# Bandpass Filters with Localized Temperature Compensation in LTCC

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Low temperature cofired ceramic (LTCC) is a multilayer 3D packaging, interconnection, and passive integration technology. For LTCC modules with embedded resonator functions targeting radio frequency applications, the temperature coefficient of resonant frequency ($\tau_f$) is a critical parameter. The base dielectrics of commercial LTCC systems have a $\tau_f$ in the range -50 ~ -80 ppm/°C. This study explores a method to achieve zero or near zero $\tau_f$ embedded resonators by incorporating $\tau_f$ compensating dielectrics locally into a multilayer LTCC structure. A stripline bandpass filter (BPF) with near zero $\tau_f$ is demonstrated in a non-zero $\tau_f$ DuPont 951 GreenTape™ LTCC.
Key words: LTCC, $\tau_f$, temperature compensation, filter

## 1. INTRODUCTION

Compact, low-cost, highly integrated passive and active component capabilities are sought after by wireless device manufacturers. The low temperature cofired ceramic (LTCC) is one of several attractive technologies that offers these capabilities. LTCC provides layout flexibility and three dimensional integration capabilities to produce embedded compact passive components, such as resistors, inductors, capacitors, filters, duplexers, and antennas [1-5]. External passive and active components can be surface mounted on LTCC boards to achieve low-cost, compact RF modules.

The mechanically-tuned temperature-compensated filters [6] and bulk-acoustic-wave (BAW) filters [7] demonstrated excellent temperature compensation. However, compared to LTCC filters, the mechanically-tuned filter was a larger size, and was difficult to integrate with other electronic components on printed-circuit-board. The BAW filters as individual components occupied more space and cost more than the embedded LTCC filters.

There were other approaches to obtain temperature stable bandpass filters [8-13]. One common method of realizing a near zero $\tau_f$ was to mix different dielectric ceramics that had opposite $\tau_f$. This method has been applied to resonator and filter applications [8-9], as well as to those using LTCC base dielectrics [10-11]. The other method was to fabricate hybrid-layered structure where layers with opposite $\tau_f$ were formed into a monolithic stack by either sequential sintering [12] or bonding processes to obtain temperature compensation [13].

In this paper, strontiun titanate $SrTiO_3$ (STO) based compensation dielectrics cofireable with DuPont 951 LTCC are characterized. A four-pole bandpass filter (BPF) incorporating the compensation dielectric is characterized over -20 °C to 80 °C to demonstrate the temperature stability.

## 2. TEMPERATURE COMPENSATION MATERIALS

The DuPont 951 GreenTape™ LTCC has a standard tape thickness of 0.254 mm before firing. The sintered LTCC dielectric has a dielectric constant of 7.88 and loss tangent of 0.006 at 3 GHz. The formulation and sintered density of STO compensation materials are listed in Table I, where the V-glass enables cofiring of the compensation dielectric to DuPont 951 LTCC, the $Al_2O_3$ ceramic serves as filler material and STO is used to adjust $\tau_f$. The weight fraction of the V-glass was fixed at 55wt%. The base formulation, designed as STO0, is 55wt% V-glass and 45wt% $Al_2O_3$ ceramic powders. Part of $Al_2O_3$ was replaced by STO to form a series of composition materials up to STO30. The mixture of V-glass, $Al_2O_3$ and $SrTiO_3$ was co-milled to a median particle size from 2.0 to 2.2 μm using $Al_2O_3$ media. Pellets of the compositions were pressed and sintered in air at 850 °C for 30 minutes. Gold was sputtered on to both sides of the pellets for dielectric property measurement. The temperature dependent capacitance of the sintered pellets was measured using a HP4194A impedance analyzer at 1 MHz inside a temperature chamber.

Table I, Formulations and sintered density of STO compensation materials

| Composition | V-glass (wt%) | Al2O3 (wt%) | SrTiO3 (wt%) | Density (g/ccc) |
|---|---|---|---|---|
| STO 0 | 55 | 45 | 0 | 3.19 |
| STO10 | 55 | 35 | 10 | 3.21 |
| STO20 | 55 | 25 | 20 | 3.30 |
| STO25 | 55 | 20 | 25 | 3.31 |
| STO30 | 55 | 15 | 30 | 3.35 |

$\tau_f$ is a device parameter that can be expressed using basic material properties:

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

where $\tau_\varepsilon$ is the temperature coefficient of dielectric constant and $\alpha$ is the coefficient of thermal expansion (CTE). For LTCC dielectrics, $\alpha$ is typically between 4 ~ 10 ppm/°C, so $\tau_\varepsilon$ dominates $\tau_f$. CTE of Dupont 951 LTCC dielectric is 5.8 ppm/°C. The $\tau_f$ of STO compositions can be obtained by measuring the capacitance of pellets over temperature and the $\tau_\varepsilon$ is calculated from the temperature dependence.

