Two Methods for the Measurement of Substrate Dielectric Constant

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Abstract —**Two methods for the accurate and convenient measurement of the dielectric constant of a microwave substrate are proposed. Both methods use the precision measurement capability of the HP-8510 Network Analyzer system and a rigorous theoretical analysis of multilayer transmission lines [6], and hence can also be used for the measurement of the frequency dependence of the relative dielectric constant. Accuracy on the order of 1.0 percent can be obtained by use of these techniques. Measurements were done for various substrates and gave results as predicted.**

I. Introduction

THE MEASUREMENT of the dielectric constant of microwave integrated circuit (MIC) substrates can be made using various resonant methods, as described in [1]–[6]. The method described in [1] and its modified version using stripline techniques instead of microstrip line have been used to measure the dielectric constant of RT/DUROID ($\epsilon_r = 2.2$) substrates. In [2]–[5], the substrate, with copper on both sides, is treated as a cavity and the average dielectric constant is determined by measuring different resonant frequencies and substrate dimensions. In microstrip and stripline resonance techniques, the fringing fields of the dipole resonator are usually taken into account empirically, and lead to uncertainty. In the cavity resonance method, coupling from the substrate to the coaxial line is often a problem since it may be weak, and is a source of error [4]. In [6], two methods for measuring substrate permittivity using microstrip lines were described. Both of these techniques suffer from errors introduced by coax-to-microstrip transitions, since these transitions have enough reactance and/or mismatch associated with them to cause significant error in a phase measurement. In addition, none of these methods can conveniently measure the dielectric constant as it varies with frequency and position.

In this paper, two measurement methods are suggested using the HP-8510 Network Analyzer and rigorous analyses of multilayer transmission lines [7]. Because of the nature of the analysis, the technique can be used for the measurement of the variation of dielectric constant through a range of frequencies without much effort and, in fact, just by changing the frequency range over which the experiment is done. The two methods together can be flexibly used for measurement of the dielectric constant of any substrate of any thickness, and can be very useful in an industrial environment where one needs to measure the deviation of the dielectric constant from sample to sample in a large number of substrates of approximately the same dielectric constant. In both methods, the effective dielectric constant ϵ_{eff} of a particular transmission line is the quantity that is actually measured (or inferred from measurement). The dielectric constant of the substrate, ϵ_r, is then determined by working backwards, using a computer program for the rigorous analysis of the specific transmission line structure. The value of ϵ_r input to the program is varied until the resulting ϵ_{eff} agrees with the measured value. The corresponding value of ϵ_r is then the dielectric constant of the substrate. In both methods, the errors due to connector reactance/mismatch is canceled out by measuring the differences in phase between two lines. The two methods will now be discussed separately.

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II. The Two-Microstrip-Line Method

This method is capable of accurately measuring the dielectric constant of a substrate with an accuracy of the order of 0.5–1.0 percent, and also can be used to measure the dielectric constant of a substrate as it varies with frequency. Besides taking into account other possible errors affecting the measurement accuracy, this method ensures that error due to the connectors is canceled. This method is suggested for the accurate measurement of the effective dielectric constant of the "standard" substrate to be used in the second measurement technique, discussed in Section III.

A. The Test Procedure

On the test substrate, two 50-Ω microstrip lines are etched, one of them being much longer than the other (see Fig. 1). The difference between their lengths should be as large as possible to get the most accurate results. End launchers are used for most reliable results, in contrast to probe (surface launch) connectors, since the position of a probe connection is generally more uncertain than that of an end-launch connection. The difference between the electrical lengths is measured using the HP-8510 Network Analyzer system. Assuming the four connectors to be identical, the electrical length difference Δl_e between the

