Temperature Dependence of Composite Microwave Cavities

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***Abstract*—Composite microwave resonant cavities contain several regions of different dielectric materials. The variation of the resonant frequency with temperature is described in terms of a linear model. One part of the frequency variation is caused by the physical expansion of material parts, and the other by the change in the relative dielectric constant. The frequency sensitivity coefficients for both types of variation are obtained with the use of a computer code for numerical analysis of the electromagnetic field inside bodies of revolution.**

***Index Terms*—Author, please supply index terms. E-mail keywords@ieee.org for information.**

I. Introduction

RESONANT cavities used in filters and combiners for mobile communications are often comprised of a metal enclosure filled with several dielectric regions. Typically, the dielectrics are: 1) air; 2) high-permittivity low-loss dielectric (the dielectric resonator *per se*); and 3) low-permittivity moderate-loss dielectric (used as a support). The support keeps the dielectric resonator separated from the metal walls in order to reduce the losses. An example of such a composite resonant cavity of rotationally symmetric shape is shown in Fig. 1.

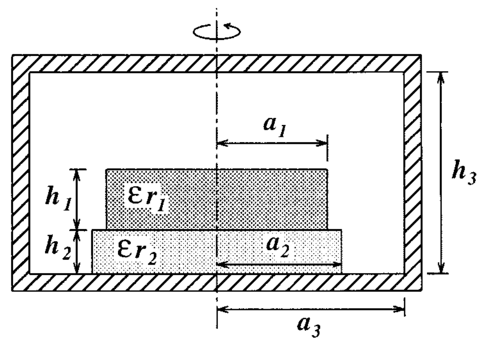

Fig. 1. Composite resonant cavity.

The individual communication channels in wireless transmission networks operating from 400 MHz to 2 GHz can be as close as 150 kHz. Therefore, the resonant cavities must exhibit very high stability of resonant frequency with power and temperature variations. To analyze the temperature stability, one must know the properties of all the materials used in the construction of the cavity. The experimental characterization of dielectric materials suitable for resonant cavities has been a subject of [1]–[4]. The temperature variation of composite resonant cavities has been analyzed in [5] and [6]. Some of these procedures have been summarized and discussed in [7, ch. 7].

This paper describes a linear analysis of temperature variations, along the lines outlined in [8]. It shows how a computer code for numerical analysis of the electromagnetic field in the bodies of revolution can be utilized to determine the sensitivity coefficients of a particular cavity. Some general relationships between the sensitivity coefficients are established, which are then utilized to check the numerical accuracy of the results. To overcome the lack of reliable data provided by manufacturers of dielectric materials, an independent measurement is performed to determine the temperature coefficient of the dielectric constant. Finally, the computed results for the behavior of the composite resonant cavity are compared with measurements in a temperature chamber.

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II. Linear Model of Frequency Versus Temperature Behavior

A composite microwave resonator consists of mechanical parts, which are either made of dielectrics or of conductors. Both dielectrics and conductors expand their size x with increasing temperature T. The dominant term, which describes this change, is a linear expansion coefficient α

$$\alpha = \frac{1}{x}\left.\frac{\Delta x}{\Delta T}\right|_{T=T_0}. \tag{1}$$

The value of α should be evaluated at room temperature T_0, which is the origin for our temperature modeling. The dependence of the relative dielectric constant ε_r with temperature is specified by the coefficient τ_ε

$$\tau_\varepsilon = \frac{1}{\varepsilon_r}\left.\frac{\Delta\varepsilon_r}{\Delta T}\right|_{T=T_0}. \tag{2}$$

For each material part of a composite resonator, α and τ_ε have different values. When the ambient temperature changes, the sizes of all mechanical parts change accordingly, as do the values of dielectric constants. Therefore, the resonant frequency of the entire system will also be affected by the change in temperature.

