2}) \cos(\frac{\theta_3-\theta_4}{2}) + 2j\sin(\frac{\theta_3+\theta_4}{2}) \cos(\frac{\theta_3-\theta_4}{2})]$$

$$= jRA_1 \cos(\frac{\theta_3 - \theta_4}{2}) \, e^{j(\frac{\theta_3 + \theta_4}{2})} \quad . \tag{2.14}$$

The power in this signal is given by

$$P_{out} = \frac{B_2 B_2{*}}{2} = \frac{R^2 A1^2}{2} \cos^2(\frac{\theta_3 - \theta_4}{2}) \quad . \qquad (2.15)$$

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

$$B_1 = \frac{[Re^{j\theta_3} A_1 + jxj\ Re^{j\theta_4} A_1]}{2}$$

$$= \frac{A_1R}{2} [e^{j\theta_3} - e^{j\theta_4}]$$

$$= \frac{A_1R}{2} [\cos\theta_3 + j\sin\theta_3 - \cos\theta_4 - j\sin\theta_4]$$

$$= \frac{A_1R}{2} [-2 \sin(\frac{\theta_3+\theta_4}{2}) \sin(\frac{\theta_3-\theta_4}{2}) + 2j\sin(\frac{\theta_3-\theta_4}{2}) \cos(\frac{\theta_3+\theta_4}{2})]$$

$$= jA_1R [\sin(\frac{\theta_3-\theta_4}{2}) [j\sin(\frac{\theta_3+\theta_4}{2}) + \cos(\frac{\theta_3+\theta_4}{2})]]$$

$$= jA_1R \sin(\frac{\theta_3-\theta_4}{2}) e^{j(\frac{\theta_3+\theta_4}{2})} . \qquad (2.16)$$

The power in this signal is given by

$$P_{out} = \frac{B_1B_1*}{2} = \frac{A^2R^2}{2} \sin^2(\frac{\theta_3 - \theta_4}{2}) . \qquad (2.17)$$

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

$$C_j(v) = C_{min}\left(\frac{\phi + V_b}{\phi + v}\right)^{\gamma} \quad , \tag{2.18}$$

where $\phi$ is the contact potential, $V_b$ is the reverse breakdown voltage, $C_{min}$ 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

$$G(v) = e/KT\ I_o e^{ev/KT} \quad , \tag{2.19}$$

where v is the reverse bias, $I_o$ is the reverse leakage current, and KT/e is the contact potential. The other quantities in the model, $C_p$ and $L_p$, 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

$$Q_s = \frac{G(v)}{\omega C(v)} \quad . \tag{2.20}$$

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

$$\Gamma = \frac{1/j\omega C(v) - Z_o}{1/j\omega C(v) + Z_o}$$

$$= \frac{(1 - jZ_o\omega C(v))^2}{1 + (Z_o\omega C(v))^2} \quad . \qquad (2.21)$$

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

$$\text{ang}(\Gamma) = 2\tan^{-1}(-Z_o\omega C(v)) \quad . \qquad (2.22)$$

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 combination of reactive elements. The voltage reflection coefficient is

$$\Gamma = \frac{j\omega L + 1/j\omega C(v) - Zo}{j\omega L + 1/j\omega C(v) + Z_o}$$

$$= \frac{-(-Z_o + j(\omega L - 1/\omega C(v)))^2}{(\omega L - 1/\omega C(v))^2 + Z_o^2} \quad . \qquad (2.23)$$

The angle of the reflection coefficient is then

$$\text{ang}(\Gamma) = 2\tan^{-1}\left(\frac{\omega L - 1/\omega C(v)}{-Z_o}\right) -180 \quad . \qquad (2.24)$$

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

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

$$= \frac{j\omega L}{1 - \omega^2 LC(v)} \quad . \qquad (2.25)$$

Using this impedance, the reflection coefficient is

$$\Gamma = \frac{j(\omega L/(1 - \omega^2 LC)) - Z_o}{j(\omega L/(1 - \omega^2 LC)) + Z_o} \quad . \tag{2.26}$$

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

$$\mathrm{ang}(\Gamma) = 2\tan^{-1}\left(\frac{\omega L}{Z_o(\omega^2 LC - 1)}\right) - 180 \quad . \tag{2.27}$$

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

$$\Gamma = \frac{j\omega L + 1/j\omega C(v) + R - Z_o}{j\omega L + 1/j\omega C(v) + R + Z_o} \quad . \tag{2.28}$$

Certainly, the magnitude of the reflection coefficient is not one. At series resonance the magnitude is

$$|\Gamma| = \frac{|R - Z_o|}{|R + Z_o|} \tag{2.29}$$

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, $Z_o$, 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

$$Z_L = \frac{jR\omega L/(1 - \omega^2 LC)}{j\omega L/(1 - \omega^2 LC) + R} \quad . \tag{2.30}$$

At parallel resonance, only R is apparent and the reflection coefficient is

$$\Gamma = \frac{R - Z_o}{R + Z_o} \quad . \tag{2.31}$$

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 Γ is changed.

The magnitude of Γ 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, $\epsilon_{ff}$, 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, $Z_o$. 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

$$\frac{w}{h} = \left(\frac{e^{H'}}{8} - \frac{1}{4e^{H'}}\right)^{-1} \qquad \text{if } Z_o > \{44 - 2\epsilon_r \text{ ohms}\} \qquad (3.1)$$

and

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2}\left\{1 - \frac{1}{2H'}\left(\frac{\epsilon_r-1}{\epsilon_r+1}\right)\left(\ln\frac{\pi}{2}+\frac{1}{\epsilon_r}\ln\frac{4}{\pi}\right)\right\}^{-2} \qquad \text{if } \frac{w}{h} < 1.3 \qquad (3.2)$$

where, for both expressions,

$$H' = \frac{Z_o \sqrt{2(\epsilon_r+1)}}{119.9} + \frac{1}{2} \left(\frac{\epsilon_r-1}{\epsilon_r+1}\right) \left(\ln \frac{\pi}{2} + \frac{1}{\epsilon_r} \ln \frac{4}{\pi}\right) \quad . \qquad (3.3)$$

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 then 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. (Manufacturerers' 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

$$Z = jZ_o \tan(\frac{2\pi}{\lambda}\frac{\lambda}{4}) = jZ_o \tan \pi/2 = jZ_o\infty = \text{open circuit} \quad .(3.4)$$

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

$$j\omega L = jZ_o \tan Bl_{BC} \quad . \qquad (3.5)$$

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 MDLSHFTR (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 general 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; Hopfer, 1979; Modelski, 1979; Ulrikkson, 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 ± 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.

# TABLES

# TABLE 1

## Continuous Phase Shifter Design Criteria

| | |
|---|---|
| Input Power | 250 mW |
| Frequency | 915 MHz |
| Bandwidth | ± 10 MHz |
| Phase Variation | 180 degrees |
| Amplitude Variation | Minimize |

# TABLE 2

## Scattering Parameters of Hybrid Coupler with Line Stretchers as Variable Loads*

| Measurement | Line Stretcher Length on 0 Degree Port (cm) | Line Stretcher Length on 90 Degree Port (cm) | $S_{11}$ Magnitude (dB) Phase (degrees) | $S_{21}$ Magnitude (dB) Phase (degrees) | $S_{12}$ Magnitude (dB) Phase (degrees) | $S_{22}$ Magnitude (dB) Phase (degrees) |
|---|---|---|---|---|---|---|
| 1 | 7.32 | 7.32 | - 11.7 ± 0.1 | - 0.90 ± 0.05 | - 0.90 ± 0.05 | - 11.6 ± 0.1 |
| | | | - 164 ± 0.5 | + 164 ± 0.5 | + 164 ± 0.5 | - 110 ± 0.5 |
| 2 | 8.64 | 8.64 | - 11.3 ± 0.1 | - 1.10 ± 0.05 | - 1.20 ± 0.05 | - 11.2 ± 0.1 |
| | | | - 179 ± 0.5 | 145 ± 0.5 | 145 ± 0.5 | - 134 ± 0.5 |
| 3 | 8.64 | 7.32 | - 13.3 ± 0.1 | - 1.10 ± 0.05 | - 1.10 ± 0.05 | - 17.2 ± 0.1 |
| | | | - 136 ± 0.5 | 154 ± 0.5 | 154 ± 0.5 | - 162 ** |
| 4 | 7.32 | 8.64 | - 8.3 ± 0.1 | - 1.40 ± 0.05 | - 1.40 ± 0.05 | - 8.1 ± 0.1 |
| | | | 171 ± 0.5 | 154 ± 0.5 | 153 ± 0.5 | - 103 ± 0.5 |

---

* 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

| Varactor in Load (pF) | Measured Phase Variation (Degrees) | Measured Loss Variation (dB) | Model Phase Variation (Degrees) | Model Loss Variation (dB) |
|---|---|---|---|---|
| 10 | 182* | 2.4 | 180.4 | 2.36 |
| 5.6 | 180.6 | 0.81 | 180.3 | 0.78 |
| 3.9 | 177.9 | 0.72 | 180.3 | 0.68 |
| 3.3 | 173.5 | 1.02 | 171.4 | 1.11 |

* 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

| Frequency (MHz) | Phase Variation (Degrees) | Loss Variation (dB) |
|---|---|---|
| 865 | 187.0 | 1.01 |
| 875 | 187.0 | 0.89 |
| 885 | 186.0 | 0.77 |
| 895 | 185.0 | 0.69 |
| 905 | 184.0 | 0.60 |
| 915 | 181.0 | 0.51 |
| 925 | 178.0 | 0.46 |
| 935 | 174.0 | 0.41 |
| 945 | 171.9 | 0.34 |
| 955 | 167.9 | 0.29 |
| 965 | 163.0 | 0.25 |

## TABLE 5

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

| Actual Power* (mW) | Phase Variation (Degrees) | Transmission Power Variation (dB) |
|---|---|---|
| 24 | 217 | 1.35 |
| 51 | 224 | 1.78 |
| 110 | 231 | 2.88 |
| 530 | 239 | 5.23 |
| 1050 | 241 | 5.83 |
| After retuning to minimize power variation | | |
| 530 | 190 | 3.44 |
| 270 | 187 | 2.69 |

---

* 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

| Phase Variation (Degrees) | Loss Variation (dB) | Varactor Capacitance (4 volt, pF) |
|---|---|---|
| 180 | 0.68 | 3.9 |
| 200 | 1.00 | 4.4 |
| 230 | 1.64 | 6.4 |
| 270 | 2.97 | 10.0 |
| 315 | 6.81 | 22.0 |

---

* 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 7

Cavity Resonance Measurements for Determination of Substrate Dielectric Constant

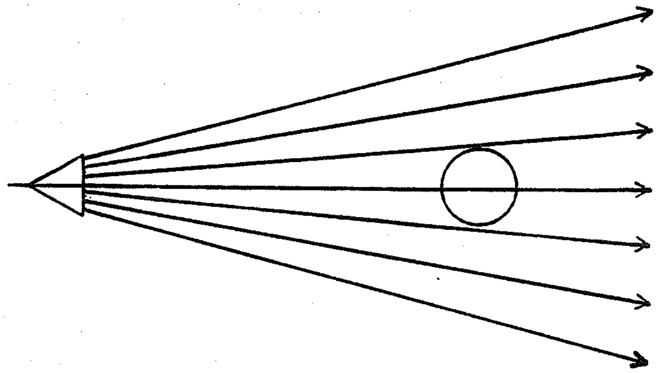
| Substrate | Frequency Measured (MHz) | Cavity Mode | Relative Dielectric Constant | |
|---|---|---|---|---|
| | | | (Calculated) | (Manufacturer specification) |
| Kepro FR-4 | 495 | 1,1 | 4.33 | |
| | 696 | 2,1 | 4.35 | |
| | 857 | 1,2 | 4.35 | |
| | 937 | 3,1 | 4.39 | |
| | 988 | 2,2 | 4.35 | |
| | | | 4.354 ± 0.0196 | 4.8@ 1 MHz |
| 3MCC250GX | 421 | 1,1 | 2.53 | |
| | 605 | 2,1 | 2.52 | |
| | 724 | 1,2 | 2.51 | |
| | 825 | 3,1 | 2.52 | |
| | 851 | 2,2 | 2.52 | |
| | 1019 | 3,2 | 2.49 | |
| | 1048 | 1,3 | 2.52 | |
| | 1061 | 4,1 | 2.51 | |
| | | | 2.51 ± 0.058* | 2.45 ± 0.04@ 10 GHz |

---

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

# FIGURES

A. Single Element



B. Array of Elements

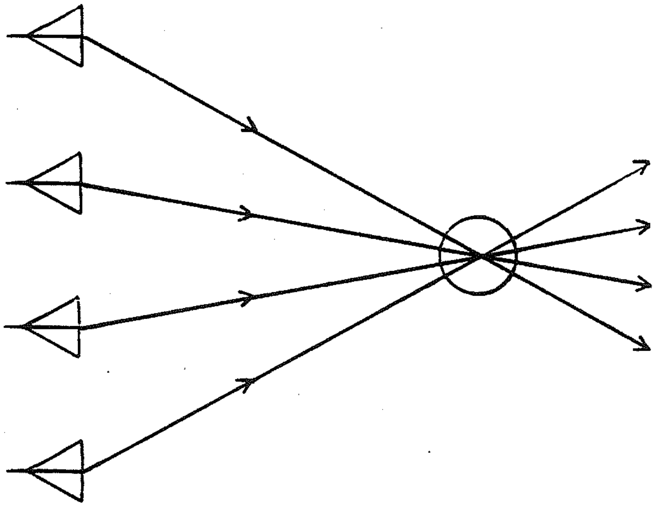


Figure 1. Field concentration for single element and focused array of elements.

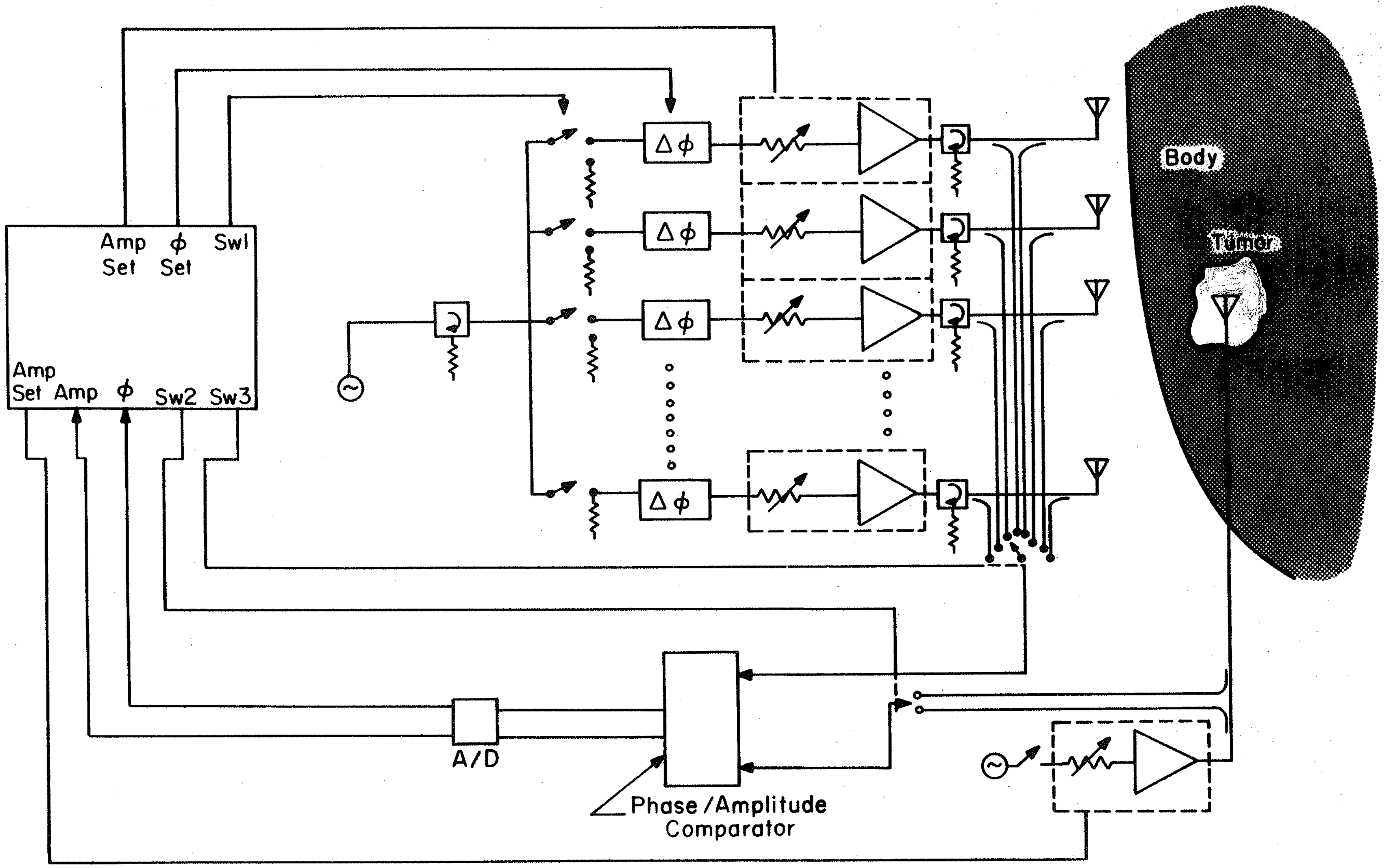
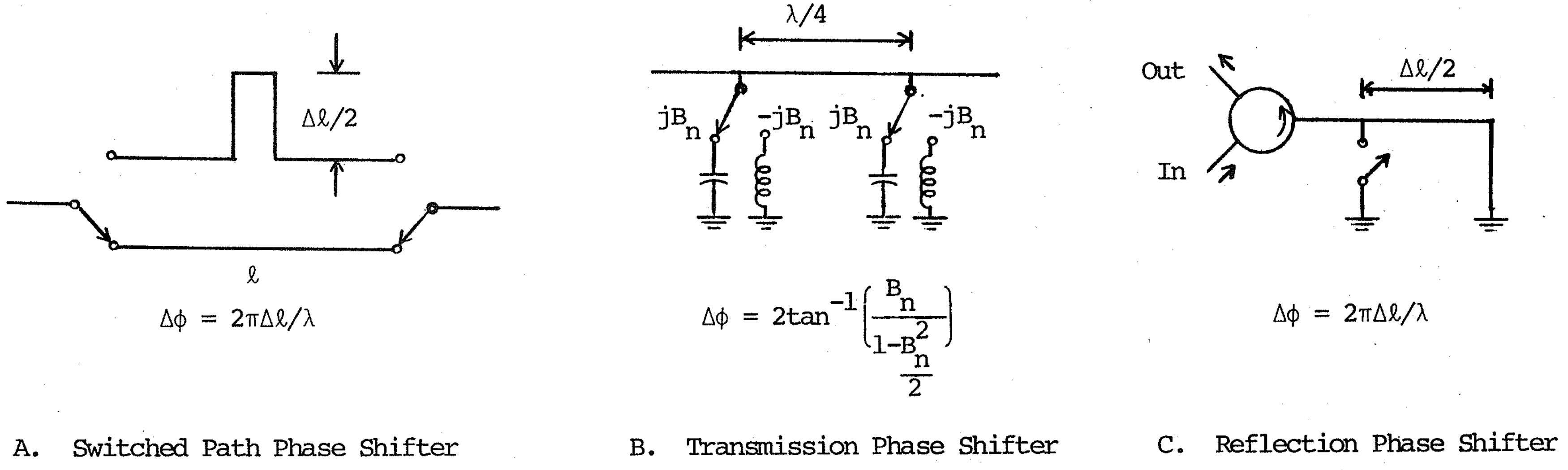


Figure 2. Block diagram of 915 MHz phased array hyperthermia system.



$\Delta\phi = 2\pi\Delta\ell/\lambda$

A. Switched Path Phase Shifter

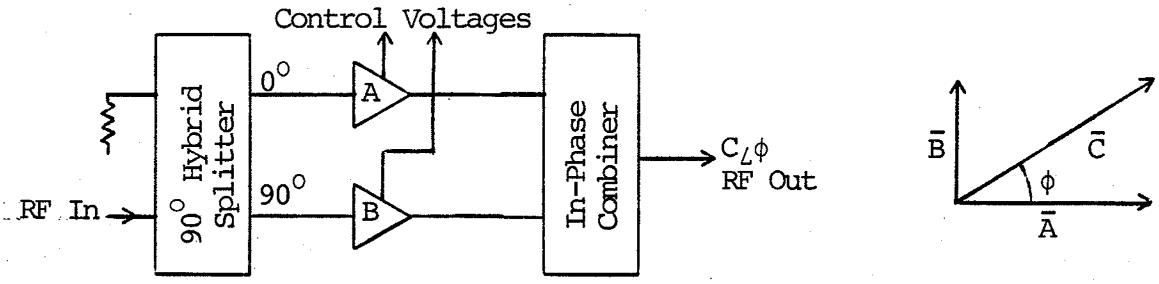
$\Delta\phi = 2\tan^{-1}\left(\frac{B_n}{1-\frac{B_n^2}{2}}\right)$

B. Transmission Phase Shifter

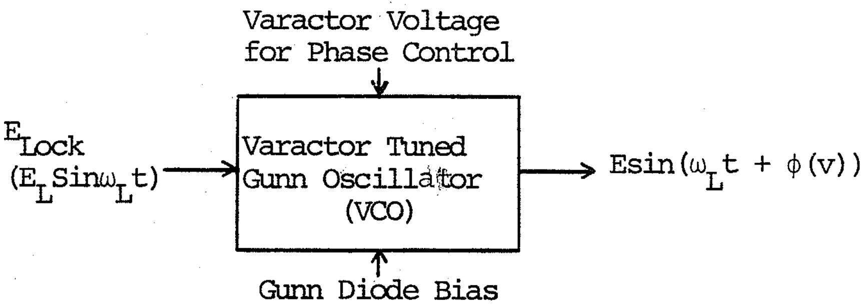
$\Delta\phi = 2\pi\Delta\ell/\lambda$

C. Reflection Phase Shifter

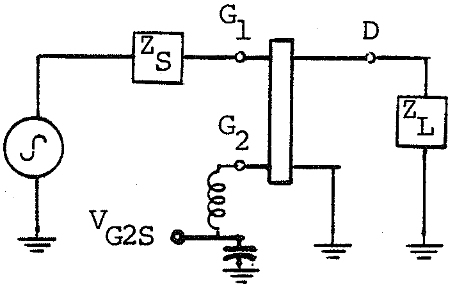
Figure 3. Three common digital phase shifter designs [Garver, 1976].



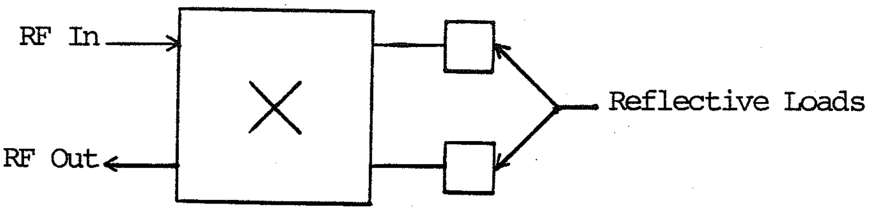
A. Vector Phase Shifter [Kumar, 1981]



B. Frequency Lock Phase Shifter [Cohen, 1984]

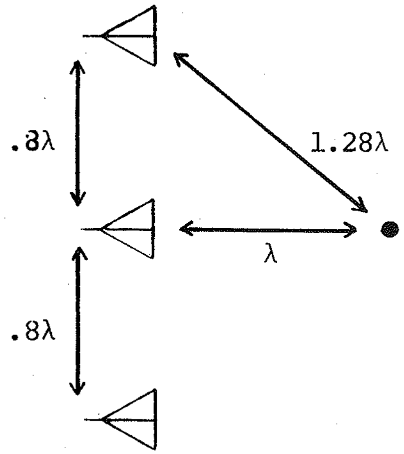


C. Dual Gate FET Phase Shifter [Tsironis, 1981]



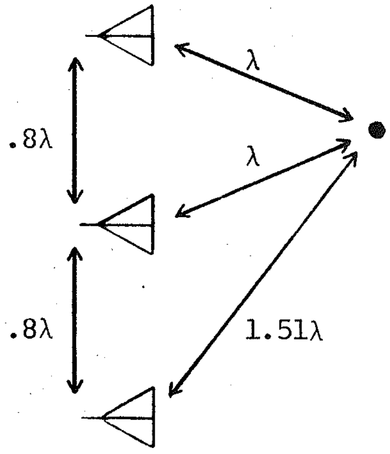
D. Hybrid Coupler Phase Shifter

Figure 4. Four different types of analog phase shifter designs.



Maximum path length difference:
.28λ or ∿ 100 degrees

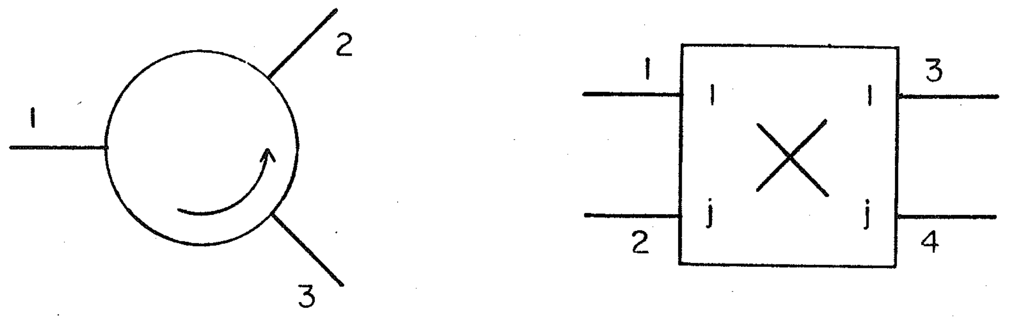
CENTERED HEATING



Maximum path length difference:
.51λ or ∿ 180 degrees

OFF CENTER HEATING

Figure 5. Geometry of applicator and heated region used to determine necessary phase shift.



A. Circulator

B. 3 dB Quadrature Hybrid Coupler

Figure 6. Central elements of reflective type analog phase shifter.

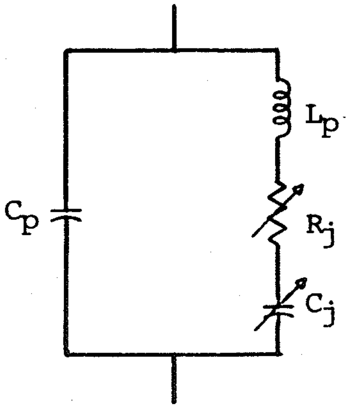
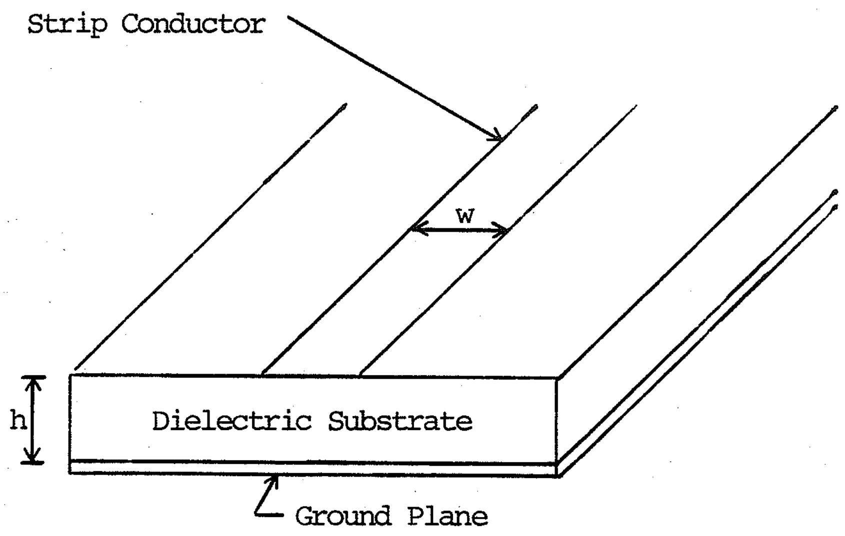
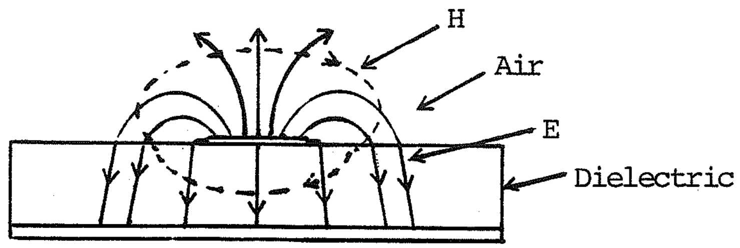


Figure 7. Circuit model of packaged varactor diode.



