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Localized Temperature Stability in A Multilayer LTCC Package

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Abstract

Low temperature cofired ceramic (LTCC) is a multilayer 3D packaging, interconnection, and integration technology. One of the advantages of LTCC is the ability it affords to integrate passive components via the cofiring processes. For LTCC modules with embedded resonator functions targeting high frequency applications, the temperature coefficient of resonant frequency (τ_f) is a critical parameter. The base dielectrics of commercial LTCC systems have a τ_f in the range -50 ~ -80 ppm/°C. This study explores a method to achieve zero or near zero τ_f embedded resonators by incorporating τ_f compensating materials locally into a multilayer LTCC structure. Chemical interactions and physical compatibility between the τ_f modifiers and the host LTCC dielectrics are investigated. A stripline (SL) ring resonator with near zero τ_f is demonstrated in a non-zero τ_f commercial LTCC.

Key words: Low temperature cofired ceramics (LTCC), temperature coefficient of resonant frequency τ_f, *compensating materials, stripline resonator.*

Introduction

A low τ_f, preferably close to 0ppm/°C, is desirable to achieve resonator functions for radio and microwave frequency (RF and MW) applications that are stable to temperature variations. By using a low τ_f resonator the temperature compensation that requires additional mechanical and electrical circuits[1,2] can be eliminated. For filter applications, low τ_f translates into efficient use of bandwidth for maximum data capacity.

There are multiple approaches to achieve temperature stable resonator functions. One common engineering method of realizing a near zero τ_f is to form solid solutions of different dielectric ceramics that have opposite τ_f. The method has been applied in resonator applications for many MW dielectrics[3-6], as well as to LTCC base dielectrics[7-10] to integrate resonator functions. The other practice is to form a hybrid layered structure incorporating alternating layers with opposite τ_f, either by sequential sintering[11] or by using bonding processes[12].

Although there are commercial LTCC dielectrics with low τ_f, (e.g., Heraues CT2000 with τ_f < 10ppm/°C), most of existing LTCC dielectrics have a τ_f in the range -50 to -80 ppm/C. Figure 1 shows τ_f data, collected in this work, of several main stream LTCC dielectrics. It is expected that, for integrated RF circuits using any of these LTCCs, the impact of τ_f will be reflected in the drift of the resonant frequency of the embedded resonator, if any, over the device's operating temperatures. This results in an extra design limitation and/or a performance compromise.

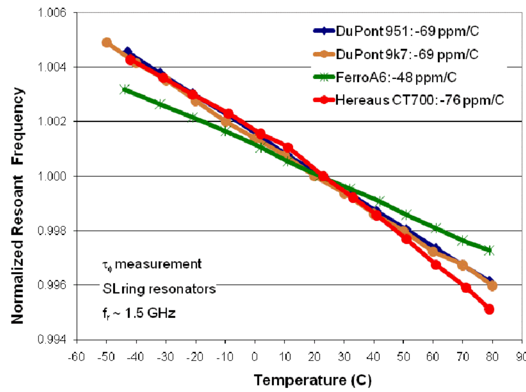

Figure 1. τ_f of several commercial LTCC base dielectrics from DuPont, Ferro and Hereaus. The resonant frequencies f_r (all ~ 1.5GHz) are collected from stripline ring resonators from -50 to 80°C, and normalized to f_r at 20°C.

τ_f is a device parameter that can be expressed in basic material properties:

$$\tau_f = -\tfrac{1}{2}\tau_\varepsilon - \alpha \qquad (1)$$

where τ_ε is the temperature coefficient of dielectric constant, and α the coefficient of thermal expansion (CTE). For LTCC dielectrics, α is typically between 4 - 10ppm/°C, so τ_ε dominates τ_f.

From eq. (1) it is clear that τ_f and τ_ε have opposite signs. To compensate for the negative τ_f of a LTCC, materials with a negative τ_ε and thus positive τ_f are necessary. Table 1 lists dielectric constant ε, τ_ε, and the normal sintering temperatures of candidate ceramics that could serve as compensating materials.

Table 1. Potential compensating materials[13].

Materials	Dielectric constant	τ_ε (ppm/°C)	Sintering Temp (°C)
TiO_2	110	-750	~ 1200
$CaTiO_3$	130	-1600	~ 1400
$SrTiO_3$	285	-2400	~ 1550

The purpose of the current study is to explore a novel approach to adjust the temperature coefficient by locally integrating a compensating dielectric with a τ_f opposite to that of host LTCC dielectric in a multilayer structure. Upon successful implementation, the method would enable temperature compensation where only the resonator functions resides in a structure without affecting other embedded functions where such implement is not necessary or undesirable. In principle the method could be applied to any existing LTCC with a proper selection and development of cofireable compensating dielectrics. A major advantage of this approach is its inherent compatability with the existing LTCC system, which enables the use of existing cofireable conductors and other functional materials, and circumvents the need to redevelope an entirely new LTCC materials system.

