Acknowledgment

The authors wish to thank Dr. J. W. Thompson for preparing the required epitaxial material. They also wish to thank R. W. Bierig for many helpful discussions.

References

[1] M. G. Adlerstein, R. N. Wallace, and S. R. Steele, "High-power C-band Read IMPATT diodes," *Electronics Letters 11*, p. 430, September 4, 1975.
[2] J. Frey, "Multimesa vs. annular construction for high average power in semiconductor devices," *IEEE Trans. on Electron Devices ED-19*, pp. 981–985, 1972.
[3] D. E. Iglesias, J. C. Irvin, and W. C. Niehaus, "10-W and 12-W GaAs IMPATT's," *IEEE Trans. on Electron Devices ED-22*, p. 200, April 1975.
[4] R. S. Harp and H. L. Stover, "Power combining of X-band IMPATT circuit modules," *1973 IEEE ISSCC, Digest of Technical Papers*, pp. 118–119.
[5] K. Kurokawa, "The single-cavity multiple-device oscillator," *IEEE Trans. on Microwave Theory and Techniques MTT-19*, pp. 793–801, 1971.
[6] K. Kurokawa and F. M. Magalhaes, "An X-band 10-watt multiple IMPATT oscillator," *Proc. IEEE 59*, p. 102, 1971.
[7] C. A. Brackett, "The elimination of tuning-induced burnout and bias-circuit oscillations in IMPATT oscillators," *Bell System Technical Journal 52*, p. 271, 1973.

Measuring Dielectric Constant of Substrates for Microstrip Applications

A. R. GERHARD

Abstract—**A new technique for measuring the dielectric constant of unmetallized ceramic substrates for microstrip applications is fast, accurate, and nondestructive. Measurement is made at the actual microwave frequency at which the ceramic will be used. Results are repeatable to within ±0.1 percent of the dielectric constant relative to a known standard substrate. A measurement rate of 100/h can easily be achieved. A circuit is described which is used at 1.4 GHz and measures an area of approximately 1/2-in diameter on 25-mil-thick alumina substrates.**

Introduction

Variations in the dielectric constant of ceramic substrates intended for use in microwave integrated circuits often fall outside the stringent limits required to meet circuit performance specifications. Typical specifications call for alumina substrates 24–26 mils thick with a dielectric constant of 9.9–10.1. Therefore, in the interests of economy, it is desirable to measure the dielectric constant of the ceramic before the generation of a circuit and the application of devices. Available methods for achieving such meausrements such as the "two-fluid method" [1] and the "resonant-substrate method" [2]–[6] are not production oriented either because of the long time required to make a measurement or the fact that the method is destructive, preventing use of the material after the measurement.

Technique

The technique described here involves temporarily holding a conductor pattern against one side of the ceramic being measured and a ground plane against the opposite side of the ceramic. A swept microwave signal, with a mean frequency approximately the same as the frequency at which the final circuit will be used, is coupled to the resonant line. Reflected signals are observed, and the resonant frequency (as indicated by a sharp dip in reflected power) is measured. By comparison with a standard substrate, the dielectric constant of the unknown may be easily obtained by using the following relationships:[1]

$$\frac{\Delta\varepsilon_r}{\varepsilon_r} = K\frac{\Delta f_{res}}{f_{res}} \qquad (1)$$

where

$\frac{\Delta\varepsilon_r}{\varepsilon_r}$ percent of change in dielectric constant;

$\frac{\Delta f_{res}}{f_{res}}$ percent of change in resonant frequency;

K −2.15 for the fixture shown in Fig. 1 when measuring alumina substrates having a nominal thickness of 25 mils [7]. The K factor is a function of linewidth, substrate thickness, frequency, and the dielectric materials used in the fixture [8], [9].

Fig. 1 shows typical fixturing that may be used with the resonant-line technique. The ceramic to be measured is placed between two films of 1-mil polyimide (such as DuPont KAPTON®). The bottom side of the lower film is completely metallized with 1 mil of copper. The top side of the upper film contains a one-half-wavelength circular pattern (Fig. 2), located near its center, with a conductor coupled to it and extending to

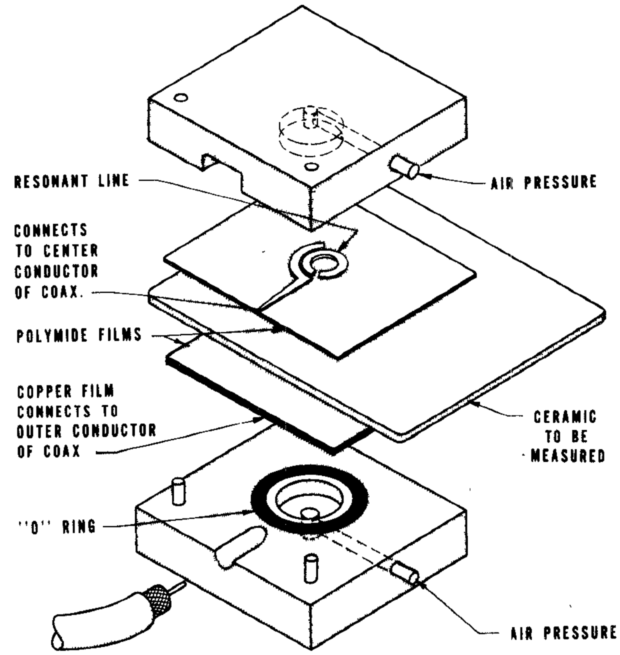

Fig. 1. Fixture for measuring dielectric constant of substrates for microstrip applications.