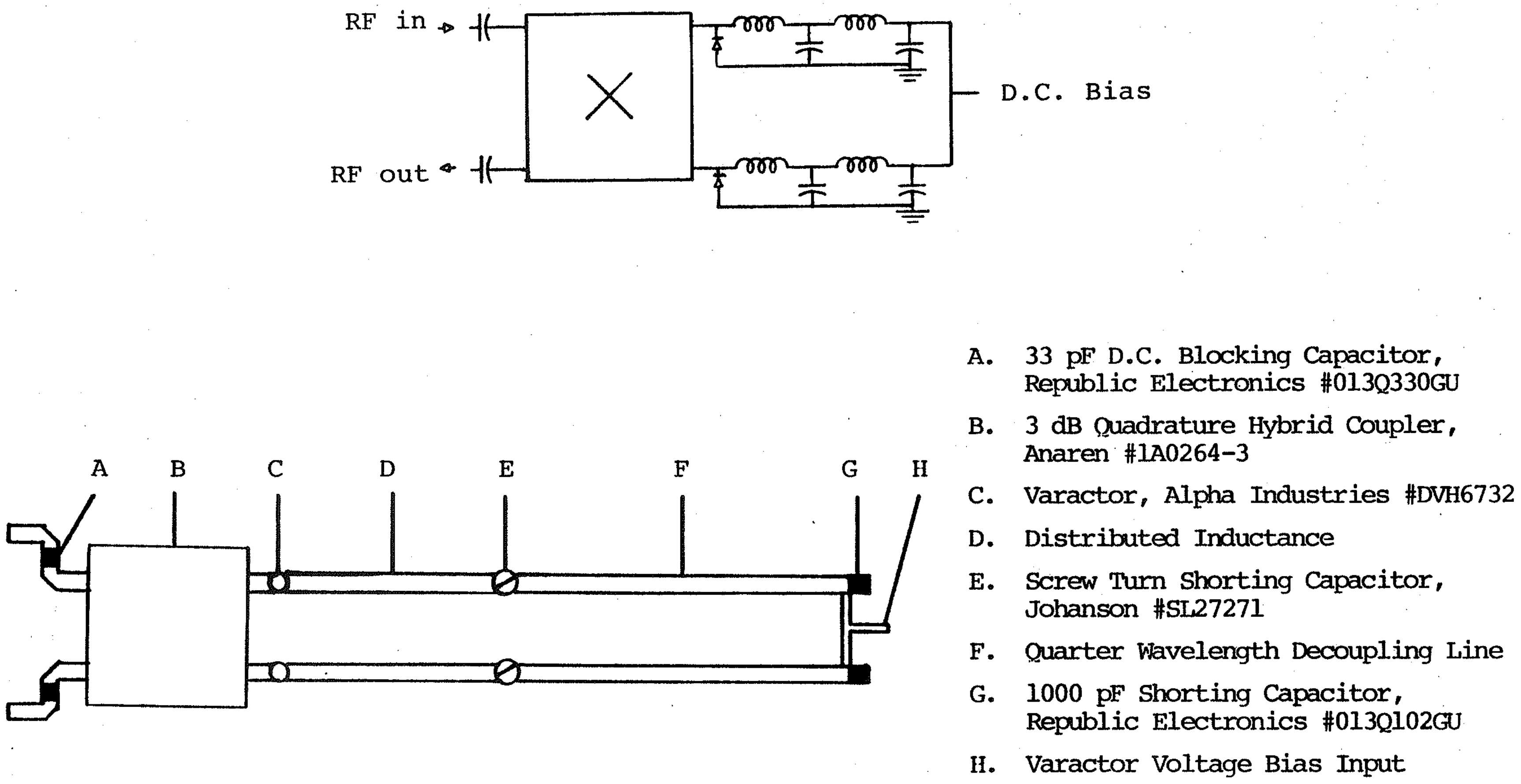
h - Substrate Thickness
w - Strip Conductor Width

A. Microstrip Transmission Line



B. Electric and Magnetic Field Lines Near Microstrip

Figure 8. General geometry of microstrip line.



A. 33 pF D.C. Blocking Capacitor, Republic Electronics #013Q330GU

B. 3 dB Quadrature Hybrid Coupler, Anaren #1A0264-3

C. Varactor, Alpha Industries #DVH6732

D. Distributed Inductance

E. Screw Turn Shorting Capacitor, Johanson #SL27271

F. Quarter Wavelength Decoupling Line

G. 1000 pF Shorting Capacitor, Republic Electronics #013Q102GU

H. Varactor Voltage Bias Input

Figure 9. Schematic and circuit realization of hybrid coupler phase shifter.

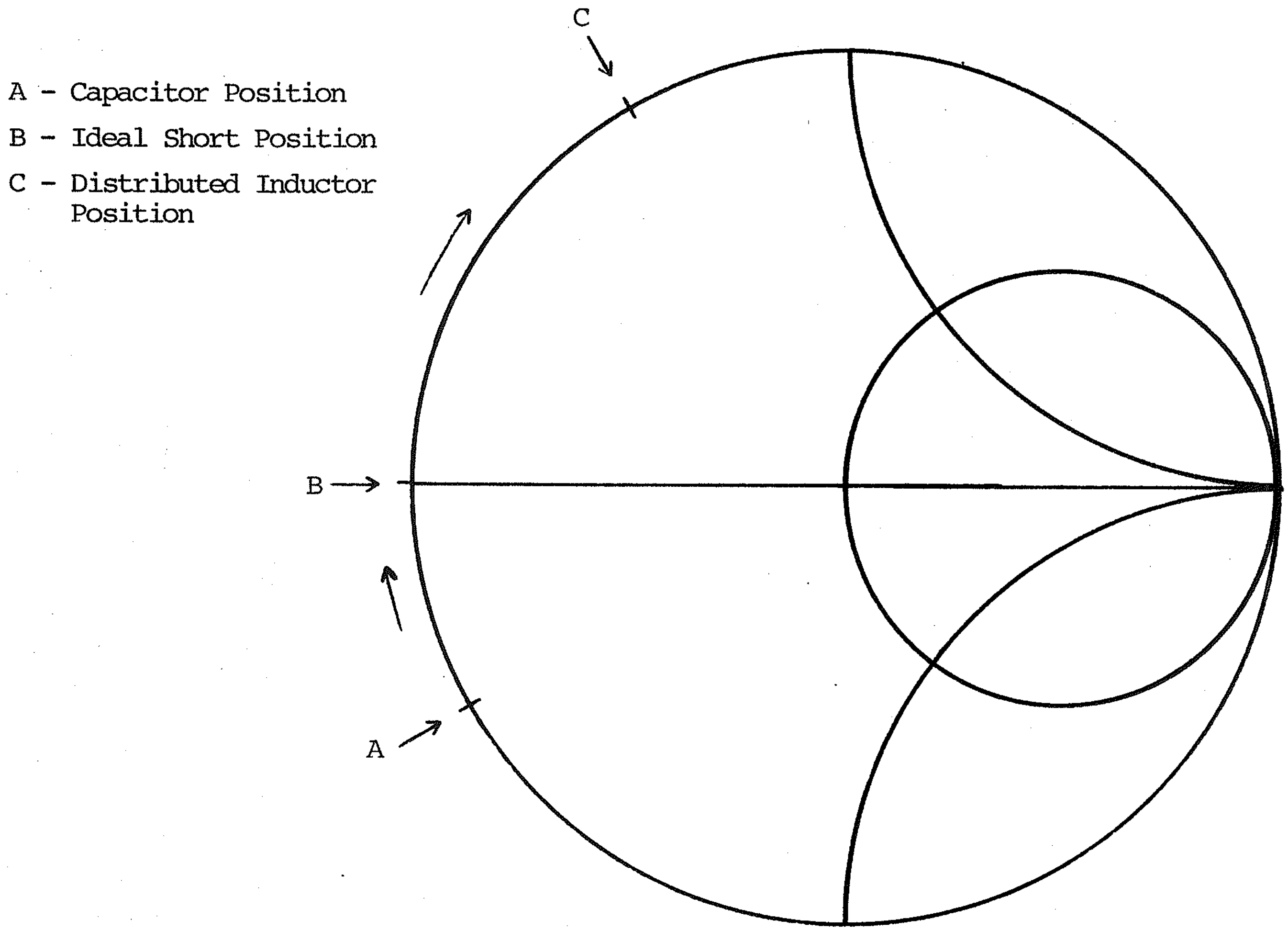


Figure 10. Smith chart showing the translation of capacitance to distributed inductance.

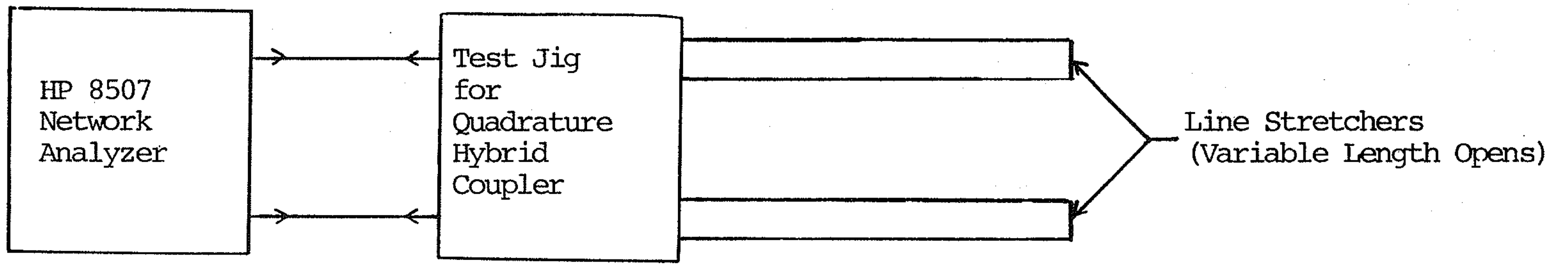


Figure 11. Test setup for hybrid coupler with line stretchers.

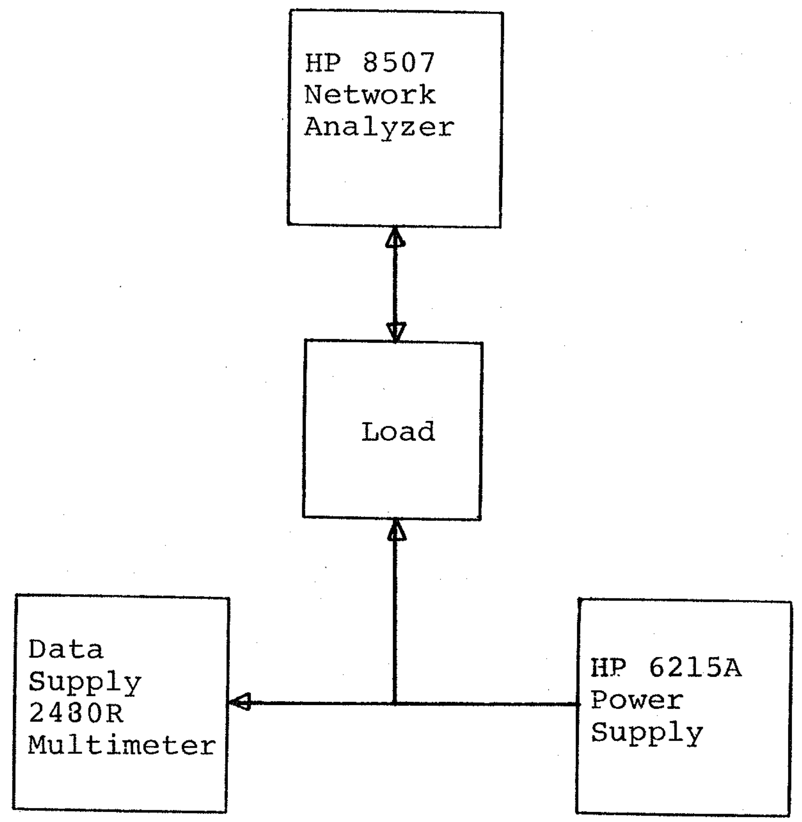


Figure 12. Manual measurement of load.

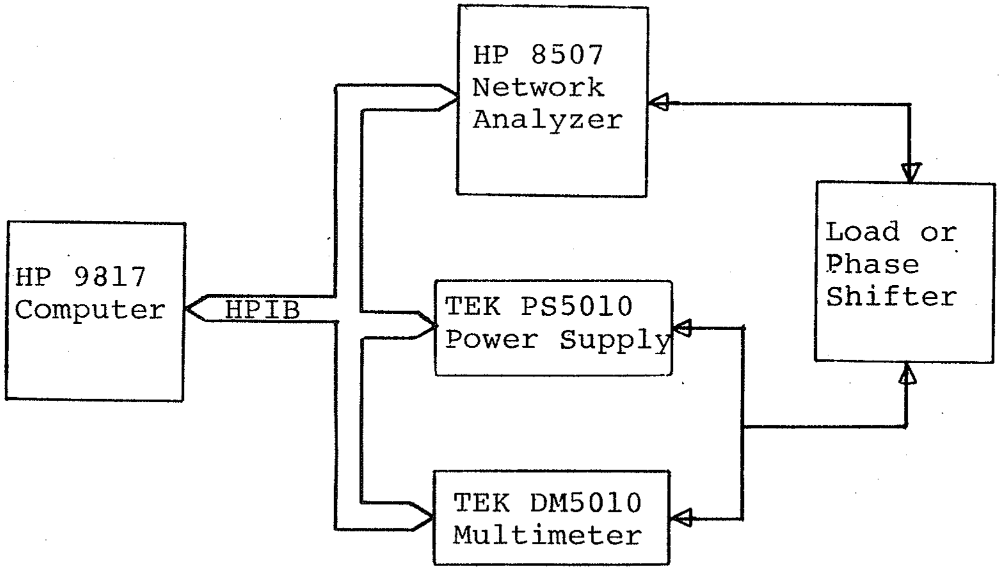


Figure 13. Automated measurement for load or phase shifter.

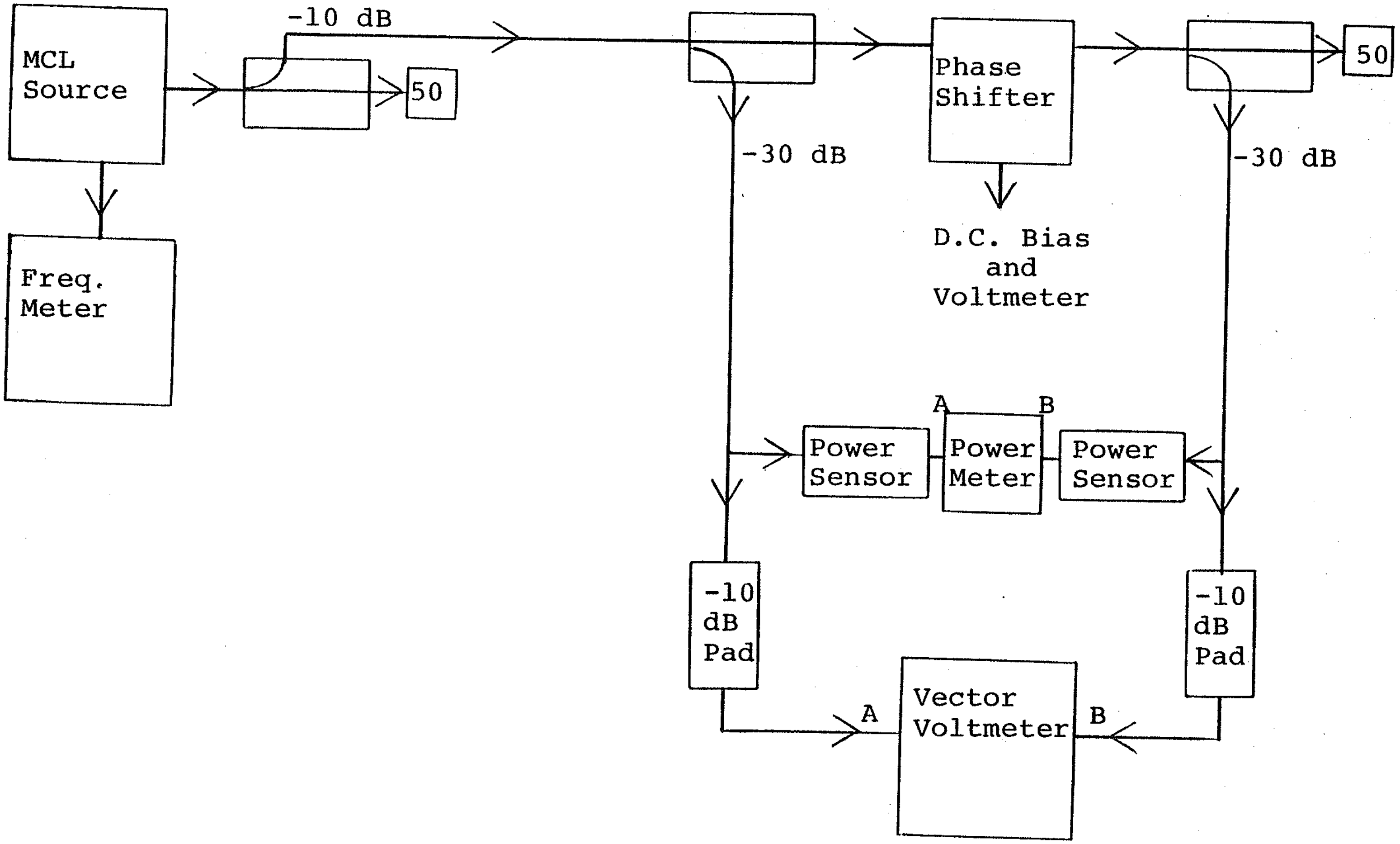


Figure 14. High power measurement of phase shifter.

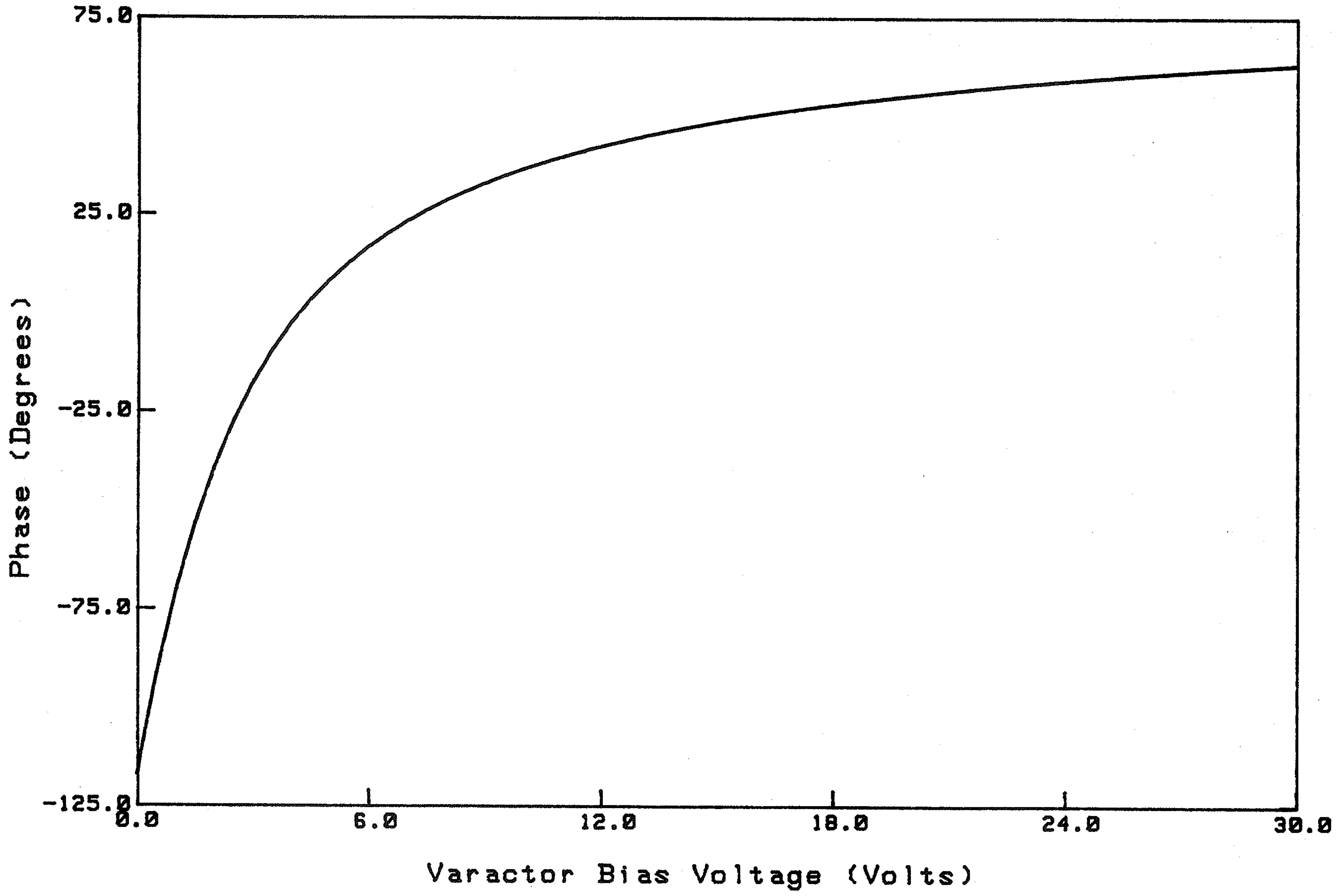


Figure 15. Phase response of 3.9 pF load model.

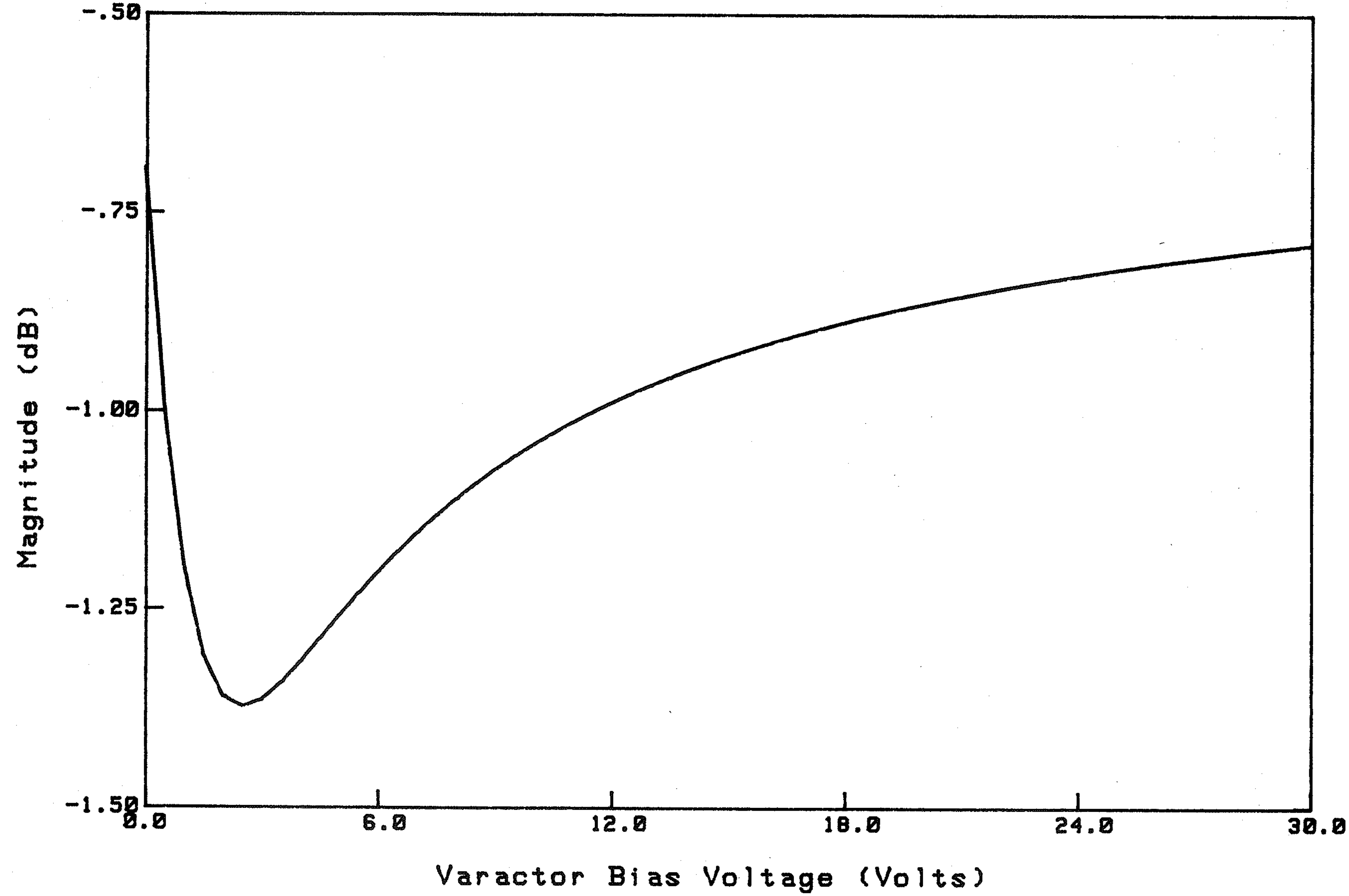


Figure 16. Amplitude response of 3.9 pF load model.

