Localized Temperature Stability in Low Temperature Cofired Ceramics (LTCC)

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Abstract

The basic dielectrics of commercial low temperature cofired ceramics (LTCC) systems have a temperature coefficient of resonant frequency ($\tau_f$) in the range -50 ~ -80 ppm/°C. In this research we explored a method to realize zero or near zero $\tau_f$ resonators by incorporating $\tau_f$ compensating materials locally into a multilayer LTCC structure. To select composition for $\tau_f$ adjustment, $\tau_f$ compensating materials with different amount of titanates were formulated, synthesized, and characterized. Chemical interactions and physical compatibility between the $\tau_f$ modifiers and the host LTCC dielectrics were investigated. Studies on stripline (SL) resonator panels with multiple compensating dielectrics revealed that: 1) compositions using SrTiO$_3$ provide the largest $\tau_f$ adjustment among titanates, 2) the $\tau_f$ compensation is proportional to the amount of SrTiO$_3$ in compensating materials, as well as the thickness of the compensating layer, and 3) the most effective $\tau_f$ compensation is achieved when the compensating dielectric is integrated next to the SL. Using the effective dielectric constant of a heterogeneous layered dielectric structure, results from Method of Momentum (MoM) electromagnetic simulations are consistent with the experimental observations.
ACKNOWLEDGMENTS

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NOMENCLATURE

\( \alpha \)  
Temperature coefficient of expansion

CTE  
Temperature coefficient of expansion

CTO  
CaTiO\(_3\)

CM  
Co-Mill

CMA  
Co-Mill powders with V-glass at 60 wt%  

CMB  
Co-Mill powders with V-glass at 55 wt%

CM  
Co-Mill powders with V-glass at 49.5 wt%

\( \varepsilon \)  
Dielectric constant

\( f_r \)  
Resonant frequency

LTCC  
Low temperature co-fired ceramics

MW  
Microwave

RF  
Radio frequency

SL  
Strip-line

STO  
SrTiO\(_3\)

TO  
TiO\(_2\)

\( \tau_c \)  
Temperature coefficient of capacitance

\( \tau_\varepsilon \)  
Temperature coefficient of dielectric constant

\( \tau_f \)  
Temperature coefficient of resonant frequency
1. INTRODUCTION

A low $\tau_f$, preferably close to 0 ppm/°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 $\tau_f$ resonator the temperature compensation that requires additional mechanical [1] and electrical circuitry [2] can be eliminated. For filter applications, a low $\tau_f$ translates into an efficient use of frequency spectrum for maximum data capacity.

There are multiple approaches to achieve temperature stable resonator functions. One common engineering method of realizing a near zero $\tau_f$ is to form solid solutions of different dielectric ceramics that have opposite $\tau_f$. Kell, Greenham and Olds [3] developed temperature-stable compositions in systems Ca(Zr,Ti)O$_3$ and (Ba,Sr)(Zr,Ti)O$_3$. Kucheiko et al [4] studied a CaTiO$_3$-Ca(Al$_{1/2}$Ta$_{1/2}$)O$_3$ ceramic solid solution to identify a temperature stable composition for microwave applications. A general survey of microwave dielectrics, with an emphasis on temperature stability for resonators and filters, has been provided by Wersing [5]. In their review on microwave dielectric ceramics for mobile phone networks, Reaney and Iddles [6] summarized key factors that affect $\tau_f$.

Other practice to realize a low $\tau_f$ is to form a hybrid layered structure incorporating alternating layers of opposite $\tau_f$ materials. Alford et al. [7] fabricated layered Al$_2$O$_3$-TiO$_2$ microwave dielectric resonators by sequential sintering of thick film TiO$_2$ ($\tau_f = +450$ ppm/°C) on Al$_2$O$_3$ ($\tau_f = -60$ ppm/°C) substrates. The $\tau_f$ of the resonators could be adjusted over a wide range, including 0 ppm/°C, by varying the thickness of TiO$_2$ layer. Li and Chen [8] adopted an approach of using adhesive-bonded Ca(Mg$_{1/3}$Nb$_{2/3}$)O$_3$ and Ba(Zn$_{1/3}$Nb$_{1/3}$)O$_3$ layered composite to form dielectric resonators. The $\tau_f$ could be tuned to 0 ppm/°C at a proper thickness ratio of the two constituents that possess opposite $\tau_f$.

Low temperature cofired ceramic (LTCC) is a multilayer 3D packaging, interconnection and integration technology. An LTCC system refers to a base tape dielectric, typically a glass or glass-ceramic, and conductors (Au, Ag, Pt, etc) that are cofireable at temperatures 850 ~ 900 °C. Passive integration in LTCC, like embedded resistors and capacitors, is realized by cofiring specially engineered dielectric and resistive materials in paste or tape forms. In the past 20 years the largest growth of LTCC technology has occurred in wireless communications. The three dielectric material parameters most important to this application space include dielectric constant, $\varepsilon$, quality factor, Q (inverse of dielectric loss), and $\tau_f$. For RF/MW LTCC circuits with embedded resonator functions, a near zero $\tau_f$ is necessary to fully utilize the communication bandwidth.

Although there are commercial LTCC dielectrics with low $\tau_f$, e.g., Heraeus CT2000 with $\tau_f < \pm 10$ppm/°C, most of existing LTCC dielectrics have a $\tau_f$ in the range -50 to -80 ppm/°C. Figure 1 shows resonant frequency ($f_r$) versus temperature curves (normalized to $f_r$ at 20 °C) for several mainstream LTCC dielectrics along with $\tau_f$ data from this study. It is expected that, for integrated RF circuits using these LTCCs, the impact of $\tau_f$ will be reflected in the drift of the $f_r$ of the embedded resonator over the device’s operating temperatures. Often this results in a reduced working bandwidth, and an extra design limitation and/or a performance compromise.
Figure 1. $\tau_f$ of several commercial LTCC base dielectrics from DuPont, Ferro and Hereaus. The resonant frequencies $f_r$ (all ~ 1.5GHz) were collected from SL ring resonators from -50 to 80 °C, and normalized to $f_r$ at 20 °C.

There have been many efforts to tune LTCC base dielectrics towards zero $\tau_f$ for MW and RF applications. Dai, Huang, and Wilcox [9] proposed using titanates (positive $\tau_f$) to compensate for the negative $\tau_f$ of a glass-ceramic LTCC dielectric. Jantumen [10] investigated optimal compositions for $\tau_f < \pm 10$ ppm/°C in a LTCC consisting of zinc borosilicate glass mixed with MgTiO$_3$–CaTiO$_3$ ceramic fillers. Kapta, Inoue and Kato [11] achieved a $\tau_f$ of 1 ppm /°C in bismuth-based low fire dielectric ceramics. Choi, Park, and Park [12] developed middle-permittivity LTCC dielectrics with an adjustable $\tau_f$.

