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MICROWAVE SENSING OF BULK ELECTRICAL PROPERTIES OF TANK PAD RUBBER

CONTRACT DAAE07-86-C-R040

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This program was initiated to develop a nondestructive test to measure the average electrical conductivity of tank pad rubber. The conductivity of tank pad rubber is related to the consistency of the rubber.

The recommended test consists of relating the measured reflection coefficient of the tank pad to the tank pad conductivity. The reliability and effectiveness of the test is being evaluated, and the measurement interpretation process is being automated.

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1.0. INTRODUCTION

This interim technical report, prepared by R. C. Robertson and M. W. Lee of Virginia Tech for the U.S. Army Tank-Automotive Command (TACOM) under Contract DAAE07-86-C-R040, describes an investigation of nondestructive measurement techniques to determine the average electrical conductivity of tank pad rubber. All of the techniques investigated are based on the measurement of a microwave signal that has been reflected by the tank pad.

2.0. OBJECTIVE

The primary goal is to devise a nondestructive test capable of making reliable measurements of the average electrical conductivity of tank pad rubber. The conductivity of tank pad rubber is directly related to the amount and uniformity of dispersion of carbon black and other impurities in the rubber; hence, the conductivity of the tank pad rubber is an indication of tank pad consistency.

3.0. CONCLUSIONS

Several microwave measurement procedures have been investigated, and the most promising test has been identified. Further evaluation is required to determine the reliability and effectiveness of the selected test.

4.0. RECOMMENDATIONS

The recommended test procedure consists of two main components: a hardware component for measuring the reflected microwave signal, and a software component for inferring the average electrical conductivity of the tank pad from the measurements. The hardware portion of the test should not contain horn antennas, and all measurements should be taken with the waveguide placed directly against the tank pad in order to minimize the effect of other objects in the vicinity. Both the magnitude and phase of the reflection coefficient should be measured at a number of frequencies. Determination of the conductivity from the measured magnitude and phase information is based on a graphical interpretation of the data. The graphical interpretation procedure is unwieldy and should be replaced with an automated interpretation procedure.

5.0. DISCUSSION

5.1. <u>System Requirements</u>

Previous research has established that the conductivity of rubber is dependent on its composition and on the procedure by which its components are mixed [1]. TACOM wishes to exploit this relationship by devising a test scheme that will measure the electrical properties of tank pad rubber during quality control. It is believed that abnormally low conductivity indicates a poor dispersion of carbon black within the rubber matrix, resulting in tank pad rubber with poor wear properties.

The goals of the test scheme are as follow:

- The devised test must be nondestructive.

- The test equipment should be capable of measuring the conductivity of rubber samples varying in thickness (2.5 inches - 8.0 inches).

- The test system should reliably detect rubber tank pads that have abnormally low conductivities.

- The test system must perform measurements with only one side of the rubber pad accessible.

5.2. Background Work

This study is a sequel to "Microwave sensing of bulk properties of tank pad rubber: a feasibility study," funded by TACOM under Contract DAAE07-83-K-R009, from July 1, 1983 to June 30, 1984. The feasibility study sought to extract the conductivity information by measuring the energy loss of a microwave signal transmitted through a rubber slab. However, the mathematical model devised for the feasibility study only roughly approximates the conditions actually found in the experiment.

When the absorption losses are sufficiently high (i.e., more than 20 decibels (dB)), then the energy loss can be described approximately by

$$P_t = e^{-2\alpha d} P_0 \tag{1}$$

where d is the thickness of the slab, P_0 is the source power, P_t is the received power, and α is the absorption coefficient given by

$$\alpha = \frac{2\pi f}{c} Im\left[\sqrt{\varepsilon_r + j\sigma/(2\pi\varepsilon_0 f)}\right] \tag{2}$$

where f is the frequency, $c = 3 \times 10^8$ m/s, σ is the conductivity in S/m, $\varepsilon_0 = 1/36\pi \times 10^{-9}$ F/m, and ε_r is the real dielectric permittivity [2,3]. The real dielectric constant, ε_r, is not known beforehand and cannot be extracted from this measurement approach. It is believed that ε_r lies somewhere between 4 and 10, and an assumption of $\varepsilon_r = 5$ was made for interpretation purposes.

It can be observed from equation (2) that when σ lies close to 1 S/m, the absorption coefficient, α, becomes independent of σ at frequencies above 5 gigahertz (GHz) or so. Therefore, it would seem desirable to use frequencies around 5-GHz or lower. On the other hand, f = 5-GHz corresponds to a wavelength of $\lambda = 6$ cm. At wavelengths that are considerably longer, waves will creep around rubber slabs of typical tank pad widths, and thus contaminate transmission measurement. This suggests that frequencies much lower than 5-GHz should be avoided in a transmission measurement scheme.

In the experiment conducted for the feasibility study, an 8.2-GHz signal was transmitted from one side of a 1/2-inch rubber slab and measured on the opposite side as shown in Figure 5-1. The energy loss created by a reflected wave off the front surface of the slab was assumed to be negligible. Although horn antennas were used in the near-field, the devised mathematical model assumed a far-field situation. Far-field modeling neglects the reactive components of the electric field found in the near-field and assumes plane traveling waves. This modeling greatly simplifies computation, but in this case, at the expense of accuracy.

Conclusions reached by the feasibility study suggest one should expect a 10 to 25-dB absorption loss per half an inch of rubber material at 8.2-GHz, implying that the rubber conductivity lies somewhere between 1 and 4 S/m. Slab width was limited to a 1/2-inch because equipment available at the time of the study was not capable of measuring losses greater than 25- to 30-dB.

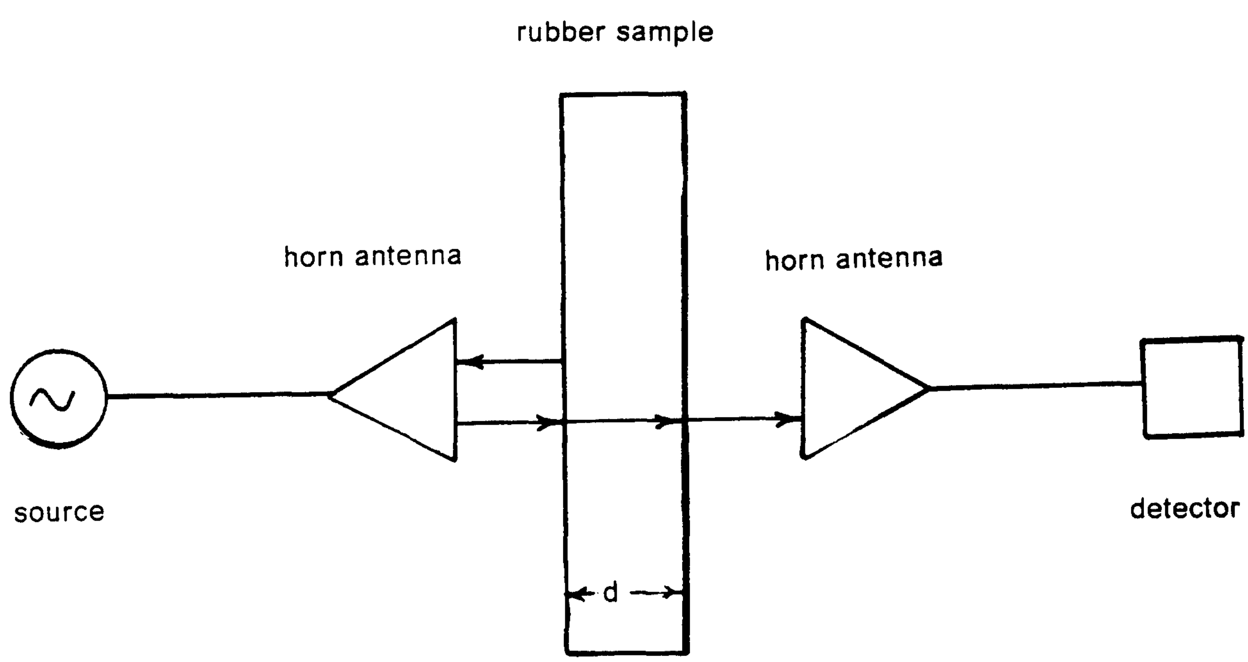

Figure 5-1. Test Configuration Used in Feasibility Study

While the feasibility study has shown that it is indeed possible to use microwaves to distinguish between various batches of tank pad rubbers in a nondestructive fashion, the differences between an actual assembly line situation and one with thin rubber slabs requires further study.

