SAND2013-3044C

Temperature Compensated Bandpass Filters in LTCC

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Sandia National Laboratories

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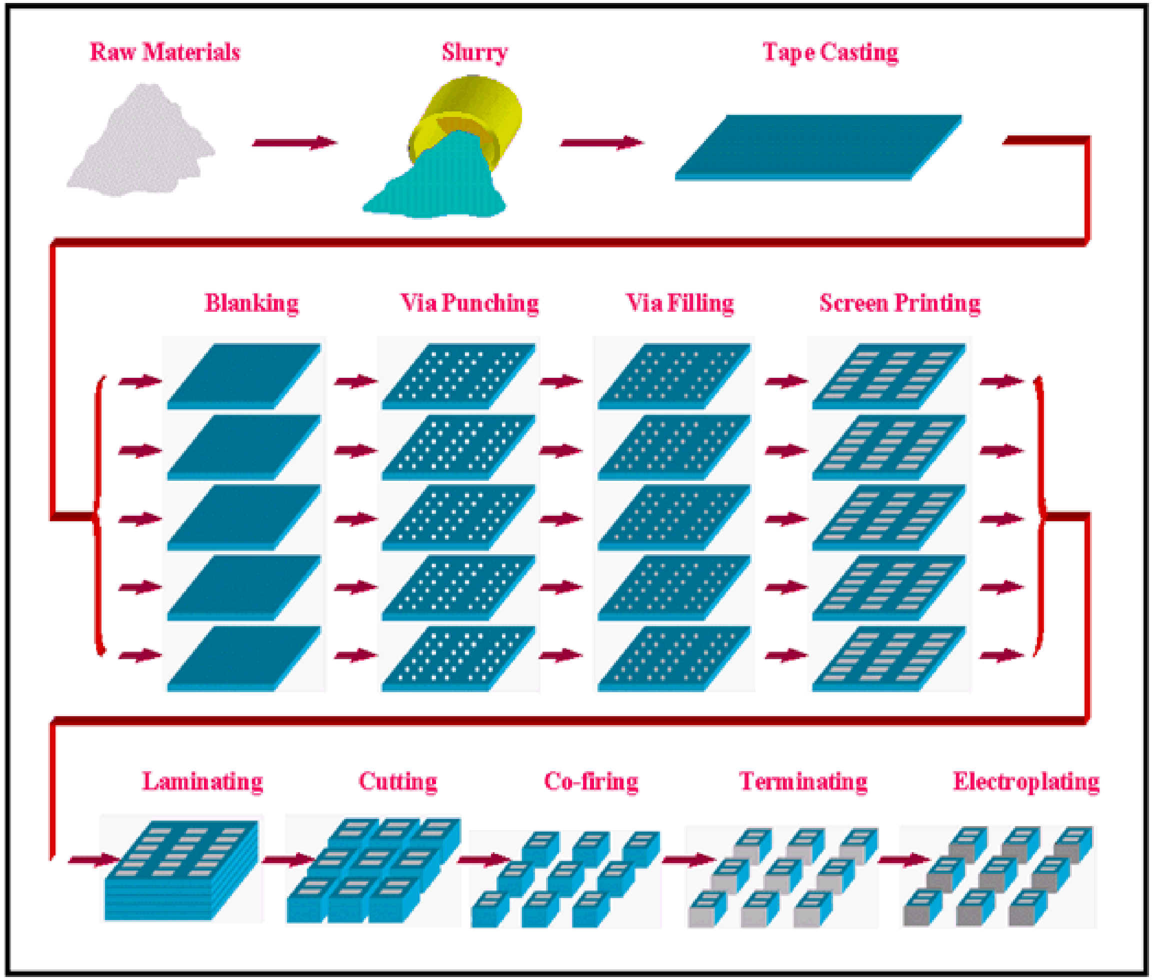
Outline

- Introduction
  - Low temperature cofired ceramic (LTCC) and RF/MW applications
  - Temperature coefficient of resonant frequency, τ_f
- Localized temperature stability – adding opposite $0\tau_f$ materials
  - Development of τ_f compensating materials
  - Simulation and experiment
  - Discussion: Energy filling factor and effective τ_f compensation
- Temperature stable S-band filters: a demo of localized $0\tau_f$
- Summary

What is LTCC?

- All glass or glass-ceramic tape at sintering temp ≤ 950 °C, typical 850 °C. Ag/Au cofireable
- Multilayer → 3D circuitry, passive integration, micro feature formation
- Parallel process → high overall yield
- Established manufacture infrastructure