The purpose of this study is to explore a novel approach to adjust the $\tau_f$ of a SL resonator in a multilayer LTCC structure by locally integrating a compensating dielectric with a $\tau_f$ opposite to that of the host LTCC dielectric. Upon successful implementation, this method would enable temperature compensation where only the resonator circuits reside in a compensating structure, which would avoid affecting other embedded functions where the implementation is unnecessary or undesirable. In principle, this method could be applied to any existing LTCC with a proper selection and development of cofirable compensating dielectrics. A major advantage of this approach is its inherent compatibility with the existing LTCC material systems, which enables the use of existing cofirable conductors and other functional materials, and circumvents the need to re-develop an entirely new LTCC materials system.
τ_f is a device parameter that can be expressed in basic material properties:

\[ \tau_f = -\frac{1}{2}\tau_\varepsilon - \alpha \]  

(1)

where \( \tau_\varepsilon \) is the temperature coefficient of dielectric constant, and \( \alpha \) the coefficient of thermal expansion (CTE). For LTCC dielectrics, \( \alpha \) is typically between 4 ~ 10 ppm/°C, thus \( \tau_\varepsilon \) dominates \( \tau_f \).

From eq. (1), it is clear that \( \tau_f \) and \( \tau_\varepsilon \) have opposite signs. To compensate for the negative \( \tau_f \) of a LTCC, materials with a negative \( \tau_\varepsilon \) and thus positive \( \tau_f \) are necessary. Table 1 lists dielectric constant \( \varepsilon \), \( \tau_\varepsilon \), and the normal sintering temperatures of candidate ceramics that could serve as compensating materials [13]. All three candidates are titanates, TiO_2, CaTiO_3 and SrTiO_3.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dielectric constant</th>
<th>( \tau_\varepsilon ) (ppm/°C)</th>
<th>Sintering Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO_2</td>
<td>110</td>
<td>-750</td>
<td>~ 1200</td>
</tr>
<tr>
<td>CaTiO_3</td>
<td>130</td>
<td>-1600</td>
<td>~ 1400</td>
</tr>
<tr>
<td>SrTiO_3</td>
<td>285</td>
<td>-2400</td>
<td>~ 1550</td>
</tr>
</tbody>
</table>

The key materials science challenges include synthesizing the \( \tau_f \) compensating material and cofiring of the material with the existing LTCC system, for example, DuPont 951 LTCC. Evidence of both physical compatibility, measured by matched shrinkage, and chemical compatibility, characterized by material interdiffusion, is provided in this study. Multiple factors that affect \( \tau_f \) adjustment, including the weight percentage of a titanate in the formulation, the thickness of the compensating layer, and the placement of \( \tau_f \) compensating materials in multilayer LTCC, are examined throughout the investigation.

Analytic equations derived from the variational method with the transverse transmission-line technique [14-17] are presented to calculate the effective dielectric constant, \( \varepsilon_{\text{eff}} \), of a SL in a symmetric multilayer LTCC structure. The Method of Moment (MoM) simulated resonant frequency \( (f_r) \) of the SL resonators at temperatures between -50 °C to 80 °C is obtained based on temperature related dielectric constants of the \( \tau_f \) adjusters and LTCC. Using this method, the thickness and configuration of STO can be optimized for the best temperature compensation. The simulated \( \tau_f \) was also compared to experimental data for model validation.
2. EXPERIMENTAL

2.1. Design of $\tau_f$ Compensating Materials

DuPont 951 LTCC GreenTape™, a widely used LTCC system in the industry over the last 20 years, was selected as the host dielectric system for the localized $\tau_f$ compensation experiments. The 951 LTCC is a tape that is cast and dried from a slurry of a mixture of glass-ceramic (LTCC glass plus $\text{Al}_2\text{O}_3$ ceramic filler) dispersed in an organic vehicle. To match the 951 LTCC chemistry, an attempt was made to formulate the $\tau_f$ compensating materials the same way, i.e., making the material a mixture of a LTCC glass and ceramic fillers. $\text{Al}_2\text{O}_3$ was used as the filler for the base compensating material. A series of compensating materials were formulated by replacing part of the $\text{Al}_2\text{O}_3$ in the composition with a titanate as the $\tau_f$ adjuster. The main factors considered were 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. Ideally, the onset temperature of shrinkage and the rate of shrinkage of the compensating materials would match those of 951 LTCC. In addition, no or minimal interaction between the compensating material and the LTCC was also desirable. One specific LTCC glass, designated as V-glass, was selected for this study after an evaluation of several commercial LTCC glasses.

2.1.1. Formulation of $\tau_f$ compensating materials

Table 2 details the formulations of the compensating materials used in this study. CM stands for co-milled powders; A, B and C refer to weight percentage of V-glass at 60, 55 and 49.5 wt%; TO = $\text{TiO}_2$, CTO = $\text{CaTiO}_3$ and STO = $\text{SrTiO}_3$; and the number represents weight percentage of an appropriate titanate that replaces $\text{Al}_2\text{O}_3$ as the filler material. Most of the compositions studies were CMB formulation where the base formulation is 55 wt% V-glass + 45 wt% $\text{Al}_2\text{O}_3$ without the addition of a titanate. There were three objectives to formulate these compositions: 1) to study the effect of the type of titanates, 2) to study the effect of the amount of a titanate, and 3) to study the effect of the LTCC glass to ceramic filler ratio on the $\tau_f$ adjustment on a SL resonator.

<table>
<thead>
<tr>
<th>Composition</th>
<th>V-glass (wt%)</th>
<th>$\text{Al}_2\text{O}_3$ (wt%)</th>
<th>$\text{TiO}_2$ (wt%)</th>
<th>$\text{CaTiO}_3$ (wt%)</th>
<th>$\text{SrTiO}_3$ (wt%)</th>
<th>Total wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB base</td>
<td>55</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CMB TO15</td>
<td>55</td>
<td>30</td>
<td>15</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CMB TO30</td>
<td>55</td>
<td>15</td>
<td>30</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CMB CTO10</td>
<td>55</td>
<td>35</td>
<td></td>
<td>10</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CMB CTO20</td>
<td>55</td>
<td>25</td>
<td></td>
<td>20</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CMB STO10</td>
<td>55</td>
<td>35</td>
<td></td>
<td></td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>CMB STO20</td>
<td>55</td>
<td>25</td>
<td></td>
<td></td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>CMB STO25</td>
<td>55</td>
<td>20</td>
<td></td>
<td></td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>CMB STO30</td>
<td>55</td>
<td>15</td>
<td></td>
<td></td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>CMA STO20</td>
<td>55</td>
<td>15</td>
<td></td>
<td></td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>CMC STO20</td>
<td>49.5</td>
<td>30.5</td>
<td></td>
<td></td>
<td>20</td>
<td>100</td>
</tr>
</tbody>
</table>
2.1.2. Synthesis of $\tau$ compensating materials

The mixture of V-glass, Al$_2$O$_3$ and titanate was co-milled to a median particle size 2.0 to 2.2 $\mu$m using Al$_2$O$_3$ media. Pellets with a diameter 12.5 mm and a thickness 1 mm were formed by dry pressing co-milled powder granulated with organic binder. A 2-step pressing process was used for pellet compaction, which involved uniaxial pressing at 43.5 MPa followed by isostatic pressing at 206.8 MPa. The pellets were sintered at 850 °C for 30 min in air. Density of all sintered materials was measured using Archimedes method. Electrodes were deposited by sputtering Au on polished sintered pellets for measurement of dielectric properties.