Consider a composite resonator shown in Fig. 1, consisting of two dielectric parts (besides air) and a conductive shielding cavity. The main element determining the resonant frequency is the dielectric resonator having the relative dielectric constant

ε_{r1}, radius a_1, and height h_1. The dielectric resonator is removed from the conductor surface by a spacer of radius a_2 and height h_2, having a relative dielectric constant ε_{r2}. The cylindrical conductive enclosure has radius a_3 and height h_3. The resonant frequency of this composite resonator is some function of the dimensions a_1 to a_3 and h_1 to h_3, and also a function of dielectric constants ε_{r1} and ε_{r2}. The air that fills the rest of the resonator has the relative dielectric constant equal to unity. The resonant frequency of this system is expressed in general form as follows:

$$f = F(a_1, a_2, a_3, h_1, h_2, h_3; \varepsilon_{r1}, \varepsilon_{r2}). \tag{3}$$

For most practical resonators, function F cannot be expressed in a simple analytical form. However, various computer codes have been developed that enable the user to determine the resonant frequency of the system, when all the dimensions and material properties are entered as input data. We have used the program AKBOR [9]. For simplicity of further derivations, various lengths (a's and h's) will be denoted by a common letter x. For instance $x_1 = a_1$, $x_2 = h_1$, $x_3 = a_2$, etc., up to $x_6 = h_3$. A small change in frequency Δf, caused by a small change in temperature ΔT, is obtained by taking a differential of F as follows:

$$\Delta f = \sum_{i=1}^{6} \frac{\partial F}{\partial x_i} \Delta x_i + \sum_{j=1}^{2} \frac{\partial F}{\partial \varepsilon_{rj}} \Delta \varepsilon_{rj}. \tag{4}$$

Increments Δx_i are now expressed with α's from (1)

$$\Delta x_i = \alpha_i x_i \Delta T \tag{5}$$

whereas increments $\Delta \varepsilon_{rj}$ are expressed with the use of τ_ε's from (2)

$$\Delta \varepsilon_{rj} = \tau_{\varepsilon j} \varepsilon_{rj} \Delta T. \tag{6}$$

Using this notation, the relative change in frequency, per degree centigrade, is expressed as follows:

$$\tau_f = \frac{1}{f} \frac{\Delta f}{\Delta T} = \sum_{i=1}^{6} \frac{\Delta x_i}{x_i} C_{xi} + \sum_{j=1}^{2} \frac{\Delta \varepsilon_{rj}}{\varepsilon_{rj}} C_{\varepsilon j}. \tag{7}$$

Coefficients C_{xi} describe the sensitivity of frequency with respect to length x_i as follows:

$$C_{xi} = \frac{x_i}{f} \frac{\partial F}{\partial x_i}. \tag{8}$$

Similarly, coefficients $C_{\varepsilon j}$ express the sensitivity of the resonant frequency with respect to the change in dielectric constant

$$C_{\varepsilon j} = \frac{\varepsilon_{rj}}{f} \frac{\partial F}{\partial \varepsilon_{rj}}. \tag{9}$$

At this point, it is of interest to introduce a useful relationship, which is valid for any composite resonator, consisting of any number of mechanical parts: *the sum of the length sensitivity coefficients must be equal to negative unity*

$$\sum_i C_{xi} = -1. \tag{10}$$

In the example from Fig. 1, subscript i goes from 1 to 6, but the above relationship is also valid for any other total number of individual dimensions. The validity of (10) can be understood by starting with (7) and assuming that the entire composite resonator has been machined for a second time in a slightly larger version. Suppose each of the lengths x_i is made to be m percent larger as follows:

$$\frac{\Delta x_i}{x_i} = \frac{m}{100}. \tag{11}$$

The newly machined resonator is kept at the same room temperature as the original smaller one. Thus, the dielectric constants of both resonators are the same, as their ambient temperatures are the same. According to (7), the relative change in frequency between the larger and smaller resonator must be equal to the relative change in size as follows:

$$\tau_f = -\frac{m}{100} = \sum_i \frac{\Delta x_i}{x_i} C_{xi}. \tag{12}$$

As each of the individual dimensions is increased by the same percentage, as specified by (11), the result must be such as described by (10), which concludes the proof.

