An Innovative Semianalytical Technique for Ceramic Evaluation at Microwave Frequencies

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***Abstract*—We have developed an innovative semianalytical technique for various substrate material characterization. The developed technique is a measurement procedure and data-reduction formulation that takes into consideration the radiation loss in a resonant structure, allowing for a more effective means of dielectric- and conductor-loss determination for a microstrip ring resonator and its substrate material. We separate dielectric and conductor loss precisely, evaluate the contribution of each term in the overall loss performance, and analytically predict the error in their respective predicted value.**

***Index Terms*—Dielectric and conductor losses, LTCC, Q measurements.**

I. Introduction

THE availability of new ceramic materials such as low-temperature co-fired ceramics (LTCC) and their compatible metallizations has fostered a need to assess their suitability for microwave applications such as packaging and multilayer RF circuits [1], [2]. For most of these applications, these substrate materials are adequately characterized by their dielectric permittivity (ε) and the metallization conductivity (σ).

We use two separate measurement techniques routinely to evaluate the ceramics and their metallizations. These measurements go hand in hand with the material development steps, and are utilized to characterize these ceramics and their metallizations at microwave frequencies. Specifically, we determine the dielectric constant (ε), loss tangent ($\tan\delta$) of the ceramics, and metallization's conductivity (σ).

First, for dielectric properties, we use a simple, fast, and accurate measurement technique (dielectrometer [3], [4]). We use a waveguide cavity resonant structure at X-band for nondestructive evaluation of the dielectric constant and loss tangent of these substrates. The sample is sandwiched between two half-resonant waveguide structures, and is evaluated using a mode-perturbation technique. This technique can also be utilized to measure the uniformity of the sample for a large wafer size.

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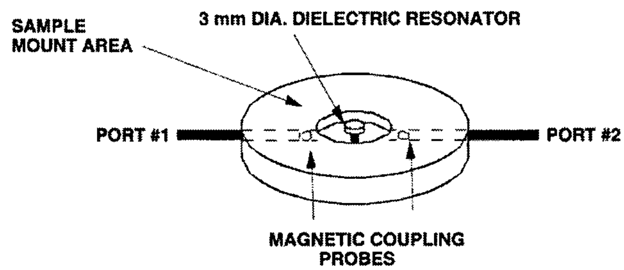

Fig. 1. Dielectric resonator test set.

Second, we evaluate thick-film-metallization conductivity using a dielectric-resonator technique [5]. This method utilizes a dielectric puck that is suspended in a circular waveguide cavity; one end plate of this cavity is normally the piece under test. The utilized test fixture is shown in Fig. 1. We utilize the measured unloaded Q [6] to evaluate the surface resistance and, hence, printed metallization layer conductivity. We use this test to perform nondestructive screening of the various thick-film metallizations (inks). However, the sensitivity of this test is not enough to show the small variations between different inks, e.g., the difference of σ between 2×10^7 S/m and 3×10^7 S/m. Therefore, we have developed a more sensitive method by which to resolve such differences, which is discussed in detail in the following sections.

II. Developed Procedure

The ring resonator measurement technique was originally described by Troughton [7] to measure wavelengths and dispersion characteristics of microstrip lines. Troughton used the ring structure to avoid end effects associated with linear resonators. Figs. 2 and 3 give a brief description of the simple calculations used for this method [8]. These calculations are based on the assumption that the mean length of the microstrip line is multiple wavelengths of the resonant mode on the microstrip ring. Pozar [8] and Wolff and Knoppik [9] indicated that the curvature of these ring resonators can influence the resonance frequency, and large resonators should be used. Obviously, if the substrate material has a relatively low permittivity or the printed lines are very wide, then the curvature effects must be taken into account. Hence, this method is suitable for dielectric constant, loss tangent, and metallization evaluation; however, it neglects radiation loss, which can be significant for thick substrates. In this paper, we present a measurement procedure and data-reduction formulation that takes into consideration the radiation loss