Pastes of selected compensating materials were made using an organic vehicle, ESL441, combined with the thinner, ESL401, (both from Electro-Science Labs) using a 3-roll mill. These pastes were screen printed on green LTCC tapes to form temperature compensation layers for SL ring resonators.

2.2. SL Resonator Panels

2.2.1. Construction of panels

Standard 254 $\mu$m thick DuPont 951 LTCC tapes were 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 1.5 GHz were fabricated in 4 layer 951 panels. Figure 2 shows the LTCC tapes, before and after sintering, of a resonator layer with a printed CMB STO20 layer between the ring resonator and the 951 dielectric. The line width of the Au ring is 0.2 mm. The width of the printed CMB STO20 is 4 mm. 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 30 min in air on Al$_2$O$_3$ setters. Sub-miniature version A (SMA) edge connectors were soldered to resonator panels to access the embedded ring resonator for $f_r$ measurements. Figure 3 shows green, sintered and finished SL resonator panels with the embedded CMB STO20.

![Figure 2. Au ring resonator and feed lines on 75×75 mm green (left) and sintered (right) 951 tape with a printed STO layer in between.](image-url)
2.2.2. Incorporation of $\tau_f$ adjusters in resonator panels

The screen printed $\tau_f$ adjusters are in a square ring pattern. The square Au ring is positioned at the center of the 4 mm wide $\tau_f$ adjusters. Using an 80 $\mu$m thick 325 mesh screen, a typical thickness of the sintered $\tau_f$ adjusters layer is 18 ~ 20 $\mu$m from a single print, and 35 ~ 40 $\mu$m from a double print using a print-dry-print process. Extra 951 tapes with the same printed $\tau_f$ adjusters were fabricated and sintered along with the resonator panels for measurement of the paste thickness using a Cobra laser profilometer. The measurement was taken after the paste was dried in an oven, as well as after the tapes were sintered. These tapes were also cross sectioned to examine the actual thickness of the pastes by optical microscopy. Inspection of the $\tau_f$ adjuster layer showed a variation in thickness, typically $\pm$ 3 $\mu$m, over the targeted thicknesses.

2.3. Characterization

2.3.1. $\tau_f$ compensating materials

2.3.1.1. Sintering behavior

Shrinkage data for the compensating material, in the form of a cylinder of diameter of 6.25 mm and thickness of 5 mm, and the 951 dielectric, in the form of a 5x5 mm stack of 20 layer tapes, were collected in air using a Netzsch DIL 402 dilatometer.

2.3.1.2. Dielectric properties

The capacitance of the compensating materials was measured on sintered pellets using a HP4194A impedance analyzer at 1 MHz over a temperature range -50 °C to 80 °C. The capacitance of the 951 dielectric was measured on 12.75x12.75x0.405 mm coupons with sputtered Au for electrode material.

2.3.1.3. Microstructure

The crystalline phases in the $\tau_f$ compensating materials were identified by X-ray diffraction (XRD) using a Siemens D500 diffractometer employing a sealed tube X-ray source (Cu K $\alpha$
radiation), fixed slits, a diffracted-beam graphite monochromator, and a scintillation detector. Typical scans were performed from 5 to 80 degrees 2θ using a 0.04° step size at 2 sec/step. Sintered microstructure was examined using a Zeiss Supra 55VP field emission scanning electron microscope (SEM), where the Energy Dispersive Spectroscopy (EDS) was performed with a Bruker Quad SDD detector and Bruker Esprit software.

2.3.2. SL resonator panels

2.3.2.1. Measurement of \(f_r\)

The SL resonators were placed inside a temperature chamber and characterized using an Agilent E5062A network analyzer from -50°C to 80°C. Figure 4 shows the experimental setup used to measure the S-parameters of a SL LTCC resonator. The panel was held by the measurement cables via the SMA connectors with a K-type thermocouple attached to the surface. Prior to conducting the measurement, a standard calibration was performed on both ports of the E5062A using an Agilent calibration kit under open/short/load/through conditions. The S-parameters, S11, S12, S21 and S22, were collected over a 0.3 GHz frequency span centered at ~1.5 GHz at each temperature. The \(f_r\) was obtained as the minimum frequency of the reflection coefficient (S11) of the ring resonator. The \(\tau_f\) of a resonator was calculated using the following equation,

\[
\tau_f = \frac{f_{ro} - \Delta f_r}{\Delta T} \quad (2)
\]

where \(f_{ro}\) is the resonant frequency at 20°C, \(\Delta f_r\) is the change of resonant frequency over -50 to 80°C, and \(\Delta T\) equals to 130°C.

![Figure 4. \(f_r\) test setup, and the mounting of a SL resonator panel.](image)

2.3.2.2. Integrated STO layers

Cross sections of some sintered SL resonator panels were made to inspect the cofired multilayer structure. The cross sections were examined by optical microscopy to measure the actual thickness of the compensating material. The same cross sections were also analyzed by SEM for possible interfacial reactions between the 951 LTCC and the compensating material.
3. CALCULATION OF EFFECTIVE DIELECTRIC CONSTANT AND SIMULATION OF RESONANT FREQUENCY

An effective dielectric constant of a SL is

\[ \varepsilon_{\text{eff}} = \frac{C}{C_0} \]  

(3)

where \( C \) is the total SL capacitance, and \( C_0 \) is the total SL capacitance in air. Using a variational method [13], \( C \) can be expressed as

\[ C = \int_0^L \beta f(x) \text{d}x \]  

(4)

where

\[ f(x) = \frac{Q}{wY} \]  

(5)

is the Fourier transform of the charge density distribution \( f(x) \), \( \beta \) is the propagation constant, \( Q \) is the total SL charge, \( w \) is the strip width, and \( Y \) is the admittance from the SL.

