DIELECTRIC MEASUREMENTS ON PRINTED-WIRING AND CIRCUIT BOARDS, THIN FILMS, AND SUBSTRATES: AN OVERVIEW[1]

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ABSTRACT

A review of the most common methods of permittivity measurements on thin films, printed-wiring and circuit boards, and substrates is presented. Transmission-line techniques, coaxial apertures, open resonators, surface-wave modes, and dielectric resonators methods are examined. The frequency range of applicability and typical uncertainties associated with the methods are summarized.

INTRODUCTION

This paper is an overview of dielectric measurement methods for thin materials. As electrical components are miniaturized, needs for low-loss dielectric measurements of thin materials increase so dielectric measurement metrology needs to keep pace with the new applications of novel, thin materials.

Accurate measurement of complex permittivity is needed for circuit design. New packaging technology requires low-dielectric constant materials, interconnections made of high-conductivity metals, and high wiring density. The use of fine-line signal conductors requires thinner, possibly laminated, low-dielectric constant printed-wiring board and substrate materials. In microelectronic applications the lower the dielectric constant, the lower the propagation delay. The propagation delay can be approximated by $T_d = l\sqrt{\epsilon'_R}/c$, where c is speed of light, l is line length and ϵ'_R is the real part of the permittivity. Propagation delay can be shortened either by decreasing signal path length by forming patterns or multilayers, or by lowering dielectric constant. The high wiring density increases cross-talk between elements. Low-dielectric constant and anisotropy can decrease the signal cross-talk between conductors by decreasing the capacitive coupling between interconnections and multichip modules.

Thin dielectric materials may be isotropic or anisotropic, epitaxial or amorphous, clad or unclad. Important properties of printed-wiring board and substrate materials include low loss, high thermal conductance, low thermal expansion, and high interfacial adhesion to metal plates and other films. Low-dielectric constant materials are usually plastics such as polytetrafluoroethylene, cross-linked polystyrene, fiberglass, polyimides, fluoropolymers, foams, or ceramics such as borosilicate glass and silicon dioxide [1, 2]. Many of the substrates are composites of various materials. Low dielectric properties can also be achieved by introducing porosity into materials or by forming hollow stripline ceramic structures [3].

High-dielectric constant substrates also have a niche in microelectronic applications. At low frequencies, well-characterized, high-dielectric constant materials are used to keep dimensions of circuits small. Compact antenna arrays require high-dielectric constant substrates for maintaining phase shifts between elements. High-dielectric constant materials include silicon nitride, polycrystalline alumina, monocrystalline materials such as quartz, sapphire, lanthanum alumina, ferromagnetic materials, titanates, and semiconductors [4]. Monolithic integrated circuit applications require semiconducting substrate materials for active device operation.

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Thin films can either be self-supporting or so thin that they require a substrate backing. Thin films used in integrated circuits usually are not self-supporting. In such cases measurements of the thin-film properties must either be performed *in situ* on the substrate or can be extrapolated from bulk-property measurements. Some applications require only a measurement of the effective value of the composite system. Thin-film dielectric properties can deviate from bulk-property measurements. In particular, thin-film dielectric properties can be anisotropic for isotropic bulk materials. In addition, loss increases for thin-film dielectric insulating materials as compared to the bulk material. *In situ* measurements allow field penetration through the film into the substrate. The polymers used in multichip modules start out as a liquid that is deposited on wafers in thin layers using spin-coating techniques. Spin-coated films are hard to remove for measurement. If the intrinsic properties of the thin film on the film-substrate composite are of importance, then the film properties must be deconvolved from the bulk measurement.

Dielectric properties depend on frequency, homogeneity, anisotropy, temperature, surface roughness, and bias field. Field orientation is important for measurements of anisotropic materials. Measurement fixtures where the electromagnetic fields are tangential to the air-material interfaces, as in TE_{01} cavities, generally yield more accurate results than fixtures where the fields are normal to the interface. Unfortunately, for many applications it is not always possible or preferable to measure in-plane field orientations. For example, circuit boards and printed-wiring boards can be anisotropic and operate with the electric field primarily normal to the plane of the sheet. Therefore this component of the permittivity is of primary interest. However, measurements with the electric field perpendicular to the sample face may suffer from air gap problems. In such cases the air gap effects must be either accepted, mitigated by metallization of sample surfaces or conductive pastes, or be corrected for by numerical techniques [5, 6].