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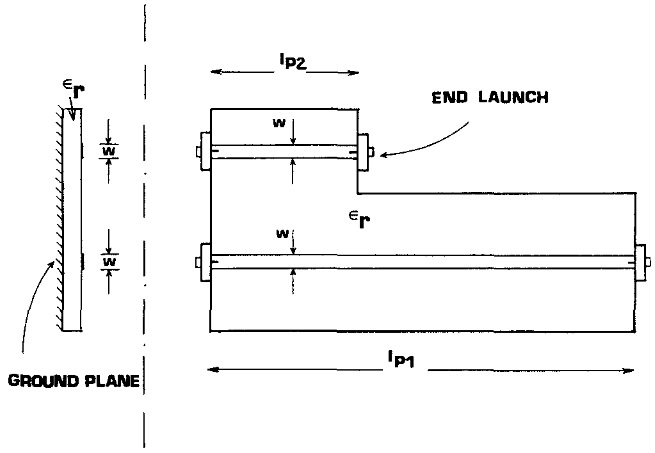


Fig. 1. Experimental setup for the two-microstrip-line method.

two lines can be expressed as $\Delta l_e = \sqrt{\epsilon_{\text{eff}}} \cdot \Delta l_p$, where ϵ_{eff} is the effective dielectric constant of the microstrip lines, and $\Delta l_p = l_{p1} - l_{p2}$ is the difference between the physical lengths of the lines. From this, we can determine the effective dielectric constant of the microstrip line and hence the dielectric constant of the substrate around the test frequency using an analysis [7] of the microstrip propagation constant (any good full-wave solution could be used here). The microstrip analysis is run for various values of ϵ_r until the measured ϵ_{eff} is obtained. The use of two lines of different lengths allows the corrupting effect of the connectors to be canceled out because all four coax-to-microstrip transitions (and any associated reactances) are identical, and cancel upon subtraction when computing Δl_e.

Improved measurement of ϵ_{eff}, and consequently ϵ_r, can be obtained by measuring the transfer phase difference $\Delta\phi$ through the two lines at a set of frequencies in the band of interest. Since $\Delta\phi = 2\pi f(\Delta l_p) \cdot \sqrt{\epsilon_{\text{eff}}}/c$, ϵ_{eff} can be determined from the measurement of Δl_p and $\Delta\phi$ at different frequencies. Table I shows some measured values of $\Delta\phi$ versus f, and the corresponding calculated ϵ_{eff}. A statistical average of these data can be used to find an accurate value of ϵ_{eff}; microstrip analysis can then be used to obtain ϵ_r.

B. Error Analysis

The use of the HP-8510 Network Analyzer with its error-correcting software results in negligible error in the measurement of Δl_e. As discussed above, connector mismatch effects cancel because of the use of two lines with identical transitions. This leaves the effect of error due to the physical measurement of l_{p1} and l_{p2} (the physical lengths of the lines).

The measured effective dielectric constant ϵ_{eff} of the microstrip line is related to the measured difference in electric lengths Δl_e and physical lengths $\Delta l_p = l_{p1} - l_{p2}$ as

$$\sqrt{\epsilon_{\text{eff}}} = \frac{\Delta l_e}{(l_{p1} - l_{p2})} = \frac{\Delta l_e}{\Delta l_p}. \tag{1}$$

TABLE I
MEASUREMENT OF $\Delta\phi$ (DEGREES) USING THE TWO-MICROSTRIP-LINE METHOD FOR RT/DUROID 5880 ($\epsilon_r = 2.20$) SUBSTRATE

f(GHz)	$\Delta\phi$(measured)	ϵ_{eff}(calculated)
1.0	58.5	1.896
1.5	88.0	1.907
2.0	117.0	1.896
2.5	146.0	1.890
3.0	175.5	1.896
3.5	205.0	1.901
4.0	234.0	1.896

$d = 0.0787$ cm $= 30$ mils, $W = 0.25$ cm, and $\Delta l_p = 3.54$ cm in the frequency range 1 0–4.0 GHz. The substrate dielectric constant ϵ_r calculated from the average value of ϵ_{eff} is 2.196.