A schematic cross section of a four tape LTCC structure with embedded SL and \( \tau_f \) compensating materials is illustrated in Figure 5. The SL is sandwiched between symmetrical three layers of dielectrics, with a dielectric constant of \( \varepsilon_{r1}, \varepsilon_{r2} \) and \( \varepsilon_{r3} \), and a corresponding layer thickness of \( h_1, h_2 \) and \( h_3 \). The surfaces are designated as the ground planes.

\[ Y_1, Y_2, Y_3 \] are the transverse transmission line admittances between the dielectric interfaces and the ground plane. The admittance can be expressed for each successive layer [15, 16] as,
At the charge plane of the SL, the total transverse admittance \( Y = 2Y_3 \),
\[
Y = 2\varepsilon_0\varepsilon_r^3 \frac{Y_2 + \varepsilon_0\varepsilon_r^3 \tanh(\beta h_3)}{\varepsilon_0\varepsilon_r^3 + Y_2 \tanh(\beta h_3)}
\]  
(9)

For an air filled SL, the total capacitance is
\[
\frac{1}{C_o} = \frac{1}{\pi} \int_0^{\infty} \frac{f(\beta)^2}{\beta Y_o} d\beta
\]  
(10)

The transverse transmission line admittance reduces to
\[
Y_{30} = \varepsilon_0 \coth(\beta (h_1 + h_2 + h_3))
\]  
(11)

The total transverse transmission line admittance at the charge plane of a SL is then,
\[
Y_o = 2Y_{30} = 2\varepsilon_0 \coth(\beta (h_1 + h_2 + h_3))
\]  
(12)

Once all three dielectrics were characterized over a temperature range, the \( \varepsilon_{\text{eff}} \) is calculated numerically at each temperature using MatLab. The \( f_r \) of the SL ring resonator at a given temperature was simulated using \( \varepsilon_{\text{eff}} \) and the Method of Momentum. Finally, a curve of \( f_r \) versus temperature was constructed, from which the \( \tau_f \) was calculated using equation (2).
4. RESULTS AND DISCUSSION

4.1. \( \tau_f \) Compensating Materials

4.1.1. Dielectric properties

Table 3 shows the dielectric constant, \( \varepsilon \), of each composition at -50 °C, -20 °C, 0 °C, 20 °C, 50 °C and 80 °C. The sintered density of compensating material, the \( \varepsilon \) at 20 °C, the \( \tau_\varepsilon \) of compensating material, and an estimated \( \tau_f \) (assuming a \( \alpha \sim 6 \) ppm/°C for all the STO compositions, and using equation (2)) are listed in Table 4 for each composition. Both CMB TO10 and CMB TO30 showed a lack of adequate densification, so these compositions were dropped from further study. Note that the estimated \( \tau_f \) of 951 LTCC is -59 ppm/°C, lower than the -69 ppm/°C (Figure 1) measured for a SL resonator in a 951 panel. The source of the discrepancy was unclear but may partially result from the measurement errors in sample dimension, and the determination of \( \varepsilon \).

Table 3. Dielectric constant of \( \tau_f \) compensating materials from -50 °C to 80 °C.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>951 LTCC</th>
<th>CMB Base</th>
<th>CMB CTO10</th>
<th>CMB CTO20</th>
<th>CMB STO10</th>
<th>CMB STO20</th>
<th>CMB STO25</th>
<th>CMB STO30</th>
<th>CMA STO20</th>
<th>CMC STO20</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.86</td>
<td>7.76</td>
<td>9.72</td>
<td>12.02</td>
<td>9.57</td>
<td>12.28</td>
<td>13.99</td>
<td>15.92</td>
<td>12.02</td>
<td>12.32</td>
</tr>
<tr>
<td>20</td>
<td>7.88</td>
<td>7.79</td>
<td>9.73</td>
<td>12.00</td>
<td>9.57</td>
<td>12.22</td>
<td>13.88</td>
<td>15.76</td>
<td>11.96</td>
<td>12.27</td>
</tr>
<tr>
<td>50</td>
<td>7.90</td>
<td>7.83</td>
<td>9.76</td>
<td>11.98</td>
<td>9.57</td>
<td>12.15</td>
<td>13.75</td>
<td>15.57</td>
<td>11.89</td>
<td>12.21</td>
</tr>
<tr>
<td>80</td>
<td>7.93</td>
<td>7.89</td>
<td>9.80</td>
<td>12.00</td>
<td>9.59</td>
<td>12.10</td>
<td>13.66</td>
<td>15.39</td>
<td>11.85</td>
<td>12.18</td>
</tr>
</tbody>
</table>

Table 4. Density, room temperature dielectric constant \( \varepsilon \), \( \tau_\varepsilon \), and estimated \( \tau_f \) of compensating materials.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Archimedes bulk density (g/cc)</th>
<th>( \varepsilon ) (1 MHz at RT)</th>
<th>( \tau_\varepsilon ) (ppm/°C)</th>
<th>Estimated ( \tau_f ) (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>951 LTCC</td>
<td>3.10</td>
<td>7.88</td>
<td>112</td>
<td>-59</td>
</tr>
<tr>
<td>CMB base</td>
<td>3.19</td>
<td>7.79</td>
<td>190</td>
<td>-99</td>
</tr>
<tr>
<td>CMB TO10</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMB TO30</td>
<td>2.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMB CTO10</td>
<td>3.20</td>
<td>9.72</td>
<td>83</td>
<td>-45</td>
</tr>
<tr>
<td>CMB CTO20</td>
<td>3.15</td>
<td>12.0</td>
<td>-58</td>
<td>26</td>
</tr>
<tr>
<td>CMB STO10</td>
<td>3.21</td>
<td>9.57</td>
<td>10</td>
<td>-9</td>
</tr>
<tr>
<td>CMB STO20</td>
<td>3.30</td>
<td>12.22</td>
<td>-240</td>
<td>117</td>
</tr>
<tr>
<td>CMB STO25</td>
<td>3.31</td>
<td>13.88</td>
<td>-379</td>
<td>186</td>
</tr>
<tr>
<td>CMB STO30</td>
<td>3.35</td>
<td>15.76</td>
<td>-525</td>
<td>259</td>
</tr>
<tr>
<td>CMA STO20</td>
<td>3.23</td>
<td>11.96</td>
<td>-241</td>
<td>117</td>
</tr>
<tr>
<td>CMC STO20</td>
<td>3.35</td>
<td>12.27</td>
<td>-192</td>
<td>93</td>
</tr>
</tbody>
</table>
It should be noted that the addition of titanates to the base V-glass + Al$_2$O$_3$ glass ceramics does result in higher dielectric constants. The higher dielectric constant is expected to decrease the $f_r$ of a SL resonator when the cofired compensating material is integrated into the LTCC.