It is important to understand the uncertainty in each measurement technique. The measurement of thin materials presents a challenge in that uncertainties in thickness of the sample translates into uncertainty in the permittivity ($\Delta\epsilon'_R/\epsilon'_R \propto \Delta l/l$).

We will review free-space techniques, coaxial and waveguide apertures, transmission line techniques, resonant cavities, dielectric resonators, open resonators, and surface-wave methods. Since this paper is an overview and the literature is vast, the reader will be referred to review papers whenever possible for specific techniques.

TRANSMISSION-LINE MEASUREMENT METHODS

Closed Transmission-line Techniques

Due to their relative simplicity, the off-resonance waveguide and coaxial line transmission/reflection methods are widely used broadband measurement techniques [6-8]. Transmission-line measurements use various terminations which produce different resonant behavior. For dielectric measurements it is advantageous to have a strong electric field. This can be achieved by an open-circuited termination. The model for an open circuit can involve a full-mode solution or a simplistic equivalent length extension model.

In these methods a precisely machined sample is placed in a section of waveguide or coaxial line and the scattering parameters are measured. The relevant scattering equations relate the measured scattering parameters to the permittivity and permeability of the material. Network analyzers have improved over the years to a point where broad frequency coverage and accurate measurement of scattering parameters are possible. Corrections for air gaps between the sample and holder can be made by analytical formulas or mitigated by use of conducting pastes or solder which is applied to the external surfaces of the sample before insertion into the sample holder [7, 8].

Transmission-line techniques have also been used for nondestructive substrate property determination [9]. In this technique the sample is inserted through a slot in the transmission line and the transmission and reflection coefficients are used to determine permittivity [11-22].

Open Transmission-line Methods

Many microelectronic applications use transmission lines that are open. For example, conductors may be deposited directly on thin films or substrates to form transmission lines [11-26]. These materials are thin and may be clad by copper, making measurements using closed transmission lines difficult . Also, many of the substrates and printed-wiring board materials are laminated and have varying surface roughness [22, 23].

The permittivity of substrate or substrate-thin film composites can be obtained by depositing conductors to form microstrip, stripline, or coplanar fixtures [24, 25]. Since the structures are open, only approximate permittivity models are usually used. The loss tangent is obtained by measurement of the quality factor, with and without sample. The real part of the permittivity can be obtained from the shift in resonance frequency. In open structures corrections due to open ends and wall losses need to be made. Accurate loss measurements are hard to obtain using open structures.

Generally, an effective dielectric constant ϵ_{eff} is defined by ratio of the measured capacitance with and without sample. Therefore ϵ_{eff} depends on the fields in the sample and the fringing fields. The effective dielectric constant is a very crude concept since complicated field structure is mapped into a very limited model. In a more fundamental approach, sample permittivity ϵ_R^* can be deconvolved from the resonant circuit measurements by using field models. Accurate full-field models that include effects of air layer, film, and substrate have been developed and hold great promise for metrology accuracy measurements.

Coaxial Apertures

Open-ended coaxial lines and waveguides [27-30] have been used for years as nondestructive testing tools. In the open-ended coaxial or waveguide measurement the probe is pressed against a sample and the reflection coefficient is measured and used to determine the permittivity or permeability [26]. The technique has been studied intensively over the years. Since the coaxial probe has electric field components in both axial and radial directions, the measurement contains elements of both the axial and radial permittivities. Although nondestructive, the method does have definite limitations. The method is quite sensitive to air gaps since the probe has both E_z and E_ρ electric field components. At low frequencies there is little field interaction with the material. In process control, such as rolling stock on assembly lines, for example, in thickness testing, a noncontacting probe may be required [27, 28]. For this reason it is important to have a model of a coaxial probe which includes *lift-off*, that is inclusion of an air gap between sample and probe [29, 30].

It is also possible to use two coaxial probes to monitor the dielectric properties of thin materials. The measurement fixture is depicted in Figure 1. In this case there may be transmission as well as reflection. An analytical solution to this problem has been derived [31]. Experimental results indicate that this method is viable for broadband material measurements on thin materials.