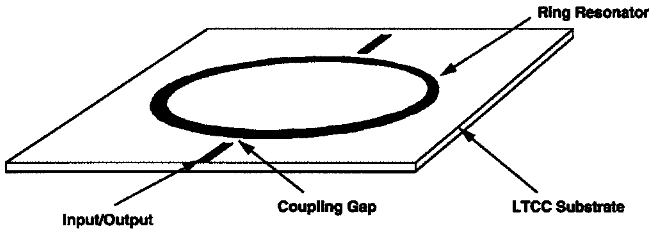

Fig. 2. Ring resonator, where the condition of resonance is ($2\pi r = n\lambda_g$), where λ_g is the wavelength in the media, and the mode order. Meanwhile, the Q of the resonator is given by $Q = \beta/ 2\alpha_{\rm tot}$, where $\beta = 2\pi/\lambda g$, and $\alpha_{\rm tot}$ is the total loss per unit length.

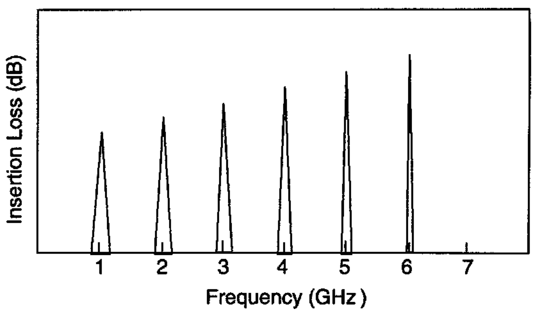

Fig. 3. Typical measured spectrum of a ring resonator.

in a resonator structure, allowing for a more effective means of determining dielectric and conductor loss for a microstrip ring resonator and its substrate material.

III. Algorithm Development

The developed semianalytical method takes into account a commonly neglected source of measurement error, i.e., radiation loss. It separates dielectric and conductor loss precisely, evaluates the contribution of each term in the overall loss performance, and analytically predicts the error in their respective predicted value. This evaluation technique ensures the accurate evaluation of any correction factor associated with those loss factor terms; thus, it accurately evaluates metallization conductivity σ, loss tangent $\tan\delta$, and radiation factor r. In addition, this technique can be extended to accurately determine the ceramic proprieties over a wide frequency range by using the higher order resonant modes of the ring resonator shown in Fig. 3.

A. Procedure

This method requires the measurement of the unloaded Q [6], [8], [10] of three distinct ring resonators. For example, three different height substrates can be utilized to manufacture three ring-resonator structures with the same ring size (diameter and width). Fortunately, this is relatively easy to accomplish with LTCC substrates because thickness can be simply adjusted by adding additional green tape layers. (LTCC material is fabricated by stacking unfired sheets of ceramic or green tape. This differs from traditional polycrystalline substrate fabrication techniques, such as those used for alumina, in which the substrates are made with one layer of green tape.) Hence, this procedure is compatible with LTCC fabrication process.

TABLE I
Almina Substrate Work Sheet

h(cm)	f(GHz)	Q(measured)
0.0254	0.8783	74.9
0.0508	0.9111	115.5
0.1016	0.92664	143.6

B. Algorithm Development

The conductor loss for a microstrip line [8], [10] (printed on sample i) is approximately given by

$$\alpha_{ci} = \frac{\sqrt{\dfrac{\omega\mu}{2\sigma}}}{Z_o W_i} = \text{constant}/\sqrt{\sigma} = g_{i1}/\sqrt{\sigma}, \ldots, Np/m \tag{1}$$

where this constant g_{i1} is a geometry-dependent parameter, Z_o is the characteristic impedance of the i line with width W_i, ω is the radian frequency, and μ_o is the permeability. Hence, if we evaluate ($\alpha_{ci}\sigma^{1/2}$), then we are in essence evaluating this geometry-dependent constant.

Similarly, the dielectric loss for a microstrip line printed on sample "i" is determined using the following formula [8], [10]:

$$\alpha_{di} = \frac{k_o\varepsilon_r\,(\varepsilon_{\text{eff}i} - 1)\tan\delta}{2(\varepsilon_r - 1)\sqrt{\varepsilon_{\text{eff}i}}} = g_{i2}\,\tan\,\delta, \ldots, Np/m \tag{2}$$

where k_o is the free-space wavenumber, $\varepsilon_{\text{eff}i}$ is the effective dielectric constant for sample i, and ε_r and $\tan\delta$ are its relative dielectric constant and loss tangent, respectively. Again, if we evaluate ($\alpha_{di}/\tan\delta$), then the ratio is the constant (g_{i2}) parameter, which is related to geometry and not a material parameter.