The normalized error in ϵ_{eff} is then

$$\frac{\delta\epsilon_{\text{eff}}}{\epsilon_{\text{eff}}} = 2\frac{\delta\sqrt{\epsilon_{\text{eff}}}}{\sqrt{\epsilon_{\text{eff}}}} = 2\left(\frac{\delta\Delta l_e}{\Delta l_e} + \frac{\delta\Delta l_p}{\Delta l_p}\right) \tag{2}$$

where δ implies error in measurement, and

- l_{p1}, l_{p2} physical lengths of the two microstrip lines respectively ($l_{p1} > l_{p2}$),
- Δl_p difference ($l_{p1} - l_{p2}$) in physical lengths of the two lines,
- Δl_e difference in electrical lengths of the two lines.

In a typical case, ϵ_{eff} is approximately the same order of magnitude as the dielectric constant ϵ_r of the substrate. Hence, the percentage error introduced in determining ϵ_r of the substrate by using the value of ϵ_{eff} is of the same order as that of ϵ_{eff}. Thus,

$$\frac{\delta\epsilon_r}{\epsilon_r} \approx \frac{\delta\epsilon_{\text{eff}}}{\epsilon_{\text{eff}}} = 2\left(\frac{\delta\Delta l_e}{\Delta l_e} + \frac{\delta\Delta l_p}{\Delta l_p}\right). \tag{3}$$

It can now be noted that the error in measurement of the dielectric constant ϵ_r is proportional to the percentage error in the measurement of Δl_p and hence can be improved by using a large value of Δl_p.

For example, if $\delta(\Delta l_p) \sim 0.1$ mm, $\Delta l_p \sim 10.0$ cm, $\delta(\Delta l_e) \sim 0.1$ mm, and $\Delta l_e \sim 15.0$ cm (for $\epsilon_r = 2.2$), we would have $\delta\epsilon_r/\epsilon_r \approx 0.4$ percent. This accuracy can still be improved by increasing the difference between the lengths of the two microstrip lines.

C. Discussion

The error in the measurement of the dielectric constant by the two-microstrip-line method is mainly due to the error in measuring the difference between the physical lengths Δl_p of the two lines. The accuracy of measuring Δl_p is limited by the uncertainity in the position of the connector, as well as the accuracy of measuring the line lengths. Thus, end-launch connectors are found to be more reliable than probe connectors. Also, the assumption that the four connectors are identical may be more valid for end launchers than for probe connectors.

For this measurement method, two microstrip lines have to be etched on the substrate and four connectors fastened before the substrate can be tested. Thus, this is not a quick method for the measurement of the dielectric constant of substrates and does not have the flexibility of measuring the dielectric constant as it varies with position on a large substrate. The next method overcomes these disadvantages.

III. The Two-Layer Stripline Method

This method is an improvement over the two-microstrip-line method and overcomes the difficulties encountered in it. Instead of using the two microstrip lines of different lengths, it uses one stripline with two different substrates on both sides of the conductor. One of them is referred to as the "standard" substrate, whose dielectric constant is accurately known beforehand; the other is referred to as the "test" substrate, whose dielectric constant is to be determined. The standard substrate is permanently connected to the test setup, but the test substrate can be very easily removed and replaced by another one to be tested, and hence can be very flexible to use for measurement of a large number of substrates.

As in the previous method, this technique involves the measurement of the change in phase between two lines (a stripline with or without a cover substrate), and so connector mismatch effects are again canceled.

A. The Test Procedure

This method uses a 50-Ω microstrip line on a "standard" substrate, whose dielectric constant is determined using some other accurate measurement technique. One suggested method is the two-microstrip-line method, described earlier in Section II. In the case where one is interested in the deviation of the dielectric constant from sample to sample rather than in the absolute dielectric constant, the rigorous determination of the dielectric constant of the standard substrate is not very important.