The key technical challenges include: the development of τ_f compensating materials, and the cofiring of such materials in a LTCC. Following is a case study in which compensating glass-ceramic compositions are developed, and the compensating materials in paste form are successfully cofired in a commercial LTCC. Evidence of both physical compatibility, measured by matched shrinkage, and chemical compatibility, characterized by material interdiffusion, is provided. SL ring resonators in LTCC were fabricated and characterized to verify and quantify the effect of the temperature compensation.

Experiments

Compensating materials:

Several commercial LTCC glasses have been evaluated. The main factors considered included the chemical constituents of the glass, and the glass softening point T_g which correlates closely to the onset temperature of shrinkage of the compensating material. One LTCC glass, designated as V-glass, was selected for this study. Table 2 details the formulations of the compensating materials. The weight fraction of the V-glass was fixed at 55% in the study. The base formulation is 55wt% V-glass + 45wt% Al_2O_3. Part of Al_2O_3 was replaced with different titanates at several weight percentages to form a series of different compositions. The mixture of V-glass, Al_2O_3 and titanate was co-milled to a median particle size 2.0 to 2.2 μm using Al_2O_3 media. Dielectric property measurements were made on ϕ12.5x1 mm pellets formed by dry pressing of co-milled powder granulated with organic binder. A 2-step pressing process was used, which involved uniaxial pressing at 43.5 MPa followed by isostatic pressing at 206.8 MPa. The pellets are sintered at 850°C for 30min in air. Electrodes were formed by sputtering Au on polished sintered pellets.

Table 2. Formulations of compensating materials.

Composition	V-glass (wt%)	Al_2O_3 (wt%)	TiO_2 (wt%)	$CaTiO_3$ (wt%)	$SrTiO_3$ (wt%)
Base	55	45			
TO15	55	30	15		
TO30	55	15	30		
CTO10	55	35		10	
CTO20	55	25		20	
STO10	55	35			10
STO20	55	25			20

Pastes of selected compensating materials were made using an organic vehicle, ESL441, combined with thinner ESL401 (both from Electro-Science Labs) using a 3-roll mill. These pastes were screen printed on green LTCC tapes below and/or over conductor lines to form temperature compensation layers.

LTCC and SL resonator:

Standard 254 μm thick DuPont 951 LTCC tapes are used throughout this study. The conductors used include DuPont 5738 Au for the via fill, 5734 Au for the internal conductors, and 6143 Ag/Pd for the post-fired external metallization. SL ring resonators having a designed base resonance of 1.5GHz were fabricated in 4 layer 951 panels. All panels were laminated using a standard process that included 20.7 MPa isostatic pressing at 70°C for 10 minutes. Panels were sintered at 850°C for 30min in air on Al_2O_3 setters. Sub miniature version A (SMA) edge connectors were soldered to resonator panels to access the embedded ring resonator for the resonant frequency measurement.

Characterization:

The capacitance of the compensating material was measured on a sintered pellet using a HP4194A at 1MHz inside a temperature chamber. The τ_f is calculated from

$$\tau_f = -\tfrac{1}{2}(\tau_c + \alpha) \qquad (2)$$

where τ_c is the temperature coefficient of capacitance, and α is again the CTE.

Shrinkage data for the compensating material, in the form of a ϕ6.25x5 mm cylinder at, and the 951 dielectric, in the form of a 5x5 mm stack of 20 layer tapes, were collected using a Netzsch DIL 402 dilatometer. Scanning Electron Microscopy (SEM) was used to analyze the microstructure and the interface of the cofired materials.

The SL resonators were placed inside a temperature chamber and characterized using an Agilent E5062A network analyzer from -50 to 80°C. The resonant frequency f_r was obtained as the minimum frequency of the reflection coefficient (S11) of the ring resonator. τ_f was calculated using the following equation,

$$\tau_f = \frac{1}{f_{ro}} \left(\frac{\Delta f_r}{\Delta T}\right) \qquad (3)$$

where f_{ro} is the resonant frequency at 20°C, Δf_r is the change of resonant frequency over -50 to 80°C, and ΔT equals to 130°C.