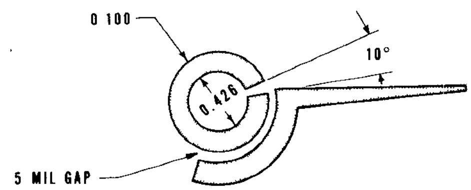

Fig. 2. Resonant circuit and coupling line.

[1] Propogation assumed to be in the TEM mode.
® Registered service mark of E. I. DuPont de Nemours & Co., Wilmington, DE.

Manuscript received November 3, 1975; revised January 9, 1976.
The author is with the Western Electric Company, Allentown, PA 18103.

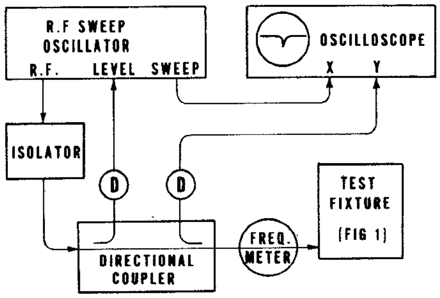

Fig. 3. Test equipment configuration for measuring resonant frequency to determine dielectric constant of substrate.

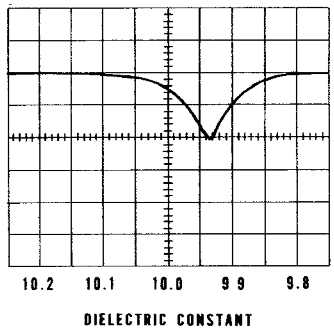

Fig. 4. Typical oscilloscope display of resonance indicated directly as dielectric constant.

the edge of the film. These patterns also consist of 1 mil of copper. The fixture is closed and clamped, and 30 lb/in^2 of air pressure is applied directly to the upper and lower conductor patterns pushing them against the ceramic under test. Intimate contact is important since it can be shown that an air gap of only 25 μin between the ceramic and the KAPTON will produce an error of 1 percent.

A swept-frequency microwave signal is applied to the fixture as shown in the block diagram of Fig. 3. The center conductor of the coaxial input line is connected to the upper conductor pattern at the edge of the film, and its outer conductor is connected to the copper on the lower film. The resulting reflected signal is detected and displayed as amplitude versus frequency. Fig. 4 is a typical display. The aforementioned relationship (1) of resonant frequency to dielectric constant may be used to calibrate the scope graticule directly in terms of dielectric constant.

Measurements can easily be made at a rate of 100/h with a repeatability of ± 0.1 percent of the dielectric constant relative to a known substrate.

Conclusions

The speed and simplicity of the resonant-line technique make it now practical to measure the dielectric constant of each piece of ceramic intended for critical microwave use before the circuit and components are applied. Also, since the area included in the measurement is less than the size of a dime, many measurements can be taken across a single substrate to determine its variation in dielectric constant. The described technique should result in lower cost microstrip circuits by assuring a compatible substrate before expending time and material to construct the circuit.

Appendix

Dependence on Accuracy of Ceramic Thickness

The technique described actually measures the resonant frequency of the test pattern with a given piece of ceramic. This is a measure of the propagation constant of the ceramic which depends not only on the dielectric constant of ceramic but also to a lesser degree its thickness. (Also involved are the polyimide films which, however, are a constant.)

In the present manufacture of ceramic substrates for microstrip applications, a thickness of 25 mils $\pm$ 1 is considered acceptable. This variation in thickness would produce an error in dielectric-constant measurement of ± 0.18 percent as determined by the following calculations.

From field analysis for $\varepsilon_r \approx 10$, $h \approx 25$ mils for 50-Ω line, where

ε_r relative dielectric constant;
v_r relative propagation velocity;
h thickness of substrate;

$$\frac{\Delta v_r}{\Delta \varepsilon_r} \quad -0.018;$$

$$\frac{\Delta v_r}{\Delta h} \quad 0.0008 \text{ mil}^{-1} \text{ [7]}.$$

Taking a ratio of the previous two relations: $(\Delta v_r/\Delta h/\Delta v_r/\Delta \varepsilon_r) = (\Delta \varepsilon_r/\Delta h) = -(0.0008/0.018) = 0.044$-percent change of ε_r for a 1-percent change of h since ± 1 mil in 25 = ± 4 percent; $-0.044 \times 4 = -0.176$-percent change of ε_r for a 4-percent change of h.

We therefore conclude that small changes in thickness cause negligible changes in relative propagation velocity.