Equation (10) comes in very handy when the length sensitivity coefficients C_{xi} are evaluated numerically. Namely, each C_{xi} is computed from (8) by incrementing the dimensions x_i by a small percentage m (1% or less), and computing the change in the resonant frequency. When all the C_{xi}'s have been computed, their sum must be equal to negative unity, verifying that the entire computation has been done correctly.

III. Epsilon Sensitivities

A similar relationship holds for C_ε coefficients: *the sum of the epsilon sensitivity coefficients must be equal to negative one-half* as follows:

$$\sum_j C_{\varepsilon j} = -0.5. \tag{13}$$

This relationship can be justified by the theory of material perturbations in cavities [10, p. 328]. The change in frequency due to a small change $\Delta \varepsilon_{rj}$ of the relative dielectric constant of the jth region is

$$\frac{\Delta f_j}{f} = -\frac{\dfrac{\Delta \varepsilon_{rj}}{\varepsilon_{rj}} W_{ej}}{2W_e}. \tag{14}$$

In the above, W_{ej} is the electric stored energy in the jth region, and W_e is the total stored electric energy in the resonator (thus, $W_e = \Sigma W_{ej}$). Suppose the relative dielectric constants in all the dielectric regions have been changed by the same percentage m as follows:

$$\frac{\Delta \varepsilon_{rj}}{\varepsilon_{rj}} = \frac{m}{100}. \tag{15}$$

In such a case, the total relative change in resonant frequency would become

$$\frac{\Delta f}{f} = \sum_j \frac{\Delta f_j}{f} = -\frac{m}{100}\,\frac{\sum_j W_{ej}}{2W_e} = -\frac{m}{100}\cdot\frac{1}{2}. \tag{16}$$

Starting with (4), the same change in relative dielectric constants by m% will result in the following frequency change:

$$\frac{\Delta f}{f} = \frac{m}{100}\sum_j C_{ej}. \tag{17}$$

Comparing (16) with (17), one obtains (13), which concludes the proof.

Another useful corollary of the above derivation is the following: *epsilon sensitivities are equal to a negative one-half of the corresponding electric filling factors*

$$C_{\varepsilon j} = -\frac{1}{2}\,p_{ej}. \tag{18}$$

The electric filling factors are simply the ratios of the stored electric energies in the jth dielectric region to the total stored electric energy in the entire resonator [7, p. 332]

$$p_{ej} = \frac{W_{ej}}{W_e}. \tag{19}$$

The differential change in frequency, caused by a change of a dielectric constant in the jth region, is

$$\Delta f = \frac{\partial F}{\partial \varepsilon_{rj}}\,\Delta\varepsilon_{rj}. \tag{20}$$

Using (9), the above relation becomes

$$\frac{\Delta f_j}{f} = C_{\varepsilon j}\,\frac{\Delta\varepsilon_{rj}}{\varepsilon_{rj}}. \tag{21}$$

Comparing (21) with (14), we obtain (18), which demonstrates the validity of the corollary.

The practical significance of (18) is the following. Instead of computing the individual derivatives in (9) by numerical differentiation of the resonant frequency, coefficients $C_{\varepsilon j}$ can be obtained by computing the ratios of stored electric energies. When the computer code is capable of producing explicitly the required partial stored energies, the numerical integration implicit in (19) will provide more accurate results, and the frequency of operation will have to be evaluated only once.