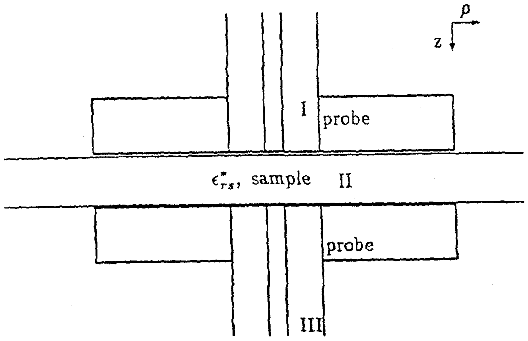

Figure 1: Two-port thin material tester

FREE-SPACE MEASUREMENTS

Antenna Systems

Free-space measurements have been carried out using antennas from 50 Mhz to 20 GHz. In these methods the transmission and reflection coefficients are used to obtain the material properties [32, 33]. Numerical reduction algorithms for frequency-domain free-space techniques are very similar to transmission-line techniques. The calibration used is generally a variation of transmission-reflection-line (TRL). The transmission standard is accomplished by setting the antennas a known distance apart, usually twice the focal length. The short-circuited termination is a metal plate at the reference plane. The delay measurement is obtained by separating the antennas by another, different known distance. Although the wave front is spherical, to a good approximation the electromagnetic fields can be assumed to be plane waves. This assumption simplifies the inversion algorithm. The measurement may use a metal-backed sample or a sample open on both sides. For electrically thin samples a short-circuit termination is not useful since the tangential electric field component approaches 0 on the metal. In the case of electrically thin materials, a transmission measurement is preferred. In this case both S_{11} and S_{21} can be used. However, at frequencies where the reflected signal becomes small, the phase of S_{11} becomes inaccurate. The technique lends itself well to elevated- temperature measurements. Much of the associated measurement uncertainty stems from uncertainty and variability in sample thickness.

Microwave tomographic techniques for dielectric measurements are an area of active research [34, 35]. In this technique waves are launched by dipoles or an antenna array and the reflected and transmitted waves are detected at various locations. The permittivity is found by solving the nonlinear inverse problem. The goal of these techniques is to determine the permittivity as a function of spatial position. At this time the measurements are not of metrology precision.

Coherent-Microwave Transient Spectroscopy

Thin materials have been measured successfully using picosecond transient radiation from opto-electronically pulsed antennas. This is a coherent-microwave transient spectroscopy technique [36].

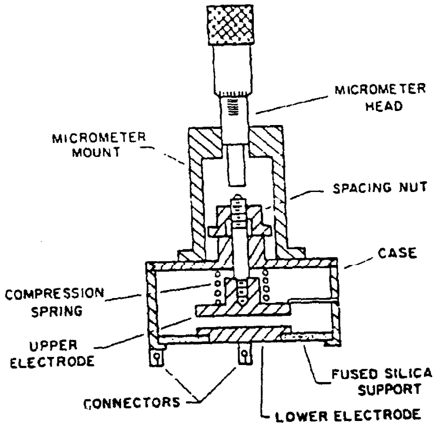

Figure 2: Capacitance dielectrometer

In this method the decay of a laser pulse impinging on sample is used to determine permittivity. The technique is attractive since it is relatively broadband and can be used for measurements of thin materials in the 10-100 GHz band. Measurements on dielectric thin-film anisotropy are given in [37].

CAPACITANCE METHODS

Capacitance techniques are important at frequencies from 1 Hz to 1 MHz [38, 39]. In Figure 2 a typical capacitor device is displayed. In these techniques the electric fields are nearly normal to the sample plane. The difficulty with these measurements resides in minimizing fringing field effects. The fringe field is usually partially eliminated by measuring the capacitance with and without sample and subtracting the results. Guards also can protect from fringing fields by minimizing field bending near probe edges. Permittivity measurements using capacitor fixtures are influenced by air gaps between capacitor and sample. An air gap at the sample-capacitor interface will make the calculated value low for the real part of the permittivity. Liquids and solids have been successfully measured at elevated temperatures with capacitors [40]. Typical measurement uncertainties in ϵ'_R using capacitors are 1-10%.

Two-fluid capacitor measurements are used on printed-wiring board materials. The technique has the advantage that the material thickness does not enter the calculation. The capacitance is measured in air and then in a fluid, with and without sample. The equations are then solved for the permittivity. The fluids used in the method, such as n-heptane, must have very low loss and have a well-characterized permittivity [41, 42].

RF impedance analyzers use a capacitive approach to obtain material measurements of thin materials from 1 to 500 MHz [43]. The test fixture consists of two electrode probes, which are basically extended sections of a coaxial center conductor. The top section of the probe is spring-loaded to allow temporary separation for sample insertion and also to minimize air gap problems as much as possible. The impedance measurement is made directly by sampling the current and voltage, as opposed to measuring the reflection coefficient. This technique is valid in the frequency range where lumped circuit parameters can be used. Printed-wiring board materials have been successfully measured with this method [1]. The performance of radio frequency material analyzers varies with the materials being measured. For materials with low real permittivity, uncertainties range from 2 to 10 % range. In addition to uncertainties incurred by the use of approximate models, there are also problems created by air gaps between the sample and the electrode faces. This technique offers quick, medium-accuracy, broadband information at frequencies less than 500 MHz.