5.3. Proposed Free Space, Far-field Test Configurations

5.3.1. Theory. A transmission scheme such as the one used in the feasibility study cannot be applied to actual tank pads because a metal backing prohibits electromagnetic wave transmission through the tank pad. The first test system to be investigated is a modification of the configuration used in the feasibility study but does not change the theoretical approach. The transmitting and receiving horns were placed on the same side of the rubber slab and the source wave was launched from various angles of incidence as shown in Figure 5-2. The transmitting horn directs a source wave toward the rubber sample. When the source wave reaches point A, a reflected and a transmitted wave are generated. The reflected signal may be regarded as noise and the transmitted wave may be regarded as the information-bearing signal. At point B, the transmitted wave is redirected toward the receiving horn by the metal backing. The reflected noise that appears at the receiving horn from point A is many times larger than the signal that transverses the path A-B-C. For example, the information signal is expected to be 20- to 50-dB less than the reflected noise for a 1/2-inch sample. In addition to the reflected wave, the direct wave from the transmitting horn to the receiving horn is another problematic source of noise. The influence of the direct wave becomes more troublesome as the angle of incidence increases. A shield was proposed to isolate unwanted noise from the receiving horn.

Because a shield substantially reduces the received power level, a possible alternative to shielding is to measure the total power from the reflected wave and the transmitted wave. Higher received power levels result in measurements that are easier to make. However, interpreting results from this configuration is a much more difficult task. The influence of the direct and reflected waves on received power is not eliminated by this modification, and their presence must be taken into account in the mathematical model as well as absorption loss caused by the rubber sample.

With or without a shield, there is a dilemma with regard to the placement of the antennas. On one hand, it is desirable to keep the antennas as close as possible to the rubber sample to minimize the free space spreading loss. On the other hand, it is also desirable to keep the antennas out of the near-field so that far-field modeling will accurately characterize the measurement system. The free space spreading loss, L_p , is given by

$$L_p = 20 \log\left(4\pi\frac{R}{\lambda}\right) \ dB \qquad (3)$$

where R is the distance between the receiving and transmitting antennas and λ is the microwave wavelength [4]. The far-field distance, R_{ff}, is given by

$$R_{ff} > max\left[\frac{2D^2}{\lambda},\ 5D,\ 1.6\lambda\right] \qquad (4)$$

where D is the longest dimension of the horn aperture [5]. Horn antennas with 25- by 25-mm apertures, such as the ones used in the experiment, operating at 8-GHz, result in an R_{ff} of greater than 17.6 cm in order for the receiving antenna to be in the far-field of the transmitting antenna. But at R = R_{ff} = 17.6 cm, L_p = 36-dB, which represents a substantial loss of power. Thus, in an actual experiment with this

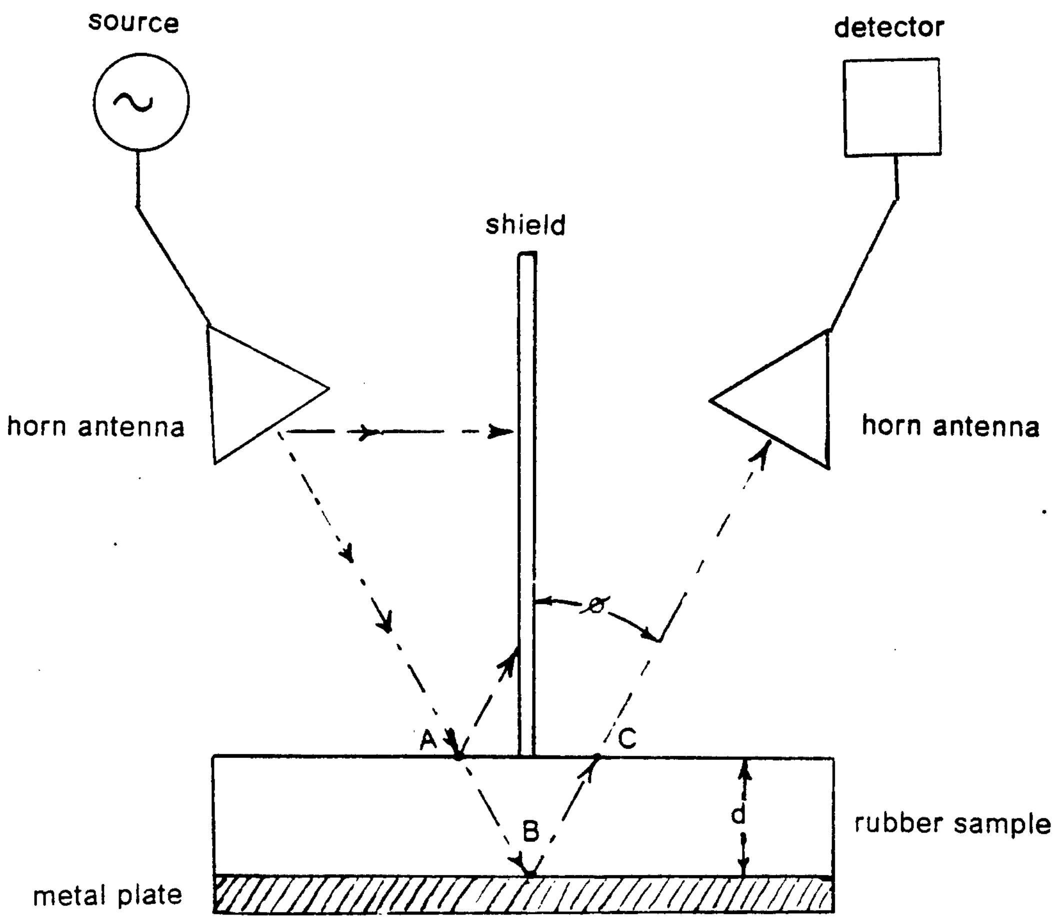

Figure 5-2. Initial Proposed Test System

scheme, measurements would be made with R less an 17.6 cm but hopefully at a distance at which the near-field effects are negligible.

5.3.2. Experimental Results. A HP8559A spectrum analyzer capable of measuring signals as small as -70 decibels above 1 milliwatt (dBm) was procured for the experiment (that is, if the rubber were to cause 100-dB of attenuation, a 1-W source is required for the spectrum analyzer to measure the minimum -70-dBm). Shielding is provided by a flat metal plate. Actual tank pads were not available and flat rectangular 1/4-inch rubber slabs backed by a metal plate were substituted in the experiment. Measurements compared received power with only a metal plate in the signal path to received power when a sample is in the signal path (L_p remains the same for both measurements).

Measurements either with or without shielding proved to be highly unreliable because of the extreme sensitivity of the received signal to the placement of both the shield and the antennas in the near-field. For example, several power loss measurements made for 1/4-inch 15NAT-42 rubber sample with shielding at a 7° angle of incidence and f = 8-GHz ranged from 41- to 60-dB (0-dB reference is power received when only a metal plate to redirect the wave is in the transmission path), a difference of 19-dB. Results from measurements made without a shield are shown in Table 5-1. The complicated nature of this configuration is demonstrated by the possibility of power gains (negative power losses). Power gains are possible if the path lengths of the direct wave and reflected wave are set such that the waves are in phase and interact constructively. Interpretation of these results is extremely difficult without knowing precisely the distance between antennas.

Other objects in the room can adversely affect measurements because the antennas used for transmitting and receiving are not flush with the sample; hence, objects other than the sample are irradiated and reflect energy. For this type of experiment, the size of the sample is also important. The small samples we have been using gives rise to differing results depending on the location of the sample with respect to the antennas (i.e., whether the sample is centered or not). It is anticipated that similar problems would be encountered with actual tank pads since their physical dimensions are on the same order of magnitude as the flat plate samples. Another difficulty with this measurement approach its inability to yield information on the real dielectric constant, ε_r, which is needed to accurately calculate the attenuation coefficient, α .