The width of the microstrip line and the thickness of the standard substrate must be measured accurately. This standard substrate is connected to the HP-8510 Network Analyzer system by two connectors at the ends of the 50-Ω line (see Fig. 2(a)). The substrate under test (the "test" substrate) is etched to remove the copper on one side, and is cut into a rectangular shape. The dimensions of the test piece need not be of any specific size, and hence the method can be flexibly used for measurement of the dielectric constant of any size substrate. It should, however, be greater than about two wavelengths wide, but can be of any suitable length. The length, of course, will be constrained by the dimensions of the clamping structure (discussed below). It can be noted here that the final result is not very sensitive to the measurement of the dimensions of the test piece.

The test substrate is used to cover a portion of the standard microstrip line and is clamped from top to bottom to form a stripline structure. The two plates (Fig. 2(a))

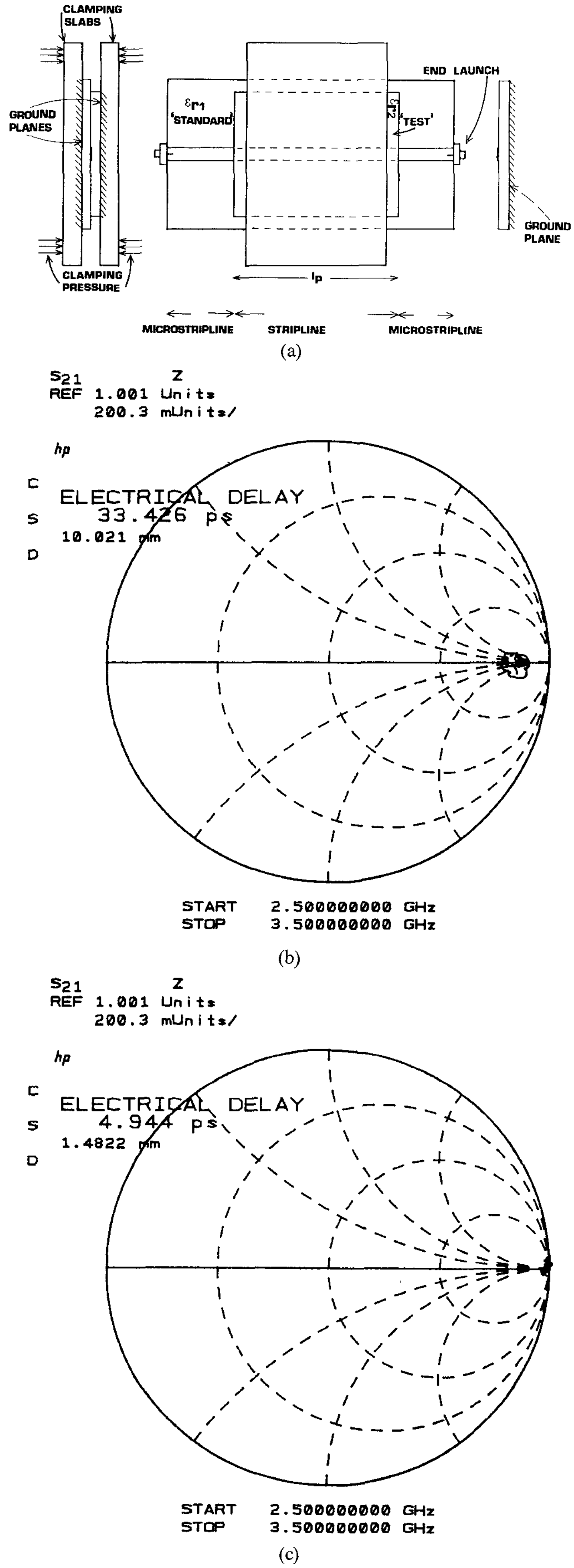


Fig. 2. (a) Experimental setup for the two-layer stripline method. Typical Smith chart plot of S_{21} (b) with and (c) without the test cover obtained from the HP-8510 Network Analyzer.

used on both sides to clamp it should not extend beyond the area of the test piece, and the clamping pressure should be enough to get rid of any air gap between the standard substrate and the test substrate. The entire transmission structure is then a cascade of microstrip line, stripline, and again microstrip line.