Meanwhile, the radiation loss factor (α_{ri}) of a microstrip-line ring resonator is approximately given by [11]

$$\begin{aligned}\alpha_{ri} &= \frac{\pi^3\eta_o\left[1-\dfrac{4}{3\varepsilon_r}+\dfrac{8}{15\varepsilon_r^2}\right]}{\lambda_o}\left(\frac{h_i^2}{\lambda_o^2\,\varepsilon_{\text{eff}}^{1.5}\,Z_{oi}}\right)\\ &= g_{i3}r, \ldots, Np/m\end{aligned} \tag{3}$$

where g_{i3} is

$$g_{i3} = \left(\frac{h_i}{\lambda_o}\right)^2 \frac{1}{\varepsilon_{\text{eff}}^{1.5}\,Z_{oi}} * 10^8 \tag{4}$$

and Z_{oi} is the characteristic impedance of the ring resonator microstrip line, η_o is $120\pi_\Omega$, λ_o is free-space wavelength, and similarly, (g_{i3}) is a function of geometry and frequency.

Now, for a given sample i (where $i = 1, 2, 3$) with a ring strip width w_i, dielectric substrate height h_i, and dielectric constant ε_r, the measured unloaded Q_i can be translated into a total loss factors α_{ti} as given by

$$Q = \beta_i/2\alpha_{ti} \tag{5}$$

where β_i is the propagation constant, which is given by

$$\beta_i = 2\pi/\text{ring\_circumference}. \tag{6}$$

It is extremely important here to evaluate the unloaded Q correctly and to take the coupling loss into consideration [6], otherwise significant effects on the overall results will be introduced.

TABLE II
Al_2O_3 LOSS WORKSHEET

INPUTS

Sample	Height (inches)	Height (cm)	Alpha Conductor1	Alpha Dielectric1	Unloaded Q	Zo	Epsilson effective	f (GHz)
A12O3-10	0.010	0.025	0.021	0.002	74.9	22.21	7.430	0.87830
A12O3-20	0.020	0.051	0.013	0.002	115.5	34.66	6.908	0.91110
A12O3-40	0.040	0.102	0.009	0.002	143.6	48.52	6.680	0.92664

CALCULATED VALUES

Sample #	beta	Q conductor	Q dielectric	alpha total	Lambda(g)	Lambda(0)	h/ Lambda(0)
A12O3-10	0.50	103.62	1036.25	0.0291	12.5310	34.1570	0.0007
A12O3-20	0.50	167.43	1072.24	0.0188	12.5280	32.9274	0.0015
A12O3-40	0.50	241.88	1133.82	0.0152	12.5263	32.3751	0.0031

beta = (2pi/c)*f*sqrt(E eff)
Q conductor = (beta/(2* alpha C))*8.68
Q dielectric = (beta/(2* alpha D))*8.68

Alpha Total = Alpha C + Alpha D + Alpha R
= ((beta/2)*8.68)/Q total
Lambda(g) = 2pi/beta= c/f*(1/sqrt(E eff))

G11 = Alpha C*sqrt(5.8)
G12 = Alpha D/0.001
G13=(h/lambda0)^2)/Zo*10e8/Eeff^1.5

COEFFICIENTS

G11 =	0.050574697	**G21 =**	0.031308146	**G31 =**	0.02167487
G12 =	2.1	**G22 =**	2.03	**G32 =**	1.92
G13 =	0.1224936	**G23 =**	0.378233	**G33 =**	1.1756

RESULTS

Sample	Height (cm)	% Conductor Contribution	% Dielectric Contribution	% Radiation Contribution
A12O3-10	0.025	97.13	1.77	1.10
A12O3-20	0.051	92.70	2.64	4.66
A12O3-40	0.102	79.78	3.11	17.11

Sigma =	**3.2117**
Tan Delta =	**0.0002**

Note 1: Alpha Conductor and Alpha Dielectric were calculated for ideal copper with sigma = 5.8 x 10^7, thickness = 5 microns, loss tangent = 0.001

Discussion of measurement error analysis is given in the following section.