For this method to be further pursued, a measurement fixture capable of placing the shield and/or the antennas precisely must be constructed. However, because the noise problem associated with this method is such a difficult obstacle to overcome and because of the extreme sensitivity of the measurements to shield and antenna placement, we believe that another test scheme offers greater potential for long-term success.

5.4. Current Test System

5.4.1. Infinite Waveguide Model. The far-field, free space modeling approach has been abandoned. Our current model requires the rubber sample to be placed at the end of a waveguide, between two metal grounding plates as shown in Figure 5-3. The grounding plates are necessary because the model considers the subsystem of two grounding plates and rubber as a waveguide with infinite cross-sectional area, filled with a lossy dielectric (rubber). This approach has many advantages over the previous one.

Table 5-1. Power loss vs. Angle of Incidence With No Shielding

Power Loss vs Angle of Incidence (dB)

1/4-inch samples		7°	12°	24°	36°	40°	48°	55°
15NAT-1	#1	10.5	10.5	5.0	4.0	5.0	2.5	0.0
	#2	11.5	10.5	5.5	3.5	3.5	0.5	1.5
15NAT-22A	#1	10.5	10.5	4.0	-0.5	1.0	-5.5	-1.5
	#2	10.5	10.0	6.0	1.5	2.0	-1.5	0.0
15NAT-42	#1	12.5	10.0	3.0	-3.0	-4.0	-11.5	-4.0
	#2	11.5	10.5	4.0	-2.0	-2.0	-8.5	-3.5
15NAT-57	#1	11.5	10.5	6.0	2.0	3.5	-0.5	-1.0
	#2	10.5	10.0	6.0	1.5	4.0	-1.5	-0.5
15OTR-5	#1	10.0	9.0	6.0	1.5	4.0	-0.5	0.0
	#2	10.5	10.5	6.0	2.0	3.0	-0.5	1.5
15OTR-6	#1	9.0	9.0	8.0	6.0	14.0	20.5	2.5
	#2	10.0	9.5	8.0	8.0	16.0	14.5	0.5
15SB12-26	#1	9.5	9.0	4.0	-1.0	0.0	-5.5	0.0
	#2	9.5	9.0	4.0	-0.5	1.0	-4.5	0.5

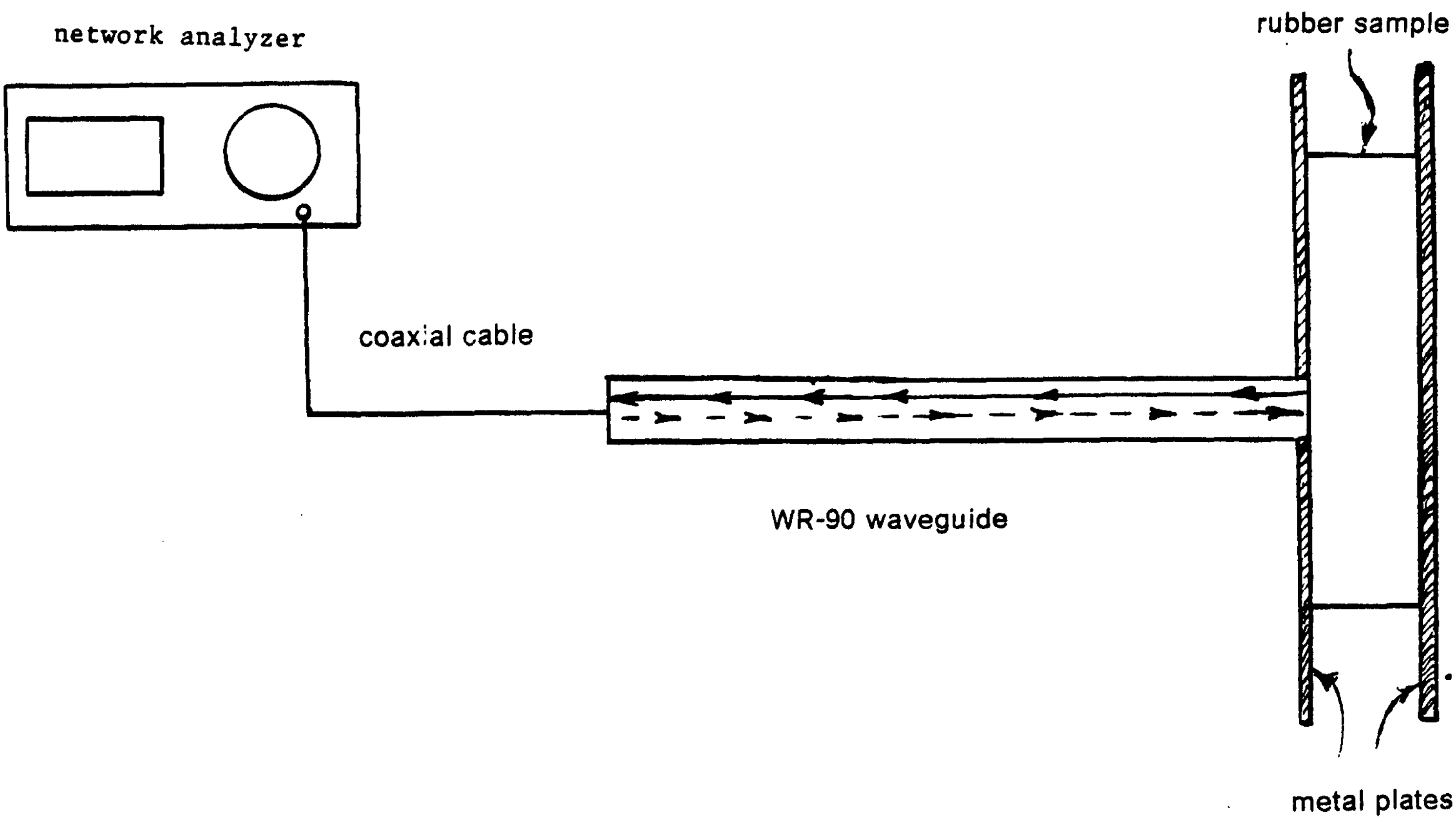

Figure 5-3. Infinite Waveguide Test Scheme

In this new approach, a transducer is set at normal incidence. This eliminates the angle of incidence as a variable and also avoids the need to construct a precise measurement fixture. The transducer is made to act as both the transmitter and the receiver by placing a directional coupler or a circulator in the signal path to separate the transmitted source wave from the reflected information wave.

The need for a shield is eliminated since total reflected power is measured. By reducing the test system to one transducer, the problem associated with the direct wave has also been eliminated. Furthermore, we have removed the effect of other objects in the room by placing the transducer as close as possible to the sample. Placing the transducer nearly against the sample also results in higher power levels, and this leads to measurements that are both easier and more accurate.

In previous test configurations, horn antennas were used as the transducers. The purpose for horn antennas is to provide a smoother transition for the microwave signal from the environment of the waveguide (or transmission line) to that of free space. By placing the antenna directly against the waveguide, the signal is never allowed to enter free space, and the principal effect of the antenna is to insert an impedance discontinuity which serves no purpose. Accordingly, the antenna has been removed from the system.

Previous test schemes measured only power magnitudes. By measuring both magnitude and phase, twice as much information on the sample is obtained at each measurement frequency. This technique offers a method to evaluate ε_r in addition to σ. By obtaining the data for several frequency points, confidence in the results can be obtained because ideally the same result should be obtained at each measurement frequency.

Probing at several different frequencies will also allow the homogeneity of the rubber to be examined. The penetration depth, δ, by the microwave signal into the rubber is given by

$$\delta = \frac{\sqrt{2}}{\omega\sqrt{\mu\varepsilon}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]^{1/2}} \qquad (5)$$

where f is the operating frequency and $\omega = 2\pi f$, $\mu = \mu_0\mu_r$ is permeability, σ is conductivity, and $\varepsilon = \varepsilon_0\varepsilon_r$ is permittivity. Since δ is inversely proportional to the frequency, we can vary f to vary δ and thereby examine σ at different depths.