RESONANT METHODS FOR LOW-LOSS MATERIALS

Resonant measurement methods are the most accurate ways of obtaining permittivity and permeability. However, there are limitations on the frequencies and loss characteristics of the materials that can be measured with this technique. In order to promote a resonance the materials must be low loss. In addition, the frequencies of measurement are usually limited to the gigahertz region [44].

Reentrant Cavities

Many applications require an accurate measurement of the component of the permittivity normal to the face of the material in the radio-frequency range. Applications include measurements of circuit boards and printed- wiring boards used in computers that operate in the low megahertz region. This type of field configuration is obtainable by capacitive structures, but not at these frequencies. The reentrant cavity, as shown in Figure 3, is an attractive alternative since it allows accurate measurement of materials at frequencies from 100 MHz to 1 GHz in a modified capacitor format. The reentrant cavity consists of a coaxial line or other transmission line with a gap between electrodes where a sample is positioned. The cavity is then resonated and the capacitance of the gap produces a frequency shift from an air measurement. If the sample gap region is at the very top or bottom of the cavity then the system is called a *singly reentrant cavity*, whereas if the sample is in between then the cavity is called *doubly reentrant*. The loss tangent is determined from Q measurements with and without sample. Typical uncertainties for a well-characterized system on low to medium permittivity values are $\Delta\epsilon_r'/\epsilon_r' = \pm 1\%$, $\Delta \tan\delta = \pm 0.0001$. There are two approaches to modeling the reentrant cavity. The first is a lumped-circuit approximation [45, 46]. The other approach is to solve for the fields by a rigorous mode-matching technique [47, 48].

TE_{01} Cavity Resonators for Thin Dielectrics

Thin materials can be measured using a split TE_{011} cavity resonator as depicted in Figure 0.4, [49]. The technique allows rapid measurement of low-loss, thin materials. In this type of resonator, the field is oriented parallel to the sample plane. The thin material is placed between the sections and a resonant mode is excited. These cavities can be constructed in various sizes to allow operation at frequencies from 8 to 20 GHz. Typical uncertainties are $\Delta\epsilon_r'/\epsilon_r' = \pm 0.2\%$ and $\Delta \tan\delta = \pm 5 \times 10^{-5}$, if conductor losses are included.

Another technique for thin material measurement is performed in TE_{01} cavities by suspending the sample above the bottom endplate and then solving the layered problem. This and a number of other cavity techniques have been described in the literature [50].

Split-post Resonators

The split-post dielectric resonator technique is another technique for measurement of thin materials. In this method a thin material or film is inserted between the posts of the resonator. The system

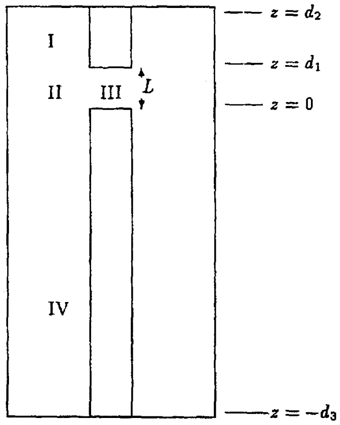

Figure 3: Reentrant cavity

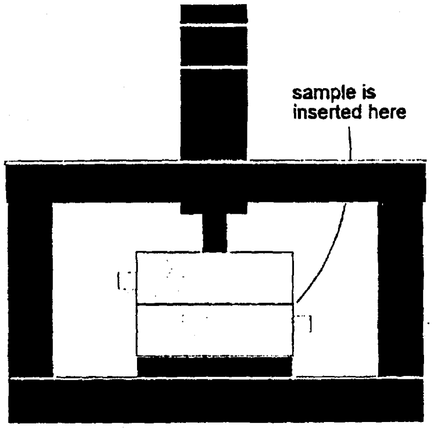

Figure 4: TE_{01} dielectric resonator for thin sheets

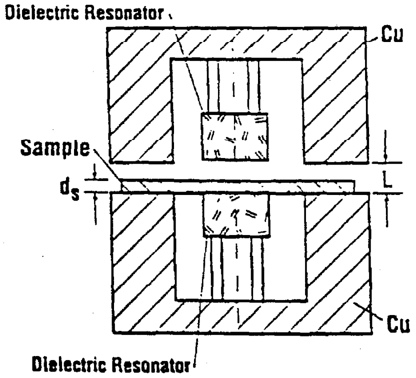

Figure 5: Dielectric resonator for substrates

is then excited in the $TE_{01\delta}$ mode and a resonance of the combined post-air-material system is obtained. Nishikawa et al. [51] have used the finite element method to analyze this system (see Figure 5). A nice feature of split-post resonators is that they can be designed to operate in the low gigahertz region.

