DIELECTRIC CONSTANT EVALUATION OF INSULATING MATERIALS: AN ACCURATE, PRACTICAL MEASUREMENT SYSTEM

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ABSTRACT

The concept, design, and illustrative results are presented for a coaxial resonant-cavity system used to determine dielectric constant and loss tangent in the UHF-microwave frequency range. Its significant practical features of convenience, simplicity, and reproducibility of measurements together with excellent accuracy make it suitable for evaluation of microcircuit substrates and other critical materials.

1. INTRODUCTION.

We report the development of an accurate and convenient resonance technique for the evaluation of complex dielectric permittivity of low-conductivity materials. Results and assessment of performance are presented on a specific embodiment of the concept. The value of this system lies in the capability which it has demonstrated for rapid generation of precise data over a wide range in the UHF and microwave bands.

The embodiment reported here incorporates a coaxial resonator terminated in an open circuit, sheltered from radiation loss by continuation of the outer conductor as circular waveguide beyond cutoff. The resonance frequencies and Q values are measured with the specimen in place and with the specimen absent. A computational analysis is performed to relate the frequency shift and change of Q to the change of effective capacitance, leading to determination of the dielectric constant and loss tangent of the specimen. Predictions are in excellent agreement with known dielectric constant values of reference materials, in the frequency range up to the maximum for which the quasistatic representation of the fields in the cutoff region are expected to be adequate in this structure.

The shielded coaxial open circuit has been the subject of detailed investigations (1,2,3,4,5) due to its favorable qualities for use as a standard of capacitance over a broad frequency range. Its utility for measurements of materials has been reviewed (6,7), and related versions have been employed in the study of lunar and terrestrial soils (8) and of liquids (9). Another configuration applying similar principles was developed for investigations in the range of high dielectric constants (10).

An embodiment of the coaxial resonator is shown in the photograph, Fig. 1. Fig. 2 is a sectional diagram of the resonator assembly designed for use in the frequency range 0.5 to 2.5 GHz, showing the open outer-conductor tube incorporating coupling probes and a collet, and coaxial center conductor supported by dielectric beads. The probes are loosely coupled so as to

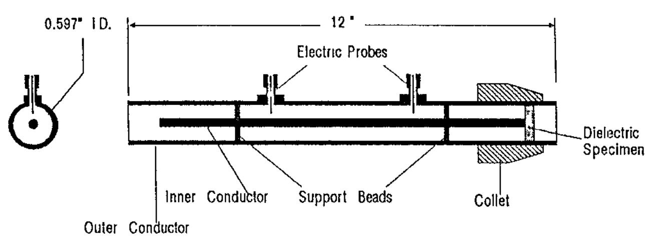

Fig. 2. Coaxial Cavity Resonator for Dielectric Measurements.

bring the resonance frequency and Q essentially to unloaded-resonator values. Normally, the resonator is mounted with its axis vertical. The specimen under test, in the form of a simple disc, is placed with its face against the flat lower end of the center conductor; reproducible contact of the cylindrical surface of the specimen with the outer conductor is established by means of the collet. The photograph, Fig. 3, shows the collet, typical specimens, and other details.

2. ANALYSIS.

This method presents the complication of a highly nonuniform fringing capacitor configuration (6). We have performed a precise numerical analysis of the capacitance to provide a theoretical basis for evaluation of the dielectric parameters. We employ a quasistatic Green's function incorporating the cylindrical symmetry and the dielectric boundary conditions, with source elements taken in the form of concentric rings on the end face of the center conductor and sleeves along the portion of its length in which fringing effects are appreciable. The technique resembles the "boundary-element" method (11), as applied to an inhomogeneous medium (12). An illustrative formulation of the Green's function is

$$G(r,z|r_s,z_s) = \frac{1}{2\pi\epsilon_o} \sum_{n=1}^{\infty}$$

$$\frac{J_o(\alpha_n r)e^{-\alpha_n z}}{\alpha_n r_b^2 J_1^2(\alpha_n r_b)} [e^{+\alpha_n z_s} - k(K,T)e^{-\alpha_n z_s}]$$

where r_s, z_s are the coordinates of a source element, J_0 and J_1 are Bessel functions, r_b is the radius of the outer conductor, $\alpha_n r_b$ is the n-th zero of J_0, and the coefficient k(K,T) depends on the dimensions of the unit source element and on the dielectric constant K and thickness T of the specimen. With the above formulation of a Green's-function basis for the potential, the array of charges required to establish the quasistatic equipotential value V = 1 on the center conductor is determined by a Gaussian elimination algorithm and summed to yield the required capacitance C. For interpretation of experimental data, a computational model of the resonator as a transmission line terminated in capacitors at each end is employed, relating the measured shift of the resonant frequency and change of Q to a corresponding change of C.