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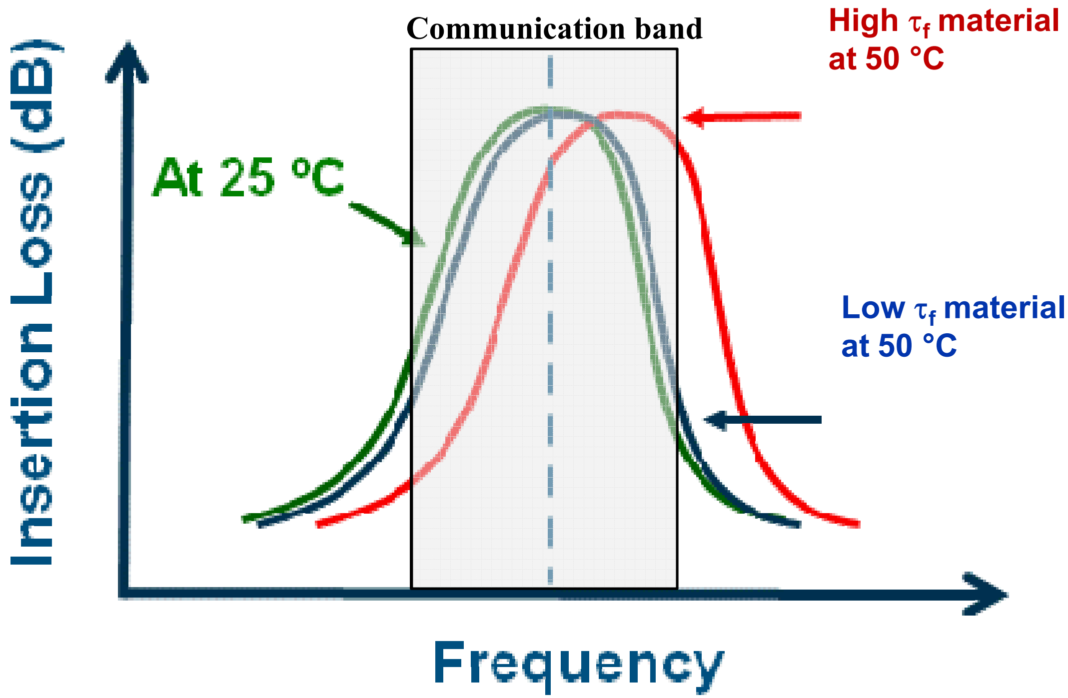
LTCC Dielectric



Example:

GSM 900 MHz
Up-/down-link BW = 25 MHz
For a τ_f = -50 ppm/°C materials,

Δf ~ 6 MHz over -50 to 80 °C

Shannon-Hartley
$C = B \log_2(1+S/N)$
C: channel capacity, B: bandwidth, S/N: signal/noise ratio

- **Critical dielectric properties for RF/MW applications: ε, Q and τ_f**
- **Low τ_f is needed:**
  - **For filtering and frequency generation circuits**
  - **Efficient use of wireless bandwidth**
  - **To eliminate costly temperature compensation mechanisms**

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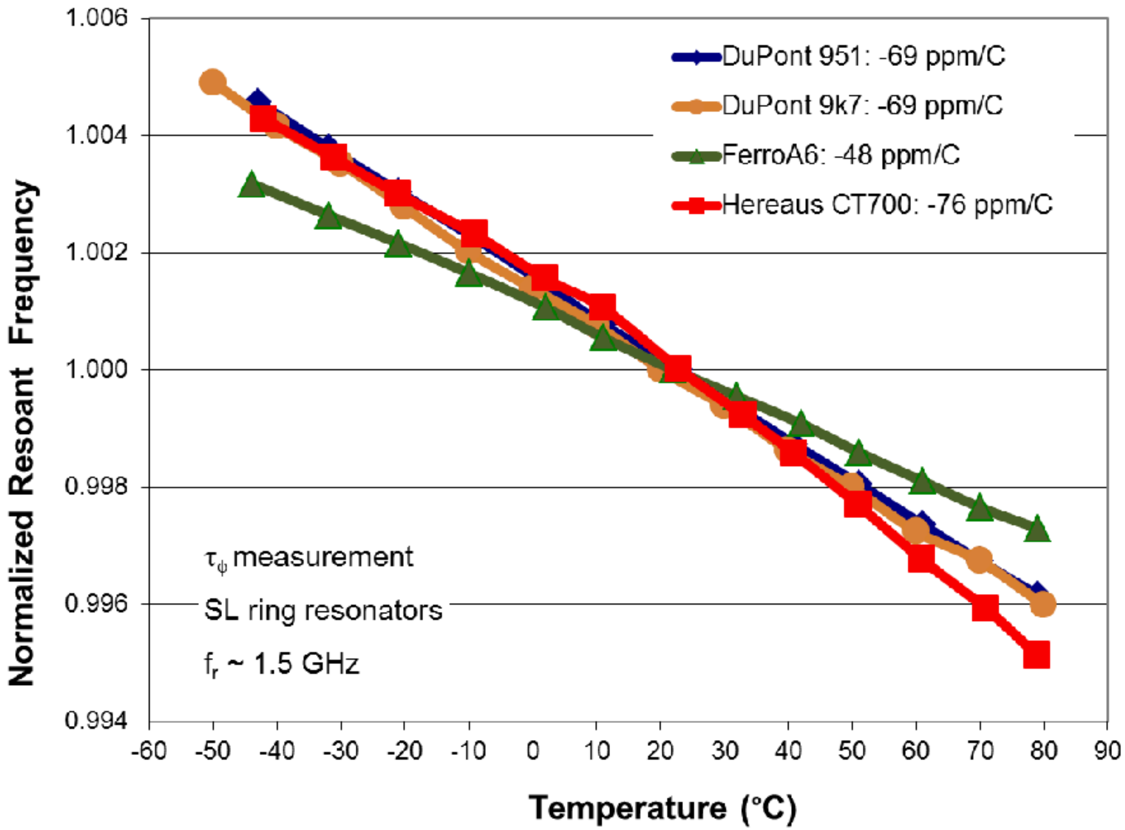
τ_f of Commercial LTCCs



- τ_f = -48 to -80 ppm/°C
- Designed primarily for packaging, not RF applications

Candidates for τ_f Adjustment

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

α= coefficient of thermal expansion (CTE)