Initially, experiments will be carried out with WR-90 waveguide so that the rubber can be analyzed within an 8- to 12-GHz range. However, to make depth probing feasible, frequency must be varied over at least a decade of frequency and ideally over several decades. This is not possible using metal hollow-structured waveguides. Thus, eventually we will substitute coaxial transmission line so that the frequency range of analysis can be expanded to cover 1- to 18-GHz.

The primary difficulty of this approach is the development of a suitable model. In a waveguide (or transmission line), there are an infinite number of modes in which a wave can propagate. It is desirable that only one mode propagate, and within a certain frequency range for a given waveguide only one mode will will propagate. This mode is called the dominant mode. The remaining modes, called evanescent modes, attenuate to negligible levels over a small distance. For example, a WR-90 waveguide will support only a TE_{10} mode in the frequency range 6.55- to 12.2-GHz. Difficulties arise when the waveguide encounters a discontinuity, such as another waveguide with different dimensions. When this occurs, new modes are generated in addition to the dominant mode. As a result, the reflection coefficient at the waveguide-rubber interface is impossible to express in simple mathematical form. Since the reflection coefficient is in essence what we are attempting to measure, it is difficult to relate measured data to the model in a simple way.

A vector network analyzer equipped with a reflectometer test kit is the ideal instrument to perform the magnitude and phase measurements. The use of a network analyzer will alleviate the task of obtaining data as a function of frequency. Unfortunately, the vector network analyzer that we had anticipated we could use is currently committed to another project and probably will not become available before August. In the meantime, we are experimenting with other test configurations. These are described in sections 5.4.3. and 5.4.4.

5.4.2. Data Interpretation. The primary difficulty associated with the proposed procedure is that of inferring the conductivity of the tank pad rubber from reflection coefficient measurements. In order to make the problem mathematically tractable, the tank pad is modeled as a homogeneous, conducting layer overlying a perfect conductor. The formal solution for the reflection coefficient when the open end of a rectangular waveguide radiates into a metal backed slab has been examined [7]. Even the simple model under consideration leads to a very complex expression for the reflection coefficient, and the process of obtaining the conductivity from the reflection coefficient is computationally intensive. Since only an approximation of the conductivity is desired, the reflection coefficient at the waveguide-sample interface is approximated by neglecting evanescent modes and by representing the rubber sample with an effective wave impedance. The relationship between the effective wave impedance and the actual rubber is dependent on the expected electrical thickness of the sample. The effective wave impedance for an electrically thin sample is taken to be the wave impedance obtained when the end of the waveguide is filled with a layer of rubber the same thickness as the tank pad and terminated with a short circuit. For an electrically thick sample, the effective wave impedance is taken to be the wave impedance of an infinite sheet of rubber the same thickness as the tank pad and backed by a perfect conductor. The effective wave impedance of samples that are neither electrically thick nor thin is obtained as a weighted average of the wave impedance at the two extremes. Normal tank pads are expected to be electrically thick, while the electrical thickness of defective tank pads will range from moderate to thin. The preceding assumptions allow a much simpler and less computationally intensive interpretation of the tank pad conductivity from the reflection coefficient data.

Using the model and the simplifying assumptions discussed above, we have developed a FORTRAN program to generate magnitude and phase information for a metal backed rubber sample that is assumed to be vertically heterogeneous. This program is used to generate plots of the magnitude and phase for various combinations of the conductivity and dielectric constant of the rubber and for differing frequencies. By comparing the experimental data with these plots, we hope to infer the general value of the rubber conductivity and dielectric constant. We are examining the possibility of a graphical interpretation based on either magnitude and phase data at a single frequency or an interpretation based on measurement of both magnitude and phase at a number of frequencies.

As an example of a graphical interpretation based on the measurement of magnitude and phase information at a single frequency, consider Figures 5-4. through 5-7. For a three inch thick sample, suppose we measure a power loss of -2.7-dB and a phase of 171° at a frequency of 8-GHz. Figure 5-4. can be used to conclude that this power loss implies that $4.0 > \sigma > 3.7$ S/m and $7.0 > \varepsilon > 3.0$ if $\sigma > 1.0$ S/m is assumed. From Figure 5-6., the measured phase of 171° removes the ambiguity associated with