Results of the analysis are illustrated in the graph, Fig. 4, in which the curves represent predicted changes ΔC of fringing capacitance at one end of the resonator upon insertion, at that end, of a specimen having the given values of dielectric constant and thickness. The four reference materials are polystyrene [ϵ_R = 2.55, "Rexolite"], fused silica [3.83, (13)], forsterite [6.30, Trans-Tech "DS-6"], and sintered alumina [9.60, Coors "Vistal"]. Resonator outer conductor radius r_b for the calculations is 0.758 cm. The value of ΔC rises with increasing thickness and approaches a limiting value, dependent on dielectric constant, as the thickness becomes comparable with the range of the evanescent fringing field ($\sim r_b$).

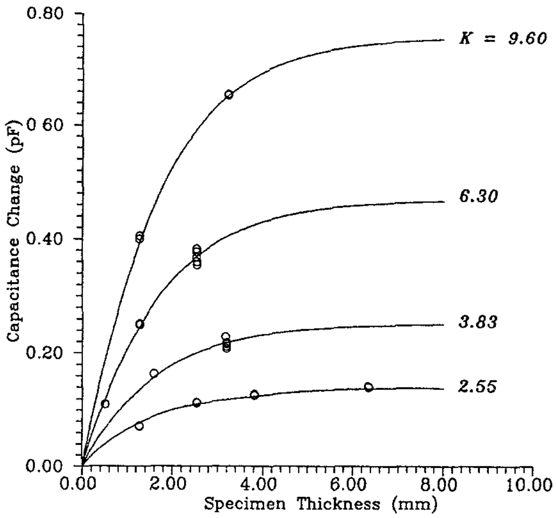

Fig. 4. Capacitance Change vs. Specimen Thickness for Four Reference Materials.

3. THE MEASUREMENT; ESTIMATE OF PRECISION.

Fig. 5 is a block diagram of the circuit for transmission resonance measurements, including swept-frequency source, frequency counter-stabilizer, network analyzer, and laboratory microprocessor which controls the measurement protocol.

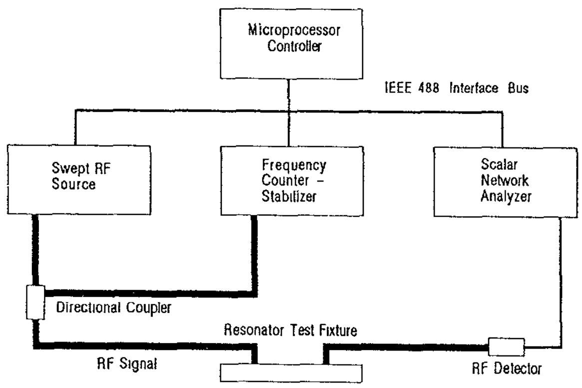

Figure 5. Dielectric Measurement Schematic

The computer graph, Fig. 6, illustrates data generated by the system for one of the resonances, displayed as insertion loss, in dB, as a function of frequency, with and without the specimen in place. The example is for resonance mode n = 3 (center-conductor length close to 3/2 wavelength). The specimen is polystyrene, thickness 1.24 mm. Upon insertion of the specimen, the resonance frequency shifts downward by 11.02 MHz from an initial value of 1.72456 GHz. To estimate

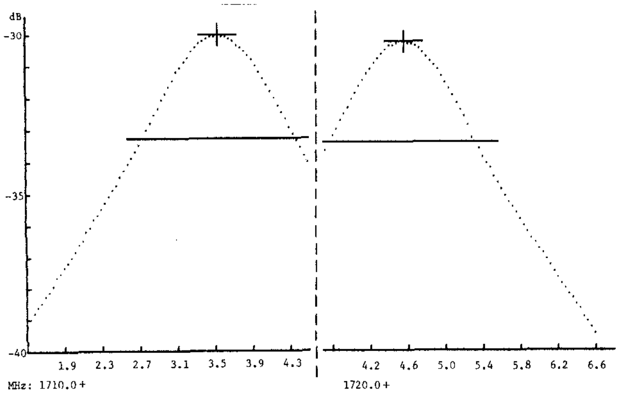

Fig. 6. Resonance with specimen absent and with specimen, polystyrene ("Rexolite"), thickness 1.24 mm, in place.