α: 3-10 ppm/°C → τ_ε dominates τ_f

τ_ε is opposite in sign to τ_f

	Materials	Density (g/cm^3)	ε	τ_ε (ppm/°C)	τ_f (ppm/°C)	Sintering Temp (°C)
Global $0\tau_f$ →	TiO_2	4.23	85	-750	370	~ 1200
	$CaTiO_3$	3.98	180	-1850	920	~ 1400
Localized $0\tau_f$ →	$SrTiO_3$	5.13	300	-3000	1500	~ 1550
	Al_2O_3	4.00	9.6	105	-60	~ 1600
Localized $0\tau_f$ →	V-glass	2.77	7.3	N/A	N/A	Tg= 625°C

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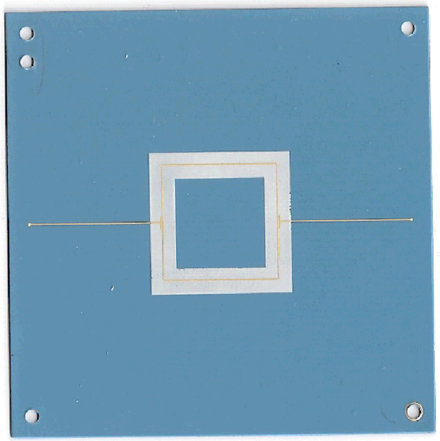
Localized $0\tau_f$ in Existing LTCC?



951 LTCC
- Non-crystallizable glass + Al_2O_3 filler
- τ_f = -69 ppm/°C
- Not designed for RF/MW
- Widely used

Localized $0\tau_f$
- Add-on solution
- Locality = only in needed area/volume

Challenges

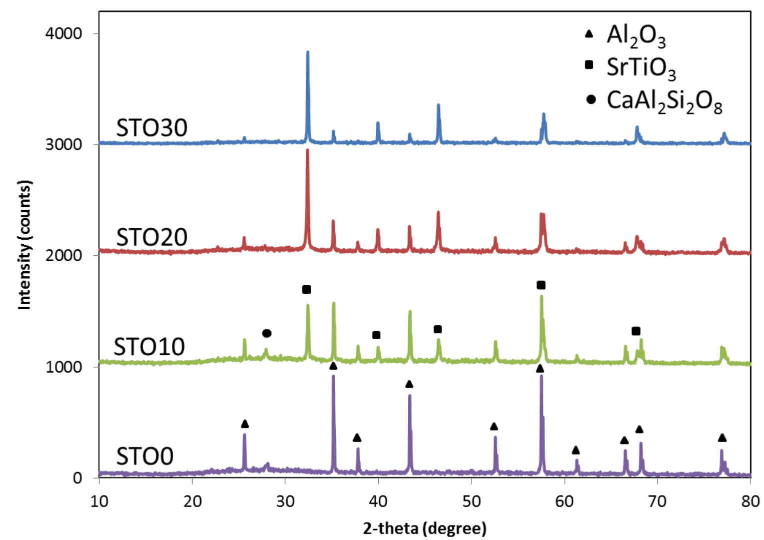
- **Developing τ_f compensating materials**
- **Cofiring of τ_f compensating materials in a multilayer LTCC**
- **Effect of thickness and placement of τ_f compensating material**

τ_f Adjuster Formulation, Property and Microstructure

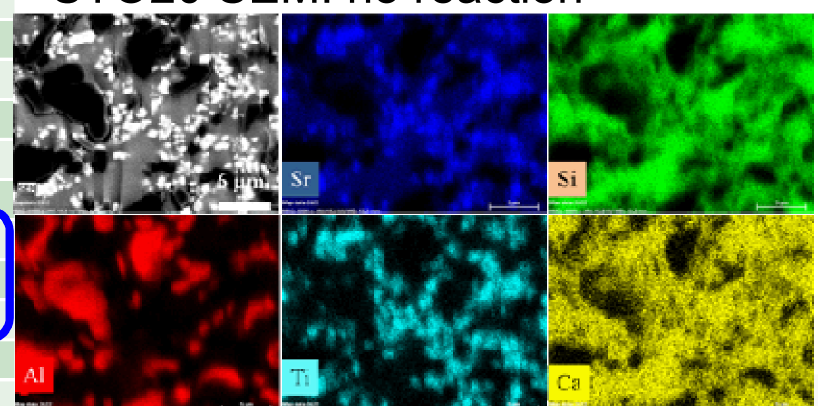
Composition	V-glass (wt%)	Al_2O_3 (wt%)	TiO_2 (wt%)	$CaTiO_3$ (wt%)	$SrTiO_3$ (wt%)	Total wt%
CMB base	55	45				100
CMB TO15	55	30	15			100
CMB TO30	55	15	30			100
CMB CTO10	55	35		10		100
CMB CTO20	55	25		20		100
CMB STO10	55	35			10	100
CMB STO20	55	25			20	100
CMB STO25	55	20			25	100
CMB STO30	55	15			30	100
CMA STO20	60	20			20	100
CMC STO20	49.5	30.5			20	100

Sample	Archimedes bulk density (g/cc)	ε (1 MHz at RT)	τ_ε (ppm/°C)	Estimated τ_f (ppm/°C)
951 LTCC	3.10	7.88	112	-59
CMB base	3.19	7.79	190	-99
CMB TO10	N/A			
CMB TO30	2.77			
CMB CTO10	3.20	9.72	83	-45
CMB CTO20	3.15	12.0	-58	26
CMB STO10	3.21	9.57	10	-9
CMB STO20	3.30	12.22	-240	117
CMB STO25	3.31	13.88	-379	186
CMB STO30	3.35	15.76	-525	259
CMA STO20	3.23	11.96	-241	117
CMC STO20	3.35	12.27	-192	93