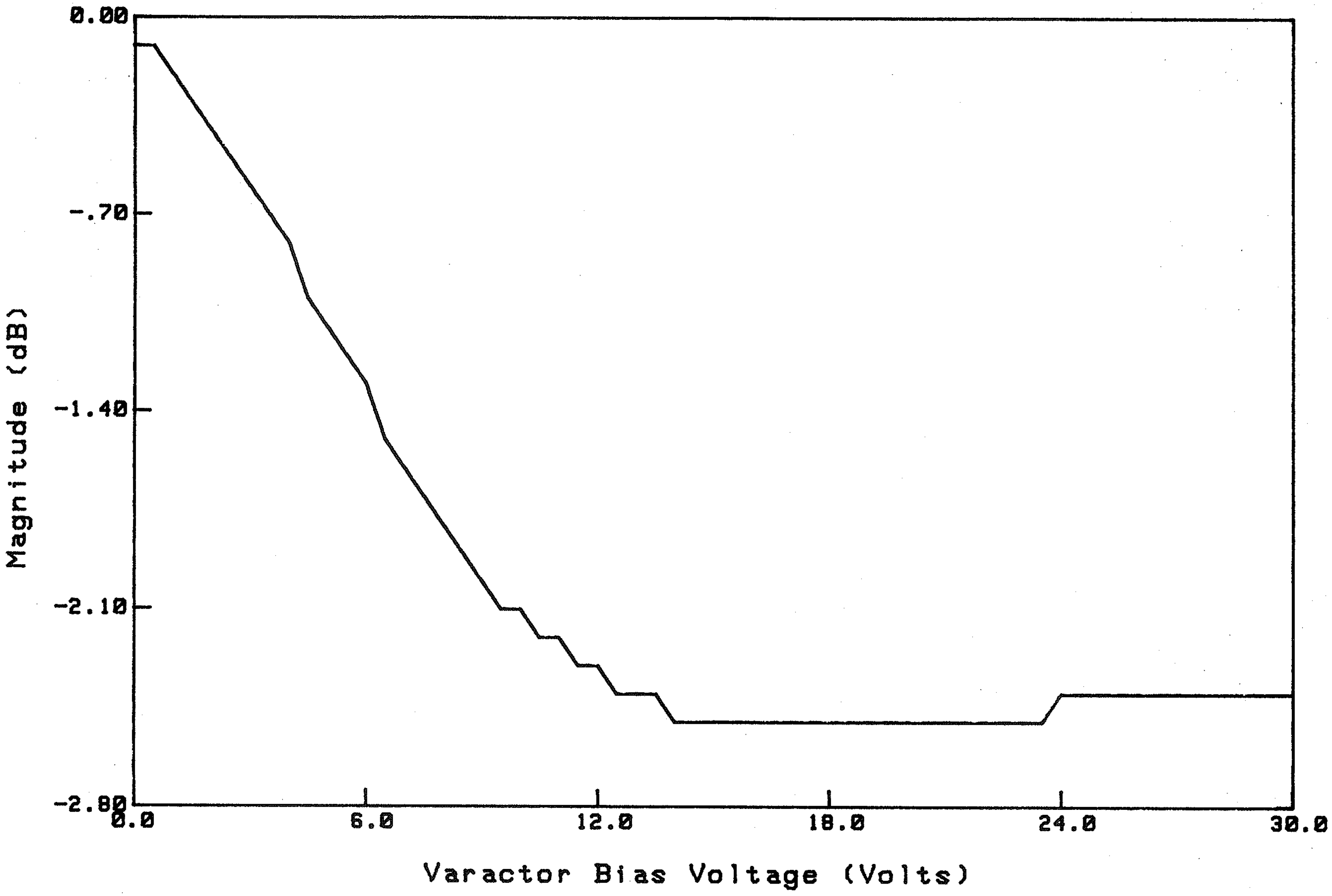


Figure 17. Measured amplitude response of 10 pF load.

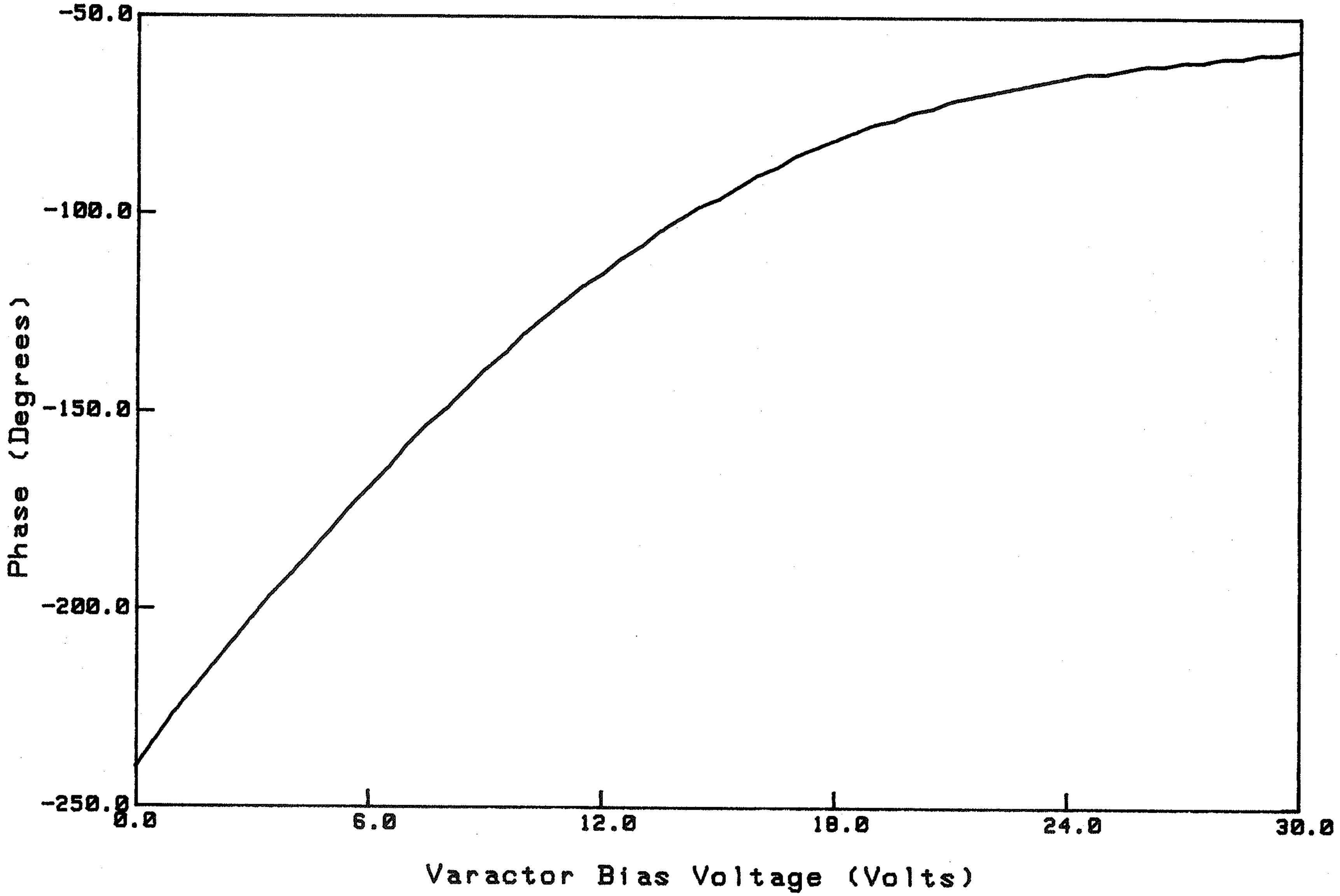


Figure 18. Measured phase response of 10 pF load.

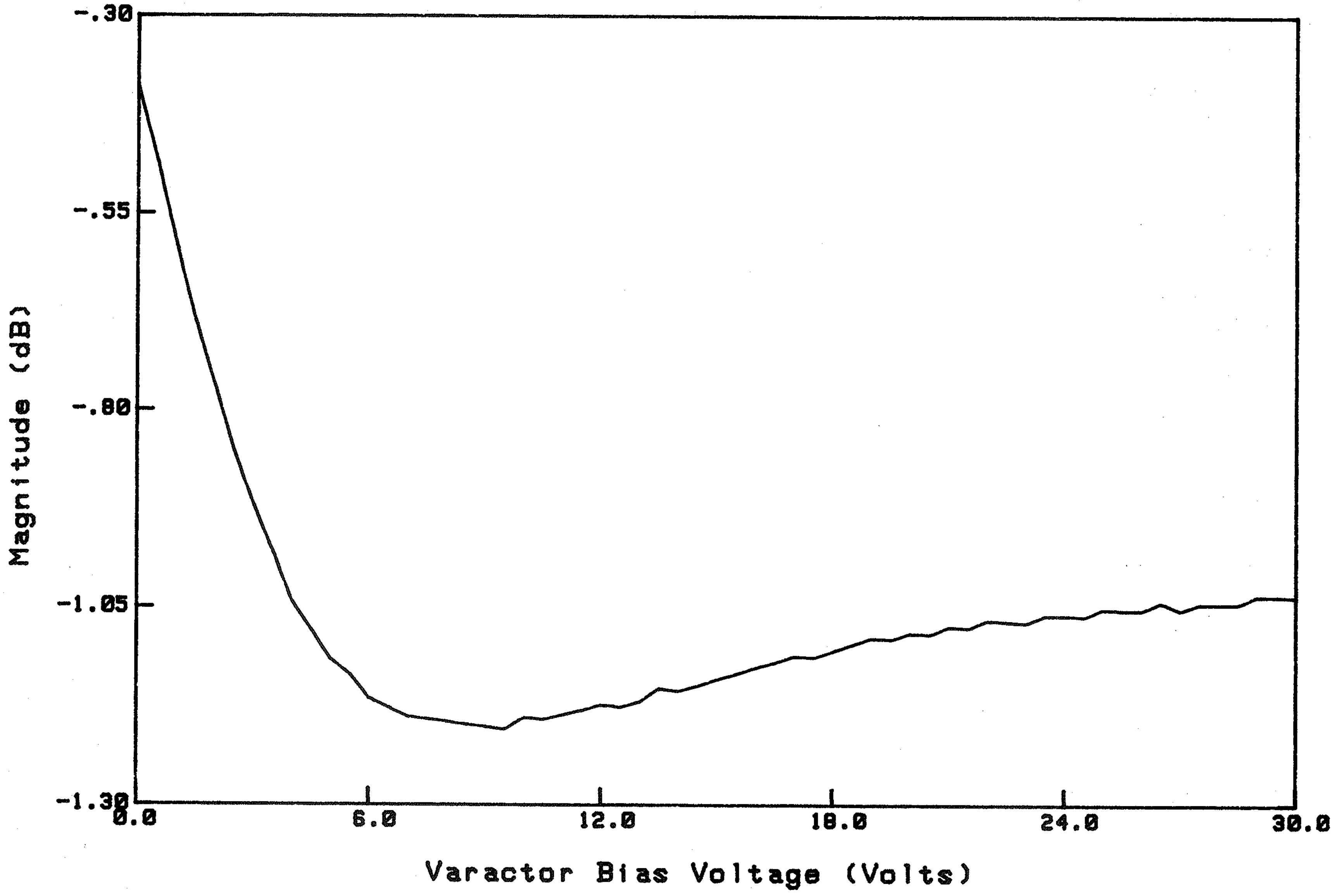


Figure 19. Measured amplitude response of 5.6 pF load.

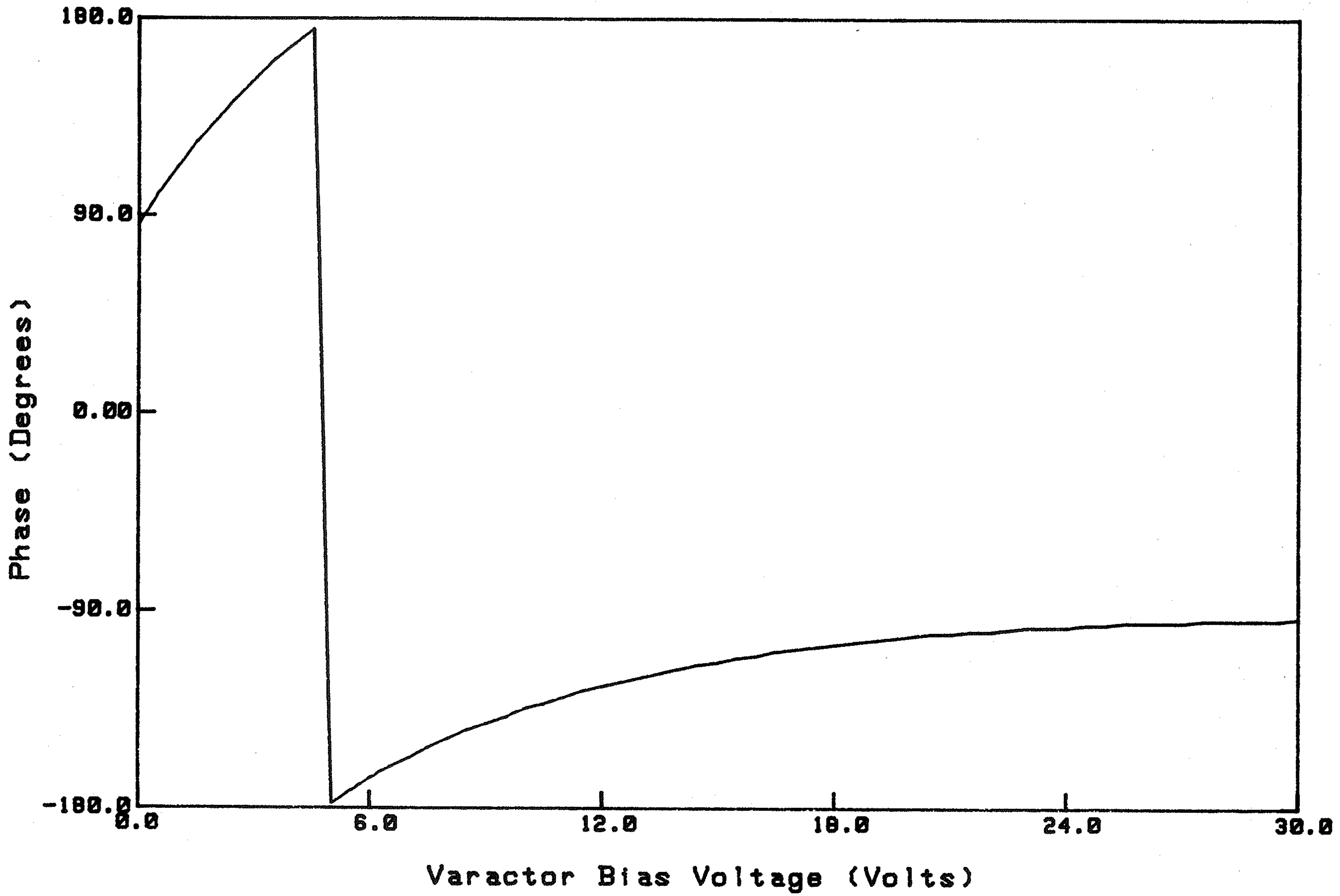


Figure 20. Measured phase response of 5.6 pF load.

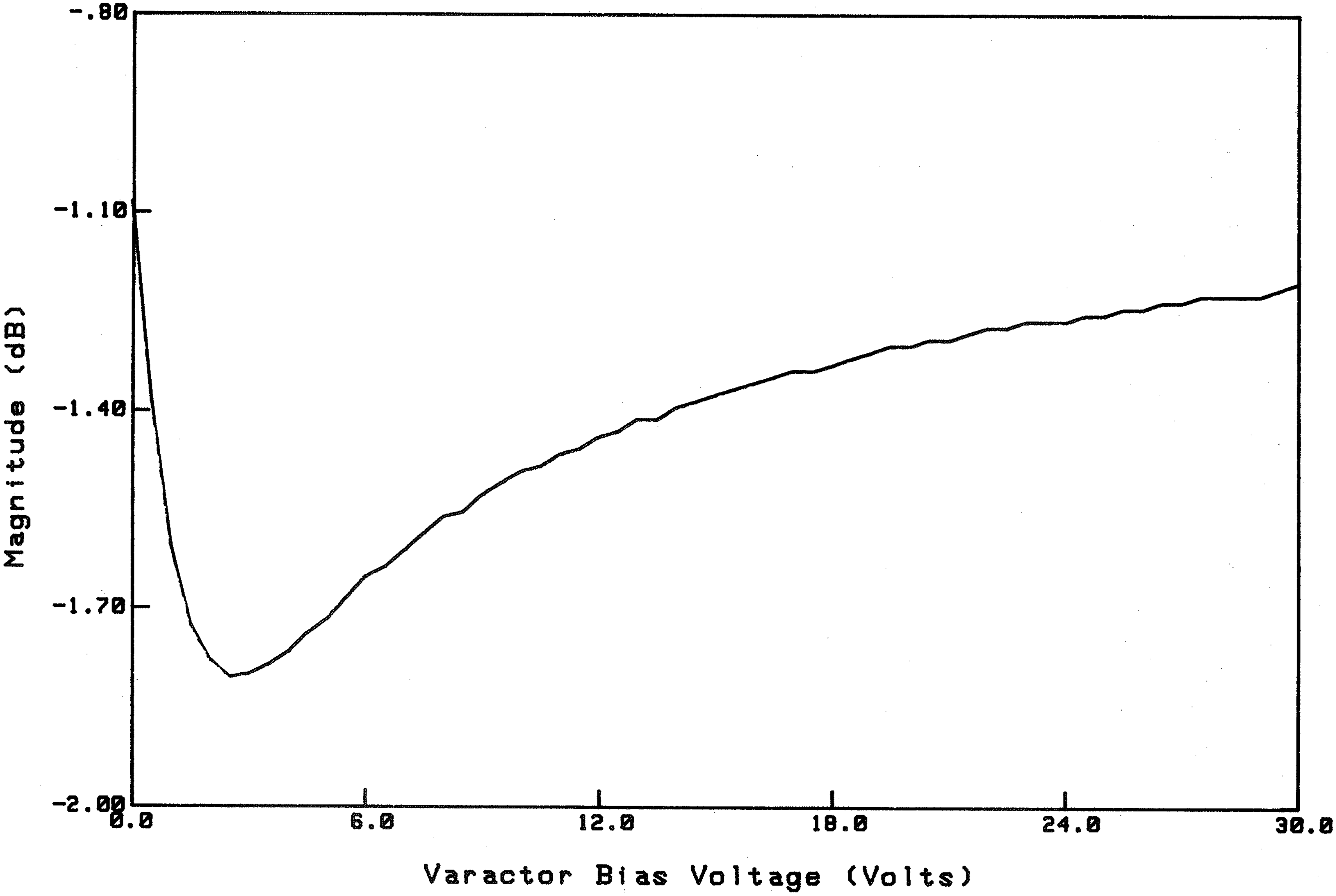


Figure 21. Measured amplitude response of 3.9 pF load.

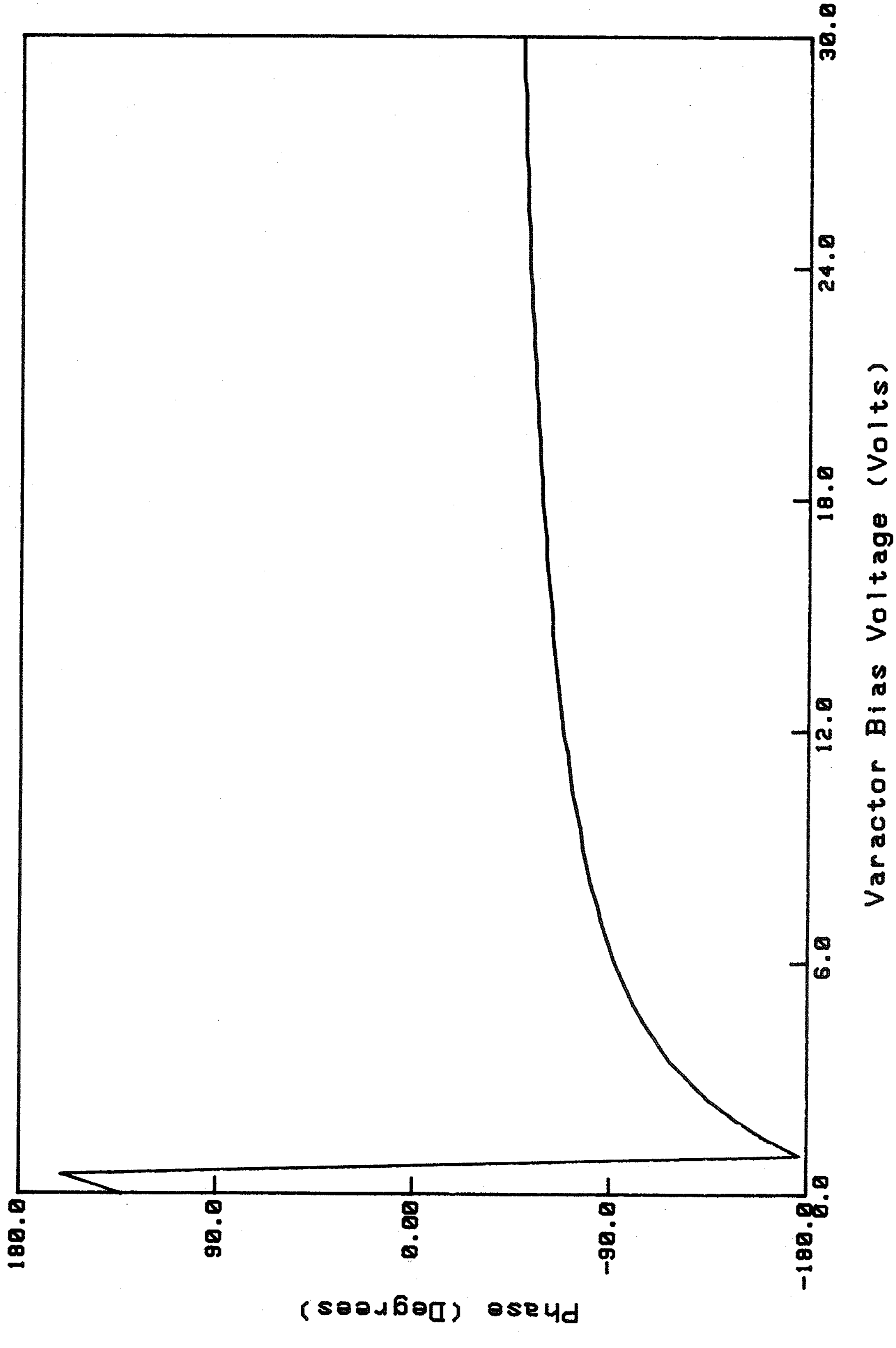


Figure 22. Measured phase response of 3.9 pF load.

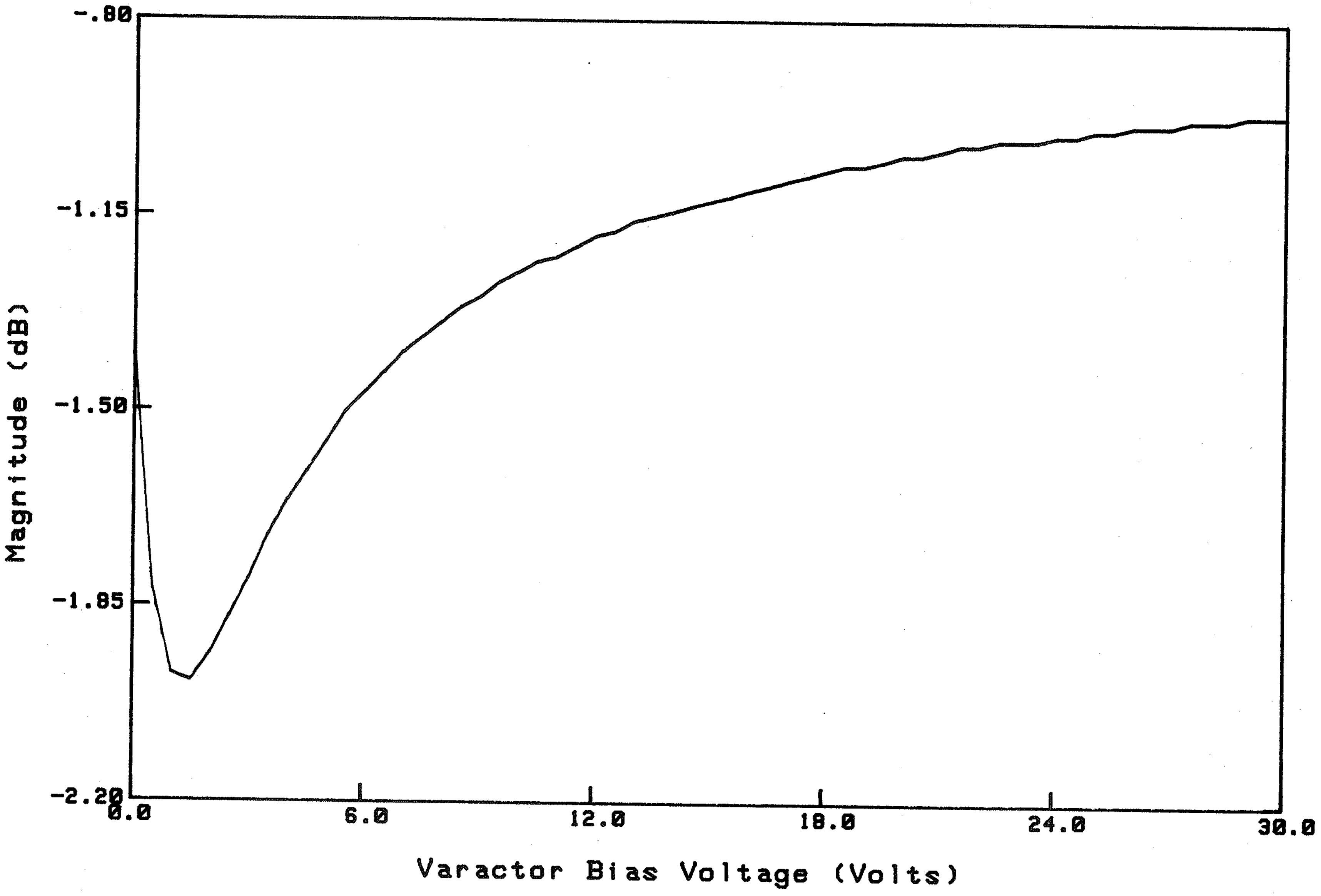


Figure 23. Measure amplitude response of 3.3 pF load.