Results and Discussion

Screening of Compensating materials:

Both TO10 and TO30 showed a lack of adequate densification so these compositions are dropped from further study. The bulk density (determined by the Archimeded's method), and the dielectric constant of the different sintered compensating materials are shown in Table 3. Figure 2 shows the normalized capacitance, scaled to the capacitance value at 20°C, for compositions CTO10, CTO20, STO10, and STO20 over the temperature range -50°C to 80°C. The τ_c and the estimated τ_f of these compositions are also listed in Table 3.

Table 3. Density and dielectric properties of the compensating materials. τ_f was calculated from τ_c using eq. (2) assuming an α of 7 ppm/°C

Sample	Archimedes bulk density (g/cc)	Dielectric constant (1 MHz)	τ_c (ppm/°C)	τ_f (ppm/°C)
Base	3.19	7.8	190	-98.5
CTO10	3.20	9.7	83	-44.9
CTO20	3.15	12.0	-58	25.5
STO10	3.21	9.6	10	-8.7
STO20	3.30	12.2	-240	116.7

The base dielectric has a τ_c of 190 ppm/°C and a τ_f of -98.5ppm/°C. So, without the addition of titanates, the base dielectric has a higher τ_f than the 951 LTCC. With the addition of 10wt% of titanates, the CTO10 and STO10 still show positive τ_c, and thus negative τ_f. Obviously, the polarity of τ_f of these two compositions is the same as that of the 951 LTCC. These compositions are not expected to adjust the τ_f towards zero, and were eliminated from further investigation. With a higher weight percentage of titanates, the CTO20 and STO20 reach a τ_f of 25.5ppm/°C and 116.5ppm/°C, respectively. Considering that the 951 LTCC has a τ_f of -69ppm/°C, the STO20 is expected to be more effective for τ_f compensation, and was thus down-selected for a cofiring study and for the fabrication of proof-of-concept SL ring resonators.

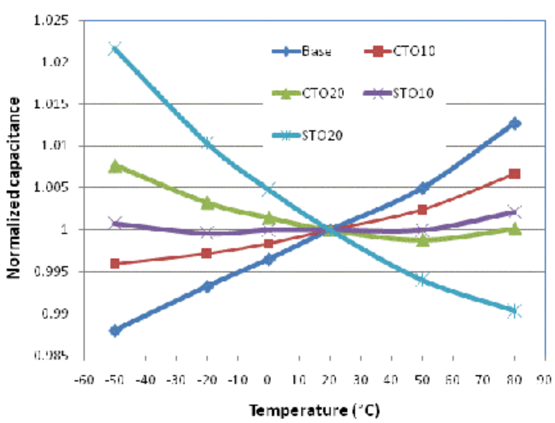

Figure 2. Normalized capacitance and corresponding τ_c of compensating materials.

Cofireability of STO20 and 951 LTCC:

Figure 3 shows the shrinkage curves of STO20 and 951 in the Z-direction (through the thickness of the tape) for a heating rate of 5°C/min from 500 to 850°C. The onset temperature for shrinkage of STO20, measured from a shrinkage-versus-temperature plot, is 741°C. Among all of the LTCC glasses evaluated, the onset temperature of V-glass based STO composition represents the closest match to the onset temperature of 766°C for the 951 LTCC. The proximity of these onset temperatures provides a solid physical base for successfully cofring STO20 with 951 LTCC.

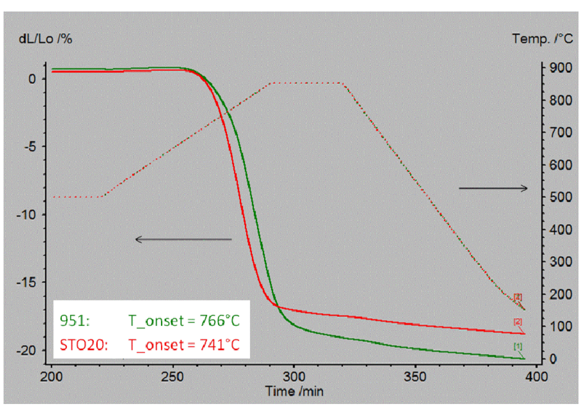

Figure 3. Shrinkage curves and onset temperature for shrinkage of STO20 and 951 LTCC.

To verify the cofireability of STO20 with the 951 tape, a square ring pattern of STO20 paste was screen printed onto a 75x75 mm 951 single layer tape and sintered using a normal profile. Figure 4 shows an optical image of a fractured cross section of the cofired structure. No deformation, in either the 951 or the STO20 is visible, indicating well-matched sintering. A close look at the STO20-951 interface by SEM is also presented in Figure 4. A relatively clean interface exists between the two cofired materials, suggesting no or minimum chemical interaction and/or interdiffusion between the two.