STO XRD: no/minimal reaction



STO20 SEM: no reaction



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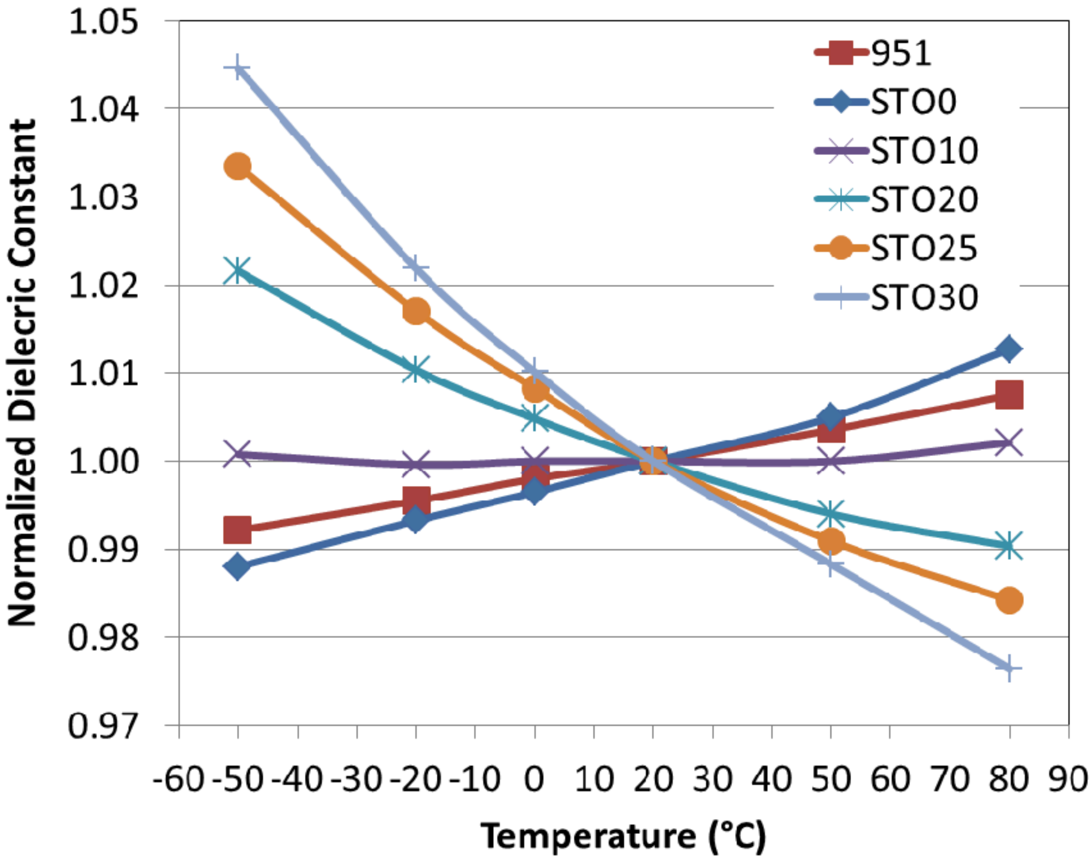
Localized $0\tau_f$

τ_ε of Compensating Materials



- τ_ε = slope of f_r vs T, positive → negative as STO increases
- STO30 has the largest τ_ε →positive τ_f

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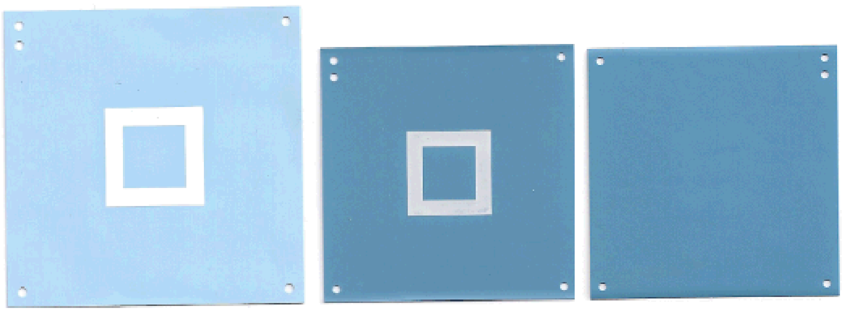
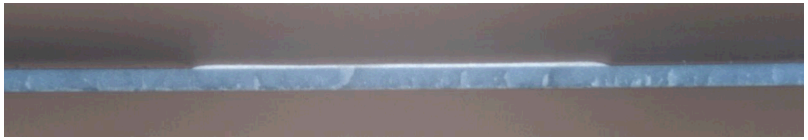
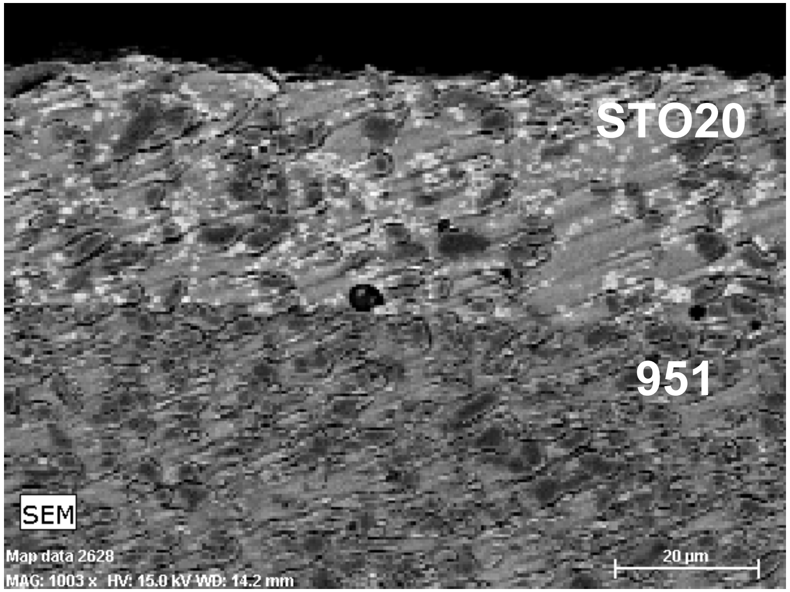
STO20 Cofireability – printed layer on 951