Now, the total loss factor α_{ti} can then be divided into three individual terms, as given by

$$\alpha_{ti} = \frac{1}{\sqrt{\sigma}} g_{i1} + \tan\delta\, g_{i2} + r\, g_{i3} \tag{7}$$

where we have used the LineCalc Program [12] to calculate the normalized conductor loss and dielectric loss factors (g_{i1} and g_{i2}, respectively) for a given substrate height h_i and we have assumed an ideal copper metallization with $\sigma = 5.8 \times 10^7 \Omega$/m, metallization thickness of 5 μm, and substrate loss factor $\tan\delta$ of 0.001.

Hence,

$$g_{i1} = \alpha_{ci}\sqrt{5.8} \tag{8}$$
$$g_{i2} = \alpha_{di}/0.001. \tag{9}$$

These calculations are repeated for three distinctive samples and, hence, we formulate the following set of equations and evaluate the following relationship based on calculating α_{ti} according to Q measurements:

$$\begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{bmatrix} \begin{bmatrix} 1/\sqrt{\sigma} \\ \tan\delta \\ r \end{bmatrix} = \begin{bmatrix} \alpha_{t1} \\ \alpha_{t2} \\ \alpha_{t3} \end{bmatrix}. \tag{10}$$

Obviously, solving the above matrix renders the three unknowns σ, $\tan\delta$, and r.

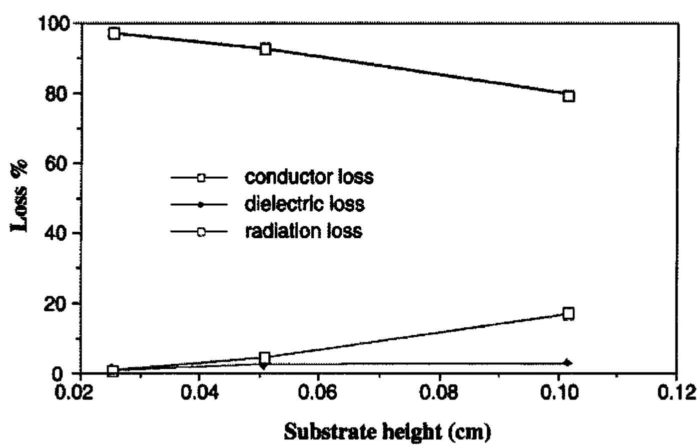

Fig. 4. Loss contributions for Al_2O_3 samples.

C. Measurements Errors

Uncertainty errors in Q measurements can be translated into an error range for the unknowns being evaluated, using the previously defined G matrix. The evaluation of these loss coefficients is as accurate as the measurements of the ring resonator's Q. Quantitatively, the following analysis can shed some light on the error that can be encountered in the Q measurements.

If we assume a slight error in the total loss factor measured $\Delta\alpha_t$, as shown in the following equation:

$$\begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{bmatrix} \begin{bmatrix} 1/\sqrt{\sigma} \\ \tan\delta \\ r \end{bmatrix} = \begin{bmatrix} \alpha_{t1} \\ \alpha_{t2} \\ \alpha_{t3} \end{bmatrix} + \begin{bmatrix} \Delta\alpha_{t1} \\ \Delta\alpha_{t2} \\ \Delta\alpha_{t3} \end{bmatrix} \tag{11}$$

TABLE III
LTCC LOSS WORKSHEET

INPUTS

Sample	Height (inches)	Height (cm)	Alpha Conductor	Alpha Dielectric	Q Total	Zo	Epsilon effective	f (GHz)
1	0.018	0.046	0.013	0.002	82.4	36.94	5.300	1.04080
2	0.025	0.064	0.011	0.002	96.1	44.22	5.180	1.05250
3	0.058	0.147	0.007	0.002	119.6	63.01	4.890	1.08290