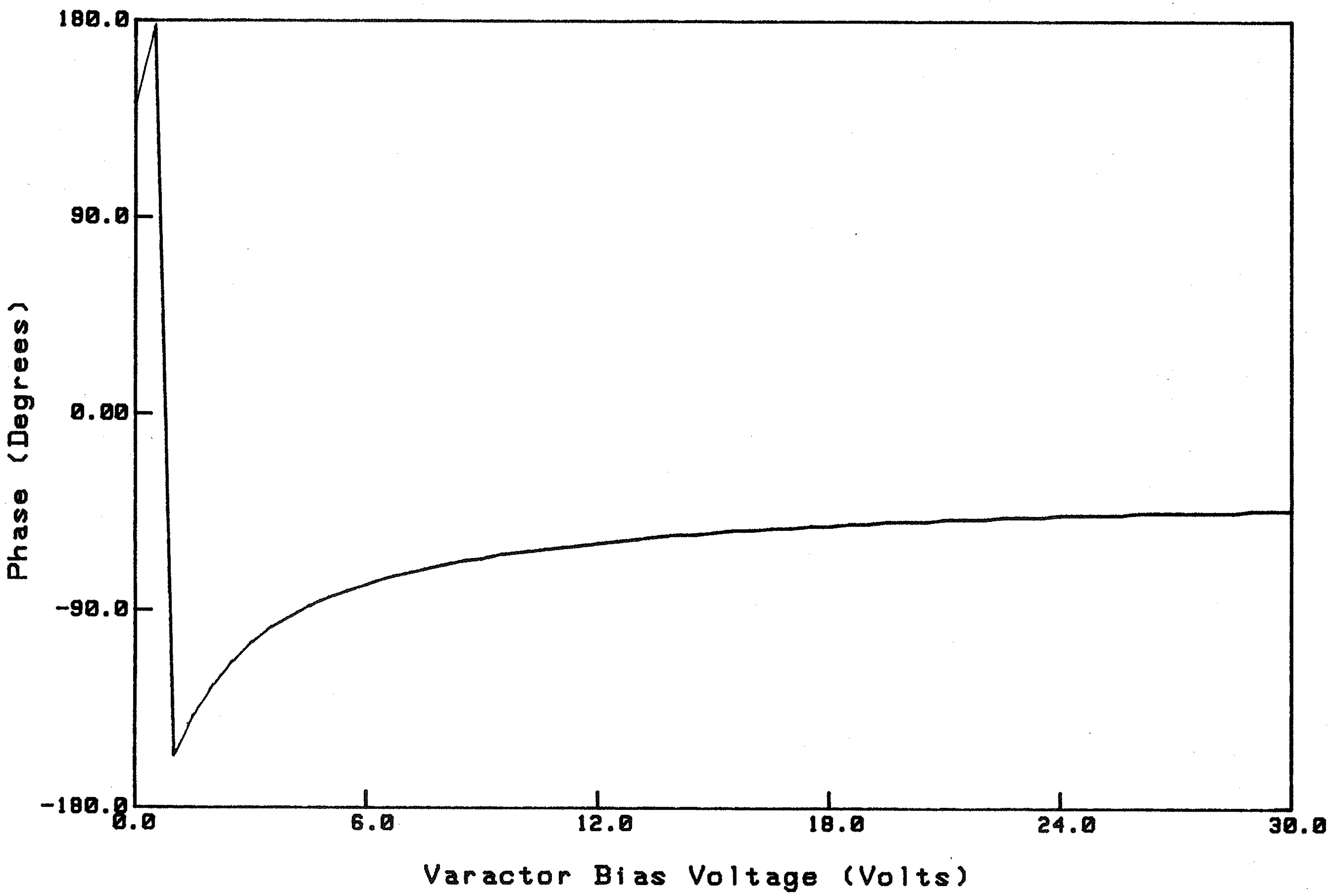


Figure 24. Measured phase response of 3.3 pF load.

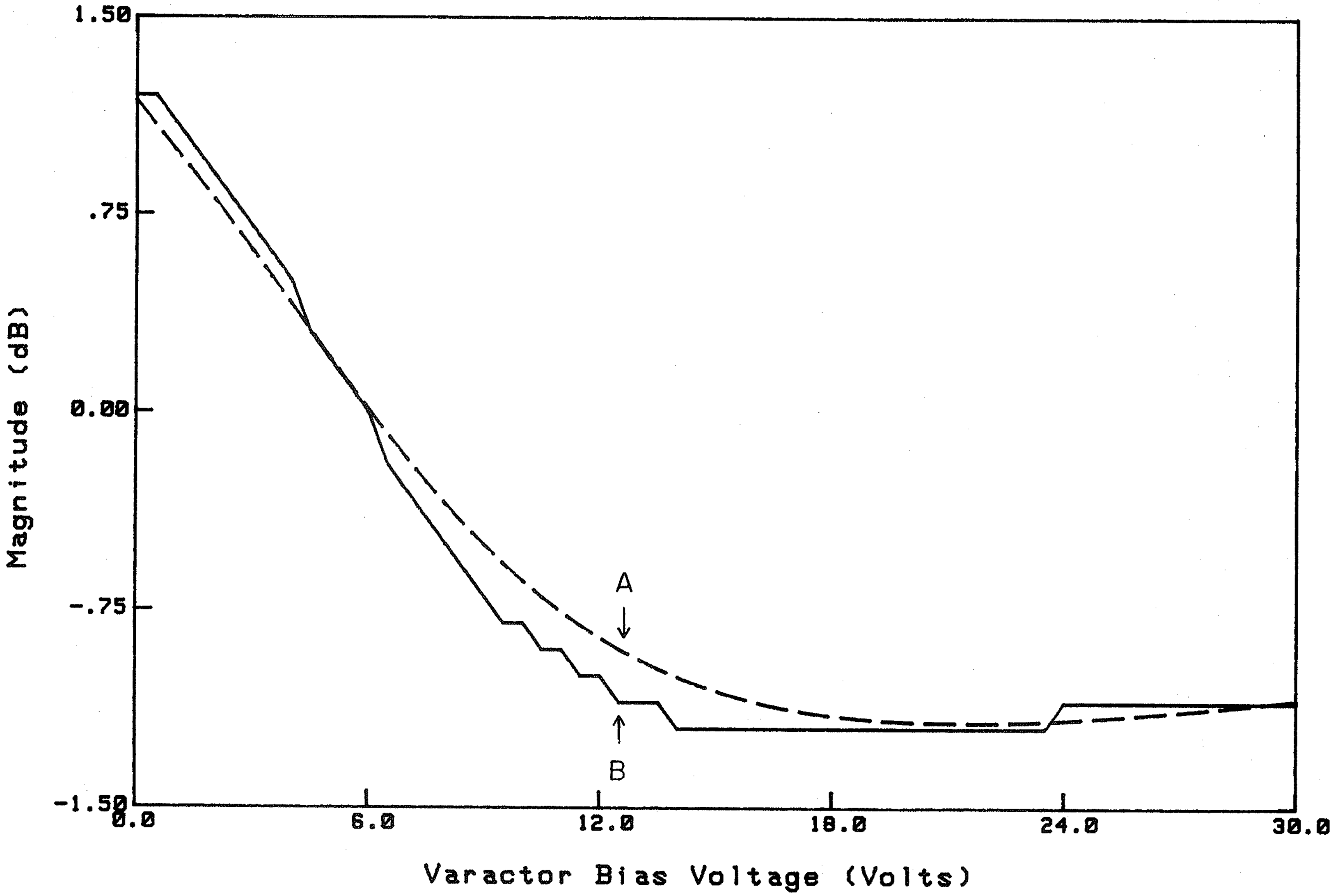


Figure 25. Comparison of simulation (Q = 21), A, and measurement, B, of phase response of 10 pF load.

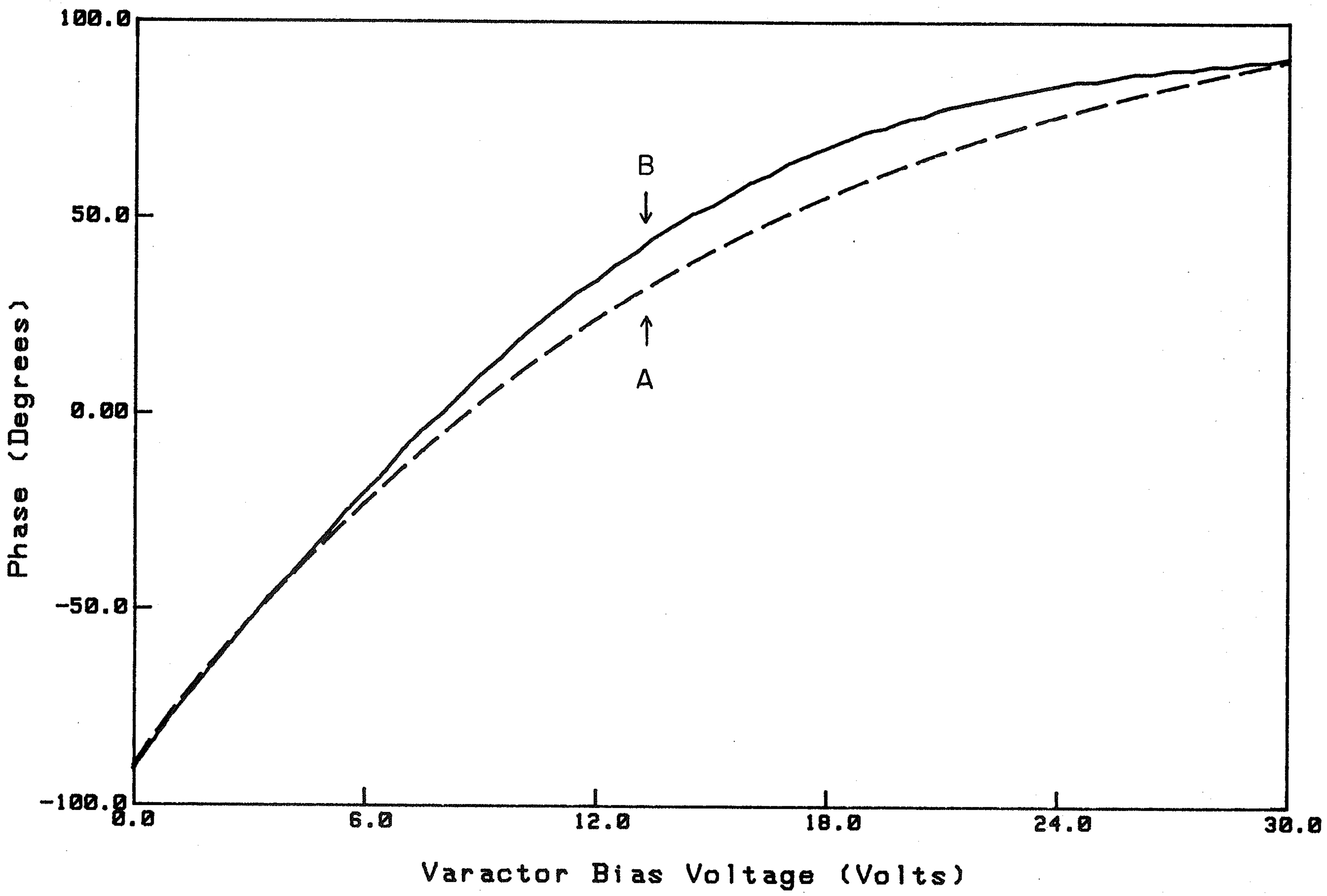


Figure 26. Comparison of simulation (Q - 21), A, and measurement, B, of phase response of 10 pF load.

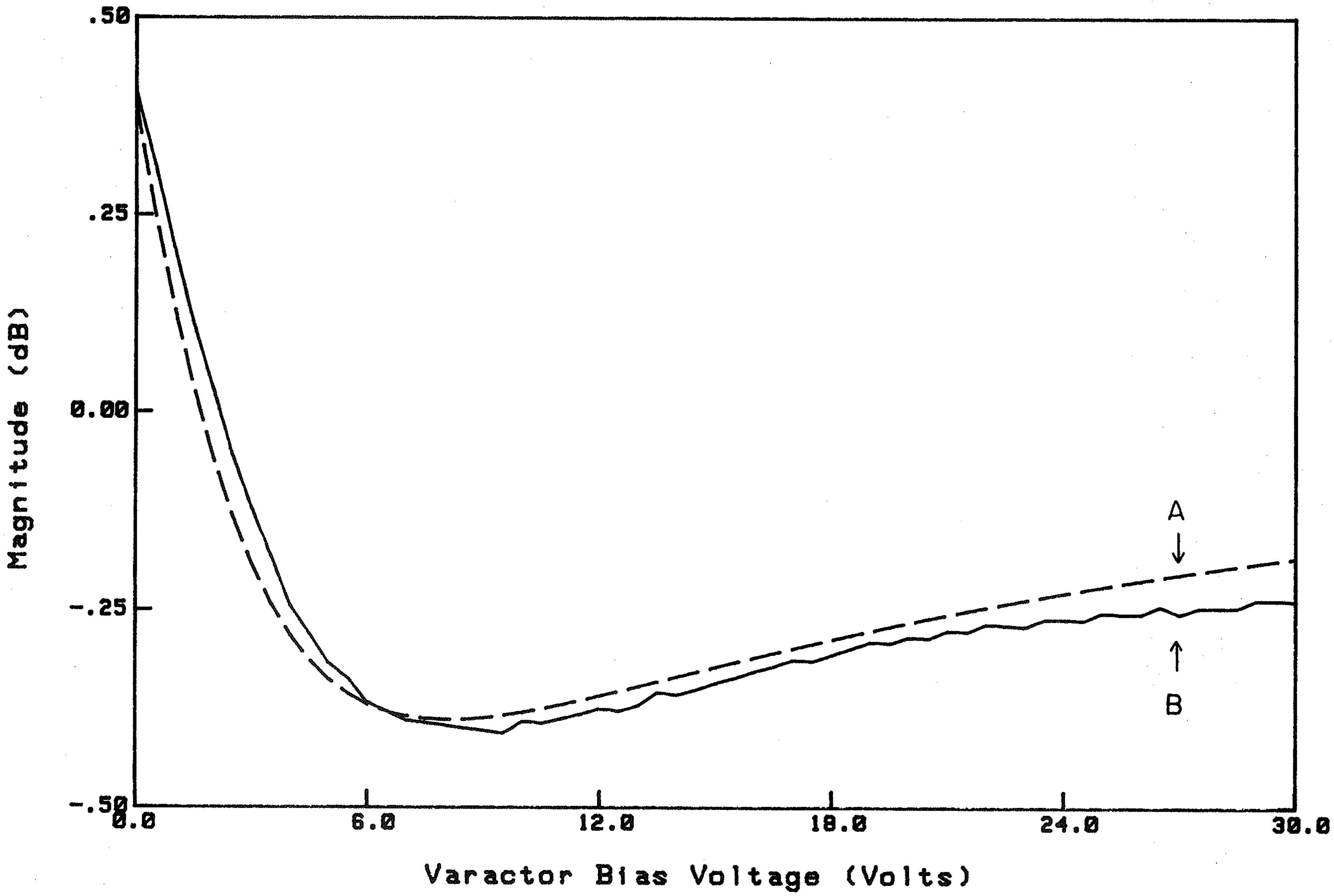


Figure 27. Comparison of simulation (Q = 41), A, and measurement, B, of amplitude response of 5.6 pF load.

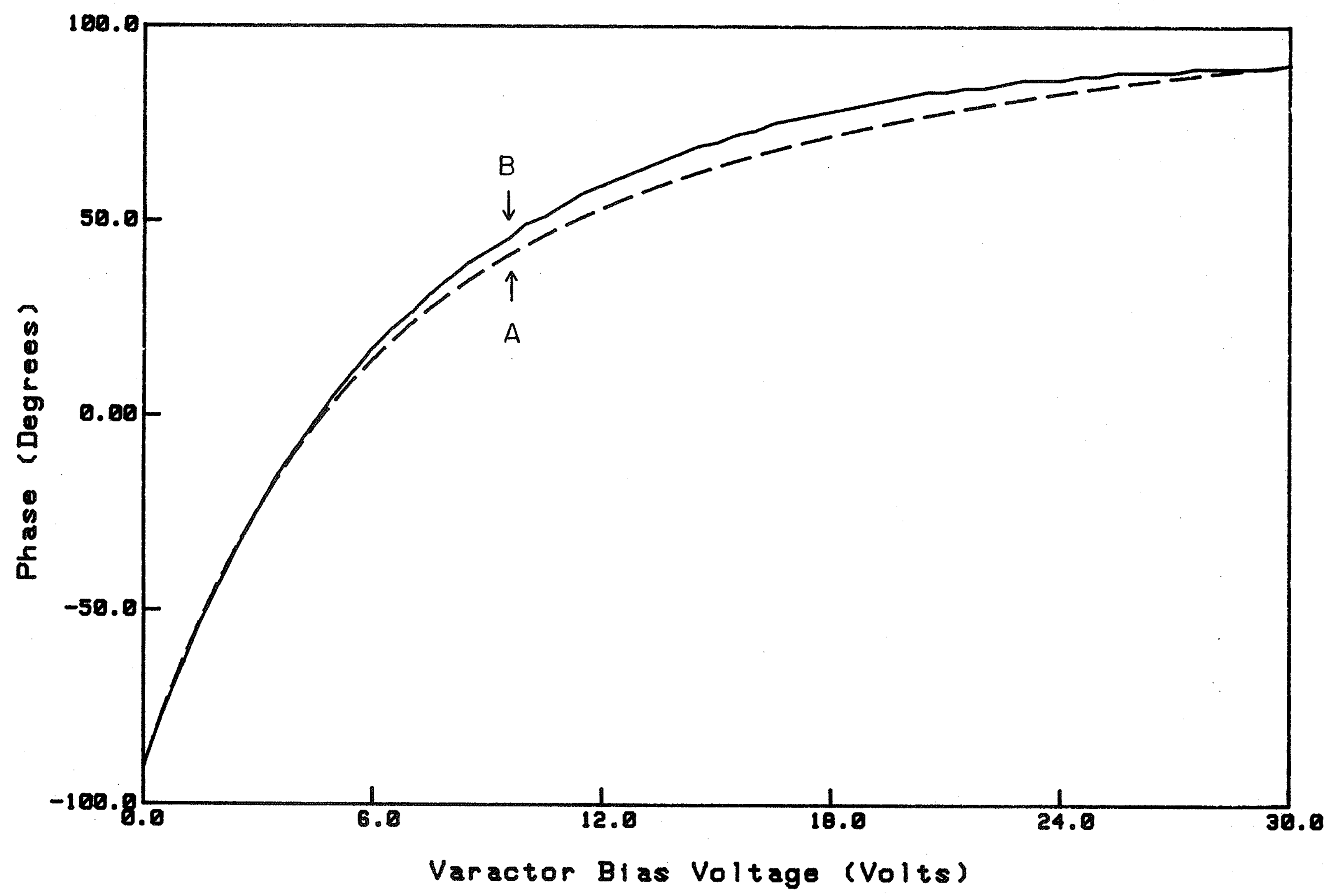


Figure 28. Comparison of simulation (Q = 41), A, and measurement, B, of phase response of 5.6 pF load.

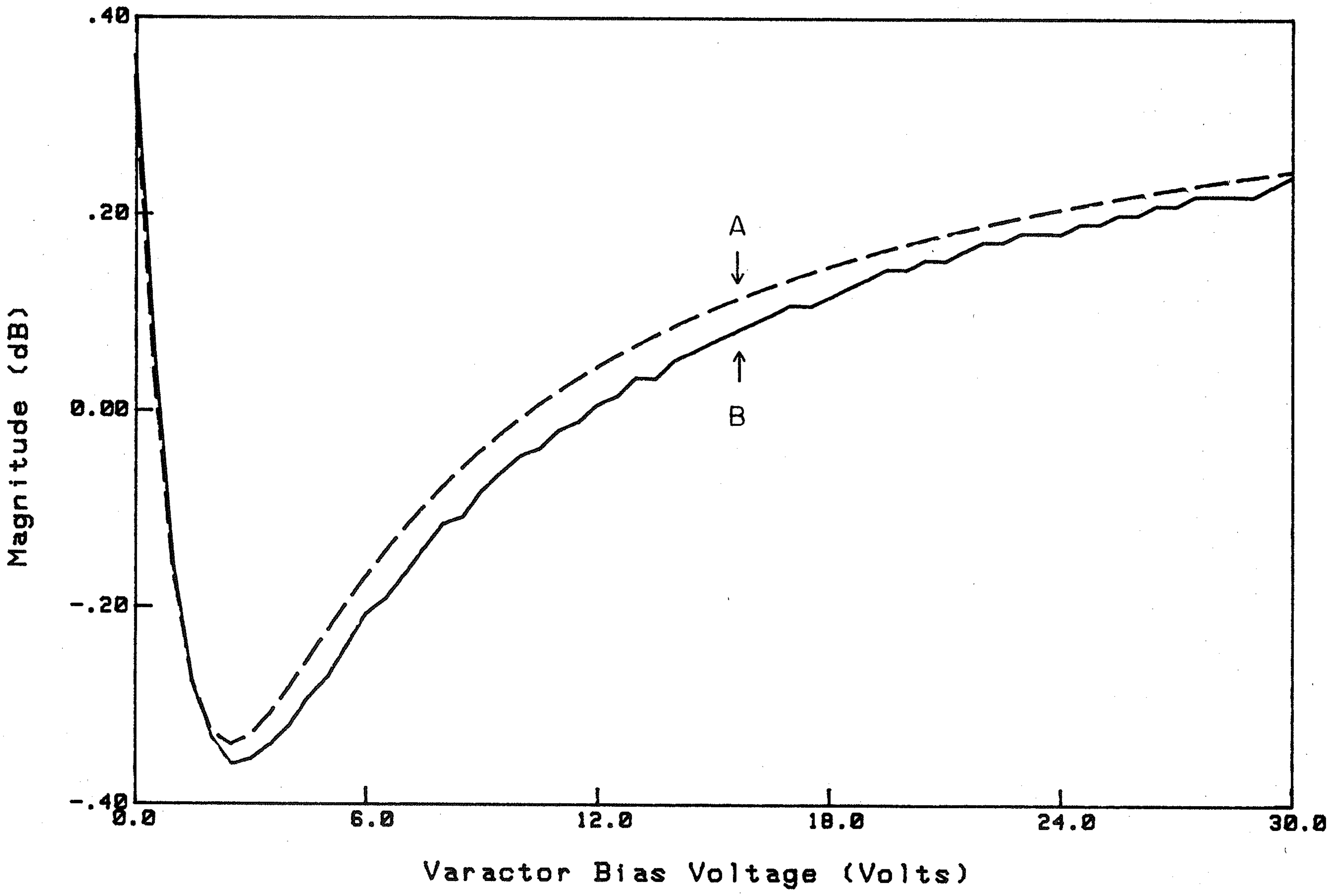


Figure 29. Comparison of simulation (Q = 41), A, and measurement, B, of amplitude response of 3.9 pF load.

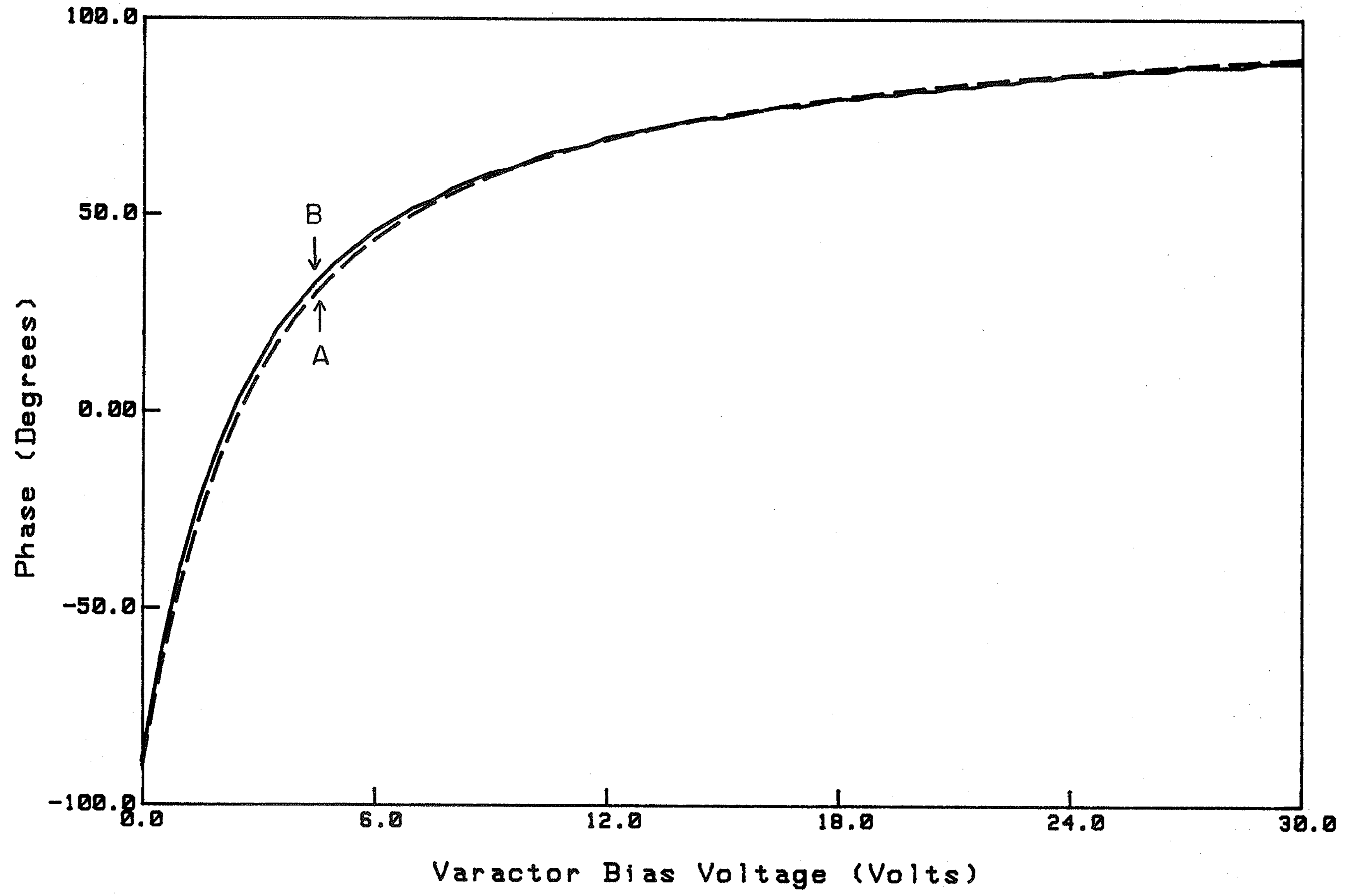


Figure 30. Comparison of simulation (Q = 41), A, and measurement, B, of phase response of 3.9 pF load.

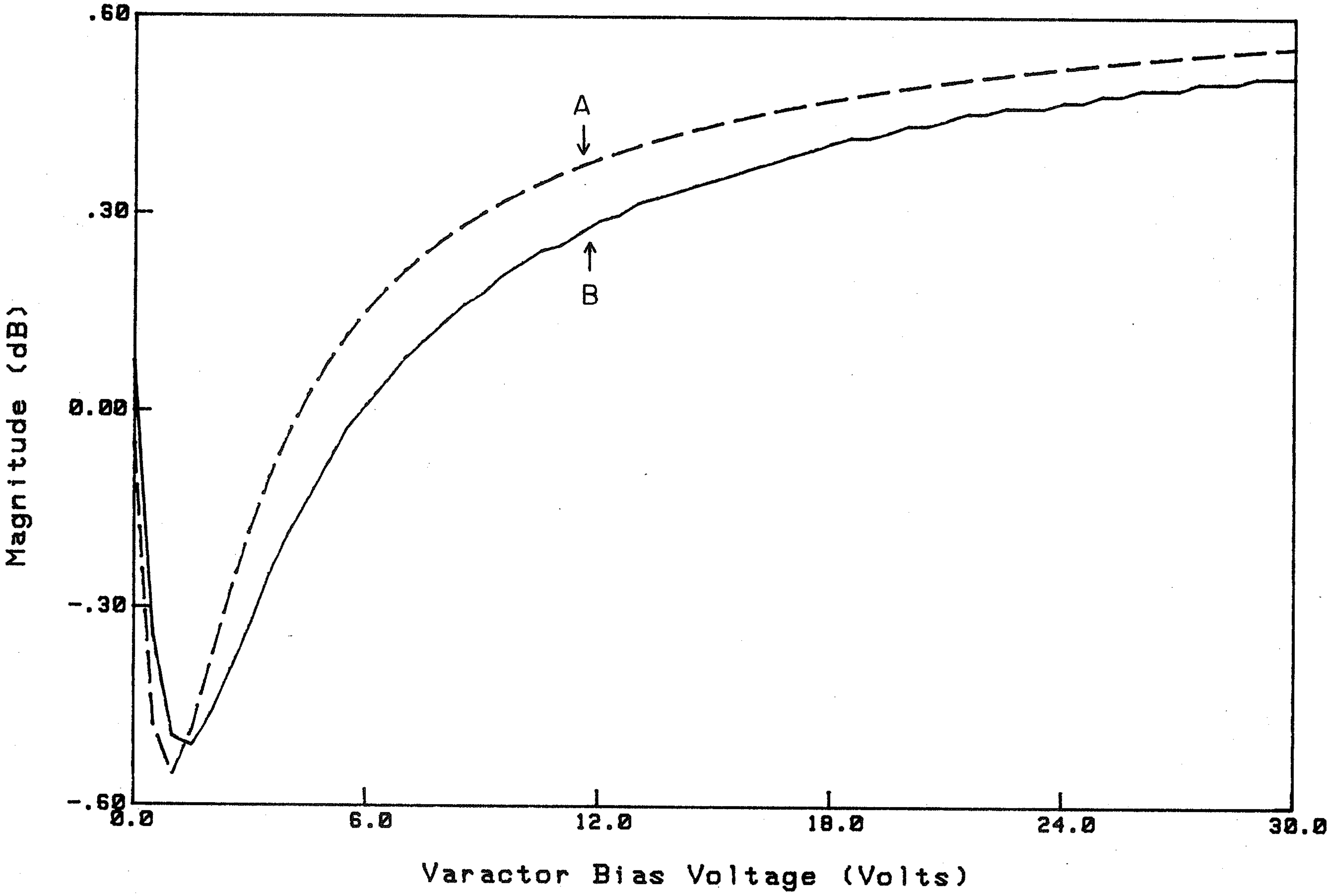


Figure 31. Comparison of simulation (Q = 41), A, and measurement, B, of amplitude response of 3.3 pF load.