Millimeter Open Resonators

Open resonators have been used for measuring low-loss materials in the millimeter range [52, 53]. An excellent review paper is [52]. Open resonators, such as Fabry-Perot resonators, consist of two separated mirrors with a coupling aperture in one of the mirrors. These resonators are based on the design of optical interferometers. In the confocal setup both mirrors are concave, whereas in the semi-confocal arrangement one of the mirrors is flat and the other is concave. The concave feature of the mirror minimizes radiation leakage from the open sides of the resonator and focuses the beam onto a smaller area of the sample under test, thereby minimizing sample edge diffraction. Fabry-Perot resonators have high quality factors and are useful for measurements on thin low-loss materials. In the semi-confocal configuration, microwave energy is coupled into the cavity from the concave mirror and the sample is placed on the flat mirror. This type of cavity is usually operated in a reflection mode. In the full confocal configuration the sample is placed approximately midway between two concave mirrors until the beam waist is near its minimum. Open resonators have been used for thin-film measurement [53, 54].

Full-sheet Resonance Method for Thin Sheets

The full-sheet resonance technique is used to determine the permittivity of clad circuit board and printed-wiring board material (see Figure 6). It is usually a nondestructive test and measures the bulk property of the substrate. The frequency of measurement is limited to the sample dimensions. The sample is usually open at the sides, however some researchers measure with the sides closed. The open sides make the electrical length of the sample slightly longer than the actual physical dimensions. The permittivity is measured by inserting a test signal using a capacitive coupling patch. This causes the cladded structure to resonant at integral multiples of one-half wavelength

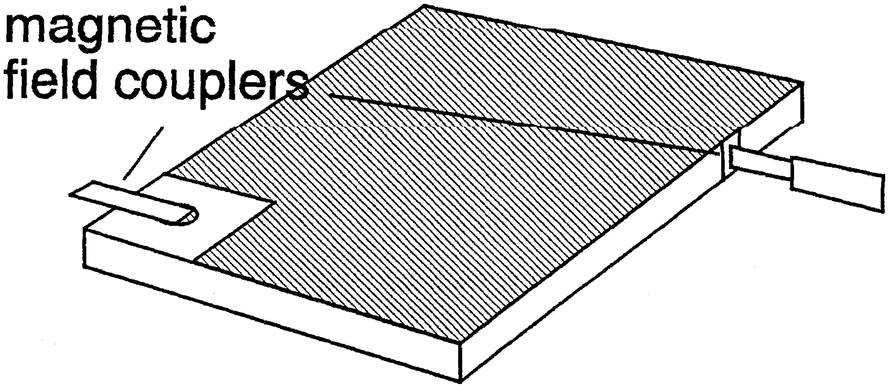

Figure 6: Full sheet resonance technique

in the sample. The main difficulty in this technique is mode identification and degenerate modes. The method has the advantage that the error introduced by the sample length is smaller than measurements of resonances across the sample such as in the split-post resonator. The full-sheet resonance method is limited in its ability to determine the loss factor since the surface area is large relative to volume. [12, 55, 23].

Other Resonance Methods

The permittivity of high-dielectric constant thin films have been measured with a waveguide resonance technique [56]. In this technique a substrate of one-half guided wavelength is resonated in a waveguide, with and without thin film attached. The change in resonant frequency and quality factor can be used to determine the permittivity. Thin polymer dielectric films for multichip modules have been measured with an on-wafer technique using T-resonators [37, 57, 58]. The technique is useful for measurement of ϵ_r', but not for ϵ_r''.

SURFACE WAVES

Low-loss dielectric thin films and layered substrates can be measured by use of surface electromagnetic waves [59, 60]. Measurements using surface waves are attractive since they have a very high quality factor and therefore are very sensitive to loss. Whispering-gallery modes were first discovered by Lord Rayleigh in acoustics. These modes can exist on the air-dielectric interface of concave surfaces. Dielectric resonators have been used for loss measurements on low-loss materials in the millimeter wave region employing whispering-gallery modes with large azimuthal wave numbers [61]. Whispering-gallery modes have been used for loss tangent measurements, but are much harder to use for the real part of the permittivity since the wavenumber is not easily determined.