Green | Sintered front | Sintered backside







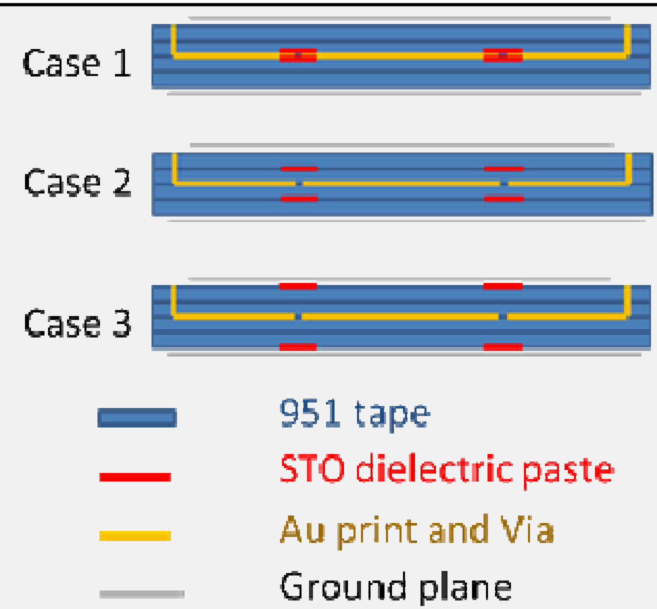
- **No deformation of cofired printed STO layer on a 10 mil 951 tape**
- **Both optical and SEM images show a clean STO20/951 interface, suggesting no or minimal reaction or inter-diffusion**

3 Variables

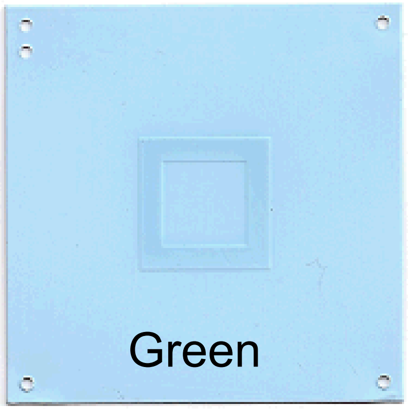
- STO content:
  - 20, 25 and 30 wt%

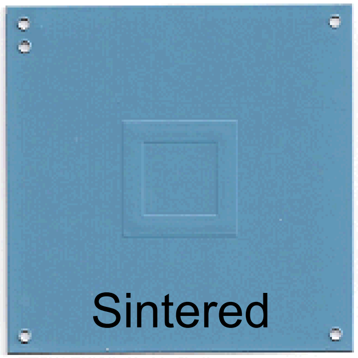
- STO thickness:
  - Simulation: 5 to 50 μm
  - Experiment: 20 and 40 μm

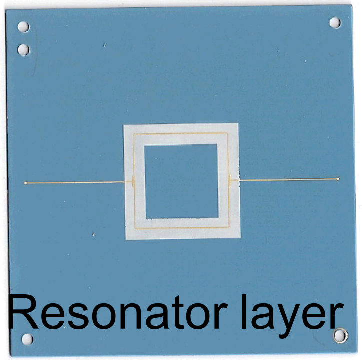
- STO placement
  - Case 1: next to SL
  - Case 2: one LTCC tape away from SL
  - Case 3: two tape layers away from SL, just under surface ground planes