4.1.2. Chemistry

XRD patterns of the base dielectric and the two SrTiO$_3$ modified compensating materials CMB STO10 and CMB STO20 are shown in Figure 6. It is evident that Al$_2$O$_3$ is the main crystalline phase in the base dielectric, with the amorphous background between 2 $\theta$ value of 20 to 35 degrees representing the V-glass. There is also a minor amount of anorthite, CaAl$_2$Si$_2$O$_8$, in the base dielectric, presumably derived from the reaction between Al$_2$O$_3$ and the V-glass. For CMB STO10, the major crystalline phases are Al$_2$O$_3$ and SrTiO$_3$, with a minor anorthite phase. As expected in CMB STO20, the SrTiO$_3$ peaks grow much stronger relative to the Al$_2$O$_3$ peaks. The anorthite phase nearly disappears in CMB STO20, indicating a suppression of the interaction between Al$_2$O$_3$ and the V-glass. For both STO10 and STO20, there is no indication of compounds forming from a glass-SrTiO$_3$ interaction. This absence of interaction is beneficial to the sintering of SrTiO$_3$ modified compensating materials since the densification is a relatively simple viscous sintering of a glass-ceramic body. It has been shown that crystallization during sintering of a glass-ceramic composite, either self-derived from the glass, or reaction-derived from glass-ceramic interaction, can significantly impede the densification process [18, 19].

![Figure 6. XRD of sintered compensating materials, STO10 and STO20, compared to the base dielectric.](image-url)
Figure 7. SEM image and element mapping of STO20.

The lack of interaction between the ceramic particles, Al$_2$O$_3$ and SrTiO$_3$, and the V-glass is further validated by SEM observations. Figure 7 shows a SEM image of a polished CMB STO20 surface along with elemental maps of Al, Sr, Ti, Si and Ca. The microstructure has three distinct phases, the fine SrTiO$_3$ particles (in white), the relatively coarse Al$_2$O$_3$ particles (in black), and a continuous glass phase (in grey). The clean boundaries of SrTiO$_3$ and Al$_2$O$_3$ particles suggest that there is no, or a minimal if any, reaction between these ceramic particles and the surrounding V-glass. There is also minimum amount of porosity in the microstructure, indicating a highly densified glass-ceramic body. This result is consistent with the measure density of 3.30 g/cm$^3$ for CMB STO20 (see Table 4).

4.2. $\tau_f$ Compensating Materials and 951 LTCC

There are several progressive levels of requirements to successfully synthesis $\tau_f$ compensating materials: 1) the materials should have large enough $\tau_f$ that is opposite to that of 951 LTCC for effective compensation, 2) the materials should have a shrinkage and shrinkage rate that closely match to the 951 LTCC to avoid warping of the cofired structures, and 3) there should be either least, or ideally no, chemical reactions or inter-diffusion between the $\tau_f$ compensating materials and the 951 LTCC to preserve the $\tau_f$ compensation properties.

4.2.1. Physical compatibility

Figure 8 plots the shrinkage curves of CMB STO20 and 951 in the Z-direction (through the thickness of the tape) for a heating rate of 5 °C/m in from 500 to 850 °C. The onset temperature for shrinkage of CMB 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. In addition, the shrinkage rates of the two materials, represented by the slopes of the shrinkage curves during the temperature ramp up period, track closely to each other. The proximity of these onset temperatures and shrinkage rates provides a solid physical basis for successfully cofiring CMB STO20 with 951 LTCC.

![Shrinkage curves and onset temperatures of CMB STO20 and 951 LTCC.](image)

**Figure 8.** Shrinkage curves and onset temperatures of CMB STO20 and 951 LTCC.

### 4.2.2. Chemical compatibility

To verify the cofireability of CMB STO20 with the 951 tape, a square ring pattern of STO20 paste was screen printed onto a 75x75 mm 951 single tape and sintered using a normal profile (similar to Figure 2 without the Au conductor). Figure 9a shows an optical image of a fractured cross section of the cofired structure. No deformation in either the 951 or the CMB STO20 is visible, indicating well-matched sintering. A close look at the STO20-951 interface by SEM is also presented in Figure 9b. A relatively clean interface exists between the two cofired materials, suggesting no or minimal chemical interaction and/or inter-diffusion between the two materials.

![Optical cross section of sintered CMB STO20 on 951, and SEM cross section of the interface between the CMB STO20 and the 951 LTCC.](image)

**Figure 9.** a) Optical cross section of sintered CMB STO20 on 951, and b) a SEM cross section of the interface between the CMB STO20 and the 951 LTCC.
To further analyze the interfaces of the embedded $\tau_f$ compensating material in the 951 LTCC, SL resonator panels with CMB STO20 were cross sectioned for both optical and SEM examination. Figure 10 is an optical image of CMB STO20 cofired in a 4 layer 951 LTCC shown, a) one side, and b) both sides of the Au conductor. The hybrid multilayer panel cofired nicely without any noticeable warping of the structure or delamination at the interfaces.

The cross section was further examined by SEM. Figures 11a and 11b show an image of a Au line embedded in the CMB STO20 dielectric, and the corresponding Si map, respectively. It appears that the Au reaches nearly a full sintered density without noticeable glass penetration from the surrounding CMB STO20. The small Si inclusion inside the Au in Figure 11b (pointed at with an arrow) may be attributed to the minor amount of glass frit in the 5734 Au paste used to match the shrinkage to that of the 951 LTCC.

Figure 10. Embedded CMB STO20 in a 4 layer 951 LTCC, a) one side, and b) both sides of the Au conductor.

Figure 11. a) SEM cross-section image of cofired STO20 dielectric and Au resonator line; b) mapping of Si element in a); c) SEM image of embedded STO20 in 951 LTCC. The correspondent element maps for Al, Sr and Ti are shown in d), e) and f).
Figure 11c shows a well-defined boundary between the 951 and the CMB STO20 in the cofired structure despite the obvious difference in the volume density and the size of Al₂O₃ particles in the two materials observed in figure 11d. The boundary is very distinct in the Ti mapping shown in Figure 11f, where Ti only exists in the CMB STO20 but not in the 951. Again the SEM analysis indicates that CMB STO20 can be cofired with 951 LTCC without noticeable inter-diffusion between the two.

4.3. τᵣ Compensation

In this section the effects of temperature compensation are examined from different perspectives. Initially, the estimated τᵣ of each compensating material was used to judge whether it provided adequate temperature compensation. Then, SL resonators panels using selected τᵣ compensating materials were built at different layer thicknesses and configurations to study the effectiveness of the temperature compensation.

4.3.1. Effect of titanates

Figure 12 shows the normalized ε, scaled to the ε value at 20 °C, for τᵣ compensating materials over the temperature range -50 °C to 80 °C. The estimated τᵣ values from τₑ data are listed in the legend (from Table 4). The plot visualizes the change in the slope as the amount of a titanate increases in the compositions. Obviously, only the compositions that have an opposite slope to that of 951 LTCC can be used to compensate the temperature effect.