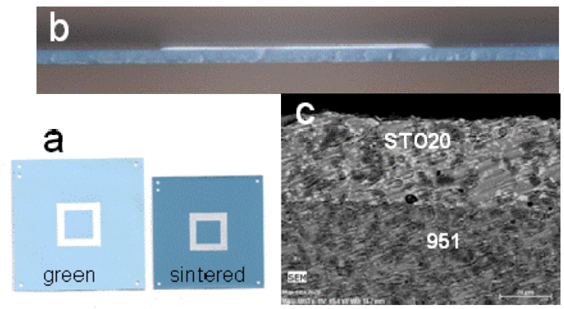

Figure 4. a) Aerial view of STO20 paste on a green and sintered single layer of 951 tape, b) optical cross section view of the sintered STO20 on 951, and c) a SEM cross section of interface between the STO20 and 951 LTCC.

Temperature compensated SL ring resonators:

The normalized resonant frequency versus temperature, and the corresponding τ_f data of 5 resonators are shown in figure 5, including a resonator in the 951 LTCC; two duplicated resonators with a single STO20 print on one side of the resonator line; and two duplicated resonators with STO20 printed on both sides of the resonator line. The picture inserts are cross section images that show the details of the layered structures.

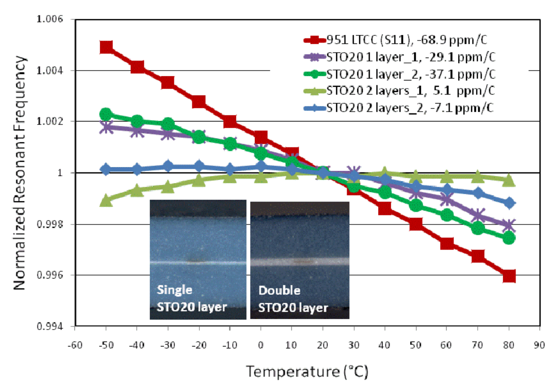

Figure 5. Normalized resonant frequency versus temperature and τ_f data of SL line resonators in 951 LTCC, in 951 with cofired single STO layer, and in 951 with double surrounding STO20 layers. The insert shows cross sections of the resonator lines.

The 951 LTCC has a τ_f at -68.9ppm/C. With the incorporation of a single layer of STO20, the τ_f dropped to 29.1 and 37.1ppm/C in the two samples evaluated. The variation in τ_f data may be due to the thickness differences in the STO20 layer in the two different resonator builds. Overall a single STO20 layer cofired next to the resonator conductor line reduces the τ_f value of the non-compensated 951 LTCC by approximately half.

For the two resonators in which the conductor lines are surrounded by the STO20 dielectric layers, one shows a τ_f of 5.1ppm/C, and the other a τ_f 7.1ppm/C. It is clear that the incorporation of two STO20 layers brings the τ_f close to zero. Again the variation of τ_f of the two samples may reflect the thickness variation of the printed STO20 layers. The fact that one resonator has a slightly positive τ_f and the other a slightly negative τ_f suggests that with tight control of the thickness of the STO20 layer, resonators with a true near zero or at zero τ_f are achievable.

It should be noted that the addition of titanates to the base V-glass + Al_2O_3 glass ceramics does result in higher dielectric constants (Table 3). The higher dielectric constant of STO20 is evidenced by a decrease in f_r of the resonators with cofired STO20 dielectric. The mechanism for the increase in dielectric constant in the STO compositions, and the subsequent effect on the resonant frequency will be addressed in future communications.

Conclusions

We have demonstrated that, with the design of a proper τ_f compensating material and successful cofiring with DuPont 951 LTCC, SL resonators with a near zero τ_f can be produced. The compensation of the τ_f is realized locally inside a LTCC structure where the resonators reside. With this approach it is anticipated that all of the existing 951 LTCC material sets and processes can remain unchanged in incorporating the τ_f compensation materials.

For future work, new formulations based on STO20 will be examined. For example, factors such as the glass to ceramic ratio and the wt% of $SrTiO_3$ will be examined. Modeling of the τ_f of a compensated resonator will be conducted based on the τ_f value, and the actual thickness/volume of the compensating material in a cofired structure. Furthermore, the concept of using localized τ_f compensation will be extended to other LTCC systems where the temperature stability of integrated RF resonators is needed.

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