In the event that ceramic thickness variation is appreciable, it would therefore be possible to correct the K factor in (1) to obtain the actual dielectric constant.

Description of Test Pattern

Fig. 2 shows the most practical pattern tested. This pattern employs a broken circular conductor which resonates at or near 1/2 wavelength of the intended operating frequency for the substrates to be measured. In the actual fixture as described, the mean length of the circular conductor pattern is 1.65 in; and the resonant frequency is approximately 1.43 GHz. The conductors are copper, 1 mil in thickness, with the circular conductor 100 mils wide to help achieve the relatively high Q of 220 attained by this pattern. The other conductor on this pattern serves as a coupling to the measuring circuit and is tapered to a width of 25 mils to provide a good match to the coaxial line. The area covered by this circuit permits small subareas of the substrates to be measured.

Experimental Data

Comparison of dielectric-constant measurements on three separate alumina substrates by three separate methods appears in the following table:

Sample	ε_r Two Fluid	ε_r Resonant Substrate	ε_r Resonant Line
A	10.10	10.15	10.20
B	10.21	10.24	10.28
C	10.29	10.30	10.32

The *two-fluid* method was made at 1 kHz and covered a circular area $2\frac{1}{2}$ in in diameter (4.9 in^2). The *resonant-substrate* method was made at approximately 1.4 GHz and involved a 2 × 2 in^2 (4.0 in^2). The *resonant-line* method was also made at approximately 1.4 GHz and covered a circular area of less than 0.7 in in diameter (<0.4 in^2). Since dielectric constant varies across a substrate, the differences measured by the three methods may be due to the averaging of different-sized areas.

Acknowledgment

The author wishes to thank R. N. Kershaw, Dr. R. H. Knerr, and H. F. Lenzing of the Bell Laboratories, and G. L. Allerton and F. M. Goll of Western Electric Company and others not mentioned by name for their advice, guidance, and encouragement on this project.

References

[1] W. P. Harris and A. H. Scott, "Precise measurement of dielectric constant by the two-fluid technique," *Proceedings of the National Bureau of Standards Conference on Electrical Insulation*, Washington, DC, 1962, pp. 51–53.
[2] H. F. Lenzing, "Measurement of dielectric constant of ceramic substrates at microwave frequencies," presented at the Electronics Division, American Ceramic Society Meeting, Washington, DC, May 10, 1972, Paper 41.
[3] L. S. Napoli and J. J. Hughes, "A simple technique for the accurate determination of the microwave dielectric constant for microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 664–665, July 1971.
[4] J. Q. Howell, "A quick accurate method to measure the dielectric constant of microwave integrated-circuit substrates," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 142–143, March 1973.
[5] P. D. Ladbrooke, M. H. N. Potok, and E. H. England, "Coupling errors in cavity-resonance measurements on MIC dielectrics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 560–562, Aug. 1973.
[6] T. Itoh, "A new method for measuring properties of dielectric materials using a microstrip cavity," *IEEE Trans. Microwave Theory Tech.*, pp. 572–576, May 1974.
[7] H. F. Lenzing, Bell Laboratories, private communications.
[8] H. E. Thomas, *Handbook of Microwave Techniques and Equipment.* Englewood Cliffs, N.J.: Prentice-Hall, 1972.
[9] M. V. Schneider, "Microstrip lines for microwave integrated circuits," *Bell System Technical Journal*, vol. 48, no. 5, pp. 1421–1444, May–June 1969.

Corrections to "Fundamental- and Harmonic-Frequency Circuit-Model Analysis of Interdigital Transducers with Arbitrary Metallization Ratios and Polarity Sequences"

W. R. SMITH AND W. F. PEDLER

In the above paper,[1] in the last paragraph on page 853, substitute "metallization ratio S_n/L_n" for "metallization ratio L_n/S_n." In the second and third lines on page 856, substitute $(-1)^n$ and $(-1)^{n+1}$ for $(-1)^m$ and $(-1)^{m+1}$, respectively. In the first paragraph on page 857, Appendix II should have read Appendix III.

In (15), the factor $(\beta L_i/2)$ should have read $(L_i/2)$, while the factor $(2\pi/A)$ should have read $(2\pi^2)$, independent of the anisotropy factor A. On page 864 the footnote should be labelled 5.

In Appendix III, in the equations for y_{11}, y_{22}, and y_{12}, substitute Y_S for Z_m; in the equations for y_{13} and y_{23}, substitute $Y_S^{1/2}$ for Y_m.

In (8) substitute $|Q_i|$ for Q_i and also take the absolute value of the sum on the right-hand side, since the capacitance contribution C_i should always be positive. Finally, with regard to (13), the significance of the reference wavenumber β_0 was ambiguous for double-electrode transducers and dispersive transducers. The proper definition in all cases is $\beta_0 = \pi/L_i$.

Manuscript received February 9, 1976.
The authors are with the Hughes Aircraft Company, Fullerton, CA 92634.
[1] W. R. Smith and W. F. Pedler, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 853–864, Nov. 1975.