CONCLUSION

Each technique has a niche for the appropriate frequency band, field behavior, and loss characteristics of materials. One technique alone is not sufficient to characterize materials over all of the necessary parameters. Permittivity component is sampled by appropriate field component. In the future there will be increasing demand to measure thinner low-loss materials of low to high dielectric constant to higher accuracy. This presents a metrology challenge since the uncertainty in thickness of materials introduces an uncertainty in calculated permittivity. Presently for low-dielectric constant materials, measurement of the real part of the permittivity has been emphasized. In the future it is expected that loss will become of more interest. In high-dielectric constant materials both components of the permittivity are very important.

REFERENCES

[1] A. Takahashi, A. Nagai, A. Mukoh, M. Wajima, and K. Tsukanishi, "Low dielectric material for multilayer printed wiring boards," *IEEE Trans. Components, Hybrids, and Manufacturing Technology*, vol. 13, pp. 1115–1120, December 1990.

[2] J. Jean and T. K. Gupta, "Design of low dielectric glass+ceramics for multilayer ceramic substrate," *IEEE Trans. Components, Packaging, and Manufacturing Technology-Part B*, vol. 17, pp. 228–233, May 1994.

[3] A. Sasaki and Y. Shimada, "Electrical design technology for low dielectric constant multilayer ceramic substrate," *IEEE Trans. Components, Hybrids, and Manufacturing Technology*, vol. 15, pp. 56–62, February 1992.

[4] I. Bahl and K. Ely, "Modern microwave substrate materials," *Microwave J.*, vol. 33, pp. 131–146, 1990.

[5] W. P. Westphal, "Techniques of measuring the permittivity and permeability of liquids and solids in the frequency range 3 c/s to 50 kMc/s," Laboratory for Insulation Research Technical Report XXXVI, MIT, 1950.

[6] J. Baker-Jarvis, M. D. Janezic, J. John H. Grosvenor, and R. G. Geyer, "Transmission/reflection and short-circuit line methods for measuring permittivity and permeability," Natl. Inst. Stands. Tech. Technical Note 1355, National Institute of Standards and Technology, 1992.

[7] J. Baker-Jarvis, "Transmission/reflection and short-circuit line permittivity measurements," Tech. Rep. TN 1341, Natl. Inst. Stands. Tech., July 1990.

[8] K. E. Mattar, D. G. Watters, and M. E. Brodwin, "Influence of wall contacts on measured complex permittivity spectra at coaxial line frequencies," *IEEE Trans. on Microwave Theory and Tech.*, vol. 39, no. 3, p. 532, 1991.

[9] R. A. York and R. C. Compton, "An automated method for dielectric constant measurements of microwave substrates," *Microwave J.*, vol. 33, pp. 115–121, March 1990.

[10] G. R. Traut, "Electrical test methods for microwave pcb's," *Microwave J.*, vol. 24, pp. 73–79, August 1981.

[11] J. Q. Howell, "A quick, accurate method to measure the dielectric constant of microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 142–143, March 1973.

[12] L. S. Napoli, "A simple technique for the accurate determination of microwave dielectric constant for microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 664–667, July 1971.

[13] K. C. Gupta, R. Garg, and I. J. Bahl, *Microwave Lines and Slotlines*. Norwood, MA: Artech House, 1979.

[14] M. V. Schneider, "Microstrip lines for microwave integrated circuits," *Bell Sys. Techn. J.*, vol. , pp. 1421–1444, May-June 1968.

[15] K. M. Fidanboylu, S. M. Riad, and A. Elshabini-Riad, "A new time-domain approach for determining the complex permittivity using stripline geometry," *IEEE Trans. Instrum. Meas.*, vol. IM-39, pp. 940–944, December 1990.

[16] R. A. Waldron, "Theory of a strip-line cavity for measurement of dielectric constants and gyromagnetic resonance line-widths," *IEEE Trans. Microwave Theory Tech.*, vol. IM-, pp. 123–131, January 1964.

[17] H. A. Wheeler, "Transmission-line properties of parallel-wide strips separated by a dielectric sheet," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 172–185, March 1965.

[18] W. J. Getsinger, "Microstrip dispersion model," *IEEE Trans. Microwave Theory Tech.*, vol. IM-, pp. 34–, January 1973.