IV. Temperature Diagram of a Composite Cavity

One can assume that the dielectric materials expand their size with temperature in an isotropic way so that in the example from Fig. 1, for each dielectric region, the value of α in the radial direction is the same as in the axial direction ($\alpha_1 = \alpha_2$, etc.). When such an assumption is valid, (7) becomes

$$\tau_f = \sum_{i=1}^{3}(C_{ai} + C_{hi})\alpha_i + \sum_{j=1}^{2} C_{\varepsilon j}\tau_{\varepsilon j}. \tag{22}$$

In the above, α_1 and α_2 denote the mechanical expansion properties of the dielectric resonator and of the support, and α_3 denotes the mechanical expansion of the conducting cavity. Analogously, $\tau_{\varepsilon 1}$ and $\tau_{\varepsilon 2}$ specify the variations of dielectric constants with temperature. The air does not change its dielectric constant with temperature, thus, it is not included in (22).

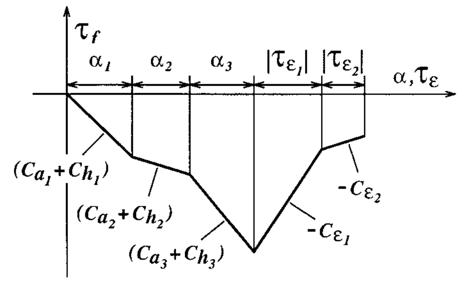

Fig. 2. Temperature diagram of a composite resonant cavity.

Each of the terms in (22) can be graphically represented by a straight-line segment, such as shown in Fig. 2. The horizontal axis contains the absolute values of α's and τ_ε's. The vertical axis represents the relative change in frequency τ_f. The units of both axes are parts per million per degree centigrade (ppm/°C). The sum of sensitivity factors, which belong to the same expansion coefficient α, represent the slopes of individual straight lines in the diagram. Thus, the negative value of $(C_{a1} + C_{h2})$ is plotted as a negative slope, and similarly for other materials. When C_ε and τ_ε are both negative, their product contributes to a positive increase in τ_f. In order to plot the absolute values of τ_ε always in the increasing horizontal direction, the slopes C_ε in such a case are plotted positive.

In the case shown, the first three terms of (22) result in a negative change in frequency due to increments in length with temperature (first line represents the puck material expansion, the second line the support material expansion, and the third line the metal cavity expansion). The next two terms contribute to positive changes in frequency because τ_ε's and C_ε's are each assumed to be negative numbers by themselves. The resulting normalized frequency change τ_f is represented by the vertical distance of the right-most point in the diagram.

The temperature sensitivity diagram from Fig. 2 is a convenient tool for spotting the critical parts of the system (those parts that contribute largest changes to the value of τ_f). Furthermore, by observing the relative sizes of individual segments in the temperature diagram, it becomes possible to decide whether the values of τ_ε should be increased or decreased in order to obtain a perfect temperature compensation, namely, $\tau_f = 0$.

V. Measured Results

The experimental resonant cavity consists of aluminum housing, a dielectric resonator, and an alumina ceramic support, both dielectric regions being of a tubular shape, as shown in Fig. 3. The cavity operates in the 2-GHz frequency region, and its tuning mechanism has been removed. The dimensions and the material properties are listed in Table I.

The variation of the resonant frequency of the mode $TE_{01\delta}$ was measured in a temperature chamber. The experimental results are shown in Fig. 4. At 25 °C, the measured resonant frequency is 1909.854 MHz. It can be seen that the temperature response is somewhat nonlinear. At the reference temperature

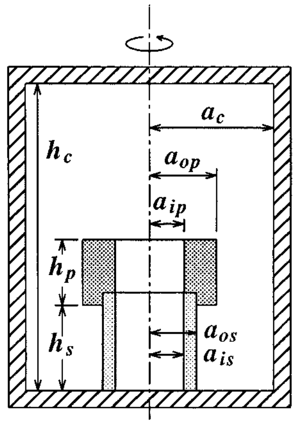

Fig. 3. Experimental cavity.