![Figure 12. Temperature dependence of normalized ε of compensating materials.](image)
The CMB base dielectric has a \( \varepsilon \) of 190 ppm/°C, and a \( \tau_f \) of -99 ppm/°C. So, without the addition of titanates, the base dielectric has a higher \( \tau_f \) than the 951 LTCC. With the addition of 10 wt% of titanates, the CTO10 and STO10 still show positive \( \varepsilon \), and thus negative \( \tau_f \). Obviously, the polarity of \( \tau_f \) of these two compositions is the same as that of the 951 LTCC. These compositions are not expected to adjust the \( \tau_f \) towards zero and were eliminated from further investigation. With a higher weight percentage of CTO and STO, the CMB CTO20 and CMB STO20 reach a \( \tau_f \) of 25.5 ppm/°C and 117 ppm/°C, respectively. Considering that the 951 LTCC has a \( \tau_f \) of -69 ppm/°C, the CMB STO20 is expected to be more effective for \( \tau_f \) compensation, and was thus down-selected for cofi ring studies, microstructure analysis, and for the fabrication of proof-of-concept SL ring resonators.

The estimated \( \tau_f \) of CMB STO25 and CMB STO30 at 180 ppm/°C and 259 ppm/°C, respectively, further increases from 117 ppm/°C for CMB STO20. Thus, it is expected that these two compositions could adjust the \( \tau_f \) much more effectively than CMB STO20. Both compositions were selected to be incorporated in SL resonator panels.

The \( \varepsilon \) and estimated \( \tau_f \) of CMA STO20 and CMC STO20 are close to those of CMB STO20 (Table 3 and 4), suggesting that the effect on \( \tau_f \) compensation from the amount of V-glass is much less significant compared to the kind and the amount of a titanate. Thus similar \( \tau_f \) adjustments are expected from these three compensating formulations.

### 4.3.2. Effect of glass and STO content

SL resonator panels were fabricated using STO compositions with a layer thickness of approximately 20 \( \mu \)m. Table 5 lists \( \tau_f \) data for two separate comparisons: 1) at a fixed STO20 concentration to assess the effect of glass to filler weight ratio from CMA of 60/40, CMB of 55/45 to CMC of 49.5/50.5, and 2) at a fixed CMB of 55 wt% glass to assess the effect of STO content of 20, 25 and 30 wt%.

The glass to filler ratio from CMA to CMB has a minimum impact on the temperature stability, as the \( \tau_f \) of the SL resonators are -29.5 and -28.8 ppm/°C, respectively. However the \( \tau_f \) of CMC STO20 is -41.3 ppm/°C, consistent with the estimated higher \( \tau_f \) of the CMC STO20 composition in Figure 13.

**Table 5.** \( \tau_f \) data for SL resonators using different STO compositions and a layer thickness of approximately 20 \( \mu \)m.

<table>
<thead>
<tr>
<th>STO compositions in SL resonator</th>
<th>( \tau_f ) (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMA STO20</td>
<td>-29.5</td>
</tr>
<tr>
<td>CMB STO20</td>
<td>-28.8</td>
</tr>
<tr>
<td>CMB STO25</td>
<td>-13.4</td>
</tr>
<tr>
<td>CMB STO30</td>
<td>0.5</td>
</tr>
<tr>
<td>CMC STO20</td>
<td>-41.3</td>
</tr>
</tbody>
</table>
The temperature stability of the resonator improves as the wt% of STO increases. The CMB STO20 with 20 wt% STO in the composition reduces the $\tau_f$ to -28.8 ppm/°C from -69 ppm/°C of the uncompensated 951 LTCC. In CMB STO25, the $\tau_f$ is further reduced to -13.4 ppm/°C. A near zero $\tau_f$ of 0.5 ppm/°C is achieved in CMB STO30. It is clear that the content of STO plays an important role in temperature compensation, and the most effective compensating material is the CMB STO30 which has the highest STO wt% in this study.

4.3.3. Effect of STO layer thickness

SL resonators made using the print-dry-print deposition of STO layers of approximately 40 µm thick were also fabricated to examine the effect of STO thickness. Table 6 displays $\tau_f$ data for resonators made using 20 and 40 µm CMB STO20, CMB STO25, and CMB STO30 layers. For CMB STO20, the doubling of thickness from 20 to 40 µm reduces the $\tau_f$ of -28.8 to a near zero 1.9 ppm/°C. The same doubling in thickness of CMB STO25, however, overcorrects the $\tau_f$ from -13.4 to 41.2 ppm/°C. It is reasonable to assume that a true zero $\tau_f$ could be achieved with a CMB STO25 thickness between 20 and 40 µm. The overcorrection of $\tau_f$ for CMB STO30 is even more pronounced, as evidenced by a $\tau_f$ of 60.8 ppm/°C with a 40 µm thick CMB STO30 versus a $\tau_f$ of 0.5 ppm/°C at 20 µm.

<table>
<thead>
<tr>
<th>STO compositions in SL resonator</th>
<th>$\tau_f$ (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 µm</td>
</tr>
<tr>
<td>CMB STO20</td>
<td>-28.8</td>
</tr>
<tr>
<td>CMB STO25</td>
<td>-13.4</td>
</tr>
<tr>
<td>CMB STO30</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Overall, the thickness of the STO layer has a significant effect on the $\tau_f$ of the resonators. A thicker STO layer results in more temperature compensation. Data in Table 6 suggest that a zero $\tau_f$ is readily achievable with a proper combination of STO composition and the layer thickness. The results bring in design flexibility and paths for process optimization. For example, if a minimum amount of compensating material is needed in a LTCC multilayer structure, then the CBM STO30 is the choice. On the other hand, if better tolerance and process consistency can be achieved using a thicker STO layer then the CMB STO20 might be used in a LTCC structure.

4.3.4. Effect of STO configuration

Three symmetrical configurations of STO placement, as shown in Figure 13, were examined in this study: 1) STO layers printed next to the Au resonator ring, 2) STO layers printed 1 LTCC tape layer away from the Au ring, and 3) STO layers printed 2 LTCC tape layers away from the Au ring, i.e., just under the top and bottom ground planes. Table 7 lists the actual stack-up of dielectric layers for each STO configuration in Figure 5 for the $\varepsilon_{eff}$ calculation.
Figure 13. Three configurations of printed STO layers examined.