The impedance of the stripline (Z_s) is different from that of the microstrip line. In the Appendix, it is shown that for 25 $\Omega \leqslant Z_s \leqslant 100$ Ω, the locus of S_{21} looks like a small circle on the right-hand side of the Smith chart if a suitable electrical delay is introduced on the reference plane. This can be very conveniently and accurately done using the HP-8510 Network Analyzer, and the value of the electrical delay should be noted.

Now remove the clamp and the test substrate, leaving the bare microstrip line. The electrical length is different from the previous value, because of the difference of the effective dielectric constants of the bare microstrip line and that of the layered stripline with the standard substrate on one side and the test substrate on the other. The connectors are not changed and do not introduce any error since the discontinuity in the connectors appears identically in both cases. The change in electrical length is due solely to the effective dielectric constant of the stripline under the test piece.

Now readjust (decrease) the electrical delay so that the S_{21} locus of the bare microstrip line looks like a small point on the right-hand side of the Smith chart ($1.0\angle 0$). Note the new electrical reference.

The difference in electrical delay Δl_e is given as

$$\Delta l_e = l_p\left(\sqrt{\epsilon_{\text{eff}s}} - \sqrt{\epsilon_{\text{eff}m}}\right) \tag{4}$$

where

- Δl_e change in electrical length,
- l_p physical length of the test piece,
- $\epsilon_{\text{eff}s}$ effective dielectric constant of the stripline (with standard and test substrates),
- $\epsilon_{\text{eff}m}$ effective dielectric constant of microstrip line (standard substrate only).

Then, from (4),

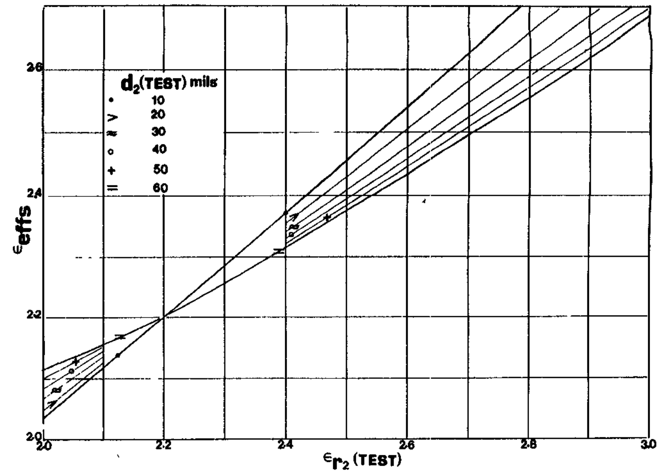
$$\sqrt{\epsilon_{\text{eff}s}} = \sqrt{\epsilon_{\text{eff}m}} + \frac{\Delta l_e}{l_p}. \tag{5}$$

From the value of Δl_e and l_p (measured) and $\sqrt{\epsilon_{\text{eff}m}}$ (theory), $\epsilon_{\text{eff}s}$ can be calculated from (5), and hence the unknown ϵ_{r2}(test) can be determined from $\epsilon_{\text{eff}s}$, ϵ_{r1}(standard), W, d_2(test), and d_1(standard) by calculation [7] or by using a set of calibration graphs, as shown in Fig. 3(a) and (b). These curves were generated using a full-wave analysis of the stripline structure with two dielectric slabs [7] for various thicknesses of the test substrate. Thus, given a value of $\epsilon_{\text{eff}s}$ as inferred from measurement, the test substrate dielectric constant ϵ_{r2} can easily be found.