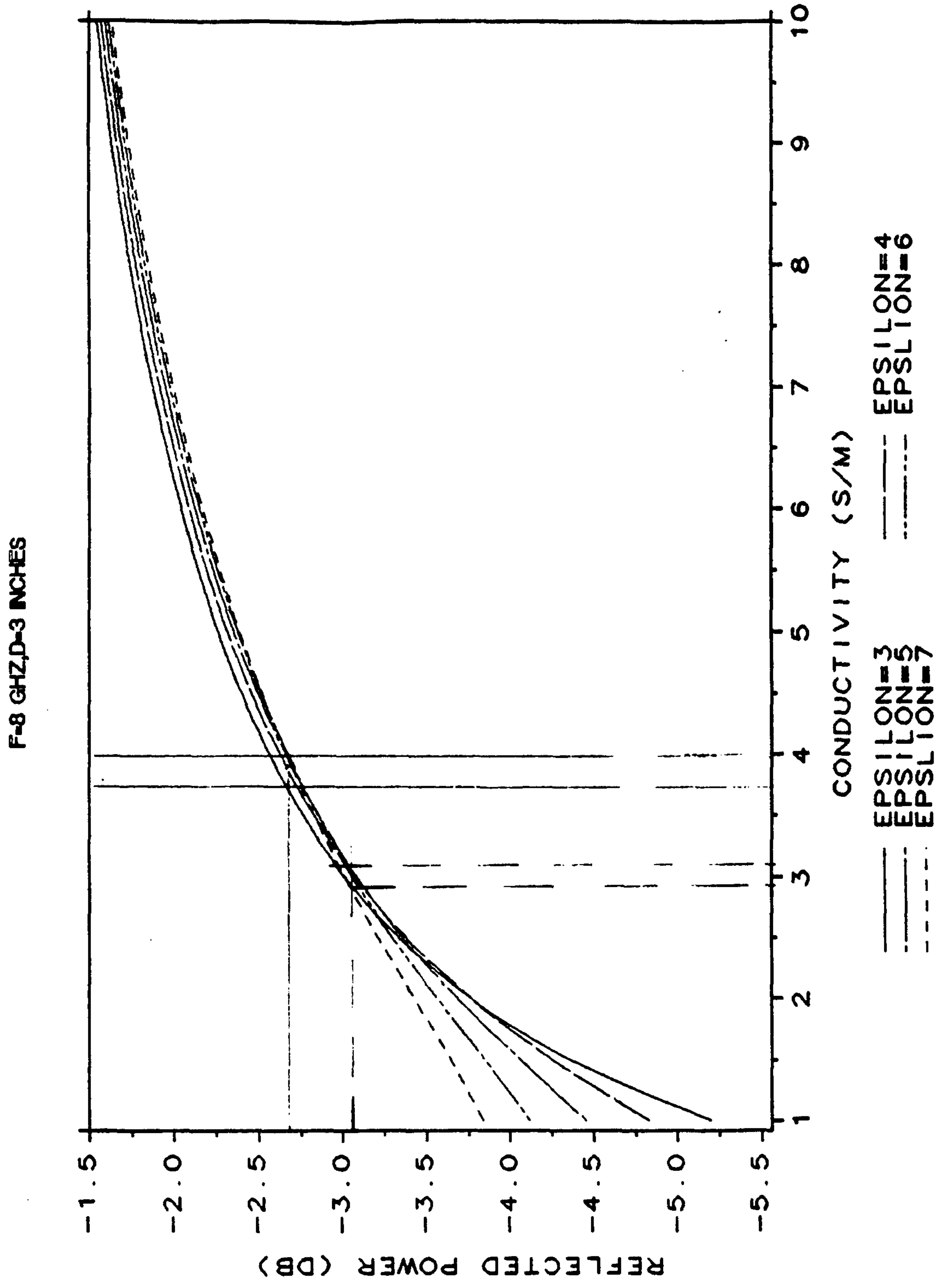

Figure 5-4. Reflected Power vs. Conductivity at 8-GHz

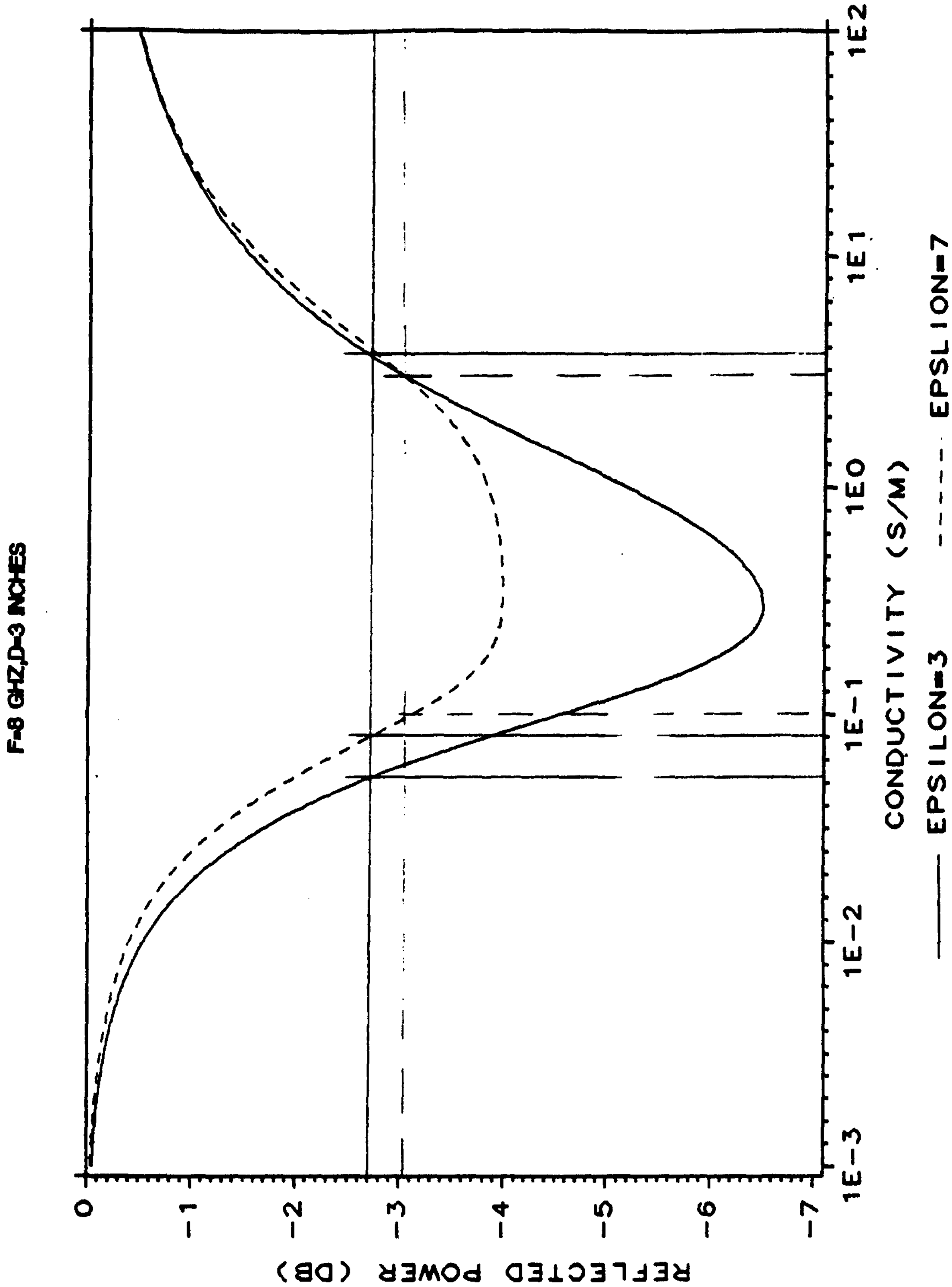

Figure 5-5. Reflected Power vs. Conductivity at 8-GHz with expanded abscissa

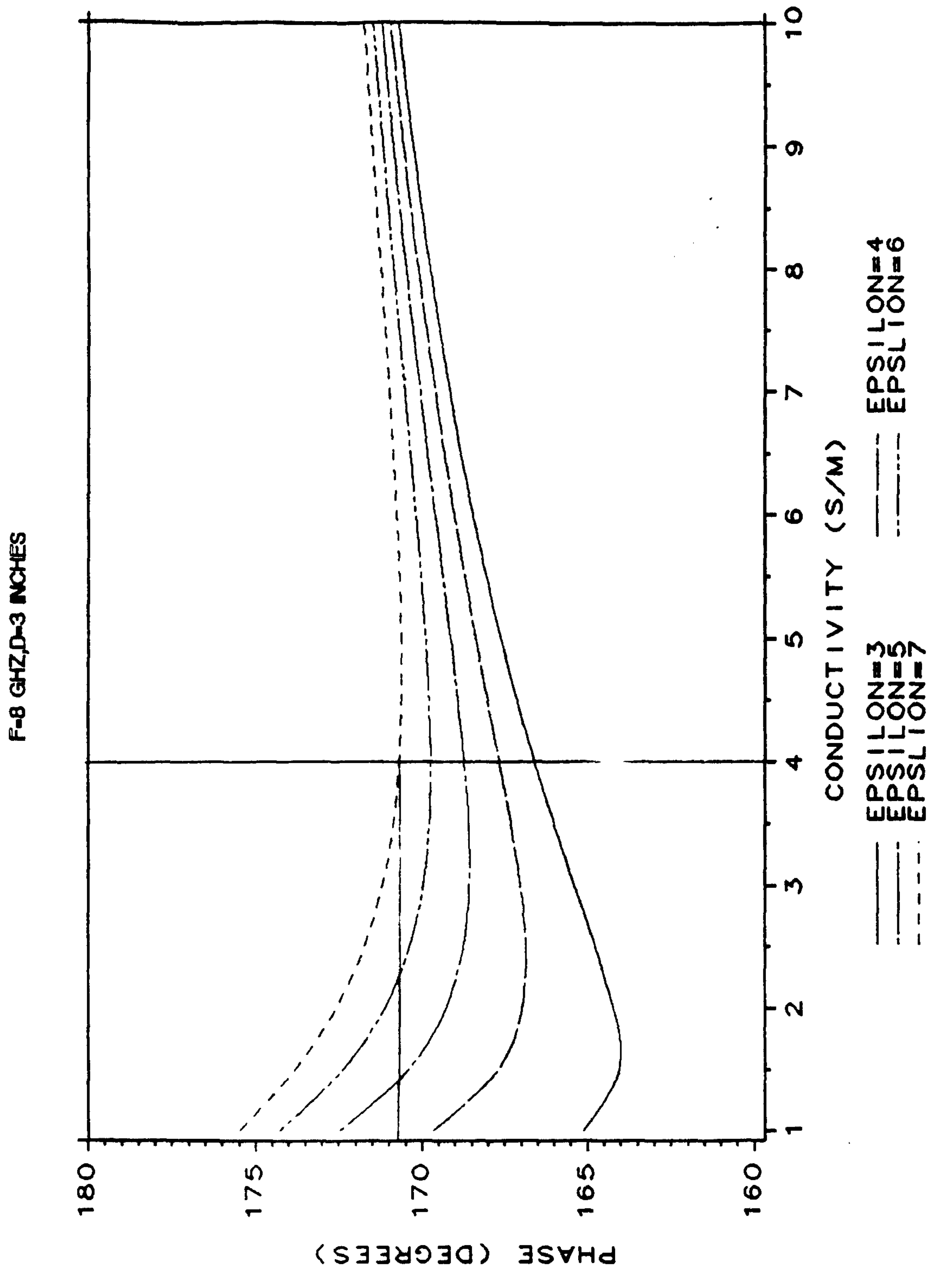

Figure 5-6. Reflection Coefficient Phase vs. Conductivity at 8-GHz

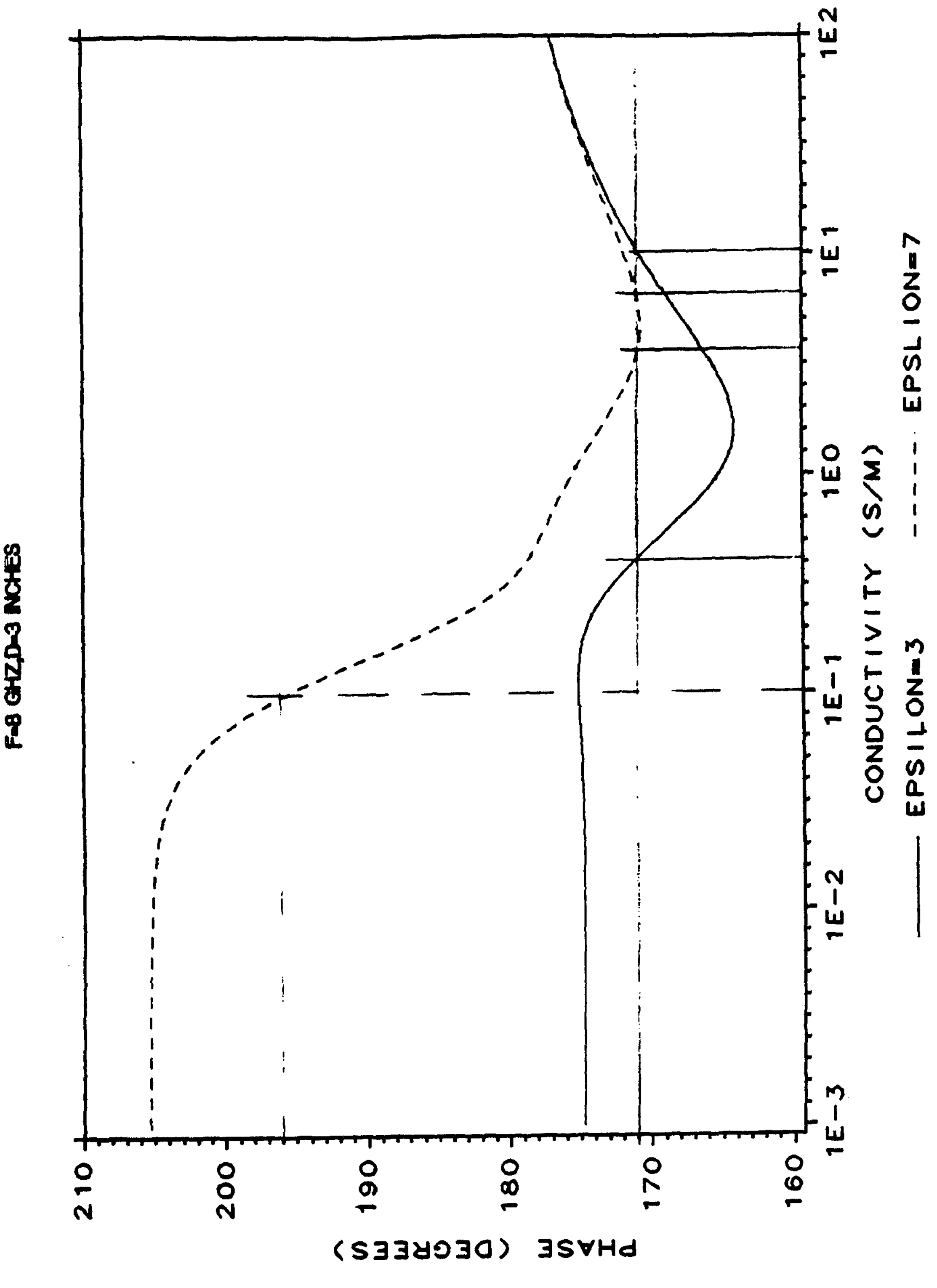

Figure 5-7. Phase vs. Conductivity at 8-GHz with expanded abscissa

consideration of the magnitude alone. We can see that this particular combination of power loss and phase is only consistent with $\varepsilon = 7.0$ and $\sigma = 4.0$ S/m as long as $\sigma > 1.0$ S/m is assumed. It now remains to determine that this assumption is correct. From Figure 5-5., we see that -2.7-dB is also consistent with values of $\sigma < 0.01$ S/m; however, from Figure 5-7., we see that 171° is only consistent with $\sigma > 0.01$ S/m. Hence, we can conclude that the sample is characterized by $\varepsilon = 7.0$ and $\sigma = 4.0$ S/m.

As a counter example, suppose we measure a power loss of -3.05-dB and a phase of 196° at a frequency of 8-GHz. From Figures 5-4. and 5-5., we see that this power loss can correspond to either $\sigma \simeq 3.0$ S/m or $\sigma \leq 0.01$ S/m. The measured phase allows us to discard $\sigma \simeq 3.0$ S/m, and we can conclude that $\sigma = 0.01$ S/m and $\varepsilon = 7.0$.

The disadvantage with the graphical interpretation procedure outlined above is that the large range of possible values of conductivity and dielectric constant requires a large number of graphs in order to account for all possibilities. As a result, the graphical procedure can be difficult to apply in the general case, and it is doubtful that an individual who is not highly trained in this area would have the judgement required to apply this method. Consequently, the graphical procedure should be replaced by a more automated interpretation procedure.

5.4.3. Reflectometer With 3-dB Coupler, Magnitude Only Measurements. The approach of this method is similar to the test system that we would like to use to measure both magnitude and phase of the reflected wave. Phase information cannot be obtained using this method and hence, we cannot reliably characterize the rubber with this method.