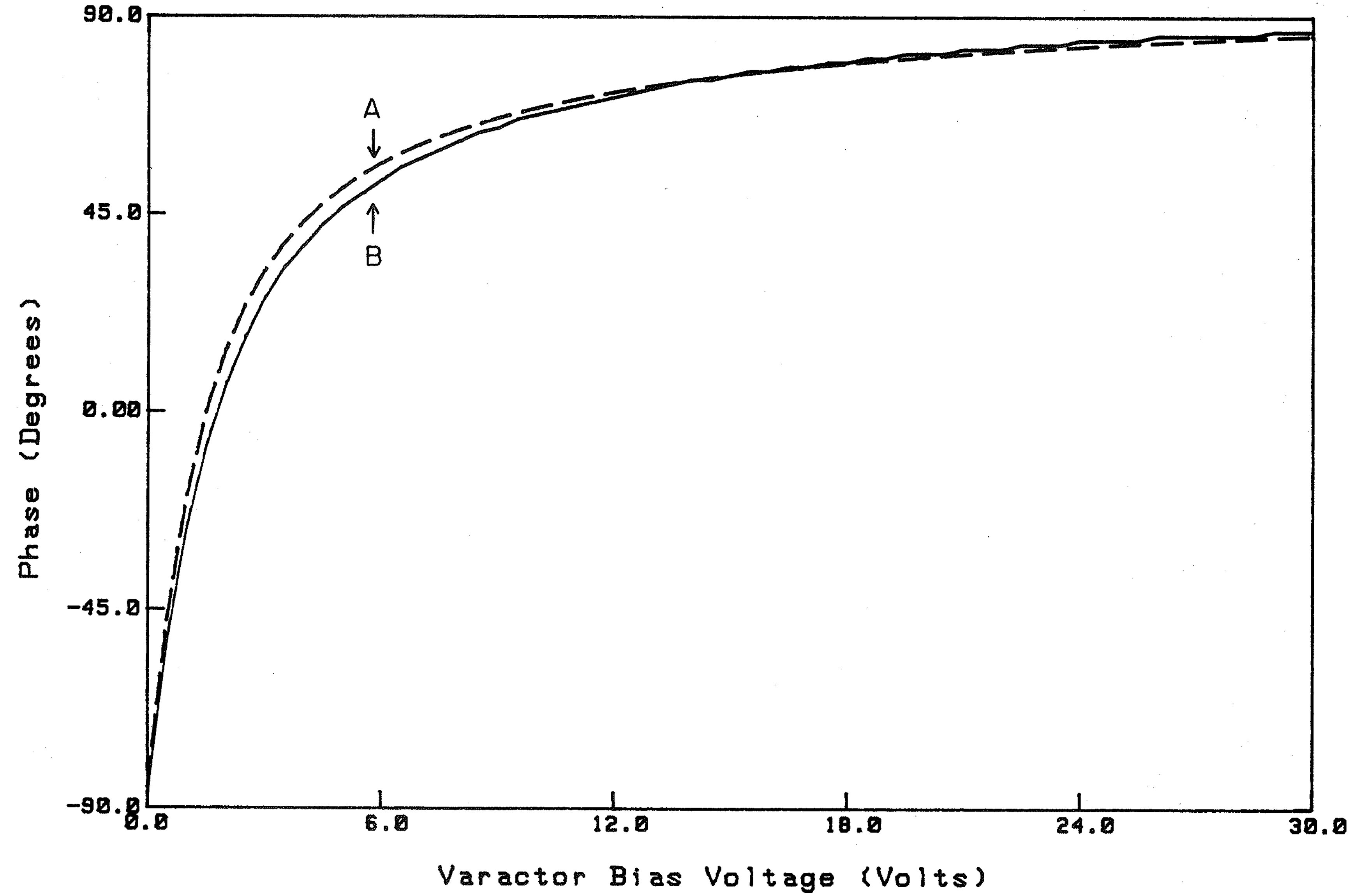


Figure 32. Comparison of simulation (Q = 41), A, and measurement, B, of phase response of 3.3. pF load.

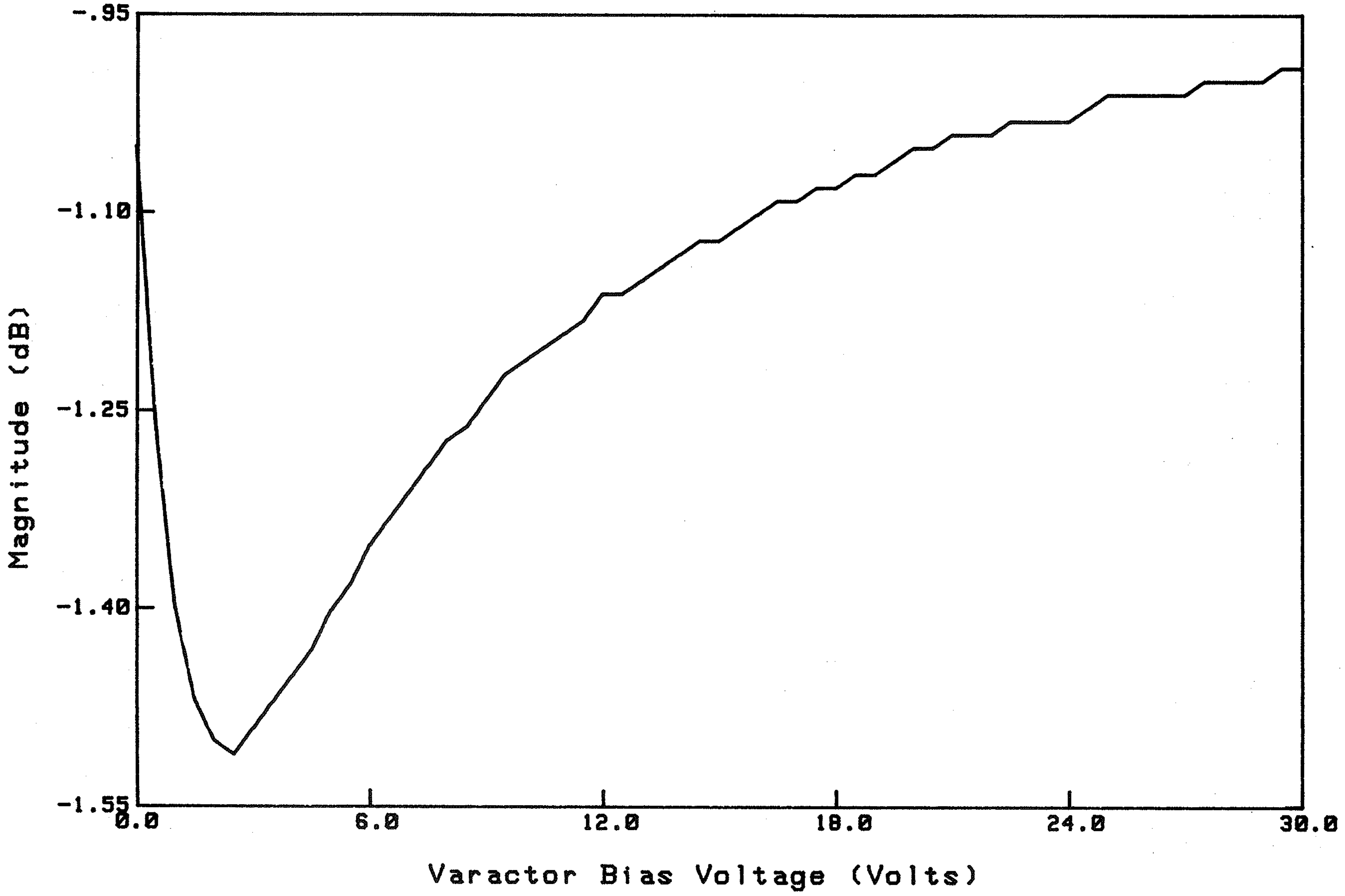


Figure 33. Amplitude response of 3.9 pF phase shifter.

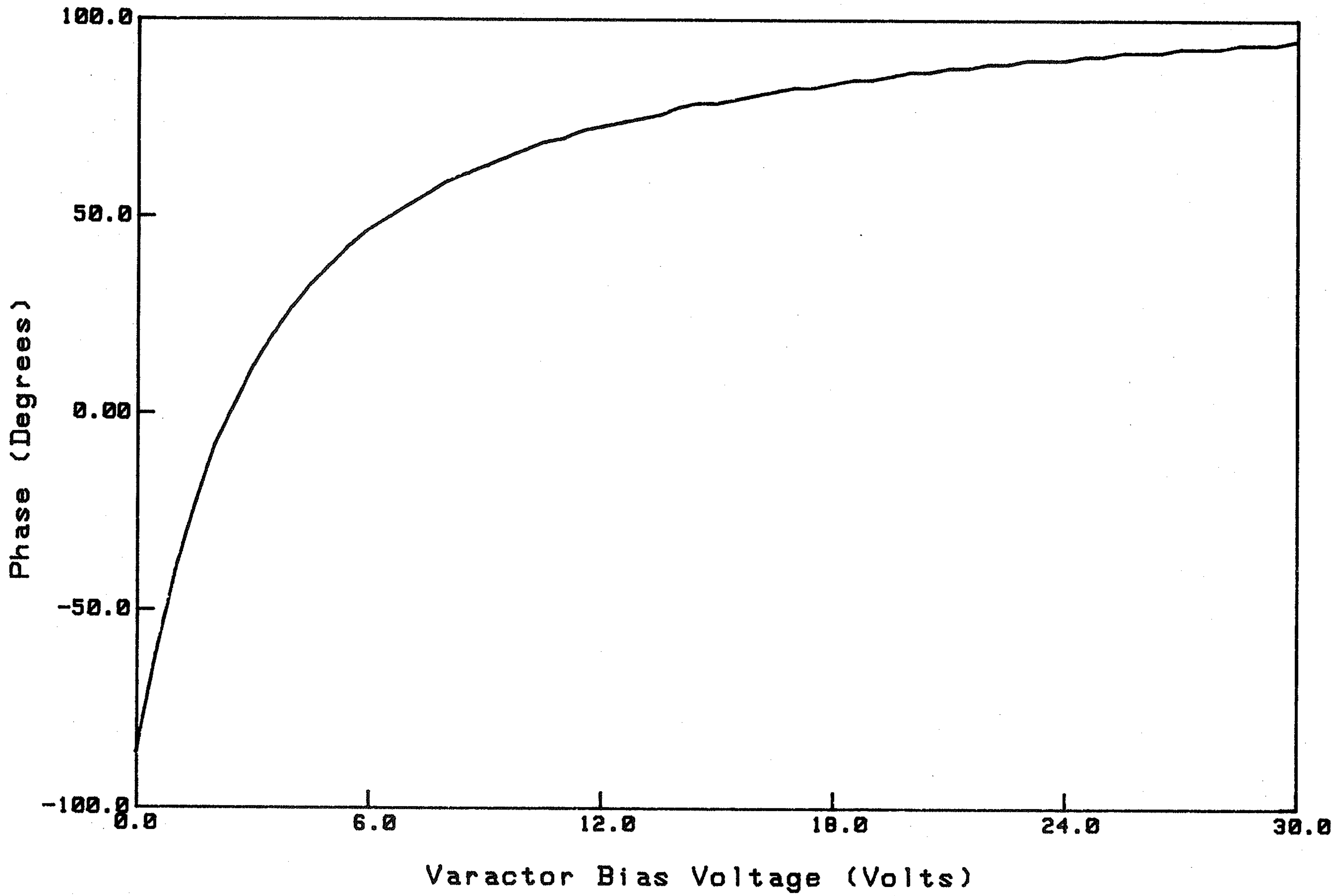


Figure 34. Phase response of 3.9 pF phase shifter.

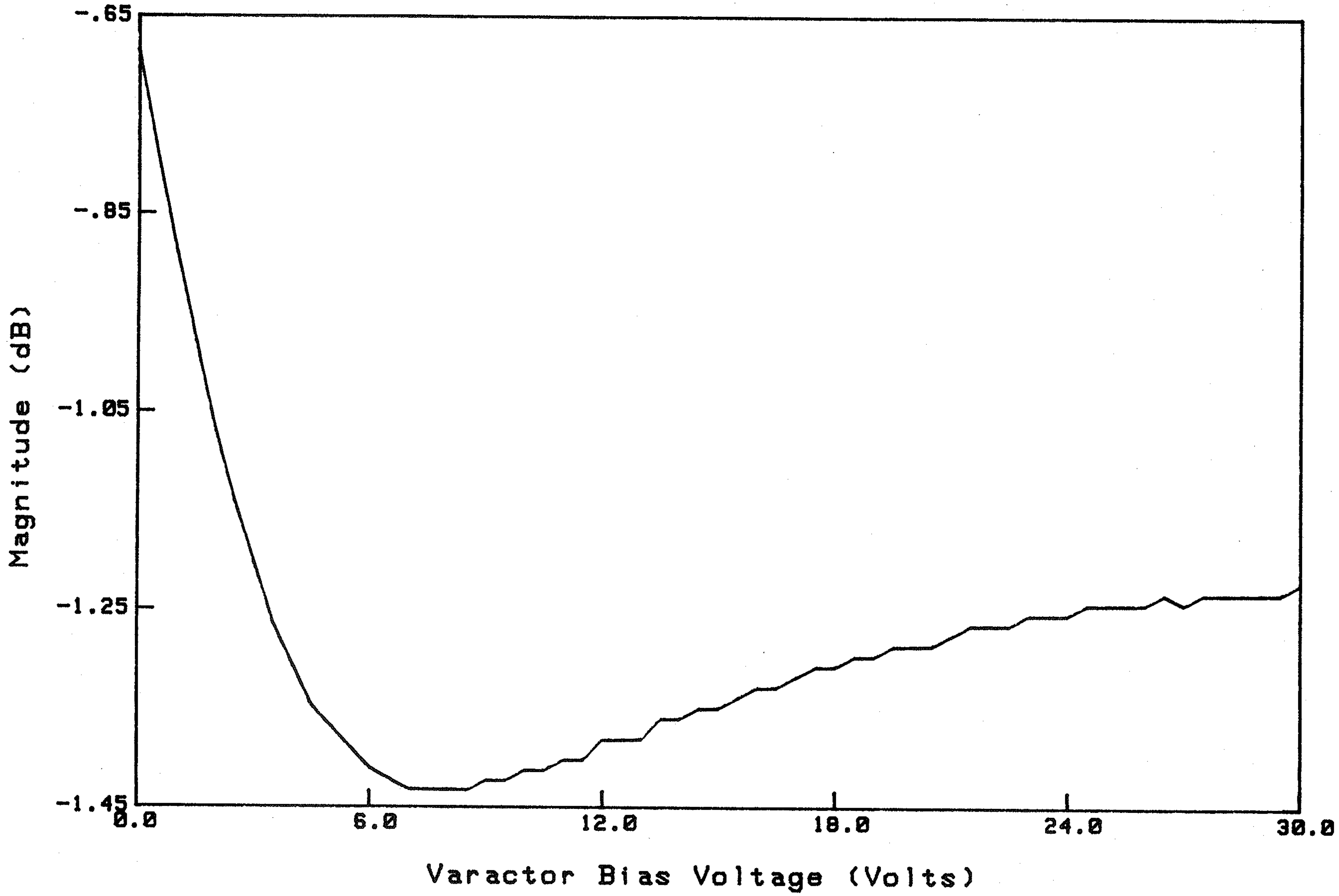


Figure 35. Amplitude response of 5.6 pF phase shifter.

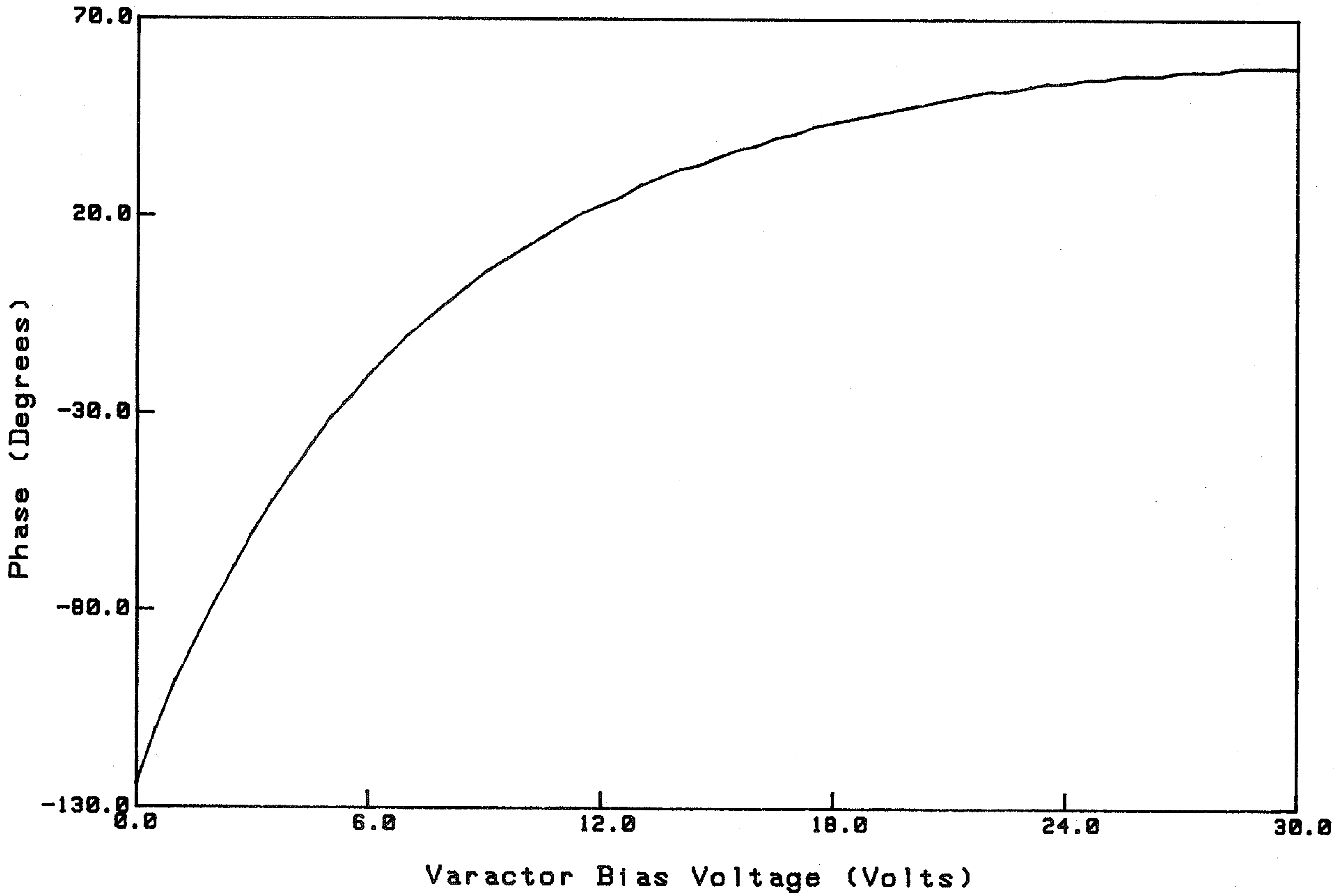


Figure 36. Phase response of 5.6 pF phase shifter.

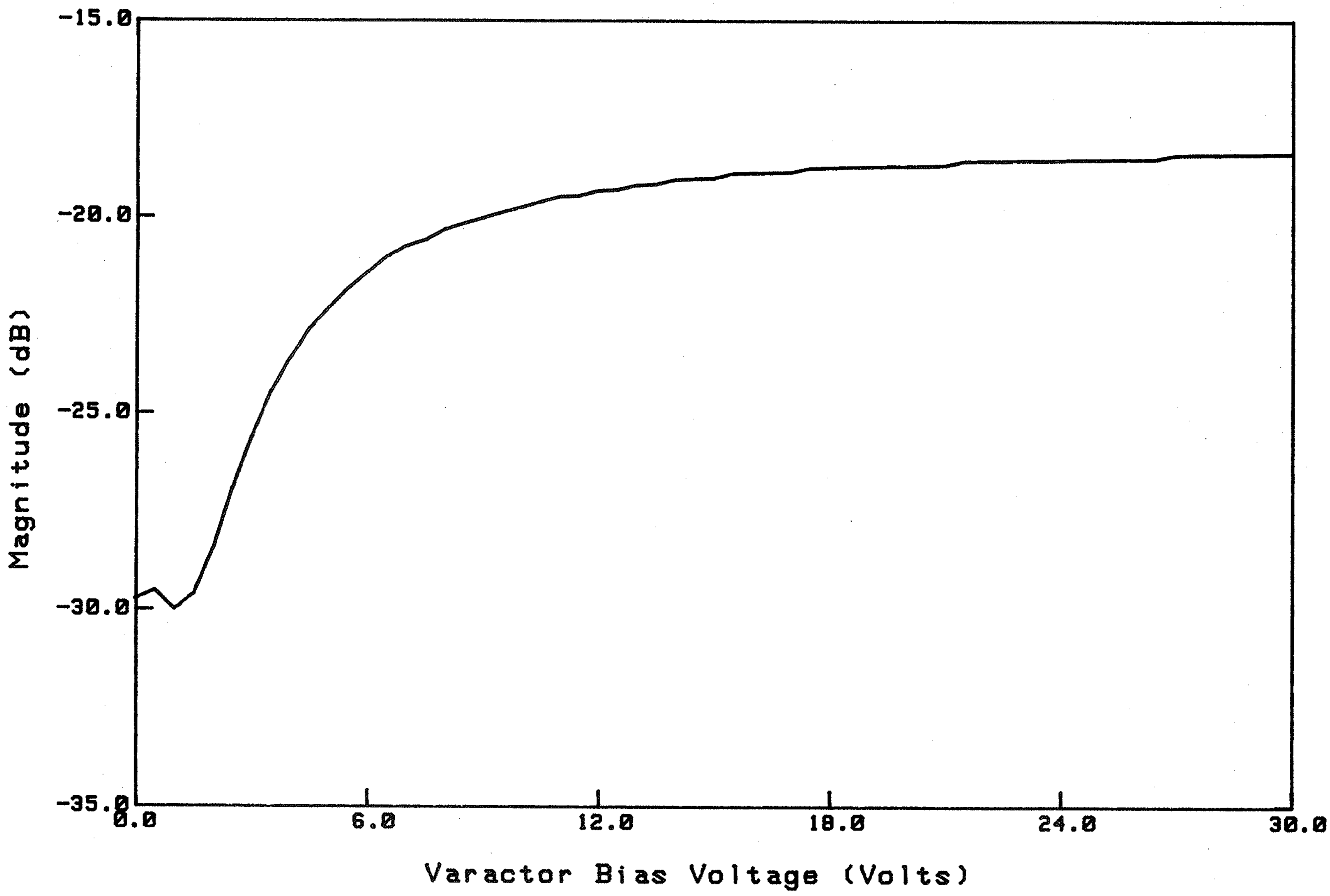


Figure 37. Return loss of 3.9 pF phase shifter.

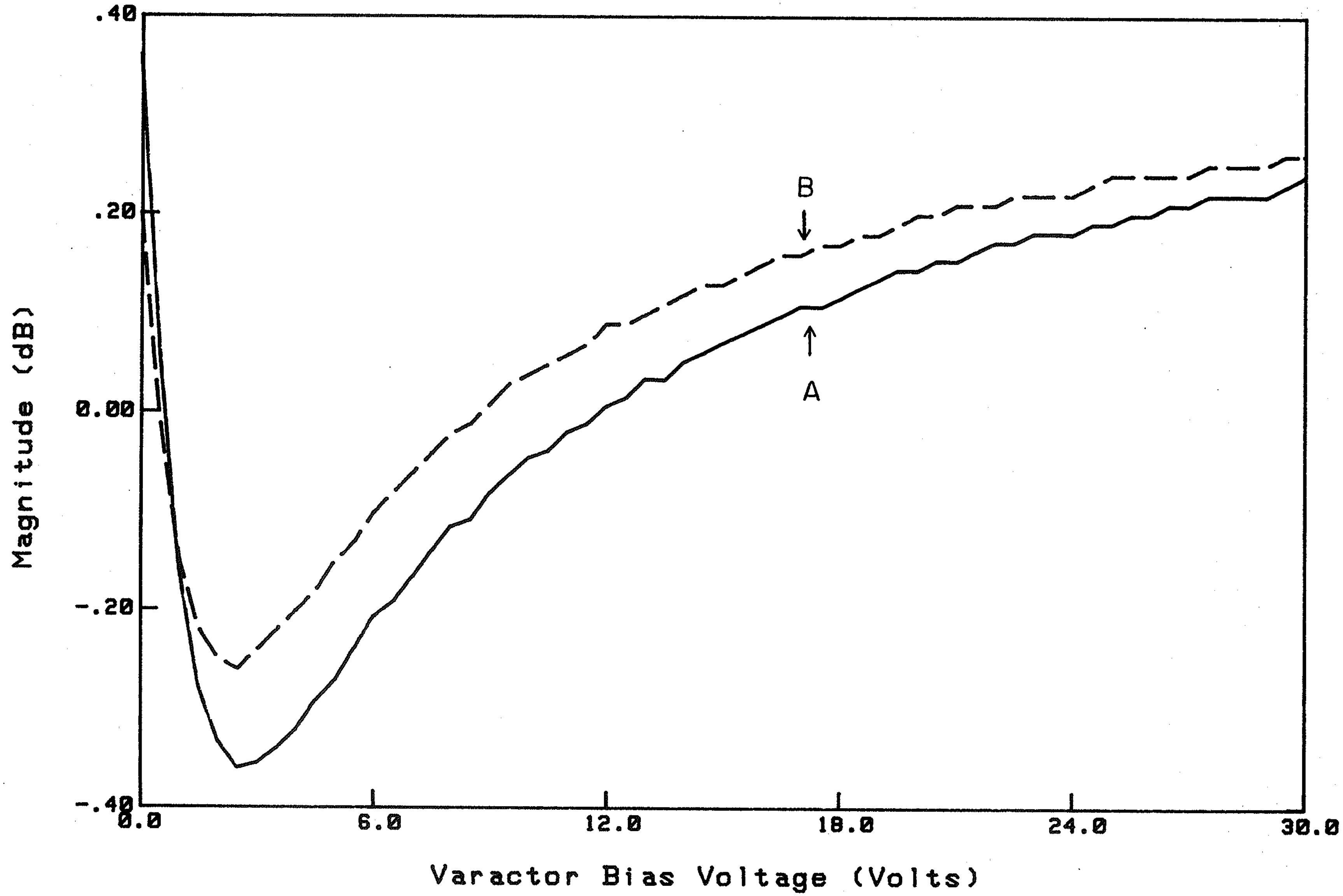


Figure 38. Comparison of amplitude response of 3.9 pF load, A, and 3.9 pF phase shifter, B.