precision on the basis of the uncertainty in determination of center frequency, we compare the frequency shift with the width of the resonance. The 3-dB width is 1.60 MHz (Q = 1071), and the resonance frequency can be determined to one-tenth of this interval or better. As this example illustrates, we have found that precision levels of the order of about 1 % or better in determination of the shift are generally available by this method. The principal factor limiting repeatability is in the placement and fastening of the specimen by means of the collet; we have adopted a design and a procedure which we believe minimizes this problem.

4. DATA AND ASSESSMENT.

Comparison of experiment with theory is illustrated by the data points (circles) plotted in Fig. 4. For each of these reference materials, we have obtained measurements of ΔC which are highly consistent and show excellent agreement between the theoretical prediction and accurately known values of dielectric constant, in observations of the first four resonant modes (approximately 0.6, 1.2, 1.7, and 2.3 GHz). Standard deviations are about 2 %, and mean values agree with published values within approximately 1 %. There is a small systematic trend with frequency which appears to signal the onset of the propagation effects to be expected when the range of the fringing field is no longer negligible compared to the wavelength. Correction is to be made for this effect, applying a more rigorous analysis of evanescent waveguide modes (1,2,3,4,5).

The array of resonances within a given frequency range can be augmented to any desired degree by making use of a number of center conductors of graduated lengths. The upper frequency limit is determined by the onset of incipient propagation effects in the fringing region, and ultimately by actual waveguide propagation in the outer tubing. By reduction of the cross-sectional dimensions the limit can be extended, up to the point at which the performance becomes degraded by the decrease of Q due to conduction loss in the coaxial transmission line.

The design can be adapted for measurement of fluid dielectric properties (5,9); in fact, preliminary work has been performed in this direction with encouraging results.

5. ACKNOWLEDGMENTS.

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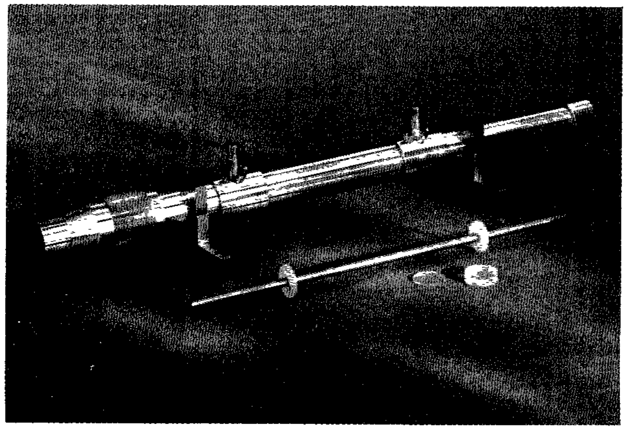

Fig. 1. View of the Coaxial Cavity Resonator.

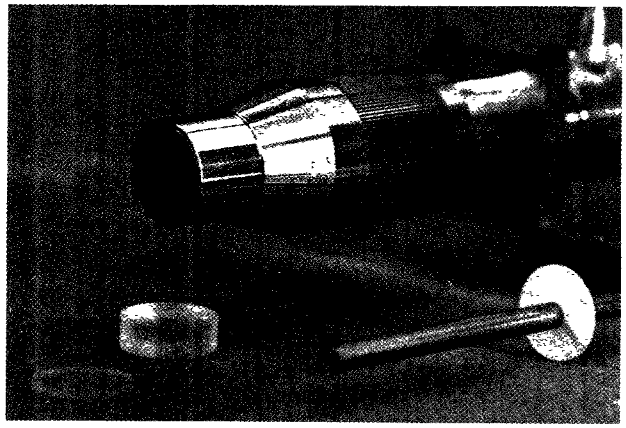

Fig. 3. Detail View of the Collet and Parts.