Table II shows the measured dielectric constant of DuPont 951, STO0, STO10, STO20, STO25 and STO30 over -20 °C to 80 °C. The dielectric constant normalized to that at 20 °C of each composition was plotted in Fig. 1. As seen in Fig. 1, the STO0 has the same slope as that of DuPont 951 so this composition cannot be used to

compensate the temperature drift of the DuPont 951. In contrast, the STO30 has the greatest slope among the STO compositions that is opposite to that of 951 LTCC, thus it was selected to build temperature compensated bandpass filters. The best temperature compensation was achieved when the STO compensation materials were placed directly next to the strip line and the DuPont 951 was placed at outer layer close to ground [10].

TABLE II. Dielectric constants of DuPont 951, STO0, STO10, STO20, STO25, and STO30 over temperature.

| Temperature (°C) | DuPont 951 | STO 0 | STO10 | STO20 | STO25 | STO30 |
|---|---|---|---|---|---|---|
| -20 | 7.84 | 7.74 | 9.57 | 12.4 | 14.12 | 16.17 |
| 0 | 7.86 | 7.76 | 9.57 | 12.33 | 13.99 | 15.98 |
| 20 | 7.88 | 7.79 | 9.57 | 12.27 | 13.88 | 15.82 |
| 50 | 7.91 | 7.83 | 9.57 | 12.2 | 13.75 | 15.64 |
| 80 | 7.94 | 7.89 | 9.59 | 12.15 | 13.66 | 15.45 |

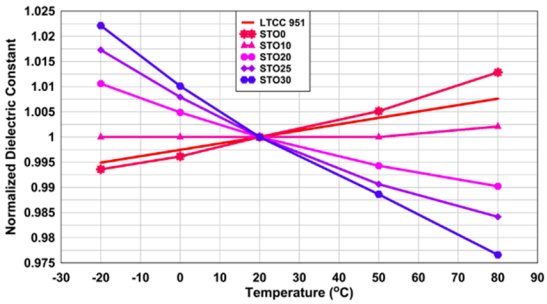


Fig.1, The diagram of the dielectric constants of DuPont 951 and STO dielectrics over temperature

## 3. TEMPERATURE COMPENSATED BPF

### 3.1 Filter design

Fig. 2 shows the layout of a wide stopband bandpass filter. The filter was designed at center frequency of 3.5 GHz with 3dB bandwidth of 500 MHz. The design procedure of finding the physical tapping at input and output locations as well as gap sizes between resonators can be found in reference [14].

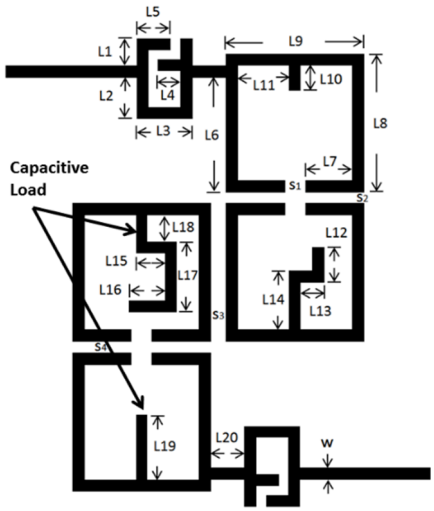


Fig. 2, Configuration of the bandpass filter.

The filter consists of capacitor-loaded open-loop ring resonators and lowpass filters. The effect of the capacitive loads at ring resonators is to push its harmonics to higher frequency range to obtain a wide stopband [15]. The lowpass filters, at the input and output of the filter, are used to filter out harmonics of the capacitive load ring resonators, and also to obtain the wide-stopband effects [16].

The dimensions of the filter are: w = 0.36 mm, L1 = 0.82 mm, L2 = 1.25 mm, L3 = 1.68 mm, L4 = 0.7 mm, L5 = 1.02 mm, L6 = 3.44 mm, L7 = 1.42 mm, L8 = 4.16 mm, L9 = 4.16 mm, L10 = 0.75 mm, L11 = 1.54 mm, L12 = 1.08 mm, L13 = 0.7 mm, L14 = 1.78 mm, L15 = 0.88 mm, L16 = 1.07 mm, L17 = 2.13 mm, L18 = 0.78 mm, L19 = 1.95 mm, L20 = 0.99 mm, s1 = 0.6 mm, s2 = 0.334 mm, s3 = 0.44 mm, and s4 = 0.328 mm. The final fabricated bandpass filter is shown in Fig. 7. The size of the filter is 22.7 mm x 23.7 mm.

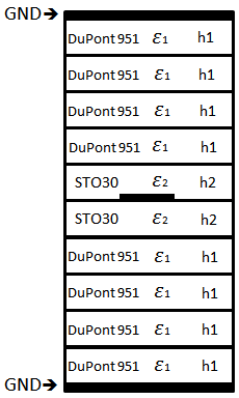


Fig. 3, Cross-section of the best temperature compensated configuration of DuPont 951 and STO30

The filter uses a 10-layer structure, shown as a cross sectional view in Fig. 3, with the thickness of STO30 optimized and set at h2 = 40 um [17]. There are 4 LTCC layers on each side of the center strip line. The fired thickness of each layer is h1= 0.216 mm. The final fabricated bandpass filter is shown in Fig. 4, as a 3-D see-through view, at a size 22.7 mm x 23.7 mm.