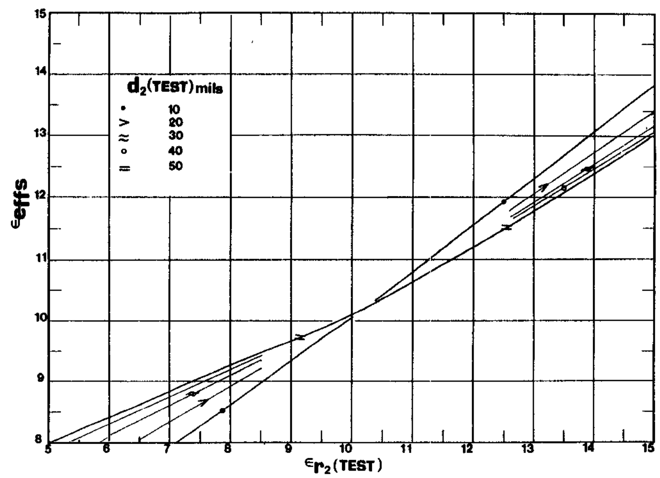
B. Error Analysis

In this method, it is assumed that we know ϵ_{r1}(standard), and $\epsilon_{\text{eff}m}$ for the standard substrate, accurately. Hence,

$$\delta(\epsilon_{\text{eff}m}) = 0. \tag{6}$$



(a)



(b)

Fig. 3. Calibration graph for (a) ϵ_{r1}(standard) = 2.2, d_1(standard) = 0.1575 cm = 62 mils, W = 0.5 cm, ϵ_{r2}(test) = 2.0–3.0, d_2(test) = 10–60 mils, and frequency = 3.0 GHz and for (b) ϵ_{r1}(standard) = 10.2, d_1(standard) = 0.127 cm = 50 mils, W = 0.12 cm, ϵ_{r2}(test) = 5.0–15.0, d_2(test) = 10–60 mils, and frequency = 3.0 GHz.

Now from (5) and (6),

$$\delta\left(\sqrt{\epsilon_{\text{eff}s}}\right) = \delta\left(\frac{\Delta l_e}{l_p}\right) = \frac{\Delta l_e}{l_p}\left(\frac{\delta \Delta l_e}{\Delta l_e} + \frac{\delta l_p}{l_p}\right)$$
$$= \frac{\delta \Delta l_e}{l_p} + \frac{\delta l_p \cdot \Delta l_e}{l_p^2}. \tag{7}$$

Of the two factors in (7), the first one is dominant, while the second one is of second order. So,

$$\delta\left(\sqrt{\epsilon_{\text{eff}s}}\right) \approx \frac{\delta \Delta l_e}{l_p} \tag{8}$$

or

$$\frac{\delta \epsilon_{\text{eff}s}}{\epsilon_{\text{eff}s}} = 2\frac{\delta\sqrt{\epsilon_{\text{eff}s}}}{\epsilon_{\text{eff}s}} \approx 2\frac{\delta \Delta l_e}{l_p \cdot \epsilon_{\text{eff}s}}. \tag{9}$$

It may be noted here that the inaccuracy in measuring the physical length (l_p) does not contribute significantly to the error in $\epsilon_{\text{eff}s}$ and hence in ϵ_{r2}(test).

When $\epsilon_{\text{eff}s}$ is used to calculate ϵ_{r2}(test), the error introduced in ϵ_{r2}(test) is not the same as the error in $\epsilon_{\text{eff}s}$.

However, the contribution of the top cover (test substrate) to the ϵ_{effs} of the stripline is about the same as that of the standard substrate when the dielectric constants of test and standard are about equal. In this case,

$$\delta\epsilon_{effs} \sim 1/2\delta\epsilon_{r2}(\text{test}). \tag{10}$$

This rough estimate can be checked from Fig. 3.(a) and (b). Finally,

$$\frac{\delta\epsilon_{r2}(\text{test})}{\epsilon_{r2}(\text{test})} = 2\frac{\delta\epsilon_{effs}}{\epsilon_{effs}} = 4\frac{\delta\Delta l_e}{l_p\cdot\epsilon_{effs}}. \tag{11}$$

For example, if $l_p \sim 5.0$ cm, $\epsilon_{effs} \sim 2.0$, and $\delta\Delta l_e \sim 0.1$ mm, we have

$$\frac{\delta\epsilon_{r2}(\text{test})}{\epsilon_{r2}(\text{test})} \approx 0.4 \text{ percent}. \tag{12}$$