The experiment that was performed compared power reflected from a 15NAT22A rubber sample with a metal short circuit at normal incidence. Both the rubber sample and the short circuit were placed at the end of a waveguide without a horn as illustrated in Figure 5-8. 15NAT22A samples were stacked together until there was no measurable influence from a metal plate placed behind the rubber stack. The FORTRAN program discussed in the previous section was used to generate a plot of the reflected power (normalized by reflected power from a short circuit) versus frequency for various values of σ and $\varepsilon_r = 5$. This plot is shown in Figure 5-9. Measurements of reflected power were made from 8.0- to 12.0-GHz (the usable frequency range of WR-90 waveguide) and compared to the computer generated plot. Results from this comparison indicate that conductivity of the sample is approximately 5 S/m if the $\varepsilon_r = 5$. This result is consistent with the conclusions reached in the feasibility study.

This method of approach may be sufficient for detection of abnormally low conductivity in spite of its inability to yield accurate results (ε_r must be assumed). However, if ε_r does not vary widely, then this method could be an inexpensive method to implement.

5.4.4. Microwave Interferometer. The basic approach of the interferometric method is the division of the transmitted source wave between two transmission lines (or waveguides). One transmission line carries a reference wave whose amplitude and phase are constant in time. A probing wave propagates along the other line and a rubber sample is placed in the path of this wave. A wave reflects off the rubber sample and carries information on the complex permittivity of the rubber sample. This information wave is then made to interfere with the reference wave, and the resulting wave is dependent on both the phases and amplitudes of the two interfering waves.