[19] I. J. Bahl and S. S. Stuchly, "Analysis of a microstrip covered with a lossy dielectric," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 104–109, February 1980.

[20] H. Tanaka and F. Okada, "Precise measurements of dissipation factor in microwave printed circuit boards," *IEEE Trans. Instrum. Meas.*, vol. IM-38, pp. 509–514, April 1989.

[21] J. Murray Olyphant and J. H. Ball, "Stripline methods for dielectric measurements at microwave frequencies," *IEEE Trans. Elec. Insul.*, vol. EI-5, pp. 26–32, March 1970.

[22] C. S. Chang and A. P. Agrawal, "Fine line thin dielectric circuit board characterization," in *44th Electronic Components and Technology Conference*, pp. 564–569, Components, Hybrids and Manufacturing Technology Society, 1994.

[23] "Thin material measurement," Tech. Rep. Military Specification MIL-P-13949G, 1983.

[24] N. K. Das, S. M. Voda, and D. M. Pozar, "Two methods for the measurement of substrate dielectric constant," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 636–641, July 1987.

[25] G. R. Traut, "Electrical performance of microwave boards," *IEEE Trans. Components, Packaging, and Manufacturing Technology-Part B*, vol. 18, pp. 106–111, February 1995.

[26] S. Bringhurst and M. F. Iskander, "New metallized ceramic coaxial probe for high-temperature broadband dielectric properties of low permittivity materials," in *Microwaves: Theory and Application in Materials Processing II*, pp. 503–510, Amer. Ceram. Soc.: Ceramics Trans., 1993.

[27] S. Jenkins, T. E. Hodgetts, G. T. Symm, A. G. P. Warhamm, and R. N. Clarke, "Comparison of three numerical treatments for the open-ended coaxial line sensor," *Elect. Lett.*, vol. 24, pp. 234–235, 1992.

[28] J. Baker-Jarvis and R. G. Geyer, "Nondestructive testing with a coaxial probe," in *URSI Digest*, URSI, January 1992. Presented at URSI, Boulder, CO.

[29] R. Zoughi and M. Lujan, "Nondestructive microwave thickness measurements of dielectric slabs," *Materials Evaluation*, vol. 48, pp. 1100–1105, 1989.

[30] J. Baker-Jarvis, M. D. Janezic, P. D. Domich, and R. G. Geyer, "Analysis of an open-ended coaxial probe with lift-off for nondestructive testing," *IEEE Trans. Instrum. Meas.*, pp. 711–718, October 1994.

[31] J. Baker-Jarvis and M. D. Janezic, "The two-port coaxial probe for thin materials (in review)," *IEEE Trans*, vol. , p. , .

[32] D. K. Ghodgaonkar, V. V. Varidan, and V. K. Varadan, "A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies," *IEEE Trans. Instrum. Meas.*, vol. 37, pp. 789–793, 1989.

[33] J. Muscil and F. Zacek, *Microwave Measurements of Complex Permittivity by Free-Space Methods and Their Applications.* New York: Elsevier, 1986.

[34] D. K. Ghodgaonkar, O. P. Gandhi, and M. J. Hagmann, "Estimation of complex permittivities of three-dimensional inhomogeneous bodies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, no. 6, pp. 442–446, 1983.

[35] J. C. Bolomey and C. Pichot, "Microwave tomography: from theory to practical imaging systems," *Int. J. Imag. Syst. Tech.*, vol. 1, pp. 119–131, 1990.

[36] G. Arjavalingam, Y. Pastol, J. Halbout, and G. V. Kopcsay, "Broad-band microwave measurements with transient radiation from optoelectronically pulsed antennas," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 615–621, May 1990.

[37] A. Deutsch, "Measurement of dielectric anisotropy od bpda-pda polyimide in multilayer thin-film packages," *IEEE Trans. Components, Packaging, and Manufacturing Technology-Part B*, vol. 17, pp. 486–492, November 1994.

[38] R. B. Goldfarb and H. E. Bussey, "Method for measuring complex permeability at radio frequencies," *Rev. Sci. Instrum.*, vol. 58, no. 4, pp. 624–627, 1987.

[39] H. E. Bussey, "Measurement of rf properties of materials- a survey," *Proc. IEEE*, vol. 55, pp. 1046–1053, June 1967.

[40] S. Jenkins, T. E. Hodgetts, R. N. Clarke, and A. W. Preece, "Dielectric measurements on reference liquids using automatic network analyzers and calculable geometries," *Meas. Sci. Technol.*, vol. 1, pp. 691–702, 1990.