CALCULATED VALUES

Sample #	beta	Q conductor	Q dielectric	alpha total	Lambda(g)	Lambda(0)	h/ Lambda(0)
1	0.50	166.26	1045.60	0.0264	12.5203	28.8240	0.0016
2	0.50	201.61	1066.30	0.0227	12.5237	28.5036	0.0022
3	0.50	329.80	1119.11	0.0182	12.5279	27.7034	0.0053

beta = (2pi/c)*f*sqrt(E eff)
Q conductor = (beta/(2* alpha C))*8.68
Q dielectric = (beta/(2* alpha D))*8.68

Alpha Total = Alpha C + Alpha D + Alpha R
= ((beta/2)*8.68)/Q total
Lambda(g) = 2pi/beta= c/f*(1/sqrt(E eff))

G11 = Alpha C*sqrt(5.8)
G12 = Alpha D/0.001
G13 = ((h/lambda0)^2)/Zo*10e8/Eeff$^{1.5}$

Coefficients

G11 =	0.031548978	**G21 =**	0.026009844	**G31 =**	0.0158949
G12 =	2.083	**G22 =**	2.042	**G32 =**	1.945
G13 =	.557	**G23 =**	.9516	**G33 =**	4.149

RESULTS

Sample	Height (cm)	% Conductor Contribution	% Dielectric Contribution	% Radiation Contribution
Al2O3-10	0.046	89.56	7.97	2.47
Al2O3-20	0.064	86.14	9.11	4.75
Al2O3-40	0.147	65.53	10.80	23.66

Sigma =	**1.7761**
Tan Delta =	**0.0010**

Note 1: Alpha Conductor and Alpha Dielectric were calculated for ideal copper with sigma = $5.8 \times 10^{+7}$, thickness = 5 microns, loss tangent = 0.001

then the error in the evaluation of the conductivity and the loss tangent can be determined from the second term of the right-hand terms of the following equations:

$$\begin{bmatrix} 1/\sqrt{\sigma} \\ \tan\delta \\ r \end{bmatrix} = G^{-1}\begin{bmatrix} \alpha_{t1} \\ \alpha_{t2} \\ \alpha_{t3} \end{bmatrix} + G^{-1}\begin{bmatrix} \Delta\alpha_{t1} \\ \Delta\alpha_{t2} \\ \Delta\alpha_{t3} \end{bmatrix}. \tag{12}$$

Typical errors can be significantly high, especially for thick substrates. It is essential to correct the measured Q values for coupling and loading effects.

IV. ALGORITHM VALIDATION

First, we have used three different Alumina (Al_2O_3) substrate samples for the validation of the proposed algorithm. These samples have thin-film metallization of Cu/Au 5-μm thick, and their conductivity was measured at 24 GHz using the dielectric-resonator technique. Their measured thin-film conductivity was ($\sigma = 3.5\times 10^7$ S/m). The measured Q values are listed in Table I.

In general, a lower limit of metallization conductivity can be predicted if we consider the thinnest sample and assume the conductor loss is the only dominant loss factor. Based on Sample 1 (the thinnest sample), we predicted a lower limit of the conductivity σ to be 3.03×10^7 S/m. Also, an estimate of the radiation Q can be evaluated by measuring the unloaded Q of the ring resonator both when it is enclosed in a cavity under cutoff and when the resonator is in an open structure and relate the difference to the effect of radiation.

Meanwhile, based on our developed procedure, the conductivity is $\sigma = 3.2\times 10^7$ S/m, and this value is consistent also with our dielectric resonator probe measurements of the conductivity.

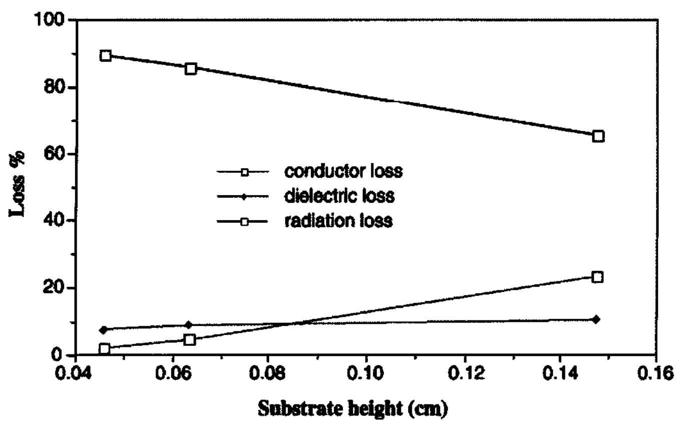

Fig. 5. Loss contributions for LTCC samples.