Table 7. Dielectric layer in the three configurations used in this study.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\varepsilon_{r1}$</th>
<th>$\varepsilon_{r2}$</th>
<th>$\varepsilon_{r3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>STO</td>
<td>951</td>
<td>951</td>
</tr>
<tr>
<td>Case 2</td>
<td>951</td>
<td>STO</td>
<td>951</td>
</tr>
<tr>
<td>Case 3</td>
<td>951</td>
<td>951</td>
<td>STO</td>
</tr>
</tbody>
</table>

The $\tau_f$ data for multiple SL resonator panels incorporating CMB STO20 and CMB STO30 are shown in Table 8. 20 and 40 $\mu$m STO layers were printed on to different LTCC tapes according to Figure 13. Resonators with 40 $\mu$m CMB STO20 in cases 2 and 3 were not fabricated and measured, since it is clear from Table 8 that even resonators using 40 $\mu$m CMB STO30 are far from reaching a zero $\tau_f$.

It becomes evident that, only in case 1, where the STO layers are placed next to the SL resonator, can a zero $\tau_f$ be achieved using localized STO compensation. In case 3, the $\tau_f$ for a 20 $\mu$m thick layer of either STO20 or STO30 is very close to the uncompensated $\tau_f = -69$ ppm/°C of the 951 LTCC. There is essentially no $\tau_f$ adjustment. At a layer thickness 40 $\mu$m, the $\tau_f$ of CMB STO30 drops only to –62.3 ppm /°C. Moving the STO layers closer to SL in case 2 does reduce $\tau_f$ slightly, but the $\tau_f$ compensation is very limited, and far from reaching a true 0 ppm /°C. Placing the compensating STO materials next to the SL resonator appears to be the most effective, and may be the only practical, way to achieve $\tau_f$ compensation.

Table 8. $\tau_f$ of SL resonators with different STO layer thicknesses and configurations.

<table>
<thead>
<tr>
<th>Composition</th>
<th>STO thickness ($\mu$m)</th>
<th>$\tau_f$ (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Case 1</td>
</tr>
<tr>
<td>CMB STO20</td>
<td>20</td>
<td>-28.8</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>1.9</td>
</tr>
<tr>
<td>CMB STO30</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>60.8</td>
</tr>
</tbody>
</table>
4.4. Simulated $\tau_f$ Results

4.4.1. Effect of STO composition and thickness

For case 1 where the STO is placed next to the SL, Figure 14 shows calculated $\varepsilon_{\text{eff}}$ as a function of temperature for CMB STO20 and CMB STO30 at a thicknesses from 5 $\mu$m to 50 $\mu$m. As the STO20 layer becomes thicker, the $\varepsilon_{\text{eff}}$ increases accordingly. At the same time, the slope of $\varepsilon_{\text{eff}}$ changes from positive at 5 $\mu$m to nearly flat at 50 $\mu$m. Larger changes in $\varepsilon_{\text{eff}}$ over the same thickness range are seen for CMB STO30 since the CMB STO30 has a higher $\varepsilon$ to begin with. One important distinction for the $\varepsilon_{\text{eff}}$ of CMB STO30 is the change of the slope. Similar to CMB STO20, the slope of $\varepsilon_{\text{eff}}$ starts as negative at 5 $\mu$m layer thickness, but ends as positive at 50 $\mu$m. The $\varepsilon_{\text{eff}}$ is nearly flat over temperature for a 20 $\mu$m layer thickness.

**Case 1**

![Diagram showing $\varepsilon_{\text{eff}}$ as a function of temperature and STO layer thicknesses from 5 to 50 $\mu$m.](image)

Figure 14. $\varepsilon_{\text{eff}}$ of SL as a function of temperature and STO layer thicknesses from 5 to 50 $\mu$m.

Figure 15 plots the simulated $f_r$ versus temperature for the same STOs from 5 $\mu$m to 50 $\mu$m thick, with the corresponding $\tau_f$ values (slope of the $f_r$ $\sim$ T curves) shown in the legend. The simulated $f_r$ reflects the changes in $\varepsilon_{\text{eff}}$: $f_r$ decreases as $\varepsilon_{\text{eff}}$ increase, as $f_r$ correlates to $\varepsilon$ by $f_r \sim 1/\varepsilon$. For CMB STO20, $\tau_f$ decreases as the layer becomes thicker. At a thickness 20 $\mu$m the simulated $\tau_f$ is equal to -26.9 ppm/°C, which is very close to the -28.8 ppm/°C measured from the SL resonator (Table 6). The simulated $\tau_f$ reaches 0.5 ppm/°C at a thickness 50 $\mu$m, while the measured $\tau_f$ is 1.9 ppm/°C at a thickness 40 $\mu$m, suggesting that the simulation might underestimate the $\tau_f$ when a STO layer becomes thicker.
For CMB STO30, there is a crossover thickness where the $\tau_f$ changes polarity from negative to positive as thickness increases. The crossover thickness is about 20 $\mu$m where the simulated $\tau_f$ is equal to 1.2 ppm/°C. The simulation is consistent with the experiment in which a $\tau_f$ of 0.5 ppm/°C is measured at 20 $\mu$m (Table 6). Again, the simulation underestimates $\tau_f$ at thicker STO layers, as evidenced by the simulated $\tau_f$ of 31.9 ppm/°C versus the measured 60.8 ppm/°C at the same 40 $\mu$m CMB STO30 thickness. The cause of this underestimation is not clear at the moment, and warrants further investigation.

4.4.2. Effect of STO configurations

Figure 16 compares the temperature and thickness dependence of $\varepsilon_{\text{eff}}$ for CMB STO30 between cases 1 and 2. The $\varepsilon_{\text{eff}}$ is higher in case 1. For example, at 20 °C and 5 $\mu$m thick, the $\varepsilon_{\text{eff}}$ is 8.20 in case 1, and 7.91 in case 2, which is an increase of ~ 3.5%. Similar increase in $\varepsilon_{\text{eff}}$ is observed at all temperatures and CMB STO30 thicknesses for case 1. The results indicate that the SL sees more of the CMB STO30 when the material is placed next to it, compared to the configuration where the same material is placed one LTCC tape layer away.

The relative change in $\varepsilon_{\text{eff}}$ with STO30 thickness is also more substantial in case 1. For example, at 20 °C, the $\varepsilon_{\text{eff}}$ is 8.20 at 5 $\mu$m, and 9.94 at 50 $\mu$m, which is an increase of ~ 21.2%. In contrast, for case 2, the $\varepsilon_{\text{eff}}$ is 7.91 at 5 $\mu$m, and 8.17 at 50 $\mu$m, which is an increase only of ~ 3.3%. Certainly, for $\tau_f$ compensation by adjusting the amount of STO30, the result is more pronounced when the compensating dielectric is integrated next to the SL resonator.
Figure 16. $\varepsilon_{\text{eff}}$ of STO30 as a function of temperature for cases 1 and 2.