TABLE I
CAVITY DIMENSIONS AND MATERIAL PROPERTIES

	Puck	Support	Conductor
Inner radius (mm)	a_{ip}= 8.57	a_{is}= 8.44	a_c= 30.48
Outer radius (mm)	a_{op}= 16.51	a_{os}= 11.56	N/A
Height (mm)	h_p= 23.88	h_s= 22.86	h_c= 76.20
Relative dielectric constant	ε_{rp}= 30.51	ε_{rs}= 9.7	N/A
Expansion coefficient (ppm/°C)	α_p= 10.0	α_s= 6.4	α_c= 23.12

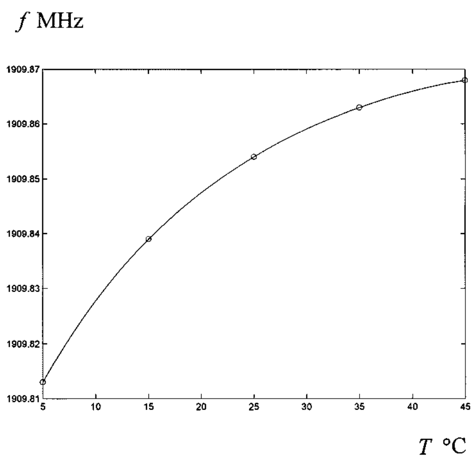

Fig. 4. Measured frequency variation with temperature for a cavity from Fig. 3.

$T_0 = 25\,°\mathrm{C}$, the temperature slope is estimated to be $\tau_f = 0.63$ ppm/°C.

The sensitivity coefficients were computed with the use of the computer program AKBOR [9], which is based on the surface integral-equation formulation and the method of moments for the analysis of axi-symmetric objects. The code can be used to compute the radar cross section of scatterers, radiation patterns of antennas, and the resonant frequency and Q-factor of dielectric resonators in free space or in closed cavities. For the dielectric resonator in free space, the resonant frequency and the radiation Q-factor are computed directly from the zeros of the determinant of the method-of-moment matrix by searching in the complex frequency plane for the roots of the determinant, as in [7, ch. 6]. For resonators enclosed by a conducting cavity, the Q factor is computed using perturbation theory from the stored energies and dissipated power inside the cavity.

Although the dielectric resonator has a short counter-bore to fit the support, this detail has been ignored in the electromagnetic model. It is believed that this detail is not likely to change the overall results in any significant way. The resonant frequency at room temperature was computed to be $f = 1905.571$ MHz. Although all these digits are not accurate, they are retained because they become meaningful when incremental changes are needed in the computation of the sensitivity coefficients. The computed sensitivity coefficients are listed in Tables II and III.

TABLE II
EXPANSION SENSITIVITY COEFFICIENTS

	Dielectric resonator	Support	Cavity
Inner radius	C_{aip}= +0.2562	C_{ais}= +0.0213	C_{ac}= -0.1686
Outer radius	C_{aop}= -0.8400	C_{aos}= -0.0300	N/A
Height	C_{hp}= -0.2299	C_{hs}= -0.0003	C_{hc}= -0.0002

Total sum ΣC_i= -0.9914

TABLE III
EPSILON SENSITIVITY COEFFICIENTS

Dielectric Resonator	Support	Air
$C_{\varepsilon p}$= -0.4751	$C_{\varepsilon s}$= -0.0059	$C_{\varepsilon a}$= -0.0150

Total sum $\Sigma C_{\varepsilon i}$= -0.4960

The dielectric-resonator-type D-8734 is manufactured by Trans-Tech, Adamstown, MD (a subsidiary of Alpha Industries). The manufacturer's value of the expansion coefficient is $\alpha_p = 10$ ppm/°C, and the frequency temperature coefficient is quoted as $\tau_f = 1.2$ ppm/°C. The alumina support is manufactured by Superior Technical Ceramics (STC), Monrovia, CA, with quoted expansion coefficient of $\alpha_s = 6.4$ ppm/°C and the dielectric constant of 9.7. As the manufacturer does not specify the value of τ_ε, we take the value to be $\tau_{\varepsilon s} = +116$ ppm/°C, according to [1]. This value is also similar to the one quoted in [2] for somewhat less pure alumina, namely, $\tau_{\varepsilon s} = +110$ ppm/°C. We measured the empty cavity expansion coefficient to be 23.12 ppm/°C.