We have calculated $\tan\delta = 2.5\times 10^{-4}$, which is consistent with the manufacturer's data of $\tan\delta = 0.0001 - 0.0002$. Table II shows the loss contribution due to conductor/dielectric/radiation losses in each case. The results are also shown graphically in Fig. 4, where the losses are dominant by conductor loss for thin samples; thicker samples have relatively high radiation loss.

For the LTCC substrate evaluation, we used three independent measurements of three different height ceramic samples ($h1 = 0.4572$ cm , $h2 = 0.635$ cm, $h3 = 0.14732$ cm), and a silver metallization thickness of roughly 12–18 μm (which exceeds 2–3 times the skin depth at the operating frequencies $>$0.8 GHz). Using the thinnest sample where $h1 = 0.4572$ cm, the lower limit of the conductivity is $\sigma = 1.41\times 10^7$ S/m. Similarly based on our algorithm, we calculated: $\tan\delta = 0.001$ and $\sigma = 1.77\times 10^7$ S/m. Additionally, the loss contribution due to conductor/dielectric/radiation for each height is shown in

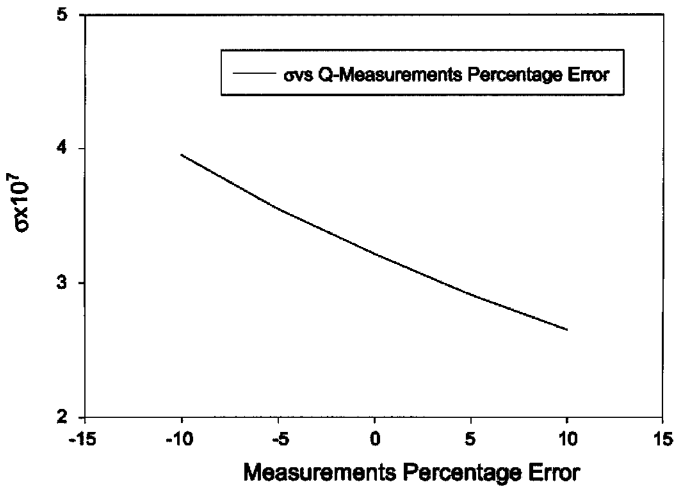

Fig. 6. Effect of errors in Q measurements on the predicted metallization conductivity estimate.

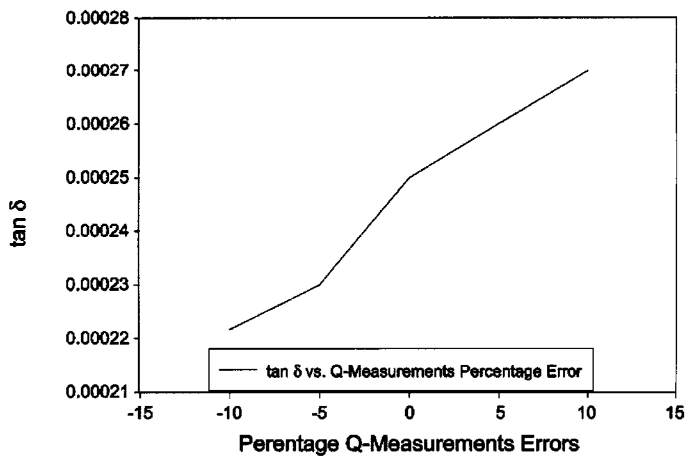

Fig. 7. Effect of errors in Q measurements on the predicted dielectric-constant loss-tangent estimate.

Table III, and Fig. 5 illustrates these results graphically, where again, radiation losses can significantly exceed dielectric losses for thick substrates.

We have also utilized (12) [see (10)] to evaluate the error bars in the evaluation of the predicted values of both the metallization conductivity and substrate loss tangent. As an example, for the alumina substrate, the metallization conductivity is within (2.91–3.55) $\times$ 10^7 S/m and the loss tangent is within (0.0023–0.0026) for a $\pm$5% Q-measurements error, as shown in Figs. 6 and 7.