Figure 17. $f$ of STO30 as a function of temperature for cases 1 and 2.
Both of these effects are reflected in the simulated $\tau_f$ over temperature in Figure 17 with the corresponding $\tau_f$ shown in the legend. For the CMB STO30 in case 1, the $\tau_f$ reaches 1.2 ppm/°C at a thickness of 20 μm. For the same thickness in case 2, the $\tau_f$ is calculated as -52.1 ppm/°C. In fact, in case 2, the $\tau_f$ does not have a crossover point where it changes polarity, as evidenced by the negative slope of all $f_r$ vs. T curves at STO thicknesses from 5 to 50 μm. Rather, the $\tau_f$ remains negative, and only drops to -43.9 ppm/°C at a thickness 50 μm. In short, when placed one LTCC tape layer away from the SL resonator, the CMB STO30 does not effectively adjust the $\tau_f$ of the resonator to 0 ppm/°C.

Similar analysis is extended to CMB STO30 in case 3, where the STO layer is two LTCC tape layers away from the SL. The $\tau_f$ compensation in this configuration is even less effective than that in case 2. As expected, the analysis also shows the CMB STO20 has less effect on $\tau_f$ adjustment than CMB STO30 for both cases 2 and 3. The simulated $\tau_f$ for cases 1, 2 and 3 using CMB STO20 and CMB STO30 at thicknesses of 5 to 50 μm are plotted in Figure 18. It is clear that, only in case 1, does the $\tau_f$ reach 0 ppm/°C. For both cases 2 and 3, the effect of STO on the adjustment of $\tau_f$ is very limited, and far from reaching 0 ppm/°C, as evidenced by the clustering of $\tau_f$ data points in a -40 and -60 ppm/°C range. Figure 18 also includes the measured $\tau_f$ data for case 1. The simulated $\tau_f$ fit the experimental data well at a layer thickness of 20 μm for both STOs. However, the simulation underestimates the $\tau_f$ for the 40 μm layer.

![Figure 18. $\tau_f$ of SL resonators from simulation (solid lines) and experiment (discrete points).](image)
4.5. Mechanisms of Effective $\tau_f$ Compensation

In this section we try to explain the effectiveness of $\tau_f$ compensation in case 1 by addressing energy distribution in a heterogeneous dielectric multilayer structure. The discussion is based more on physical principles rather than detailed analytical analysis.

4.5.1. Energy filling factor

The overall $\tau_f$ of a dielectric composite is given by [7]:

$$\tau_f = \sum_i P_i \tau_{f_i}$$

(14)

where $\tau_{f_i}$ is the temperature coefficient of resonant frequency of dielectric $i$, and $P_i$, the electromagnetic (EM) energy filling factor, which is the fraction of the total energy confined within the volume occupied by dielectric $i$. $P_i$ is determined by the dielectric constant, volume, and geometry of dielectric $i$, as well as the EM field distribution inside the dielectric.

For a dielectric composite with simple geometry, such as a cylindrical puck with alternating layers of two dielectrics, the calculation of $P_i$ is straightforward [7, 8]. However, for a SL with a finite conductor width inside a multilayer dielectric, such as the integration of dissimilar $\tau_f$ compensating dielectrics in a host LTCC dielectric, the calculation of $P_i$ is complicated by the complex EM field distribution, as well as the reflection/refraction of EM waves at the dielectric interfaces.

4.5.2. Energy concentration in STO dielectrics in case 1

The total sintered thickness of a 4-tape 951 LTCC panel is 0.844 mm, resulting in a distance of 0.422 mm between the SL and the ground planes. At a line width of 0.2 mm, the aspect ratio of the “SL capacitor” is less than $\frac{1}{2}$. Hence the electric field distribution between the SL and the ground plane is very different from an ideal parallel plate capacitor (which typically has an aspect ratio $\geq 10$), in which the electric field is confined within the capacitor dielectric with no or minimum fringing effect. Rather, the fringing electric field of the SL in this study dominates the field distribution.

With the STO layers next to the SL, the oblique incidence of the fringing electric field at the STO-LTCC dielectric interface follows Snell’s law. Using the CMB STO30 as an example, the dielectric constant $\varepsilon_{STO30} = 15.76$ is twice the $\varepsilon_{LTCC} = 7.88$ at 20 $^\circ$C, so there is an existence of a critical, or total internal reflection, angle $\theta_c$,

$$\theta_c = \arcsin \left( \frac{n_{LTCC}}{n_{STO30}} \right) = \arcsin \left( \frac{\sqrt{\varepsilon_{LTCC}}}{\sqrt{\varepsilon_{STO30}}} \right) = 45^\circ$$

(15)

where $n_{LTCC}$ and $n_{STO30}$ are the refractive indices of the 951 LTCC and STO30, respectively. At an incident angle lower than $\theta_c$, part of the fringing electric field is reflected back to the STO30, and part is transmitted into the LTCC. At an incident angle higher than $\theta_c$, the fringing field is totally reflected back to the STO layer. The partial and total reflections of the field at the STO-LTCC interface confine a disproportionally higher amount of electric energy within the STO layers.
According to equation (14), the higher energy filling factor, $P_{\text{STO}}$, amplifies the contribution from the STO, while the relatively lower $P_{\text{LTCC}}$ reduces the effect from the 951 LTCC. This combination results in a much more effective $\tau_f$ compensation when a STO is placed next to the SL.

For cases 2 and 3, the oblique incidence of the fringing electric field at the LTCC-STO interface do not lead to a total reflection of the field inside the STO layers at any incident angle, since the EM waves hit the interface from the side having a lower dielectric constant. The energy in the STO is equal to $\frac{1}{2} \varepsilon_{\text{STO}} E^2 V_{\text{STO}}$, where $E$ is the electric field transmitted through the STO layers, and $V_{\text{STO}}$ is the volume of STO. For a STO layer thickness of 40 $\mu$m, its volume fraction is fairly small compared to the volume of the 422 $\mu$m thick LTCC. The $\tau_f$ of the SL resonator is, thus, largely dominated by the $\tau_f$ of the 951 LTCC.
5. CONCLUSIONS

We have demonstrated that, with the design of proper $\tau_f$ compensating materials and successful cofiring of the materials with DuPont 951 LTCC, SL resonators having a near zero $\tau_f$ can be produced. The compensation of the $\tau_f$ is realized locally inside a LTCC structure where the resonators reside. Among the examined titanate materials, SrTiO$_3$ is the best $\tau_f$ adjuster due to its higher $\varepsilon_r$. The adjustment of $\tau_f$ scales with the amount of a titanate in a compensating material, as well as the thickness of the screen printed compensating material. More importantly, the most effective compensation of $\tau_f$ is achieved by incorporating a given compensating material next to the SL resonator. $\tau_f$ compensation is diminished when the compensating material is placed away from the SL. The electric energy concentration at the compensating layers surrounding the SL is attributed to the effectiveness of the $\tau_f$ compensation. EM simulation of $\tau_f$ using $\varepsilon_{\text{eff}}$ calculated using a variational method confirms the experimental observation.
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