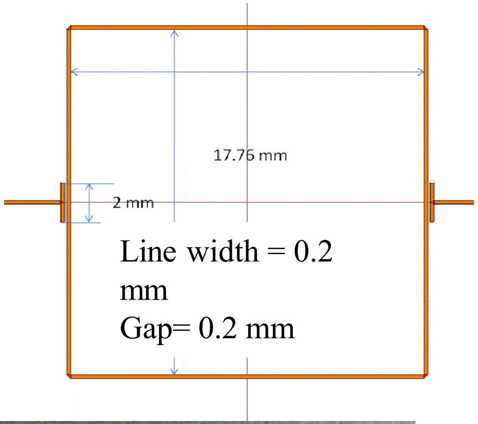


SL Resonator Panels

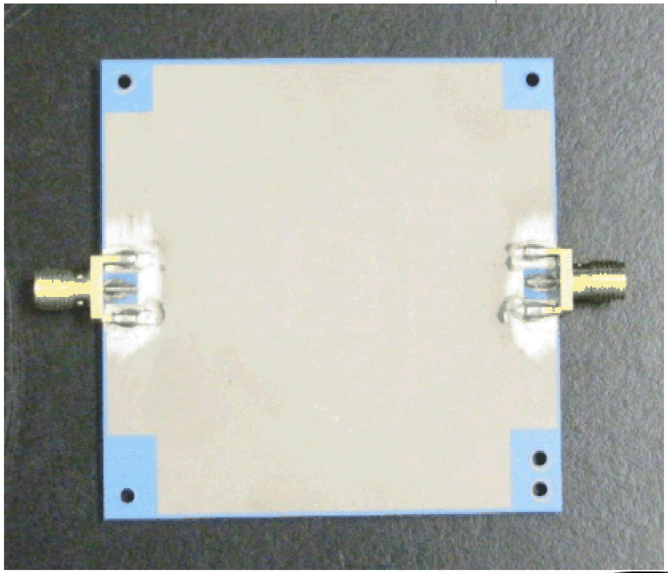




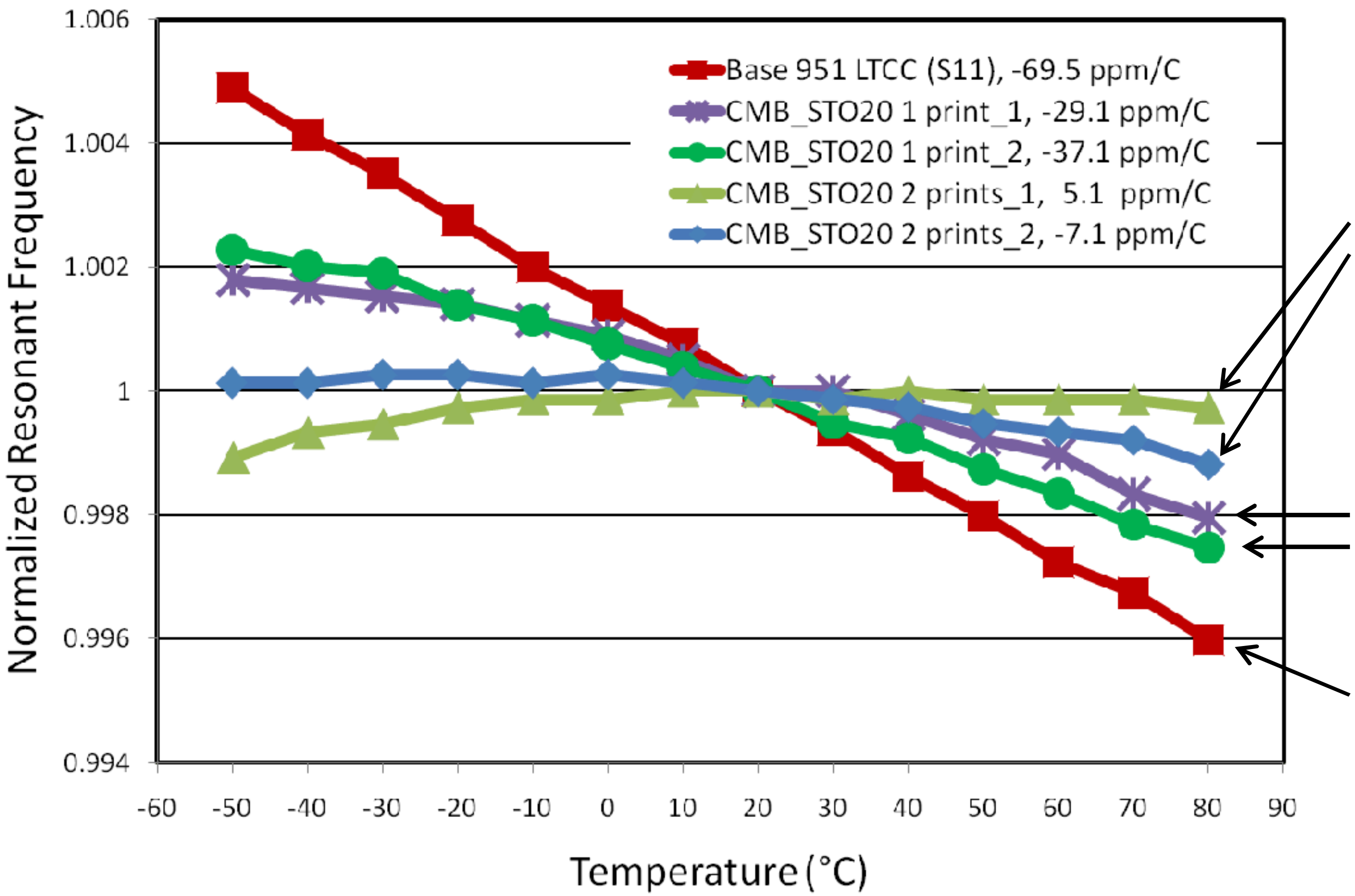


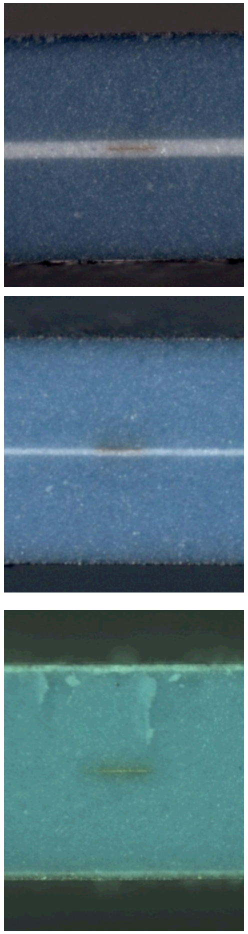


- **Standard LTCC fabricated with 951 matching conductors**
- **4 layers of 10 mil 951 tape. 50 Ω lines. f_r = 1.5 GHz**
- **No localized deformation, indicating no sintering mismatch**
- **Embedded STO shown as "embossed" feature on the non-contact side during lamination**



τ_f Results





- A true, near zero or zero τ_f is achievable
- Variation of τ_f, possibly by varying the STO20 thickness

SL Resonators

STO composition	Appx STO Thickness (μm)	τ_f (ppm/°C)		
		Case 1	Case 2	Case 3
STO20	20	-28.8	-67.5	-71.2
	40	1.9		
STO30	20	1.0	-61.7	-69.3
	40	60.0	-54.8	-62.3