C. Discussion

A few important points can be mentioned regarding the above measurement technique.

i) One side of the test substrate can quickly be etched free of copper and made ready for test. The size of the substrate need not be of any particular dimensions and need not be measured very accurately (accuracy of an ordinary ruler is good enough).

ii) This method measures the dielectric constant of a small area and can be used to measure the variation of dielectric constant from one place to another on a sample just by shifting it sidewise or turning it in a different direction.

iii) In a large number of substrates of approximately the same dielectric constant, the deviation from sample to sample can quickly be determined using this method.

iv) A fixed test setup can be used for a number of different types of substrates of different dielectric constants and different thicknesses.

v) The error introduced in the measurement because of the tolerances of dimensions of the substrate is negligible (see error analysis) and also is insensitive to discontinuities in connectors and microstrip–stripline junctions.

vi) The method requires the accurate determination of the dielectric constant of the standard substrate, but needs to be done only once; hence it is possible to characterize it very accurately using a variety of methods. The two-microstrip-line method is a suggested method.

vii) The main problem with this method is avoiding the air gap between the standard and test substrates, and this may determine the final accuracy of the result. An air gap is avoided by using sufficient uniform pressure from both sides and, if necessary, controlling the temperature for very accurate results, as was done in [1].

vii) To suit a specific application, the system can be optimized for best results, since it is preferable to have the dielectric constant of the substrate under test close to that of the standard to minimize errors due to large discontinuities in the microstrip–stripline junction, which introduces uncertainties (not error) in the measurement process. Similarly, better results will be obtained if the thicknesses of the test and standard substrates are not markedly different. The calibration graphs were obtained for a specific standard substrate. Similar graphs for other standards can be obtained.

ix) The variation of the dielectric constant over a frequency range can be easily measured. This is done by changing the frequency of the test and using the theoretical data corresponding to that frequency. The analysis of [7] can take care of this frequency dependence accurately. None of the previously reported methods can so conveniently take care of this aspect of measurement.

TABLE II
MEASUREMENT OF DIELECTRIC CONSTANTS OF DIFFERENT SUBSTRATES USING METHOD I (TWO-MICROSTRIP-LINE METHOD) AND METHOD II (TWO-LAYER STRIPLINE METHOD) AT 3.0 GHz

	Substrate tested	thickness	manufacturer's ϵ_r	method used	measured ϵ_r
1	RT/DUROID 5880	62mils	2.2	I	2.189
2	RT/DUROID 5880	31mils	2.2	I	2.19
3	RT/DUROID 6010.2	50mils	10.2	I	10.80
4	OAK	60mils	2.55	II	2.54
5	OAK	30mils	2.55	II	2.53
6	RT/DUROID 5880	62mils	2.2	II	2.20
7	RT/DUROID 5880	20mils	2.2	II	2.19
8	RT/DUROID 6010.2	50mils	10.2	II	10.15

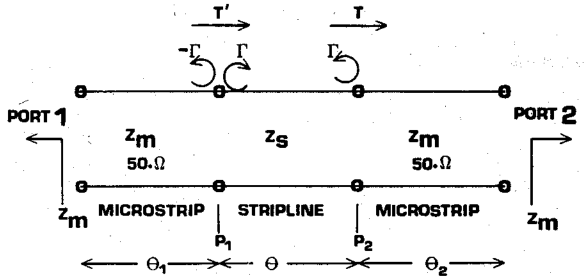
IV. RESULTS AND CONCLUSIONS

Two methods, the two-microstrip-line method and the two-layer stripline method, were used to measure the dielectric constants of a few different dielectric substrates. The air gaps between two substrates were avoided by applying sufficient clamping pressure. The results are given in Table II. It was observed that the RT/DUROID 6010.2 substrates have a large variation of dielectric constant from sample to sample, and even from place to place on a single piece of substrate. Dielectric constants in different samples of these substrates have been measured from as high as 10.80 to as low as 9.87.