V. Conclusions

We have developed a semianalytical technique, which is compatible with the LTCC fabrication process and accurately determines the ceramic proprieties over a wide frequency range. Our newly developed technique for the evaluation of metallization conductivity and the complex dielectric constant ensures the accurate evaluation of any correction factor associated with those semianalytical terms. The developed scheme is a measurement procedure and data-reduction formulation that takes into consideration the radiation loss in a resonant structure, enabling a more effective means of dielectric- and conductor-loss determination for a microstrip ring resonator and its substrate material. It separates dielectric and conductor loss precisely, evaluates the contribution of each term in the overall loss performance, and analytically predicts the error in their respective predicted value.

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Mr. Geller was co-chair of IEEE MTT-20 (Wireless Communications) and has been an active member of the Technical Program Committee (TPC) of the International Microwave Symposium (IMS). He has helped organize workshops and special sessions at the IMS, as well as at the European Microwave Conference, and has served on the TPC of the Radio and Wireless Conference (RAWCON) for the last several years. He chaired the TPC of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Topical Symposium on Technologies for Wireless Applications, Vancouver, BC, in 1999 and, in 2000, was chairman of the Sarnoff Symposium on Advances in Wired and Wireless Communications. He was the recipient of an Achievement Award at the Sarnoff Corporation for his work in the LTCC area.

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In 1963, he joined RCA at the Advanced Communications Laboratories, NY. For the next three years, while with in the Microwave Circuits Group, he was involved with low-frequency active filter techniques, parametric upconverters, parametric amplifiers, and UHF solid-state power amplifiers and multipliers. In 1966, he co-founded National Electronica Laboratories (NEL), where he was responsible for the design and development of oscillators, multiplier chains, and power amplifiers covering the range from 100 MHz to 14 GHz. NEL was purchased by Harvard Industries in 1967. After joining RCA Laboratories, Princeton, NJ, as a Member of the Technical Staff in 1973, he was involved in TV tuner design, nonlinear distortion analysis of RF signal processors, and computer-aided design and measurements. He has been involved in both the theoretical and practical aspects of RF and microwave-circuit developments. He has authored several design and analysis programs, which have been used throughout the RCA corporate structure. He is currently the Head of the Wireless Components Group, Sarnoff Corporation (the successor to RCA Laboratories). He has authored, coauthored, or presented over 50 technical papers. He holds five U.S. patents. He is an Editorial Board member of *Microwave Journal*.

Mr. Perlow is a member of Eta Kappa Nu. He has served as a research proposal reviewer for the National Science Foundation. He is on the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was cited for achievements as an outstanding young engineer and was used as an example in RCA's college recruitment literature.

Ellen S. Tormey received the B.S. degree in ceramic engineering from the New York State College of Ceramics, Alfred University, Alfred, in 1976, and the Ph.D. degree in ceramic science from the Massachusetts Institute of Technology (MIT), Cambridge, in 1982.

She has spent the majority of her career involved with materials and process development for multilayer cofired-ceramic/metal electronic packaging systems, including both high-temperature co-fired ceramic (HTCC) and LTCC development. From 1994 to 2001, she was with the Sarnoff Corporation, where she developed the low-temperature cofired-ceramic on metal (LTCC-M) system with Kovar as the metal base for commercial electronic applications. She is currently with Lamina Ceramics, Westampton, NJ, which manufacture and sells electronic packages based on LTCC-M technology. She has authored or coauthored 12 technical publications. She holds nine patents.

A. Prabhu (M'82), photograph and biography not available at time of publication.

Sadahiro Tani (S'80–M'81) received the B.S. and M.S. degrees in electronic engineering from Osaka University, Osaka, Japan, in 1979 and 1981, respectively.

In 1981, he joined the Sharp Corporation, Nara, Japan, where he was engaged in research on computer-aided-design systems of large-scale integration (LSI) and printed circuit boards (PCBs). His research interests are primarily concerned with simulation models and algorithms of the signal integrity of the circuits.

Mr. Tani is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, and the Information Processing Society of Japan.