- **Only in case 1 a ~ 0 τ_f is realized**
  - **STO20**
    - **τ_f = -28.8 ppm/°C at 20 μm**
    - **τ_f = +1.9 ppm/°C at 40 μm**
  - **STO30**
    - **$0\tau_f$ = +1.0 ppm/°C at 20 μm**
    - **τ_f over-corrected at 40 μm**

- **In cases 2 and 3, the τ_f is far from 0 ppm/°C**

- **Placing τ_f adjuster next to SL is essential for τ_f compensation**

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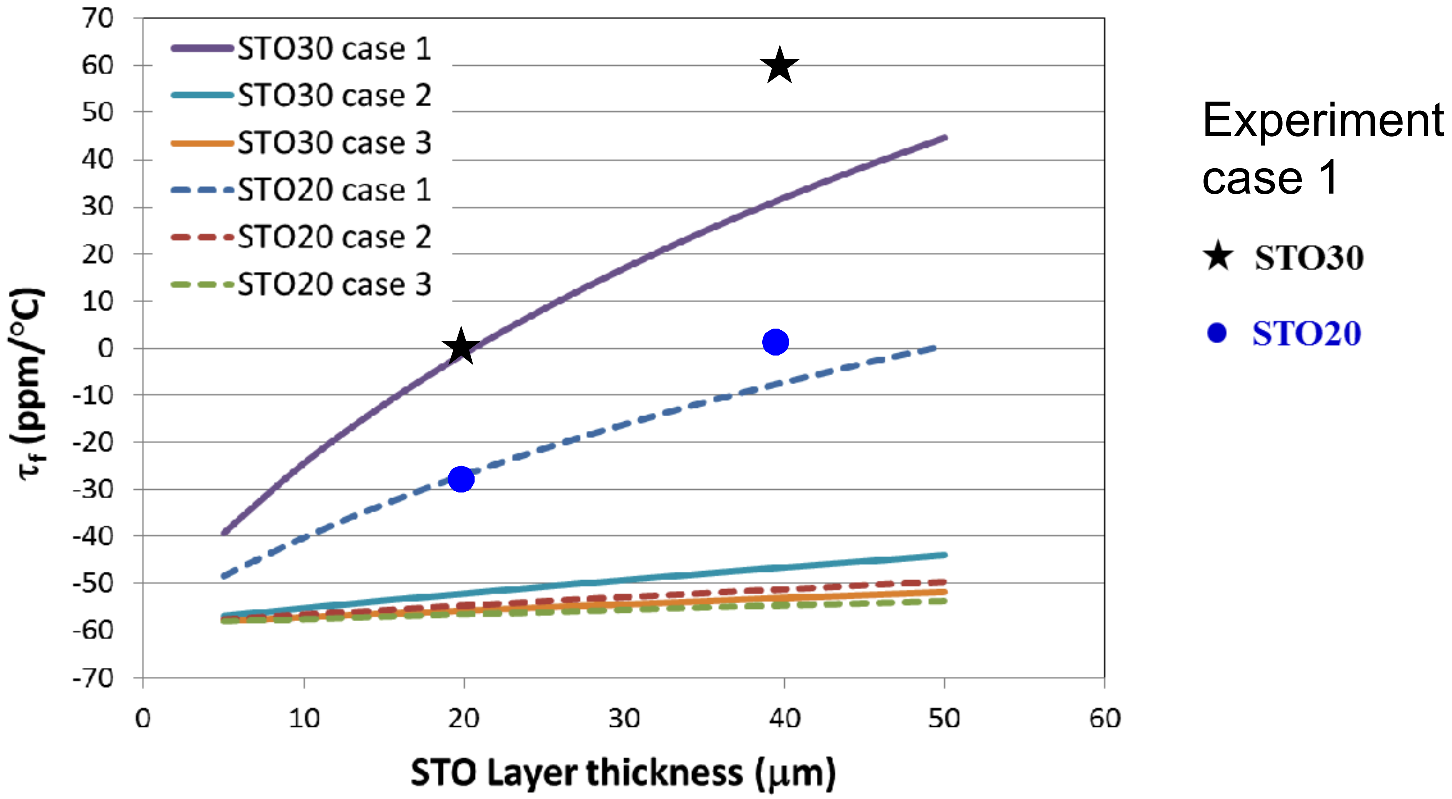
Experiment Versus Simulation



- Good match for STOs at 20 μm
- Simulation underestimate at thicker STO

τ_f of a Dielectric Composite

- τ_f expressed as

$$\tau_f = \sum_i P_i \tau_{fi} \qquad\qquad P_i = E_i / E_{total}$$

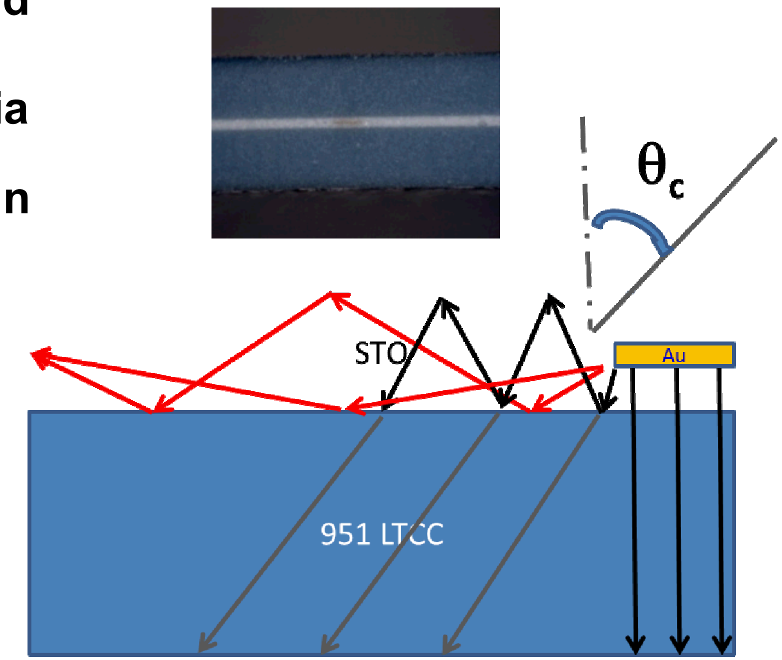
where P_i is defined as the energy filling factor, the fraction of total EM energy confined in dielectric phase *i*