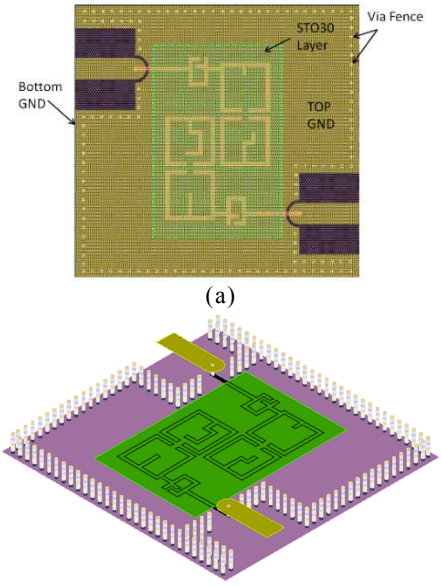


Fig. 4, (a) 2-D final fabricated bandpass filter, and (b) 3-D configuration without top ground plate.

3.2 Filter characterization

The measured frequency response of the filter is shown in Fig. 5(a). The filter was tested from -20 °C to 80 °C. The $\tau_f$ of the filter is 0.7 ppm/°C. The insertion loss of the filter is 2.45 dB at 20 °C. The insertion loss variance over the temperature is 0.28 dB. In Fig. 5(b), the maximum-difference group delay of the filter is 37pS.

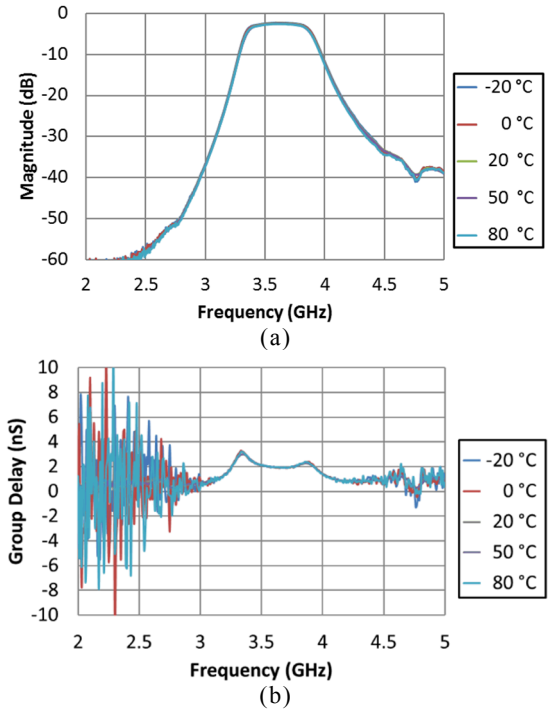


Fig. 5, (a) Measured S21 and (b) measured group delay of the filter over temperature.

The temperature coefficient of resonant frequency $\tau_f$ is calculated as:

$$\tau_f = \frac{1}{f_{ro}} \left(\frac{\Delta f_r}{\Delta T}\right) \quad (2)$$

where fro is the center frequency at 20°C, Δfr is the change of the center frequency over -20 to 80°C, and ΔT is equal to 100°C. The center frequency is calculated by

$$f_{center} = \frac{f_{L\_3dB} + f_{H\_3dB}}{2} \quad (3)$$

where $f_{L\_3dB}$ is the 3dB frequency at low side of the passband and $f_{H\_3dB}$ is the 3 dB frequency at high side of the passband.

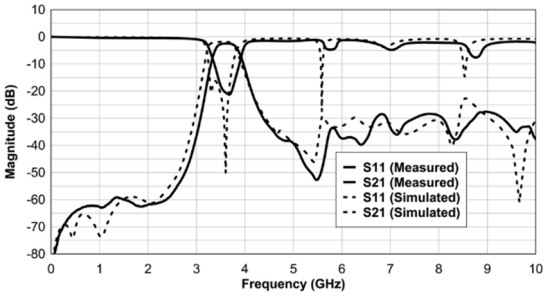


Fig. 6, Measured and simulated results of the filter.

Fig. 6 shows the measured and simulated wide-rage frequency response of the filter. The measured insertion loss of the filter is better than 2.45 dB, the stopband greater than 27.6 dB from 4.3 GHz to 10 GHz, and the 3 dB bandwidth is 0.5 GHz. The simulation is performed by using Agilent ADS EM simulator.

4. CONCLUSIONS

A temperature-compensated bandpass filter using modified $SrTiO_3$ materials cofirable with DuPont 951 LTCC is demonstrated. The filter has a temperature coefficient of resonant frequency $\tau_f$ = 0.7 ppm/°C. The insertion loss at 20 °C is greater than 2.45 dB. The variance of insertion loss of the filter over the wide range temperature is 0.28 dB. The wide stopband is better than 27.6 dB from 4.3 to 10 GHz.

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