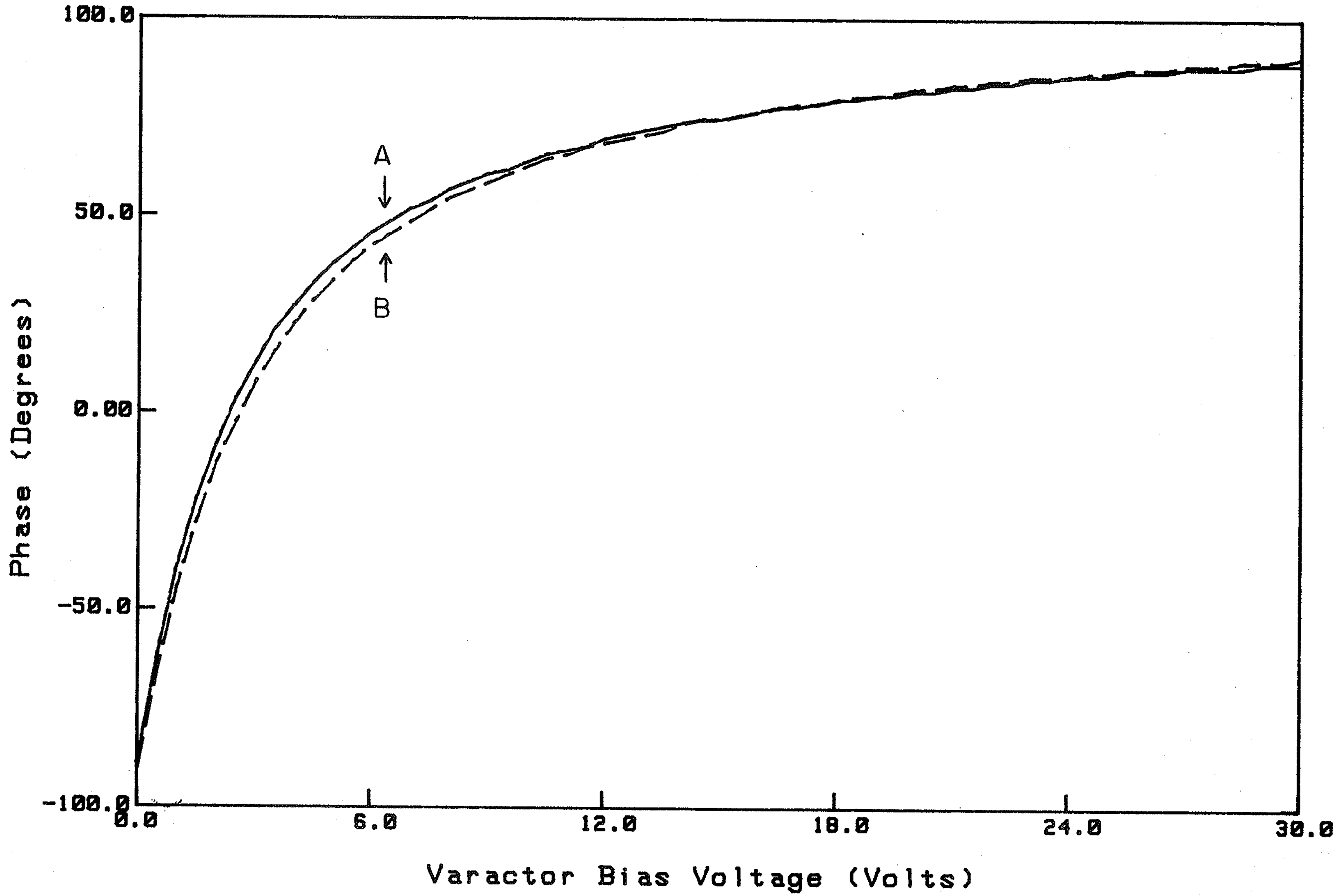


Figure 39. Comparison of phase response of 3.9 pF load, A, and 3.9 pF phase shifter, B.

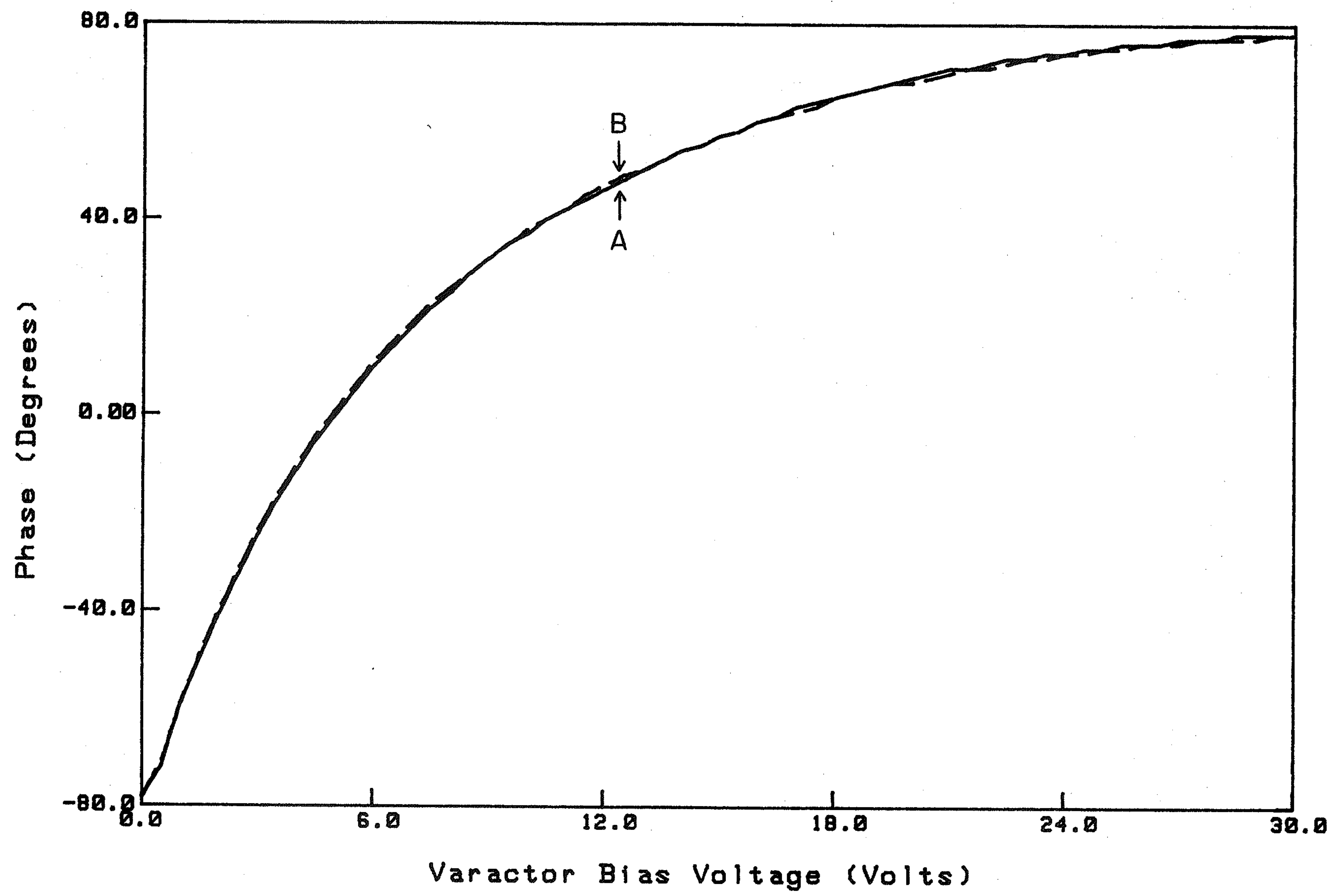


Figure 40. Comparison of phase response of 0 degree port load, A, and 90 degree port load, B, in 5.6 pF phase shifter.

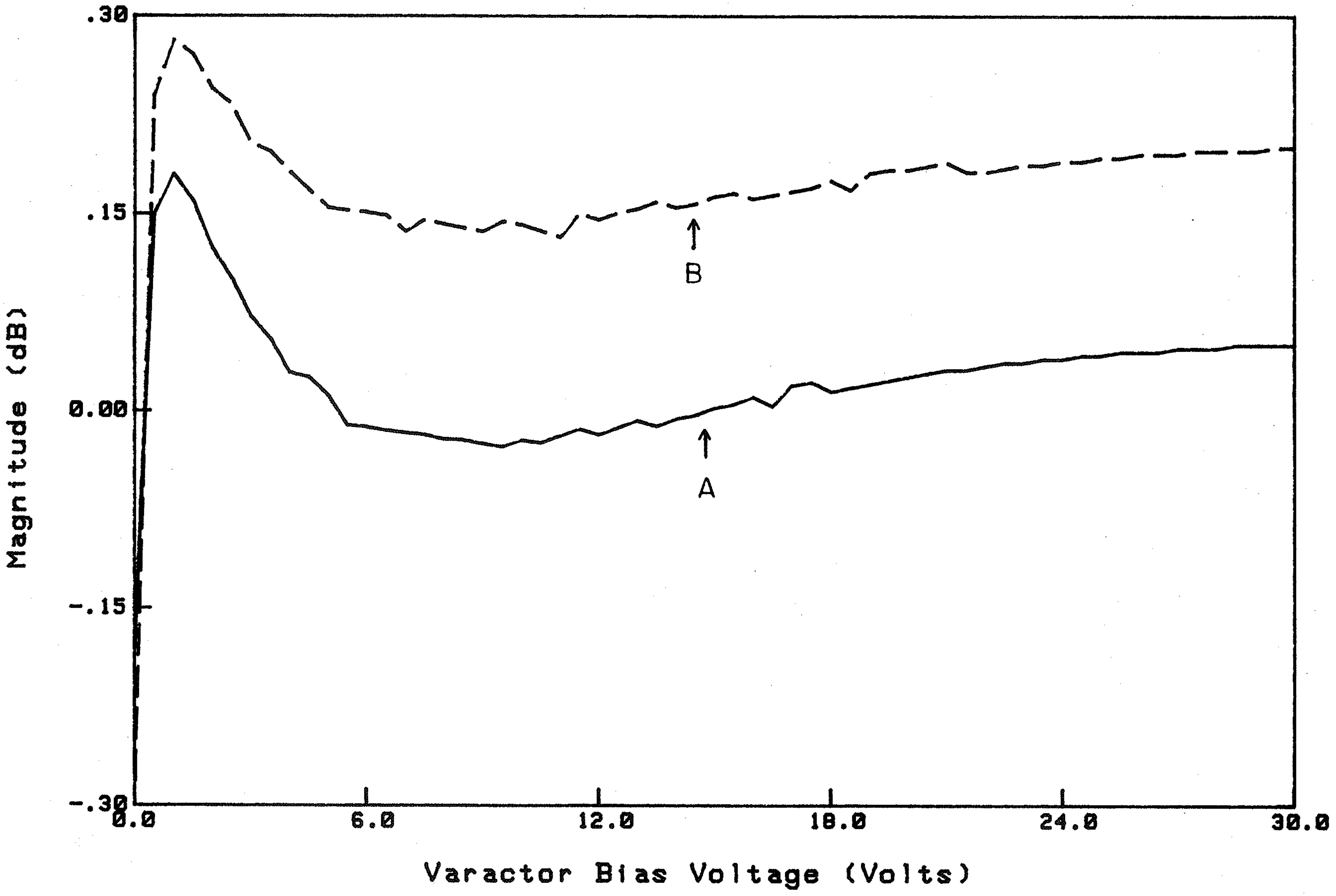


Figure 41. Comparison of amplitude response of 0 degree port load, A, and 90 degree port load, B, in 5.6 pF phase shifter.

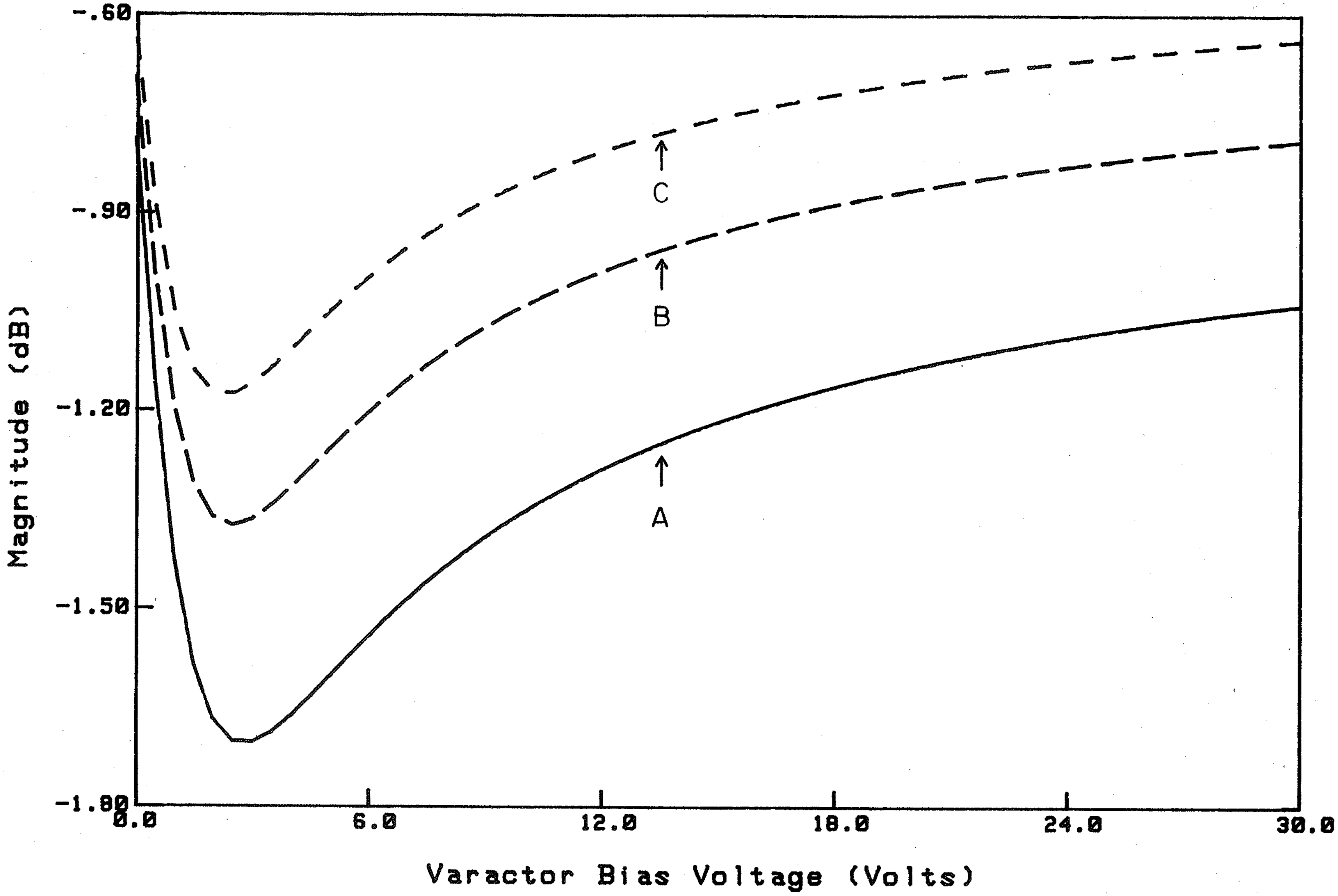


Figure 42. Comparison of amplitude response of 3.9 pF simulation for (A) Q = 31, (B) Q = 41, and (C) Q = 51.

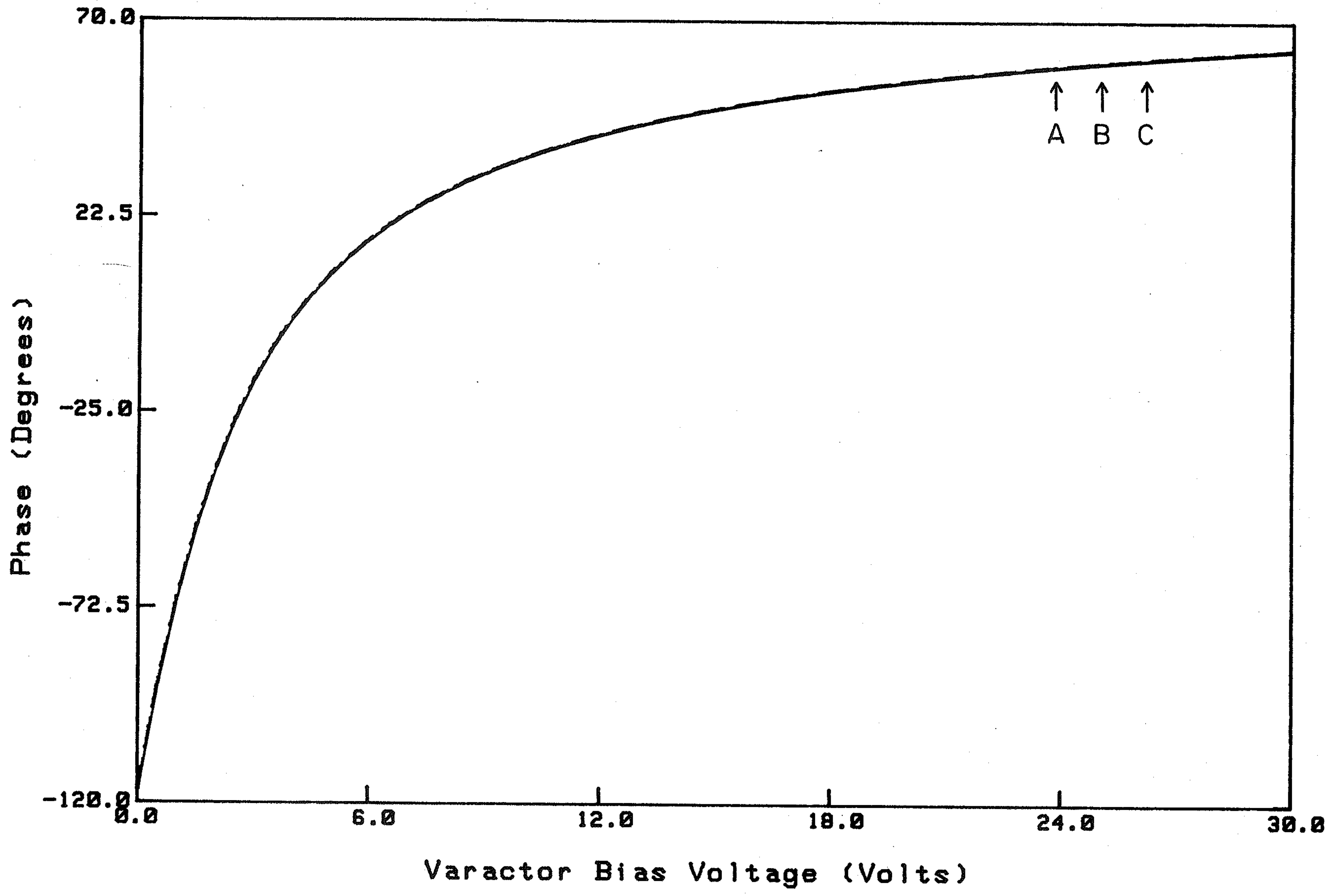


Figure 43. Comparison of phase response of 3.9 pF simulation for (A) Q = 31, (B) Q = 41, and (C) Q = 51.

# 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

$$f_{n,m} = \frac{c}{2\pi\sqrt{\epsilon_r}}\left[\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2\right]^{1/2} \qquad \text{(A.1)}$$

where c is the speed of light, $\epsilon_r$ 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 perimttivity gives

$$\epsilon_r = \frac{c^2}{4f_{n,m}}\left[\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2\right] \quad . \qquad \text{(A.2)}$$