All the coefficients needed for substitution in (22) are now available, except for $\tau_{\varepsilon p}$ of the dielectric resonator. As lamented in [7, p. 361], manufacturers of dielectric resonators do not measure this quantity, although the measurement procedure developed by Courtney [1] is quite straightforward. The value of τ_f is measured in the manufacturer's standard cavity, which has a cavity radius and cavity height about three times larger than the dielectric resonator. If we use the value $\tau_f = 1.2$ ppm/° in the approximate equation [7, p. 359]

$$\tau_\varepsilon = -2(\tau_f + \alpha) \tag{23}$$

we obtain $\tau_{\varepsilon p} = -22.4$ ppm/°C.

When this value is substituted in (22), the temperature diagram looks such as shown by a dashed line in Fig. 5. As can be seen from the figure, the computed result $\tau_f = -2.1$ ppm/°C differs considerably from the measured one. Also apparent from the diagram is that the product $C_{\varepsilon p}\tau_{\varepsilon p}$ is the most significant part of the total value τ_f. As has been shown in [7, p. 361], the uncertainty in $\tau_{\varepsilon p}$ when using the approximate equation (23) can reach 25%. Due to this, we decided to measure this coefficient directly, as described in the Appendix. Using our measured value $\tau_{\varepsilon p} = -28.56$ ppm/°C in (22) results in a computed frequency sensitivity $\tau_f = +0.78$ ppm/°C. This result is much closer to the measured value (see the solid line).

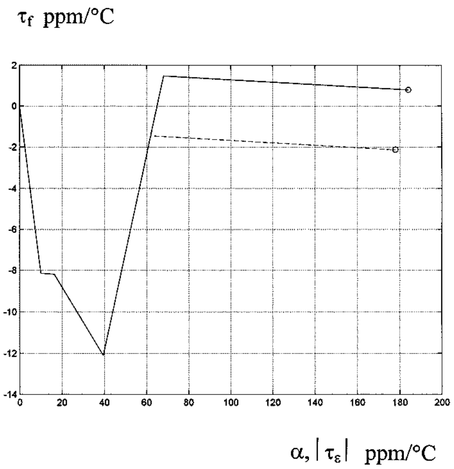

Fig. 5. Computed temperature diagram of the experimental cavity. Dashed line: $\tau_\varepsilon = -22.4$ ppm/°C, solid line: $\tau_\varepsilon = -28.56$ ppm/°C.

It is now possible to compute the desired value of $\tau_{\varepsilon p}$ that would yield a perfect temperature compensation. In order for τ_f from (22) to vanish, the dielectric resonator should be made of material with $\tau_{\varepsilon p} = -26.91$ ppm/°C.

VI. Conclusions

When a dielectric resonator is placed on a dielectric support and enclosed within a conducting cavity, a composite resonant cavity is created. Equations (7) and (22) describe a linear model governing the temperature variation of such composite microwave resonant cavities. The sensitivity coefficients, needed in this model, depend on the particular construction of the composite cavity. For given dimensions and given material properties, the sensitivity coefficients can be evaluated with the use of a computer program, which solves for the resonant frequency in the cavity filled with inhomogeneous dielectrics. Equations (10) and (13) specify the theoretical limits on the sensitivity coefficients obtained by such a numerical procedure.

A practical example of a composite resonator has been analyzed and experimentally verified. It has been concluded that the crucial role in the overall frequency variation with temperature is played by the material property $\tau_{\varepsilon p}$, the temperature coefficient of the dielectric constant of the "puck." At present, manufacturers of dielectric resonators do not measure τ_ε. Instead, they characterize the temperature behavior of their materials by providing the value of τ_f that has been determined inside a metallic test cavity. Whereas such a value of τ_f is valid for a particular test cavity only, operating in a particular resonant mode only (typically $\mathrm{TE}_{01\delta}$), the customers really need the value of τ_ε that will be valid for a cavity of any size, operating in any resonant mode.