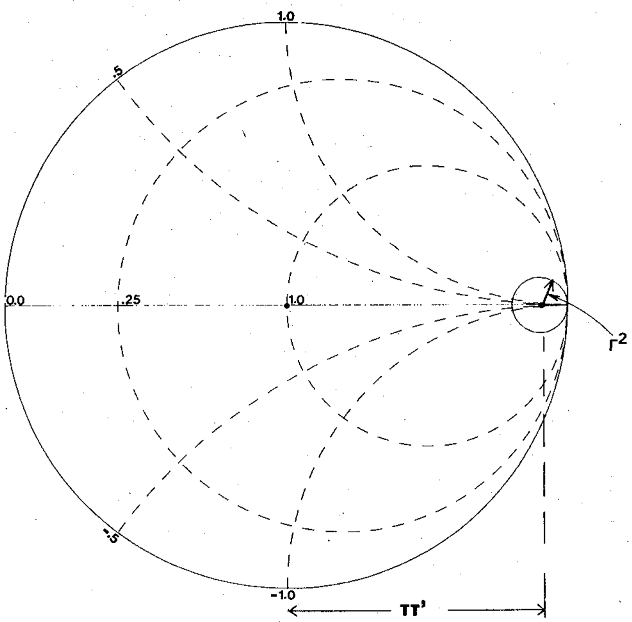
Using an optimized measurement setup, it is concluded that the two-layer stripline method, along with the two-microstrip-line method, can be used for quick, reliable measurement of the dielectric constant of microwave substrates in a very flexible way.

APPENDIX
S_{21} OF A CASCADE OF THREE TRANSMISSION LINE SECTIONS

A signal of unit amplitude incident on port 1 (see Fig. 4(a)) on the forward path reaches plane p_2 with an amplitude $T'e^{-j(\theta+\theta_1)}$. Part of it gets transmitted to the third section and to port 2 ($=T'T\cdot e^{-j(\theta+\theta_1+\theta_2)}$); the other part gets reflected back to the second section ($=T'\Gamma e^{-j(\theta+\theta_1)}$) and undergoes an electrical delay equivalent to 2θ and a reflection at plane $p_1(=\Gamma)$ back at p_2 again. This wave partly gets transmitted to the third section and to port 2,



(a)



(b)

Fig. 4. (a) Cascade of three transmission lines, i.e., microstrip line, stripline, and microstrip line. (b) S_{21} of the cascade for small mismatch.

and partly gets reflected to the second section, and so on [9].

Thus, the generalized expression for S_{21} can be written as

$$S_{21} = TT'e^{-j(\theta+\theta_1+\theta_2)}(1+\Gamma^2e^{-2j\theta}+\Gamma^4e^{-4j\theta}+\cdots) = \frac{TT'e^{-j(\theta+\theta_1+\theta_2)}}{1-\Gamma^2e^{-2j\theta}}. \tag{A1}$$

For small mismatches between the microstrip and stripline such that $25\ \Omega \leqslant Z_s \leqslant 100\ \Omega$, or $|\Gamma| < 1/3$, $|\Gamma|^2 \leqslant 0.1$, (A1) can be approximated as

$$S_{21} \approx TT'e^{-j(\theta+\theta_1+\theta_2)}(1+\Gamma^2e^{-2j\theta}). \tag{A2}$$

For small Γ, we have $T = 1+\Gamma$, and $T' = 1-\Gamma$; $TT' \approx 1$. Thus, S_{21} looks like a small circle toward the right-hand side of the Smith chart with center at TT' and radius $= \Gamma^2$ if an electrical delay equivalent to $(\theta+\theta_1+\theta_2)$, that is, the sum of the electrical lengths of the three sections, is added on the reference (Fig. 4(b)).

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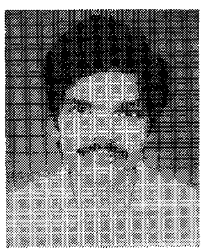

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