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 dimensionx 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.E-7
160   Freperm=8.854E-12
170   INPUT "WHAT IS THE RELATIVE PERMITIVITY?",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 PERMITIVITY",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         Itemp=Indx(I+1)
520         Indx(I+1)=Indx(I)
530         Indx(I)=Itemp
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)),Bfrq(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

```
10     ! This program is used as an interactive optimizer to find the optimum
20     ! varactor-inductance combination to get a minimum loss variation for a
30     ! 180 degree phase variation.  The simulation uses a five element varactor
40     ! model with package capacitance (Cpack) of 18 pF, junction inductance
50     ! (Lj) of .4 nH and package inductance (Lp) of .05 nH.  The loss of the
60     ! varactor is modeled by a Q that varies with bias (modeled by a quadratic
70     ! fit of manufacturer's data).  The 4 volt Q is also a function of the 4
80     ! volt capacitance and is chosen according to manufacturer's specifica-
90     ! tions (Alpha Industries).  The progran prompts for the total 4 volt
100    ! capacitance (given by manufacturer) and different values are tried
110    ! until the minimum loss variation is achieved.  The inductance chosen
120    ! to resonate is modeled with a constant Q which represents the Q of all
130    ! the elements needed to realize the composite inductance (tuning cap,
140    ! transmission line loss, etc.).
150    ! STORED AS MDL_SHFTR
160    !July 3,1986 by Ron Boesch
170    OPTION BASE 1
180    DIM X(200),Y(200)
190    DIM X$[50],Y$[50],D$[50]
200    PRINTER IS CRT
210 Begin:   !
220    INPUT "What is the Capacitance at 4 V (including package capacitance)",C4
230    Z=50
240    Qpar=30.887
250    Omega=2*PI*9.15E+8
260    Cpack=1.8E-13
270    Lp=5.E-11
280    Lj=4.E-10
290    Ca=((1/(Omega*C4)+Omega*Lp)*Omega)^(-1)
300    Cb=Ca-Cpack
310    Cj4=((1/(Omega*Cb)+Omega*Lj)*Omega)^(-1)
320    Cj0=Cj4*((1+(4/.8))^.47)
330    Q915=(50/915)*1600
340    Qstart=Q915*(12/16)
350    Q4=(13/12)*Qstart
360 Startc:    !FINDING APPROPRIATE Q FOR C4
370    IF C4<3.31E-11 THEN Q4=(14/12)*Qstart
380    IF C4<2.21E-11 THEN Q4=(16/12)*Qstart
390    IF C4<1.81E-11 THEN Q4=(18/12)*Qstart
400    IF C4<1.51E-11 THEN Q4=(20/12)*Qstart
410    IF C4<1.21E-11 THEN Q4=(22/12)*Qstart
420    IF C4<1.01E-11 THEN Q4=(24/12)*Qstart
430    IF C4<8.21E-12 THEN Q4=(26/12)*Qstart
440    IF C4<6.81E-12 THEN Q4=(28/12)*Qstart
450    IF C4<5.61E-12 THEN Q4=(30/12)*Qstart
460    IF C4<4.71E-12 THEN Q4=(32/12)*Qstart
470    IF C4<3.91E-12 THEN Q4=(34/12)*Qstart
480    IF C4<3.31E-12 THEN Q4=(36/12)*Qstart
490    IF C4<2.71E-12 THEN Q4=(38/12)*Qstart
500    IF C4<2.21E-12 THEN Q4=(40/12)*Qstart
510    L=1/(Omega^2*Cj0)
520    CALL R_pmodel(Cj0,0,L,Cpack,Lp,Lj,Omega,Q4,Cmin,Rmin)
530    CALL R_pmodel(Cj0,30,L,Cpack,Lp,Lj,Omega,Q4,Cmax,Rmax)
540    Cmed=(Cmin+Cmax)/2
550    L=1/(Omega^2*Cmed)
560    Lres=L
570    Lfract=.2*L
580    L=L-Lfract
590    PRINTER IS 701
```

```
600   PRINT "FINDING LARGER INDUCTANCE THAT PROVIDES 180 SHIFT"
610   PRINTER IS CRT
620 Start:   L=L+Lfract
630   FOR I=0 TO 30 STEP 30
640   CALL R_pmodel(Cj0,I,L,Cpack,Lp,Lj,Omega,Q4,Copt,Ropt)
650   K1=1-((Omega^2)*L*Copt)
660   K2=Omega*L*(Ropt^2)*K1
670   K3=(Omega*L)^2+(Ropt*K1)^2
680   K4=(Omega*L)^2*Ropt-Z*K3
690   K5=(Omega*L)^2*Ropt+Z*K3
700   Ang1o=ATN(K2/K4)
710   IF K2<0 AND K4<0 THEN Ang1o=Ang1o-PI
720   IF K4<0 AND K2>0 THEN Ang1o=Ang1o-PI
730   Ang2o=ATN(K2/K5)
740   IF K2<0 AND K5<0 THEN Ang2o=Ang2o-PI
750   IF K2>0 AND K5<0 THEN Ang2o=Ang2o-PI
760   Ango=Ang1o-Ang2o
770   Angdego=(Ango*360)/(2*PI)
780   Angdego=Angdego MOD 360
790   IF ABS(Angdego)>180 THEN Angdego=Angdego-360*SGN(Angdego)
800   IF I=0 THEN Anglow=Angdego
810   IF I=30 THEN Angdif=Anglow-Angdego
820   NEXT I
830   PRINTER IS 701
840   IF ABS(Angdif)<190 THEN PRINT Angdif
850   IF ABS(Angdif)<200 THEN Lfract=.04*Lres
860   IF ABS(Angdif)<185 THEN Lfract=.01*Lres
870   IF ABS(Angdif)>180.5 THEN GOTO Start
880   PRINT "Q IS ASSUMED QUADRATIC, CHOSEN FOR 4 VOLT CAPACITANCE"
890   PRINT "PHASE SPAN=  ",Angdif
900   PRINT "INDUCTANCE=  ",L
910   PRINT "PACKAGE L=   ",Lj
920   PRINT "PACKAGE C=   ",Cpack
930   PRINT "Q(4)=        ",Q4
940   PRINT "CT(4)=       ",C4
950   CALL R_pmodel(Cj0,4,L,Cpack,Lp,Lj,Omega,Q4,Cp,Rp)
960   PRINT "C4(Resonant)=",Cp
970   PRINT "MEDIAN C=    ",Cmed
980   PRINT "CMAX(Res.)=  ",Cmin
990   PRINT "CMIN(Res.)   ",Cmax
1000  PRINT "C(0)/C(30)=  ",Cmin/Cmax
1010  PRINTER IS CRT
1020 Same: INPUT "Type 1 for MAG(dB) plot, 2 for PHASE plot",Flag2
1030  W=1
1040  Magdbmax=0
1050  Magdbmin=-100
1060  IF Flag2=1 THEN Label$="Mag(dB)"
1070  IF Flag2=2 THEN Label$="Phase"
1080  X$="Varactor Bias (Volts)"
1090  IF Flag2=1 THEN Y$="Return Loss (dB)"
1100  IF Flag2=2 THEN Y$="Phase (Degrees)"
1110  FOR I=0 TO 30 STEP .5
1120  X(W)=I
1130  CALL R_pmodel(Cj0,I,L,Cpack,Lp,Lj,Omega,Q4,Cp,Rp)
1140  K1=1-((Omega^2)*L*Cp)
1150  K2=Omega*L*(Rp^2)*K1
1160  K3=(Omega*L)^2+(Rp*K1)^2
1170  K4=(Omega*L)^2*Rp-Z*K3
1180  K5=(Omega*L)^2*Rp+Z*K3
1190  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  Ang1=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 Flag2=1 THEN PRINT "Maximum return loss",Magdbmax
1430  IF Flag2=1 THEN PRINT "Minimum return loss",Magdbmin
1440  IF Flag2=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 gragh 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  Col=2
1640  INPUT "What is the FILNAME?",Flname$
1650  CREATE BDAT Flname$,2*Total+10,8
1660  DISP "Saving simulation to disk."
1670  ASSIGN @Path1 TO Flname$
1680  OUTPUT @Path1,1;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 Same
```

```
1800  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,Xtitl$,Ytitl$,Dev$,Flag)
1920  C$=CHR$(255)&"K"
1930  Vxmin=1.E+49
1940  Vymin=1.E+49
1950  Vymax=-1.E+49
1960  Vxmax=-1.E+49
1970  FOR J=1 TO Numbf
1980  IF Valx(J)<Vxmin THEN Vxmin=Valx(J)    !Look into the file to
1990  IF Valx(J)>Vxmax THEN Vxmax=Valx(J)    !find the minimum and
2000  IF Valy(J)<Vymin THEN Vymin=Valy(J)    !maximum values to be
2010  IF Valy(J)>Vymax THEN Vymax=Valy(J)    !plotted
2020  NEXT J
2030  X1=Vxmin
2040  X2=Vxmax
2050  Y1=Vymin
2060  Y2=Vymax
2070  OUTPUT KBD;"|;"
2080  Startx=X1                              !Set X graph limits to the
2090  Stopx=X2                               !min and max found
2100  Starty=Y1-(Y2-Y1)/10                   !Set Y graph limits to the min
2110  Stopy=Y2+(Y2-Y1)/10                    !and max plus .1*(the span)
2120  Stepx=(Stopx-Startx)/10
2130  Stepy=(Stopy-Starty)/8
2140  ON KBD GOTO Exit              ! Provide exit
2150  OUTPUT 2 USING "#,K";C$       ! Clear screen for graph
2160  GINIT                         ! Initialize various graphics parameters.
2170  IF Flag=1 THEN PLOTTER IS 3,"INTERNAL"      ! Use the internal screen
2180  IF Flag=2 THEN PLOTTER IS 705,"HPGL"
2190  GRAPHICS ON                   ! Turn on the graphics screen
2200  LORG 6                        ! Reference point: center of top of label
2210  X_gdu_max=100*MAX(1,RATIO)    ! Determine how many GDUs wide the screen is
2220  Y_gdu_max=100*MAX(1,1/RATIO)  ! Determine how many GDUs high the screen is
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 smaller characters
2300  MOVE 0,Y_gdu_max/2            ! Move to center of left edge of screen
2310  LABEL USING "#,K";Ytitl$        ! Write Y-axis label
2320  LORG 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";Xtitl$      ! Write X-axis label
2360  VIEWPORT .1*X_gdu_max,.98*X_gdu_max,.15*Y_gdu_max,.9*Y_gdu_max
                                    ! Define subset of screen area
2370  WINDOW 0,100,16,18            ! Anisotropic scaling: left/right/bottom/top
2380  AXES 1,.05,0,16,5,5,3         ! Draw axes intersecting at lower left
```

```
2390  AXES 1,.05,100,18,5,5,3       ! Draw axes intersecting at upper right
2400  IF Flag=2 THEN 2420
2410  LINE TYPE 3
2420  GRID 10,.25,0,16,1,1          ! Draw grid with no minor ticks
2430  LINE TYPE 1
2440  CLIP OFF                      ! So labels can be outside VIEWPORT limits
2450  CSIZE 2.6,.6                  ! Smaller chars for axis labelling
2460  LORG 6                        ! Ref. pt: Top center      |\
2470  FOR I=0 TO 100 STEP 10        ! Every 10 units           | \
2480    MOVE I,15.99                ! A smidgeon below X-axis |  >  Label X-axis
2490    Fqw=Stepx/10*I+Startx
2500    IF ABS(Fqw)>=1000 THEN LABEL USING "#,5D.D";Fqw   ! Compact; no CR/LF
    | /
2510    IF ABS(Fqw)>=100 AND ABS(Fqw)<1000 THEN LABEL USING "#,4D.D";Fqw   ! Com
pact; no CR/LF        | /
2520    IF ABS(Fqw)>=10 AND ABS(Fqw)<100 THEN LABEL USING "#,3D.2D";Fqw   ! Comp
act; no CR/LF        | /
2530    IF ABS(Fqw)>1 AND ABS(Fqw)<10 THEN LABEL USING "#,2D.3D";Fqw
2540    IF ABS(Fqw)<1 THEN LABEL USING "#,D.3D";Fqw
2550  NEXT I                        ! et sequens               |/
2560  LORG 8                        ! Ref. pt: Right center     |\
2570  FOR I=16 TO 18 STEP .25       ! Every quarter              | \
2580  Valu=Stepy/.25*(I-16)+Starty
2590    MOVE -.5,I                  ! Smidgeon left of Y-axis  |  > Label Y-axis
2600   IF ABS(Valu)>=10 THEN LABEL USING "#,4D.D";Valu  ! DD.D; no CR/LF
   | /
2610   IF ABS(Valu)<10 AND ABS(Valu)>1 THEN LABEL USING "#,2D.2D";Valu
2620   IF ABS(Valu)<1 THEN LABEL USING "#,D.3D";Valu
2630  NEXT I                        ! et sequens                |/
2640  PENUP                         ! LABEL statement leaves the pen down
2650  PEN 2
2660  LINE TYPE 1
2670  FOR I=1 TO Numbf              ! Points to be plotted...
2680  Fry=16+.25/Stepy*(Valy(I)-Starty)
2690  Frx=10/Stepx*(Valx(I)-Startx)
2700  PLOT Frx,Fry
2710                                ! Get a data point and plot it against X
2720  NEXT I                        ! et cetera
2730  PEN 0
2740  LINE TYPE 1
2750  PAUSE
2760  OUTPUT KBD;"|;"
2770 Exit:  GRAPHICS OFF
2780        OUTPUT 2 USING "#,K";C$
2790  GINIT
2800  GCLEAR
2810                                ! finish
2820  SUBEND
2830  !*******************************************************************
2840  ! MODEL FOR THE VARACTOR            /L-C-R\                   /-C-\
2850  !                             -L--<        >-  converted to -<      >-
2860  !                                     \--C--/                   \-R-/
2870  !*******************************************************************
2880  SUB R_pmodel(Cj0,Vb,Lres,Cpack,Lpak,Lj,Omega,Q4,Cp,Rp)
2890 !Lj=4.E-10
2900 !Lpak=5.E-11
2910  Qpar=43.887                           !Constant Q due to board and Scap
2920  Q=(.4+(.13*Vb)+(.002*(Vb^2)))*Q4      !Quadratic Q vs. V dependence
2930  Cpv=(Cj0/((1+(Vb/.8))^.47))           !Junction capacitance
2940  Zpv=(1/(Omega*Cpv))-(Omega*Lj)        !Including effect of Lj
```

```
2950  Cpvb=(1/(Zpv*Omega))                     !New Cj with Lj accounted for
2960  Ct=Cpvb+Cpack                            !Add on parallel package cap.
2970  Zres=(1/(Ct*Omega))-(Omega*Lpak)         !Adding bonding Lp
2980  Cres=(1/(Zres*Omega))                    !Final resonant capacitance
2990  Rres=(Q*(Ct^2))/(Cpvb*Omega*(Cres^2))    !Parallel resistance from AI Q
3000  Rinduct=Qpar*Omega*Lres                  !Resistance from distributed L
3010  Rp=(Rres*Rinduct)/(Rres+Rinduct)         !Combination of resistors
3020  Cp=Cres .                                !Resonant C is parallel resonant
3030  PRINTER IS CRT
3040  PRINT Vb,Cpv,Cpvb,Cp
3050  PRINTER IS 701
3060  SUBEND
```

# APPENDIX

## LISTING OF AUTOMATED MEASUREMENT PROGRAMS

### 1. TERM 4

```
10    ! This program is designed to automate the testing of the phase
20    ! shifter.  It is a modified version of a 3 term error model,
30    ! TERM3, written to error correct for reflection measurements.
40    ! Since transmission needs to be measured, TERM3 is modified
50    ! to error correct the transmission terms.  The transmission
60    ! is corrected using half of an 8 term error model.(Hence it is a
70    ! 4 term error model)  The reflections are measured as S22 on the
80    ! test set and the transmissions are measured as S12 on the test
90    ! set.
100   ! STORED AS TERM4
110   ! Written May 14,1986 by Ronald D. Boesch
120   !  **********************************
130   !
140   !
150   OPTION BASE 1
160   DIM Dirm(221),Dirp(221),Openm(221),Openp(221),Esfm(221),Esfp(221)
170   DIM Erfm(221),Erfp(221)
180   DIM Dutm(221),Dutp(221),Shortm(221),Shortp(221)
190   DIM Fq(221),S11g(100),S11p(100),S21g(100),S21p(100),Volt(100)
200   DIM Tdutd(100),Tdutp(100),Rdutd(100),Rdutp(100)
210   DIM Esfr(221),Esfi(221),Erfi(221),Erfr(221),Dirr(221),Diri(221)
220   DIM Tmr(221),Tmi(221),Tmm(221),Tmp(221)
230   DIM X$[50],Y$[50],D$[50]
240   ABORT 7
250   LOCAL 7
260   REMOTE 7
270   Source=719.4
280   Processor=716
290   Test_set=720
300   Powersupply=722
310   Voltmeter=708
320   INPUT "Do you want to manually measure for 180 degree only (Y/N)?",Ans$
330   IF Ans$="N" OR Ans$="n" THEN GOTO Auto
340   DISP "Turn on powersupply, HP8505, and then hit CONT (f2)"
350   PAUSE
360   DISP "Hand calibrate 8505 then hit CONT (f2)"
370   PRINTER IS CRT
380   !
390   !
400   PRINT "********CALIBRATION SEQUENCE*********"
410   PRINT "Set start and stop frequencies, set marker at 915 MHz"
420   PRINT "***Reflection, S22"
430   PRINT "   Connect Reverse Short"
440   PRINT "   Channel 1: MKR,B/R,POLAR MAG,ZRO (hold until display zero)"
450   PRINT "   Electrical Length: B,CLR if REL lighted"
460   PRINT "              LENGTH and VERNIER B for smallest cluster,ZRO."
470   PRINT "   Channel 1: POLAR PHASE,ZRO (hold until display zero),"
480   PRINT "              REF, REF OFFSET so display reads +-180 degrees"
490   PRINT "              ZRO, MKR."
500   PRINT "***Transmission, S12"
510   PRINT "   Connect Through"
520   PRINT "   Channel 1: A/R,POLAR MAG,POLAR FULL 1,"
530   PRINT "              MKR,ZRO (hold until display zero),"
540   PRINT "   Electrical Length: A,CLR if REL lighted"
550   PRINT "              LENGTH and VERNIER A for smallest cluster,ZRO."
560   PRINT "   Channel 1: POLAR PHASE,ZRO (hold until display zero)"
570   PRINT "              DLY,ZRO (hold until display zero)."
580   PAUSE
590   PRINT USING "25/"
```

```
600    OUTPUT Powersupply;"VPOS 0;IPOS .3;FSOUT ON"
610    OUTPUT Voltmeter;"DCV; MODE TRIG"
620    !
630    !
640    !*******"Manual" OPERATION FOR TUNING TO 180 DEGRESS OF SHIFT***********
650    !
660  Manual:   OUTPUT Powersupply;"VPOS 0"
670    WAIT .2
680    OUTPUT Voltmeter;"DT TRIG"
690    ENTER Voltmeter;Vlt
700    DISP "Record transmission phase at 0 V then CONT"
710    PAUSE
720    OUTPUT Powersupply;"VPOS 30"
730    WAIT .2
740    OUTPUT Voltmeter;"DT TRIG"
750    ENTER Voltmeter;Vlt
760    DISP "Record transmission phase at 30 V then CONT"
770    PAUSE
780    INPUT "Is the manual measurement done (Y/N)?",Ans$
790    IF Ans$="n" OR Ans$="N" THEN GOTO Manual
800    OUTPUT Powersupply;"VPOS 0"
810    WAIT .2
820    OUTPUT Voltmeter;"DT TRIG"
830    ENTER Voltmeter;Vlt
840    !
850    !
860    !******AUTOMATED MEASUREMENT OF DEVICE AFTER TUNING********
870    !
880  Auto:   !Automated measurement section
890    OUTPUT Test_set;"2"
900    OUTPUT Source;"O6V99I1R3M3W4T1FBOE"
910    OUTPUT Processor;"COB1C1D2C2D2E"
920    IMAGE "FA",K"E"
930    BEEP
940    INPUT "ENTER START FREQUENCY(in Mhz,G.E. 600 Mhz)",Fstart
950    Fstart=Fstart*1.E+6
960    BEEP
970    INPUT "ENTER STOP FREQUENCY(in Mhz,L.E. 1200 Mhz)",Fstop
980    Fstop=Fstop*1.E+6
990    BEEP
1000   INPUT "ENTER STEP FREQUENCY(in Mhz)",Fstep
1010   Fstep=Fstep*1.E+6
1020   BEEP
1030   Numb=INT((Fstop-Fstart)/Fstep)+1
1040   PRINT USING "25/"
1050   PRINT "      ******** CALIBRATION  ********"
1060   PRINT USING "10/"
1070   OUTPUT Processor;"C1I5M2S2C2I5M3S2E"
1080   IMAGE "FA",K,"E"
1090   BEEP
1100   DISP "CONNECT 50 OHM LOAD (PORT 2) THEN HIT CONTINUE."
1110   PAUSE
1120   CALL Collect(Dirm(*),Dirp(*),Fstart,Fstop,Fstep,Fq(*))
1130   IF Dirm(1)>-32 THEN
1140     DISP "Load reflected G.E. -32 dB, Program Stopped"
1150     Flgstp=1
1160   END IF
1170   IF Flgstp=1 THEN STOP
1180   DISP "CONNECT SHORT (PORT 2) THEN HIT continue."
1190   PAUSE
```

```
1200  CALL Collect(Shortm(*),Shortp(*),Fstart,Fstop,Fstep,Fq(*))
1210  DISP "CONNECT OPEN (PORT 2) THEN HIT continue."
1220  PAUSE
1230  CALL Collect(Openm(*),Openp(*),Fstart,Fstop,Fstep,Fq(*))
1240  OUTPUT Processor;"C1I4C2I4E"
1250  DISP "CONNECT THROUGH THEN HIT continue."
1260  PAUSE
1270  CALL Collect(Tmm(*),Tmp(*),Fstart,Fstop,Fstep,Fq(*))
1280  PRINT USING "20/"
1290  DISP "Calculating intermediate calibration results"
1300  FOR I=1 TO Numb
1310  CALL Db_mag(Dirm(I),Dirmt)     ! CONVERT dB READINGS TO MAGNITUDE
1320  CALL Db_mag(Shortm(I),Shortmt)
1330  CALL Db_mag(Openm(I),Openmt)
1340  CALL Db_mag(Tmm(I),Tmmt)
1350  CALL P_r(Dirmt,Dirp(I),Dirr(I),Diri(I)) !CONVERT POLAR MAGNITUDE AND PHASE
1360  CALL P_r(Shortmt,Shortp(I),Shortr,Shorti) ! TO RECTANGULAR
1370  CALL P_r(Openmt,Openp(I),Openr,Openi)
1380  CALL P_r(Tmmt,Tmp(I),Tmr(I),Tmi(I))
1390  Esfrnum=Openr+Shortr-2*Dirr(I)    ! CALCULATE THE ERROR TERMS
1400  Esfinum=Openi+Shorti-2*Diri(I)    ! AND THE CORRECTED VALUES
1410  Esfrden=Openr-Shortr             ! rnum= REAL PART OF NUMERATOR
1420  Esfiden=Openi-Shorti             ! iden= IMAGINARY PART OF DENOMINATOR, ETC.
1430  CALL Cdiv(Esfrnum,Esfinum,Esfrden,Esfiden,Esfr(I),Esfi(I))
1440  Erfmr=Dirr(I)-Shortr
1450  Erfmi=Diri(I)-Shorti
1460  Erfrnum=2*Openr-2*Dirr(I)
1470  Erfinum=2*Openi-2*Diri(I)
1480  Erfrden=Openr-Shortr
1490  Erfiden=Openi-Shorti
1500  CALL Cdiv(Erfrnum,Erfinum,Erfrden,Erfiden,Em,Ei)
1510  CALL Cmult(Em,Ei,Erfmr,Erfmi,Erfr(I),Erfi(I))
1520  NEXT I  !END OF ERROR TERM GATHERING AND COMPUTATION
1530  !
1540  !
1550  !******DEVICE TRANSMISSION AND REFLECTION MEASUREMENT*****
1560  !
1570 Fques:  INPUT "FREQUENCY OF DEVICE MEASUREMENT(MHZ)",Fmeas
1580  INPUT "What is the title if this is to be plotted(<50)",D$
1590  Fmeas=Fmeas*1.E+6
1600  Num=INT((Fstop-Fstart)/Fstep)+1
1610  Fmeasi=-1
1620  FOR I=1 TO Num
1630    IF Fq(I)=Fmeas THEN Fmeasi=I
1640  NEXT I
1650  IF Fmeasi=-1 THEN
1660    DISP "Frequency out of range (or not integral multiple)"
1670    WAIT 1.5
1680    GOTO Fques
1690    DISP "                                     "
1700  END IF
1710  CALL Measdut(Fmeas,Tdutd(*),Tdutp(*),Rdutd(*),Rdutp(*),Volt(*))
1720  K=Fmeasi
1730  DISP "Performing error correction on measured data."
1740  !
1750  !
1760  !**********ERROR CORRECTION OF DEVICE MEASUREMENT*************
1770  !
1780  FOR I=1 TO 61
1790  CALL Db_mag(Rdutd(I),Rdutm)
```

```
1800  CALL P_r(Rdutm,Rdutp(I),Rdutr,Rduti)
1810  Sarnum=Rdutr-Dirr(K)
1820  Sainum=Rduti-Diri(K)
1830  CALL Cmult(Sarnum,Sainum,Esfr(K),Esfi(K),Ctemr,Ctemi)
1840  Sarden=Ctemr+Erfr(K)
1850  Saiden=Ctemi+Erfi(K)
1860  CALL Cdiv(Sarnum,Sainum,Sarden,Saiden,Sar,Sai)
1870  CALL R_p(Sar,Sai,Sam,Sap)
1880  CALL Mag_db(Sam,Sadb)
1890  S11g(I)=Sadb
1900  S11p(I)=Sap
1910  CALL Cmult(Esfr(K),Esfi(K),Sar,Sai,Ctmpr,Ctmpi)
1920  Ctmpr=1-Ctmpr
1930  CALL Db_mag(Tdutd(I),Tdutm)
1940  CALL P_r(Tdutm,Tdutp(I),Tdutr,Tduti)
1950  CALL Cmult(Tdutr,Tduti,Ctmpr,Ctmpi,Tnumr,Tnumi)
1960  CALL Cdiv(Tnumr,Tnumi,Tmr(K),Tmi(K),Trnsr,Trnsi)
1970  CALL R_p(Trnsr,Trnsi,Trnsm,Trnsp)
1980  CALL Mag_db(Trnsm,Trnsdb)
1990  S21g(I)=Trnsdb
2000  S21p(I)=Trnsp
2010  NEXT I
2020  !
2030  !
2040  !*************PLOTTING OF MEASUREMENT*************
2050  !
2060  X$="Varactor Bias (Volts)"
2070  INPUT "Would you like to make a plot(Y/N)?",Ans$
2080  IF Ans$="n" OR Ans$="N" THEN GOTO Save
2090 Reques:  INPUT "SCREENPLOT(1) or PAPERPLOT(2)",Flag
2100  IF Flag=1 THEN GOTO Pass
2110  IF Flag=2 THEN GOTO Pass
2120  GOTO Reques
2130 Pass:  INPUT "Transmission(1) or Reflection(2) plot",Flag3
2140  IF Flag3=1 THEN GOTO Transmit
2150  INPUT "Mag(1) or Phase(2) plot",Flag4
2160  IF Flag4=1 THEN GOTO Magplot1
2170  Y$="Reflected Phase (Degrees)"
2180  CALL Plotit(Volt(*),S11p(*),61,X$,Y$,D$,Flag)
2190  GOTO Ques
2200 Magplot1:  Y$="Reflected Return (dB)"
2210  CALL Plotit(Volt(*),S11g(*),61,X$,Y$,D$,Flag)
2220  GOTO Ques
2230 Transmit:  INPUT "Mag(1) or Phase(2) plot",Flag4
2240  IF Flag4=1 THEN GOTO Magplot2
2250  Y$="Transmission Phase (Degrees)"
2260  CALL Plotit(Volt(*),S21p(*),61,X$,Y$,D$,Flag)
2270  GOTO Ques
2280 Magplot2:  Y$="Transmission Loss"
2290  CALL Plotit(Volt(*),S21g(*),61,X$,Y$,D$,Flag)
2300 Ques:  INPUT "Would you like to plot something else?(Y/N)",Ans$
2310  IF Ans$="Y" OR Ans$="y" THEN GOTO Reques
2320  !
2330  !
2340  !*******************SAVING AND PRINTING OF DATA*************
2350  !
2360 Save:!Storage of data has yet to be done
2370  INPUT "Do you want a hard copy of the data(Y/N)?",Ans$
2380  IF Ans$="n" OR Ans$="N" THEN GOTO Sav2
2390  DISP "Make sure printer is on to get hard copy"
```

```
2400  PRINTER IS 701
2410  PRINT D$
2420  PRINT " "
2430  PRINT " "
2440  PRINT "      Voltage       Transmission                Reflection"
2450  PRINT "      Bias          Magnitude     Phase         Magnitude     Phase
"
2460  FOR I=1 TO 61
2470  PRINT USING "6X,DDDD.DDD";Volt(I),S21g(I),S21p(I),S11g(I),S11p(I)
2480  NEXT I
2490  PRINTER IS CRT
2500 Sav2:  INPUT "Do you want to save data to disk(Y/N)?",Ans$
2510  IF Ans$="N" OR Ans$="n" THEN GOTO Terminate
2520  Total=61
2530  Col=5
2540  INPUT "What is the name of the DATA FILE",Flname$
2550  CREATE BDAT Flname$,5*Total+10,8
2560  DISP "Saving data to disk"
2570  ASSIGN @Path1 TO Flname$
2580  OUTPUT @Path1,1;Total
2590  OUTPUT @Path1,2;Col
2600  W=1
2610  FOR I=3 TO Col*Total+3 STEP Col
2620     OUTPUT @Path1,I;Volt(W)
2630     OUTPUT @Path1,I+1;S21g(W)
2640     OUTPUT @Path1,I+2;S21p(W)
2650     OUTPUT @Path1,I+3;S11g(W)
2660     OUTPUT @Path1,I+4;S11p(W)
2670     W=W+1
2680  NEXT I
2690  ASSIGN @Path1 TO *
2700 Terminate:  !
2710  INPUT "would you like to make another measurement(Y/N)?",Ans$
2720  IF Ans$="y" OR Ans$="Y" THEN GOTO Fques
2730  DISP "done"
2740  WAIT .5
2750  DISP "    "
2760  END
2770  !
2780  !
2790  !************************ SUBROUTINES ***************************
2800  !
2810  !
2820  ! ****************************************************************
2830  !                 POLAR TO RECTANGULAR CONVERSION
2840  ! ****************************************************************
2850  SUB P_r(Pv1,Pv2,Pv3,Pv4)
2860  DEG
2870  Pv3=Pv1*COS(Pv2)
2880  Pv4=Pv1*SIN(Pv2)
2890  SUBEND
2900  !
2910  ! ****************************************************************
2920  !                  RECTANGULAR TO POLAR CONVERSION
2930  ! ****************************************************************
2940  !
2950  SUB R_p(Pv1,Pv2,Pv3,Pv4)
2960  DEG
2970  Pv3=SQR(Pv1*Pv1+Pv2*Pv2)
2980  Pv4=90*(SGN(Pv2)+(Pv2=0))
```

```
2990  IF Pv1=0 THEN 3010
3000  Pv4=ATN(Pv2/(Pv1+1.E-49))+Pv4*(1-SGN(Pv1))
3010  SUBEND
3020  !
3030  ! ****************************************************************
3040  !                          COMPLEX MULTIPLICATION
3050  ! ****************************************************************
3060  !
3070  SUB Cmult(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
3080 Cmult: !
3090    Pv5=Pv1*Pv3-Pv2*Pv4
3100    Pv6=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     Pv7=Pv3*Pv3+Pv4*Pv4
3200     Pv5=(Pv1*Pv3+Pv2*Pv4)/(Pv7+1.E-49)
3210     Pv6=(Pv2*Pv3-Pv1*Pv4)/(Pv7+1.E-49)
3220     SUBEND
3230  !
3240  !*****************************************************************
3250  !                          PLOTTING SUBROUTINE
3260  !*****************************************************************
3270  SUB Plotit(Valx(*),Valy(*),Numbf,Xtitl$,Ytitl$,Dev$,Flag)
3280  C$=CHR$(255)&"K"
3290  Vxmin=1.E+49
3300  Vymin=1.E+49
3310  Vymax=-1.E+49
3320  Vxmax=-1.E+49
3330  FOR J=1 TO Numbf
3340  IF Valx(J)<Vxmin THEN Vxmin=Valx(J)
3350  IF Valx(J)>Vxmax THEN Vxmax=Valx(J)
3360  IF Valy(J)<Vymin THEN Vymin=Valy(J)
3370  IF Valy(J)>Vymax THEN Vymax=Valy(J)
3380  NEXT J
3390  X1=Vxmin
3400  X2=Vxmax
3410  Y1=Vymin
3420  Y2=Vymax
3430  OUTPUT KBD;"|;"
3440  Startx=X1
3450  Stopx=X2
3460  Starty=Y1-(Y2-Y1)/10
3470  Stopy=Y2+(Y2-Y1)/10
3480  Stepx=(Stopx-Startx)/10
3490  Stepy=(Stopy-Starty)/8
3500  ON KBD GOTO Exit              ! Provide exit
3510  OUTPUT 2 USING "#,K";C$       ! 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 is 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  LORG 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,.05,0,16,5,5,3           ! 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  LORG 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  |  >  Label X-axis
3850    Fqw=Stepx/10*I+Startx
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   ! Com
pact; no CR/LF        | /
3880    IF ABS(Fqw)>=10 AND ABS(Fqw)<100 THEN LABEL USING "#,3D.2D";Fqw   ! Comp
act; 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  LORG 8                          ! Ref. pt: Right center    |\
3930  FOR I=16 TO 18 STEP .25         ! Every quarter            | \
3940  Valu=Stepy/.25*(I-16)+Starty
3950    MOVE -.5,I                    ! Smidgeon left of Y-axis  |  > Label 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 Frx,Fry
4070                                  ! Get a data point and plot it against X
4080  NEXT I                          ! et cetera
4090  PEN 0
4100  LINE TYPE 1
4110  PAUSE
4120  OUTPUT KBD;"|;"
4130 Exit:  GRAPHICS OFF
```

```
4140       OUTPUT 2 USING "#,K";C$
4150  GINIT
4160  GCLEAR
4170                             ! finis
4180  SUBEND
4190  !
4200  ! ************************************************************
4210  !                   DECIBEL TO MAGNITUDE CONVERSION
4220  ! ************************************************************
4230  !
4240  SUB Db_mag(Valdb,Valmg)
4250  Valmg=10^(Valdb/20)
4260  SUBEND
4270  !
4280  ! ************************************************************
4290  !                   MAGNITUDE TO DECIBEL CONVERSION
4300  ! ************************************************************
4310  !
4320  SUB Mag_db(Valmg,Valdb)
4330  Valdb=20*LGT(Valmg)
4340  SUBEND
4350  !
4360  ! ************************************************************
4370  !                 DATA GATHERING ROUTINE FOR STANDARDS
4380  ! ************************************************************
4390  !
4400  SUB Collect(Mag(*),Phase(*),Fstart,Fstop,Fstep,Fq(*))
4410  Processor=716
4420  IMAGE "FA",K,"E"
4430  Source=719   ! ********* 719.4 CHANGED TO 719
4440  Num=INT((Fstop-Fstart)/Fstep)+1
4450  Freq=Fstart-Fstep
4460  OUTPUT Source USING 4420;Freq  ! RATHER THAN WAITING AN UNUSUAL
4470  ! AMOUNT OF TIME (SEE LINE 2552) FOR THE FIRST DATA POINT
4480  ! THE FREQUENCY SOURCE MAY BE STEPPED BEFORE ANY DATA IS TAKEN
4490  WAIT .3
4500  ENTER Processor;Garbage1,Garbage2
4510  WAIT .3
4520  FOR I=1 TO Num
4530  Freq=Freq+Fstep
4540  Fq(I)=Freq
4550  OUTPUT Source USING 4420;Freq
4560                        ! READING ON THE FIRST MEASUREMENT THE FIRST TIME
4570                        ! THIS SUBPROGRAM IS CALLED - WAIT 7 IS SUFFICIENT
4580                        ! SOMETIMES, WAIT 11 WAS USED AND FOUND TO BE OK
4590                        ! ABOUT 50% OF THE TIME - WAIT 15 DIDN'T FAIL IN
4600                        ! ANY OF MY TRIALS.
4610  WAIT .3
4620 !IF I<>1 THEN GOTO Grab
4630 !WAIT 15
4640 Grab:  ENTER Processor;Mag(I),Phase(I)
4650  NEXT I
4660  BEEP
4670  SUBEND
4680  !
4690  ! ************************************************************
4700  !                 Routine For Measuring Device at
4710  !               Single Frequency From 0 to 30 Volts
4720  ! ************************************************************
4730  !
```

```
4740  SUB Measdut(Freq,Transm(*),Transp(*),Reflm(*),Reflp(*),Volt(*))
4750  DISP "Turn on 8505,DVM,Powersupply then CONT"
4760  PAUSE
4770  Processor=716    !Processor address
4780  Source=719       !Source address
4790  Powersupply=722  !Powersupply address
4800  Voltmeter=708    !Voltmeter address
4810  Test_set=720     !Test set address
4820  OUTPUT Powersupply;"VPOS 0;IPOS .3;FSOUT ON"
4830  OUTPUT Voltmeter;"DCV  ;MODE TRIG"
4840  OUTPUT Test_set;"2"
4850  OUTPUT Processor;"C1M2S5E"
4860  WAIT 2
4870 Key:  IMAGE "FA",K,"E"
4880  Offset=.03*Freq
4890  Freq=Freq-Offset
4900  OUTPUT Source USING Key;Freq
4910  WAIT .3
4920  DISP "CONNECT DEVICE THEN CONTINUE(f2)"
4930  PAUSE
4940  Freq=Freq+Offset
4950  OUTPUT Source USING Key;Freq
4960  ENTER Processor;Garbage1,Garbage2
4970  DISP "Measuring test device transmission with swept voltage"
4980  FOR I=1 TO 61
4990     V=(I-1)/2
5000     OUTPUT Powersupply;"VPOS";V
5010     WAIT .25
5020     OUTPUT Voltmeter;"DT TRIG"
5030     WAIT .25
5040     ENTER Voltmeter;Volt(I)
5050     ENTER Processor;Transm(I),Transp(I)
5060  NEXT I
5070  OUTPUT Processor;"C1I5S2C2I5E"    !Switch to reflection terms
5080  ENTER Processor;Garbage1,Garbage2
5090  DISP "Measuring test device reflection with swept voltage"
5100  FOR I=1 TO 61
5110     V=(I-1)/2
5120     OUTPUT Powersupply;"VPOS";V
5130     WAIT .25
5140     OUTPUT Voltmeter;"DT TRIG"
5150     WAIT .25
5160     ENTER Voltmeter;Volt(I)
5170     ENTER Processor;Reflm(I),Reflp(I)
5180  NEXT I
5190  OUTPUT Powersupply;"VPOS 0"
5200  OUTPUT Processor;"C1I4S5C2I4E"    !Switch back to transmission terms
5210  BEEP
5220  SUBEND
```