[41] W. P. Harris and A. H. Scott, "Precise measurement of dielectric constant by the two-fluid technique," Conference on Electrical Insulation, 1962.

[42] F. I. Mopsik, "Two-fluid measurements on thin films," Tech. Rep. TN 1294, Natl. Inst. Stands. Tech., May 1992.

[43] "New technologies for wide impedance range measurements to 1.8 GHz," Product note no. 4291-1, Hewlett Packard, 1994.

[44] J. Krupka, R. G. Geyer, M. Kuhn, and J. H. Hinken, "Dielectric properties of single crystals of Al2o3, LaAlO, NdGaO3, SrTiO3, and MgO at cryogenic temperatures," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 10, pp. 1886–1890, 1994.

[45] R. D. Harrington, R. C. Powell, and P. H. Haas, "A re-entrant cavity for measurement of complex permeability in the very-high frequency region," *J. Res. Nat. Bur. Stds.*, vol. 56, no. 3, pp. 129–133, 1956.

[46] C. N. Works, T. W. Dakin, and F. W. Boggs, "A resonant cavity method for measuring dielectric properties at ultra-high frequencies," *AIEE Trans.*, vol. 63, pp. 1092–1098, 1944.

[47] A. Kaczkowski and A. Milewski, "High-accuracy wide-range measurement method for determination of complex permittivity in re-entrant cavity: Part A- theoretical analysis of the method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, no. 3, pp. 225–228, 1980.

[48] J. Baker-Jarvis and B. Riddle, "Theoretical and experimental analysis of the reentrant cavity (in prep.)," *IEEE Transactions on Microwave Theory and Tech.*, vol. , p. , .

[49] G. Kent, "Nondestructive measurements of substrate permittivity," in *Proceedings of the 3rd International Symposium on Recent Advances in Microwave Technology*, pp. 1–4, ISRAMT'91, 1991.

[50] M. McPhun and K. Mehmet, *Thin film dielectric measurements*, pp. 60–71. Guilford, U.K.: Science and Technology, 1973.

[51] T. Nishikawa, H. Tanaka, and Y. Ishikawa, "Noncontact relative measurement method for complex permittivity of ceramic substrate," *IECE of Japan Symposium Digest*, pp. 154–155, 1986.

[52] R. N. Clarke and C. B. Rosenberg, "Fabry-Perot and open resonators at microwave and millimeter wave frequencies, 2-300 GHz," *J. Phys. E.: Sci. Instrum.*, vol. 15, no. 9, pp. 9–24, 1982.

[53] P. J. Hood and J. F. DeNatale, "Millimeter-wave dielectric properties of epitaxial vanadium dioxide thin films," *J. Appl. Phys.*, vol. 79, pp. 376–381, July 1991.

[54] J. Zhao, K. D. Stephan, S. Wong, and R. S. Porter, "Tensor permittivity measurements of thin films at millimeter wavelengths," *Journal of Infrared and Millimeter Waves*, vol. 9, no. 12, pp. 1093–1105, 1988.

[55] G. I. Woolaver, "Accurately measure dielectric constant of soft substrates," *Microwave & RF*, vol. 24, pp. 153–158, August 1990.

[56] C. D. Gupta, "A new microwave method of measuring complex dielectric constant of high-permittivity thin films," *IEEE Trans. Instrum. Meas.*, vol. IM-24, pp. 61–65, March 1975.

[57] K. Laursen, D. Hertling, N. Berry, S. A. Bidstrup, P. Kohl, and G. Arroz, "Measurement of the electrical properties of high performance dielectric materials for multichip modules," in *IEPS Proceedings*, pp. 11–13, 1993. San Diego, CA.

[58] C. S. Chang, "Resistive signal line wiring net designs in multichip modules," *IEEE Trans. Components, Hybrids, and Manufacturing Technology*, vol. 16, pp. 909–918, December 1993.

[59] O. Weiming, C. G. Gardner, and S. A. Long, "Nondestructive measurement of a dielectric layer using surface electromagnetic waves," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 255–260, March 1983.

[60] J. R. W. Alexander and R. J. Bell, "The use of surface electromagnetic waves to measure material properties," *J. Noncryst. Solids*, vol. 19, pp. 93–103, 1975.

[61] J. Krupka, D. Cros, M. Aubourg, and P. Guillon, "Study of whispering gallery modes in anisotropic single-crystal dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 1, pp. 56–61, 1994.