Appendix
Measurement of τ_ε

The procedure for measurement of temperature coefficient of the dielectric constant has been described in detail by Courtney [1]. For that measurement, it is customary to use a solid cylindrical sample of the dielectric, and measure the resonant frequency of the sample placed between two parallel conductor plates. To perform such a measurement directly with the "puck" from Fig. 3 was impractical because of the receded bottom wall, which would create considerable difficulties in computing the resonant frequency when placed between parallel conducting plates. However, the manufacturer has provided us with another smaller tubular resonator made from the same production batch. The dimensions of the sample were: 1) outer radius $a_o = 8.9$ mm; 2) inner radius $a_i = 2.5$ mm; and 3) height $h = 15.0$ mm. The sample was placed between two parallel silver-plated conductors, and inserted into a temperature-controlled chamber. The resonant frequency of the mode TE_{011} was recorded as a function of temperature, with the results shown in Table IV.

TABLE IV
Measurement of τ_ε

T °C	f MHz	ε_r (corrected)
55	3556.175	30.6153
45	3556.056	30.6249
35	3555.941	30.6331
25	3555.792	30.6419
15	3555.650	30.6506
10	3555.565	30.6552
5	3555.480	30.6598

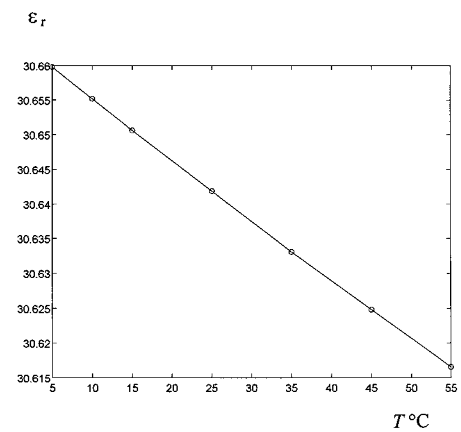

Fig. 6. Relative dielectric constant versus temperature (dimensions corrected by the temperature expansion coefficient $\alpha = 10$ ppm/°C).

The relationship between the resonant frequency and the relative dielectric constant can be expressed analytically in terms of Bessel functions. For the tubular resonator used here, the equations are somewhat more complicated than for the solid one used by Courtney. Nevertheless, they can be solved by straightforward numerical procedures. Since the thermal expansion coefficient α_p is known (see Table I), we have corrected all three dimensions a_o, a_i, and h in accordance with the operating temperature, and computed the dielectric constant for the corrected dimensions. The dielectric constant comes out to be a very linear function of temperature, as illustrated in Fig. 6. For the reference temperature 25 °C, the temperature coefficient of the dielectric constant is computed in accordance with (2)

$$\tau_\varepsilon = \frac{30.6331 - 30.6506}{30.6419 \cdot (35 - 15)} = -28.56 \text{ ppm/°C}.$$

Due to the linear behavior, the same coefficient is valid over the entire range of temperatures.

Although the composite cavity used in the example resonates around 2 GHz, the measurement of the temperature coefficient $\tau_{\varepsilon p}$ was carried at the resonant frequency of the mode TE_{011} for the sample at hand, namely, around 3.5 GHz. Nevertheless, the results are useful in the 2-GHz range, as the relative dielectric constant ε_r is practically constant over the wide frequency range.

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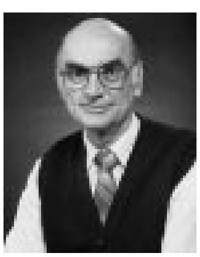

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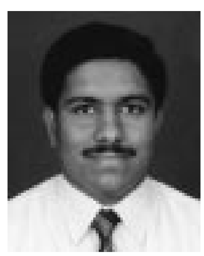

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