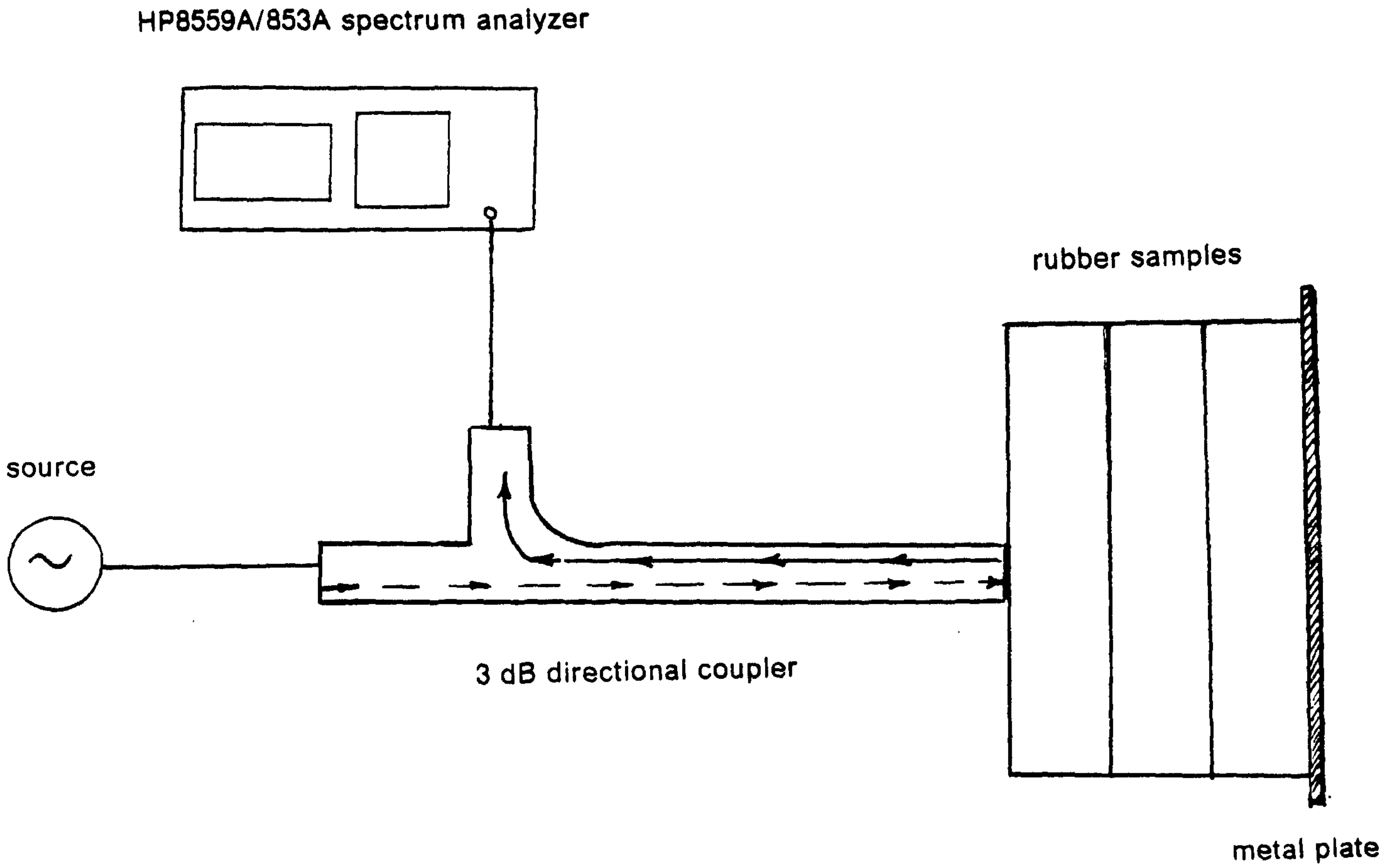

Figure 5-8. Scalar Reflectometer

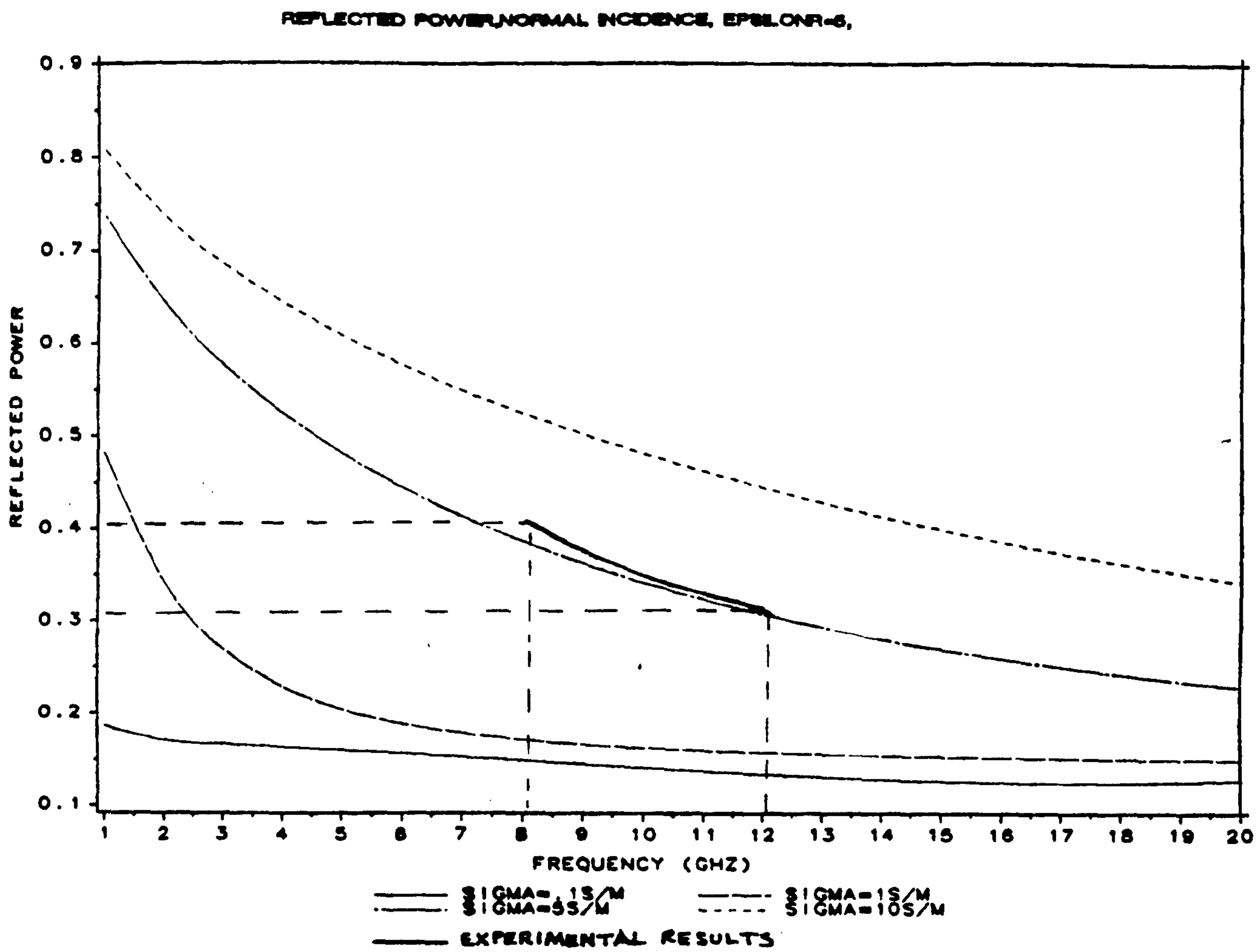

Figure 5.9. Scalar Reflectometer Results

Mixing is accomplished by hybrid tee waveguide junctions as shown in Figure 5-10. Magnitude and phase are measured by means of precision attenuators and phase shifters. All of the aforementioned measurement devices are available in our lab. Interferometric measurements have been made and data is currently being analyzed.

The basic concept behind the interferometric method is similar to the concept behind the network analyzer method. The important difference between the two methods is that mixing occurs at microwave frequencies in the interferometer, but mixing in the network analyzer occurs at an intermediate frequency (IF). The relatively small wavelengths at microwave frequencies are more sensitive to the physical dimensions of the waveguide, and thus are sensitive to the ambient temperature which causes contraction and expansion of the waveguide. Small changes in temperature can cause the interferometric measurements to drift. On the other hand, the network analyzer down converts to an IF frequency and the relatively larger wavelengths are less sensitive to waveguide dimensions. We do not expect the microwave interferometer to yield data that is as accurate as that which can be obtained with the network analyzer; however, it may be sufficient to detect unusually low values of σ. The microwave interferometer is an inferior system compared to the network analyzer but, it is far more inexpensive to implement and this warrants further investigation.

5.5. Destructive Testing

In order to have something with which to compare our nondestructive test results, we attempted to implement a commonly used destructive test that should yield both ε_r and σ of the rubber [6]. This method required that a rubber sample be cut to fit inside a WR-90 waveguide. This test system is illustrated in Figure 5-11.

Our lab results with a 15NAT22A rubber sample inserted inside the waveguide indicate that σ lies somewhere between 1 S/m and 13 S/m and ε_r lies between 4 and 7. Complete results are listed in Table 5-2. These results indicate that the destructive measurements are within the same order of magnitude as the nondestructive measurements.

The major difficulty we encountered with this method is that the rubber samples cannot be machined to the necessary exact tolerances required, preventing us from obtaining highly accurate results. Since cutting rubber samples to fit inside a waveguide does not offer a reliable check of our work, we are considering measuring a material with known electrical properties to check the validity of the nondestructive test scheme.