## 2.. TERM 3V

```
10    ! This program is designed to automate the testing of the phase
20    ! shifter.  It is a modified version of a 3 term error model,
30    ! TERM3, written to error correct for reflection measurements.
40    ! Since transmission needs to be measured, TERM3 is modified
50    ! to error correct the transmission terms.  The transmission
60    ! is corrected using half of a 8 term error model.(Hence it is a
70    ! 4 term.error model)  The reflections are measured as S22 on the
80    ! test set and the transmissions are measured as S12 on the test
90    ! set.
100   ! MODIFICATION: This program measures the phase shifting load.
110   ! That is, only the reflection coefficient.
120   ! STORED AS TERM3V
130   ! Written July 11,1986 by Ronald D. Boesch
140   !  **********************************
150   !
160   !
170   OPTION BASE 1
180   DIM Dirm(221),Dirp(221),Openm(221),Openp(221),Esfm(221),Esfp(221)
190   DIM Erfm(221),Erfp(221)
200   DIM Dutm(221),Dutp(221),Shortm(221),Shortp(221)
210   DIM Fq(221),S11g(100),S11p(100),Volt(100)
220   DIM Rdutd(100),Rdutp(100)
230   DIM Esfr(221),Esfi(221),Erfi(221),Erfr(221),Dirr(221),Diri(221)
240   DIM X$[50],Y$[50],D$[50]
250   ABORT 7
260   LOCAL 7
270   REMOTE 7
280   Source=719.4
290   Processor=716
300   Test_set=720
310   Powersupply=722
320   Voltmeter=708
330   INPUT "Do you want to manually measure for 180 degree only (Y/N)?",Ans$
340   IF Ans$="N" OR Ans$="n" THEN GOTO Auto
350   DISP "Turn on powersupply, HP8505, and then hit CONT (f2)"
360   PAUSE
370   DISP "Hand calibrate 8505 then hit CONT (f2)"
380   PRINTER IS CRT
390   !
400   !
410   PRINT "********CALIBRATION SEQUENCE*********"
420   PRINT "Set start and stop frequencies, set marker at 915 MHz"
430   PRINT "***Reflection, S22"
440   PRINT "   Connect Reverse Short"
450   PRINT "   Channel 1: MKR,B/R,POLAR MAG,ZRO (hold until display zero)"
460   PRINT "   Electrical Length: B,CLR if REL lighted"
470   PRINT "                      LENGTH and VERNIER B for smallest cluster,ZRO."
480   PRINT "   Channel 1: POLAR PHASE,ZRO (hold until display zero),"
490   PRINT "                      REF, REF OFFSET so display reads +-180 degrees"
500   PRINT "                      ZRO, MKR."
510   PRINT "***Transmission, S12"
520   PRINT "   Connect Through"
530   PRINT "   Channel 1: A/R,POLAR MAG,POLAR FULL 1,"
540   PRINT "                      MKR,ZRO (hold until display zero),"
550   PRINT "   Electrical Length: A,CLR if REL lighted"
560   PRINT "                      LENGTH and VERNIER A for smallest cluster,ZRO."
570   PRINT "   Channel 1: POLAR PHASE,ZRO (hold until display zero)"
580   PRINT "                      DLY,ZRO (hold until display zero)."
590   PAUSE
```

```
600   PRINT USING "25/"
610   OUTPUT Powersupply;"VPOS 0;IPOS .3;FSOUT ON"
620   OUTPUT Voltmeter;"DCV; MODE TRIG"
630   !
640   !
650   !*******"Manual" OPERATION FOR TUNING TO 180 DEGRESS 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;"O6V99I1R3M3W4T1FBOE"
920   OUTPUT Processor;"COB1C1D2C2D2E"
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  Numb=INT((Fstop-Fstart)/Fstep)+1
1050  PRINT USING "25/"
1060  PRINT "     ******** CALIBRATION  ********"
1070  PRINT USING "10/"
1080  OUTPUT Processor;"C1I5M2S2C2I5M3S2E"
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    Flgstp=1
1170  END IF
1180  IF Flgstp=1 THEN STOP
1190  DISP "CONNECT SHORT (PORT 2) THEN HIT continue."
```

```
1200  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 Db_mag(Dirm(I),Dirmt)     ! CONVERT dB READINGS TO MAGNITUDE
1290  CALL Db_mag(Shortm(I),Shortmt)
1300  CALL Db_mag(Openm(I),Openmt)
1310  CALL P_r(Dirmt,Dirp(I),Dirr(I),Diri(I)) !CONVERT POLAR MAGNITUDE AND PHASE
1320  CALL P_r(Shortmt,Shortp(I),Shortr,Shorti) ! TO RECTANGULAR
1330  CALL P_r(Openmt,Openp(I),Openr,Openi)
1340  Esfrnum=Openr+Shortr-2*Dirr(I)    ! CALCULATE THE ERROR TERMS
1350  Esfinum=Openi+Shorti-2*Diri(I)    ! AND THE CORRECTED VALUES
1360  Esfrden=Openr-Shortr             ! rnum= REAL PART OF NUMERATOR
1370  Esfiden=Openi-Shorti             ! iden= IMAGINARY PART OF DENOMINATOR, ETC.
1380  CALL Cdiv(Esfrnum,Esfinum,Esfrden,Esfiden,Esfr(I),Esfi(I))
1390  Erfmr=Dirr(I)-Shortr
1400  Erfmi=Diri(I)-Shorti
1410  Erfrnum=2*Openr-2*Dirr(I)
1420  Erfinum=2*Openi-2*Diri(I)
1430  Erfrden=Openr-Shortr
1440  Erfiden=Openi-Shorti
1450  CALL Cdiv(Erfrnum,Erfinum,Erfrden,Erfiden,Em,Ei)
1460  CALL Cmult(Em,Ei,Erfmr,Erfmi,Erfr(I),Erfi(I))
1470  NEXT I  !END OF ERROR TERM GATHERING AND COMPUTATION
1480  !
1490  !
1500  !******DEVICE TRANSMISSION AND REFLECTION MEASUREMENT*****
1510  !
1520 Fques:  INPUT "FREQUENCY OF DEVICE MEASUREMENT(MHZ)",Fmeas
1530  INPUT "What is the title if this is to be plotted(<50)",D$
1540  Fmeas=Fmeas*1.E+6
1550  Num=INT((Fstop-Fstart)/Fstep)+1
1560  Fmeasi=-1
1570  FOR I=1 TO Num
1580    IF Fq(I)=Fmeas THEN Fmeasi=I
1590  NEXT I
1600  IF Fmeasi=-1 THEN
1610    DISP "Frequency out of range (or not integral multiple)"
1620    WAIT 1.5
1630    GOTO Fques
1640    DISP "                                             "
1650  END IF
1660  CALL Measdut(Fmeas,Rdutd(*),Rdutp(*),Volt(*))
1670  K=Fmeasi
1680  DISP "Performing error correction on measured data."
1690  !
1700  !
1710  !**********ERROR CORRECTION OF DEVICE MEASUREMENT*************
1720  !
1730  FOR I=1 TO 61
1740  CALL Db_mag(Rdutd(I),Rdutm)
1750  CALL P_r(Rdutm,Rdutp(I),Rdutr,Rduti)
1760  Sarnum=Rdutr-Dirr(K)
1770  Sainum=Rduti-Diri(K)
1780  CALL Cmult(Sarnum,Sainum,Esfr(K),Esfi(K),Ctemr,Ctemi)
1790  Sarden=Ctemr+Erfr(K)
```

```
1800  Saiden=Ctemi+Erfi(K)
1810  CALL Cdiv(Sarnum,Sainum,Sarden,Saiden,Sar,Sai)
1820  CALL R_p(Sar,Sai,Sam,Sap)
1830  CALL Mag_db(Sam,Sadb)
1840  S11g(I)=Sadb
1850  S11p(I)=Sap
1860  NEXT I
1870  !
1880  !
1890  !*************PLOTTING OF MEASUREMENT*************
1900  !
1910  X$="Varactor Bias (Volts)"
1920  INPUT "Would you like to make a plot(Y/N)?",Ans$
1930  IF Ans$="n" OR Ans$="N" THEN GOTO Save
1940 Reques:  INPUT "SCREENPLOT(1) or PAPERPLOT(2)",Flag
1950  IF Flag=1 THEN GOTO Pass
1960  IF Flag=2 THEN GOTO Pass
1970  GOTO Reques
1980 Pass:  Flag3=2
1990  IF Flag3=1 THEN GOTO Transmit
2000  INPUT "Mag(1) or Phase(2) plot",Flag4
2010  IF Flag4=1 THEN GOTO Magplot1
2020  Y$="Reflected Phase (Degrees)"
2030  CALL Plotit(Volt(*),S11p(*),61,X$,Y$,D$,Flag)
2040  GOTO Ques
2050 Magplot1:  Y$="Reflected Return (dB)"
2060  CALL Plotit(Volt(*),S11g(*),61,X$,Y$,D$,Flag)
2070  GOTO Ques
2080 Transmit:  INPUT "Mag(1) or Phase(2) plot",Flag4
2090  IF Flag4=1 THEN GOTO Magplot2
2100  Y$="Transmission Phase (Degrees)"
2110 !CALL Plotit(Volt(*),S21p(*),61,X$,Y$,D$,Flag)
2120  GOTO Ques
2130 Magplot2:  Y$="Transmission Loss"
2140 !CALL Plotit(Volt(*),S21g(*),61,X$,Y$,D$,Flag)
2150 Ques:  INPUT "Would you like to plot something else?(Y/N)",Ans$
2160  IF Ans$="Y" OR Ans$="y" THEN GOTO Reques
2170  !
2180  !
2190  !*******************SAVING AND PRINTING OF DATA*************
2200  !
2210 Save:!Storage of data has yet to be done
2220  INPUT "Do you want a hard copy of the data(Y/N)?",Ans$
2230  IF Ans$="n" OR Ans$="N" THEN GOTO Sav2
2240  DISP "Make sure printer is on to get hard copy"
2250  PRINTER IS 701
2260  PRINT D$
2270  PRINT " "
2280  PRINT " "
2290  PRINT "      Voltage       Reflection"
2300  PRINT "      Bias          Magnitude     Phase     "
2310  FOR I=1 TO 61
2320  PRINT USING "6X,DDDD.DDD";Volt(I),S11g(I),S11p(I)
2330  NEXT I
2340  PRINTER IS CRT
2350 Sav2:  INPUT "Do you want to save data to disk(Y/N)?",Ans$
2360  IF Ans$="N" OR Ans$="n" THEN GOTO Terminate
2370  Total=61
2380  Col=3
2390  INPUT "What is the name of the DATA FILE",Flname$
```

```
2400  CREATE BDAT Flname$,3*Total+10,8
2410  DISP "Saving data to disk"
2420  ASSIGN @Path1 TO Flname$
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 GOTO Fques
2560  DISP "done"
2570  WAIT .5
2580  DISP "    "
2590  END
2600  !
2610  !
2620  !************************ SUBROUTINES ***************************
2630  !
2640  !
2650  ! *****************************************************************
2660  !                  POLAR TO RECTANGULAR CONVERSION
2670  ! *****************************************************************
2680  SUB P_r(Pv1,Pv2,Pv3,Pv4)
2690  DEG
2700  Pv3=Pv1*COS(Pv2)
2710  Pv4=Pv1*SIN(Pv2)
2720  SUBEND
2730  !
2740  ! *****************************************************************
2750  !                   RECTANGULAR TO POLAR CONVERSION
2760  ! *****************************************************************
2770  !
2780  SUB R_p(Pv1,Pv2,Pv3,Pv4)
2790  DEG
2800  Pv3=SQR(Pv1*Pv1+Pv2*Pv2)
2810  Pv4=90*(SGN(Pv2)+(Pv2=0))
2820  IF Pv1=0 THEN 2840
2830  Pv4=ATN(Pv2/(Pv1+1.E-49))+Pv4*(1-SGN(Pv1))
2840  SUBEND
2850  !
2860  ! ******************************************************************
2870  !                       COMPLEX MULTIPLICATION
2880  ! ******************************************************************
2890  !
2900  SUB Cmult(Pv1,Pv2,Pv3,Pv4,Pv5,Pv6)
2910 Cmult: !
2920    Pv5=Pv1*Pv3-Pv2*Pv4
2930    Pv6=Pv1*Pv4+Pv2*Pv3
2940    SUBEND
2950  !
2960  ! ******************************************************************
2970  !                         COMPLEX  DIVISION
2980  ! ******************************************************************
2990  !
```

```
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$(255)&"K"
3120  Vxmin=1.E+49
3130  Vymin=1.E+49
3140  Vymax=-1.E+49
3150  Vxmax=-1.E+49
3160  FOR J=1 TO Numbf
3170  IF Valx(J)<Vxmin THEN Vxmin=Valx(J)
3180  IF Valx(J)>Vxmax THEN Vxmax=Valx(J)
3190  IF Valy(J)<Vymin THEN Vymin=Valy(J)
3200  IF Valy(J)>Vymax THEN Vymax=Valy(J)
3210  NEXT J
3220  X1=Vxmin
3230  X2=Vxmax
3240  Y1=Vymin
3250  Y2=Vymax
3260  OUTPUT KBD;"|;"
3270  Startx=X1
3280  Stopx=X2
3290  Starty=Y1-(Y2-Y1)/10
3300  Stopy=Y2+(Y2-Y1)/10
3310  Stepx=(Stopx-Startx)/10
3320  Stepy=(Stopy-Starty)/8
3330  ON KBD GOTO Exit               ! Provide exit
3340  OUTPUT 2 USING "#,K";C$        ! Clear screen for graph
3350  GINIT                          ! Initialize various graphics parameters.
3360  IF Flag=1 THEN PLOTTER IS 3,"INTERNAL"        ! Use the internal screen
3370  IF Flag=2 THEN PLOTTER IS 705,"HPGL"
3380  GRAPHICS ON                    ! Turn on the graphics screen
3390  LORG 6                         ! Reference point: center of top of label
3400  X_gdu_max=100*MAX(1,RATIO)     ! Determine how many GDUs wide the screen is
3410  Y_gdu_max=100*MAX(1,1/RATIO)   ! Determine how many GDUs high the screen is
3420  FOR I=-.3 TO .3 STEP .1        ! Offset of X from starting point
3430    MOVE X_gdu_max/2+I,Y_gdu_max! Move to about middle of top of screen
3440    LABEL USING "#,K";Dev$        ! Write title of plot
3450  NEXT I                         ! Next position for title
3460  DEG                            ! Angular mode is degrees (used in LDIR)
3470  LDIR 90                        ! Specify vertical labels
3480  CSIZE 3.5                      ! Specify smaller characters
3490  MOVE 0,Y_gdu_max/2             ! Move to center of left edge of screen
3500  LABEL USING "#,K";Ytitl$          ! Write Y-axis label
3510  LORG 4                         ! Reference point: center of bottom of label
3520  LDIR 0                         ! Horizontal labels again
3530  MOVE X_gdu_max/2,.07*Y_gdu_max! X: center of screen; Y: above key labels
3540  LABEL USING "#,K";Xtitl$       ! Write X-axis label
3550  VIEWPORT .1*X_gdu_max,.98*X_gdu_max,.15*Y_gdu_max,.9*Y_gdu_max
                                     ! Define subset of screen area
3560  WINDOW 0,100,16,18             ! Anisotropic scaling: left/right/bottom/top
3570  AXES 1,.05,0,16,5,5,3          ! Draw axes intersecting at lower left
3580  AXES 1,.05,100,18,5,5,3        ! Draw axes intersecting at upper right
```

```
3590  IF Flag=2 THEN 3610
3600  LINE TYPE 3
3610  GRID 10,.25,0,16,1,1          ! Draw grid with no minor ticks
3620  LINE TYPE 1
3630  CLIP OFF                      ! So labels can be outside VIEWPORT limits
3640  CSIZE 2.6,.6                  ! Smaller chars for axis labelling
3650  LORG 6                        ! Ref. pt: Top center      |\
3660  FOR I=0 TO 100 STEP 10        ! Every 10 units           | \
3670    MOVE I,15.99                ! A smidgeon below X-axis |  >  Label X-axis
3680    Fqw=Stepx/10*I+Startx
3690    IF ABS(Fqw)>=1000 THEN LABEL USING "#,5D.D";Fqw   ! Compact; no CR/LF
    | /
3700    IF ABS(Fqw)>=100 AND ABS(Fqw)<1000 THEN LABEL USING "#,4D.D";Fqw   ! Com
pact; no CR/LF         | /
3710    IF ABS(Fqw)>=10 AND ABS(Fqw)<100 THEN LABEL USING "#,3D.2D";Fqw   ! Comp
act; no CR/LF          | /
3720    IF ABS(Fqw)>1 AND ABS(Fqw)<10 THEN LABEL USING "#,2D.3D";Fqw
3730    IF ABS(Fqw)<1 THEN LABEL USING "#,D.3D";Fqw
3740  NEXT I                        ! et sequens               |/
3750  LORG 8                        ! Ref. pt: Right center    |\
3760  FOR I=16 TO 18 STEP .25       ! Every quarter            | \
3770  Valu=Stepy/.25*(I-16)+Starty
3780    MOVE -.5,I                  ! Smidgeon left of Y-axis  |  > Label Y-axis
3790   IF ABS(Valu)>=10 THEN LABEL USING "#,4D.D";Valu  ! DD.D; no CR/LF
   | /
3800   IF ABS(Valu)<10 AND ABS(Valu)>1 THEN LABEL USING "#,2D.2D";Valu
3810   IF ABS(Valu)<1 THEN LABEL USING "#,D.3D";Valu
3820  NEXT I                        ! et sequens               |/
3830  PENUP                         ! LABEL statement leaves the pen down
3840  PEN 2
3850  LINE TYPE 1
3860  FOR I=1 TO Numbf              ! Points to be plotted...
3870  Fry=16+.25/Stepy*(Valy(I)-Starty)
3880  Frx=10/Stepx*(Valx(I)-Startx)
3890  PLOT Frx,Fry
3900                                ! Get a data point and plot it against X
3910  NEXT I                        ! et cetera
3920  PEN 0
3930  LINE TYPE 1
3940  PAUSE
3950  OUTPUT KBD;"|;"
3960 Exit:  GRAPHICS OFF
3970        OUTPUT 2 USING "#,K";C$
3980  GINIT
3990  GCLEAR
4000                                ! finis
4010  SUBEND
4020  !
4030  ! **************************************************************
4040  !                  DECIBEL TO MAGNITUDE CONVERSION
4050  ! **************************************************************
4060  !
4070  SUB Db_mag(Valdb,Valmg)
4080  Valmg=10^(Valdb/20)
4090  SUBEND
4100  !
4110  ! **************************************************************
4120  !                  MAGNITUDE TO DECIBEL CONVERSION
4130  ! **************************************************************
4140  !
```

```
4150  SUB Mag_db(Valmg,Valdb)
4160  Valdb=20*LGT(Valmg)
4170  SUBEND
4180  !
4190  ! ***********************************************************
4200  !                 DATA GATHERING ROUTINE FOR STANDARDS
4210  ! ***********************************************************
4220  !
4230  SUB Collect(Mag(*),Phase(*),Fstart,Fstop,Fstep,Fq(*))
4240  Processor=716
4250  IMAGE "FA",K,"E"
4260  Source=719   ! ********* 719.4 CHANGED TO 719
4270  Num=INT((Fstop-Fstart)/Fstep)+1
4280  Freq=Fstart-Fstep
4290  OUTPUT Source USING 4250;Freq  ! RATHER THAN WAITING AN UNUSUAL
4300  ! AMOUNT OF TIME (SEE LINE 2552) FOR THE FIRST DATA POINT
4310  ! THE FREQUENCY SOURCE MAY BE STEPPED BEFORE ANY DATA IS TAKEN
4320  WAIT .3
4330  ENTER Processor;Garbage1,Garbage2
4340  WAIT .3
4350  FOR I=1 TO Num
4360  Freq=Freq+Fstep
4370  Fq(I)=Freq
4380  OUTPUT Source USING 4250;Freq
4390                        ! READING ON THE FIRST MEASUREMENT THE FIRST TIME
4400                        ! THIS SUBPROGRAM IS CALLED - WAIT 7 IS SUFFICIENT
4410                        ! SOMETIMES, WAIT 11 WAS USED AND FOUND TO BE OK
4420                        ! ABOUT 50% OF THE TIME - WAIT 15 DIDN'T FAIL IN
4430                        ! ANY OF MY TRIALS.
4440  WAIT .3
4450 !IF I<>1 THEN GOTO Grab
4460 !WAIT 15
4470 Grab:  ENTER Processor;Mag(I),Phase(I)
4480  NEXT I
4490  BEEP
4500  SUBEND
4510  !
4520  ! ***********************************************************
4530  !                 Routine For Measuring Device at
4540  !               Single Frequency From 0 to 30 Volts
4550  ! ***********************************************************
4560  !
4570  SUB Measdut(Freq,Reflm(*),Reflp(*),Volt(*))
4580  DISP "Turn on 8505,DVM,Powersupply then CONT"
4590  PAUSE
4600  Processor=716     !Processor address
4610  Source=719        !Source address
4620  Powersupply=722   !Powersupply address
4630  Voltmeter=708     !Voltmeter address
4640  Test_set=720      !Test set address
4650  OUTPUT Powersupply;"VPOS 0;IPOS .3;FSOUT ON"
4660  OUTPUT Voltmeter;"DCV  ;MODE TRIG"
4670  OUTPUT Test_set;"2"
4680  WAIT 2
4690 Key:  IMAGE "FA",K,"E"
4700  Offset=.03*Freq
4710  Freq=Freq-Offset
4720  OUTPUT Source USING Key;Freq
4730  WAIT .3
4740  DISP "CONNECT DEVICE THEN CONTINUE(f2)"
```

```
4750  PAUSE
4760  Freq=Freq+Offset
4770  OUTPUT Source USING Key;Freq
4780  OUTPUT Processor;"C1I5S5C2I5E"     !Switch to reflection terms
4790  ENTER Processor;Garbage1,Garbage2
4800  DISP "Measuring test device reflection with swept voltage"
4810  FOR I=1 TO 61
4820     V=(I-1)/2
4830     OUTPUT Powersupply;"VPOS";V
4840     WAIT .25
4850     OUTPUT Voltmeter;"DT TRIG"
4860     WAIT .25
4870     ENTER Voltmeter;Volt(I)
4880     ENTER Processor;Reflm(I),Reflp(I)
4890  NEXT I
4900  OUTPUT Powersupply;"VPOS 0"
4910  BEEP
4920  SUBEND
```

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