5.6. Summary

A number of measurements for oblique angles of incidence, both with and without a shield, were taken with a metal plate providing the shielding. Measurements using either approach proved to be highly unreliable because of the extreme sensitivity of the received signal to the placement of both the shield and the antennas. We believe that there is another test scheme which offers greater potential for long-term success. In the desired test scheme, no horn antennas are used, and the sample is placed between two metal plates at the end of a waveguide. This configuration eliminates much of the extraneous noise found in our initial test system. Magnitude and phase measurements are to be made with a network analyzer as soon as it becomes available. Meanwhile, in order to test the feasibility of the proposed system, we have made magnitude and phase measurements with a microwave interferometer. Measurements made with the interferometer are much less accurate than those made with a network analyzer, but the cost of the network analyzer is

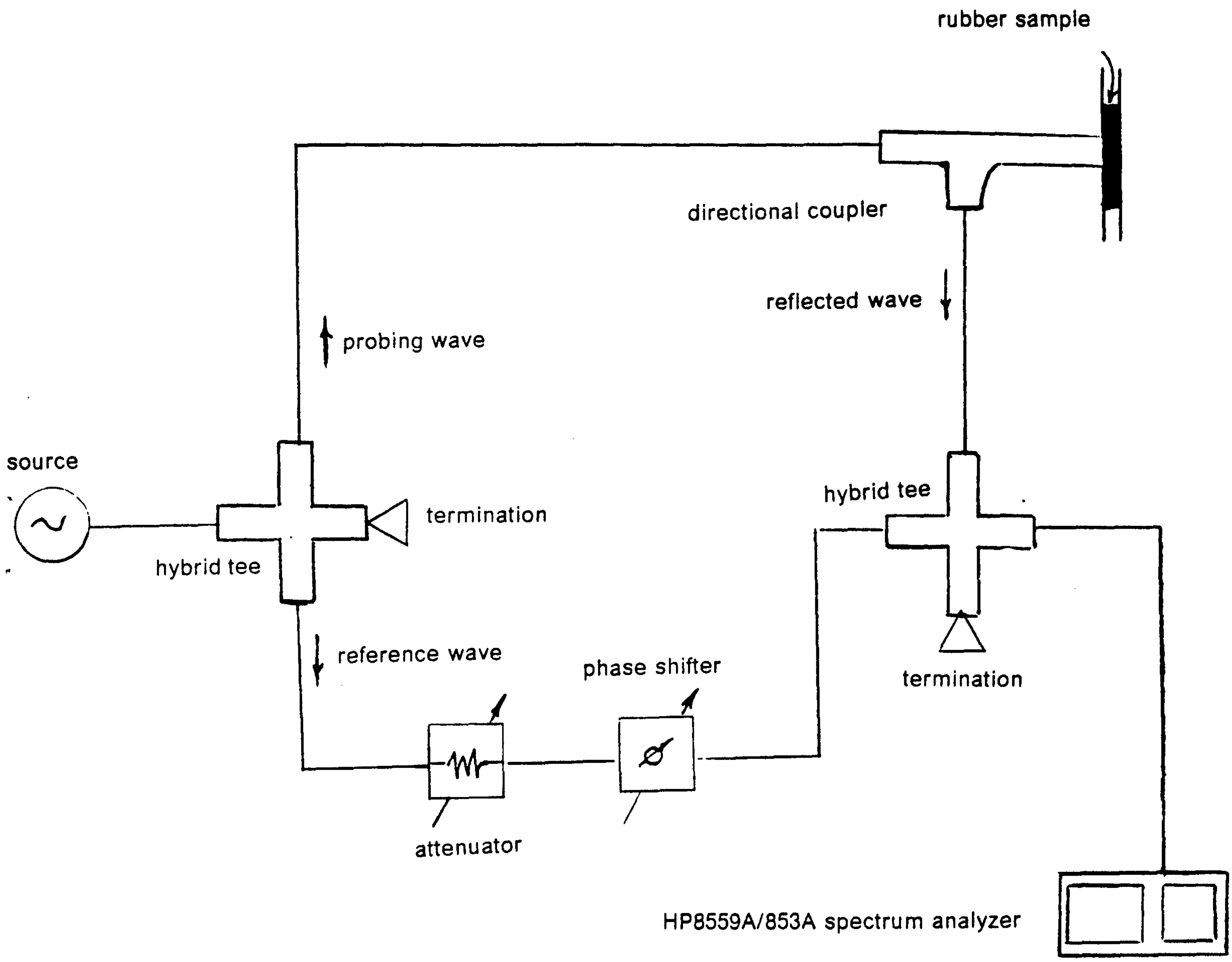

Figure 5-10. Microwave Interferometer

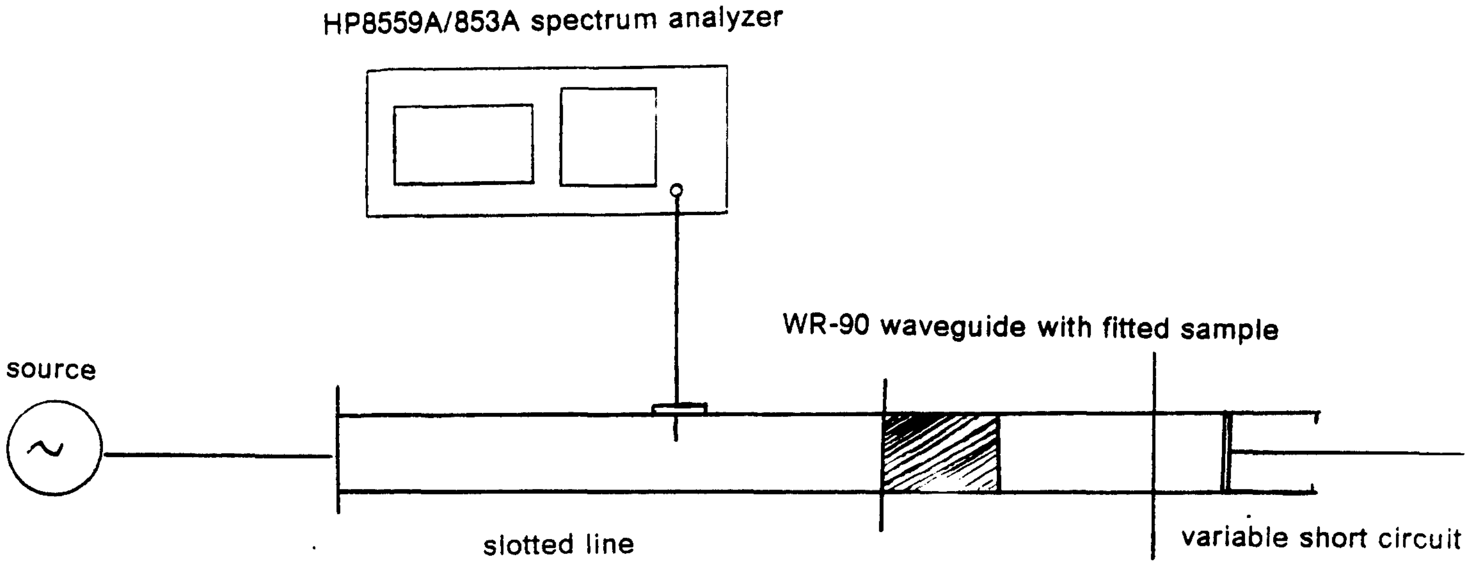

Figure 5-11. Waveguide-inserted Sample Testing

Table 5-2. Waveguide-inserted Sample Test Results at f = 8-GHz

ε_r	σ (S/m)
4.6	4.4
7.5	13
7.6	1.8
5.2	2.4
4.5	1.1

substantially greater than that of the interferometer. By measuring both magnitude and phase, we should be able to find ε_r as well as σ of the rubber. An approximate computer model that neglects modal effects has been developed. Interpretation of measurements is currently based on a graphical approach. Plots of reflection coefficient magnitude and phase as a function of conductivity, dielectric constant, and frequency are generated with the computer model, and these plots are used to interpret the data. This process is unwieldy, and we are currently working on an alternative interpretation procedure that will be more automated and require less judgement on the part of the interpreter.

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