- P_i depends on dielectric constant, volume, geometry of dielectric *i*, as well as the EM field distribution inside the dielectric

Energy Concentration in STO Layers Case 1

- **Low aspect ratio → fringing electrical field**
- **EM wave propagates high ε → low ε media**
- **Critical angle for total internal reflection in case 1**
  - ε_{STO30} = 15.76
  - ε_{LTCC} = 7.88
- **Critical angle (Snell's law)**

$$\theta_c = \operatorname{asin}\left(\frac{n_{LCTT}}{n_{STO30}}\right) = \operatorname{asin}\left(\frac{\sqrt{\varepsilon_{LTCC}}}{\sqrt{\varepsilon_{STO30}}}\right) = 45°$$



$\theta_c \geq 45°$, total internal reflection in STO

$\theta_c < 45°$, reflection/refraction at the STO-951 interfaces

Energy concentration in STO → effective τ_f compensation

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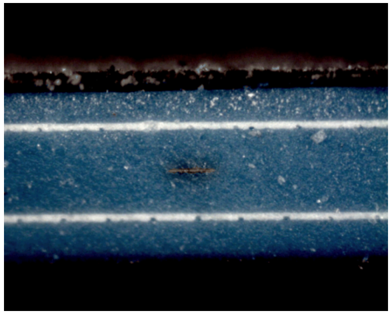
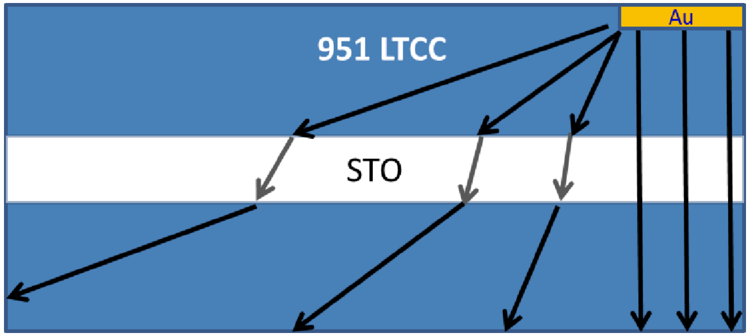
No Energy Concentration in Cases 2 and 3

- EM wave propagates low ε → high ε → low ε media
- No total internal reflection
- Energy in STO scales to volume
- Overall τ_f of SL resonator is dominated by 951 LTCC





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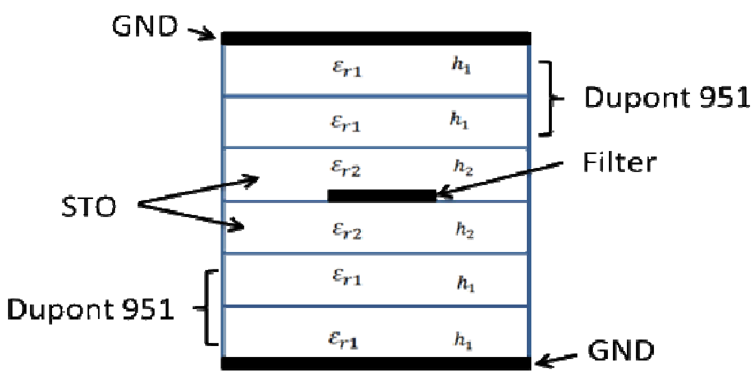
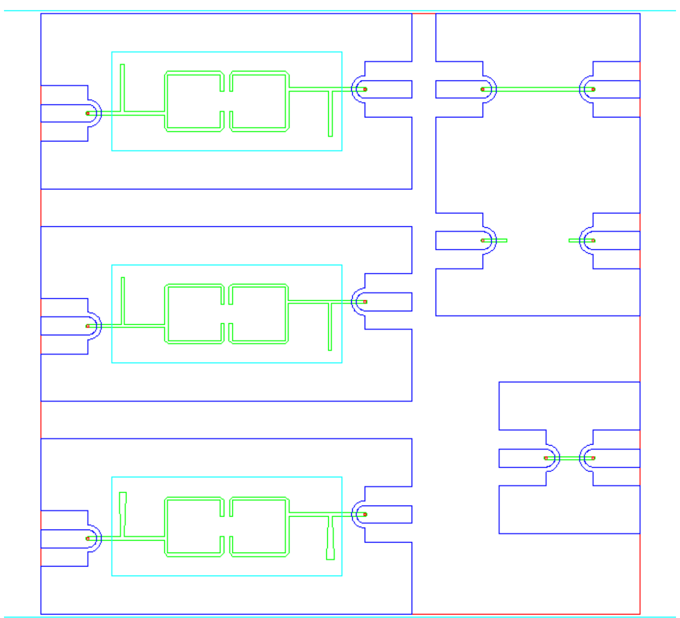
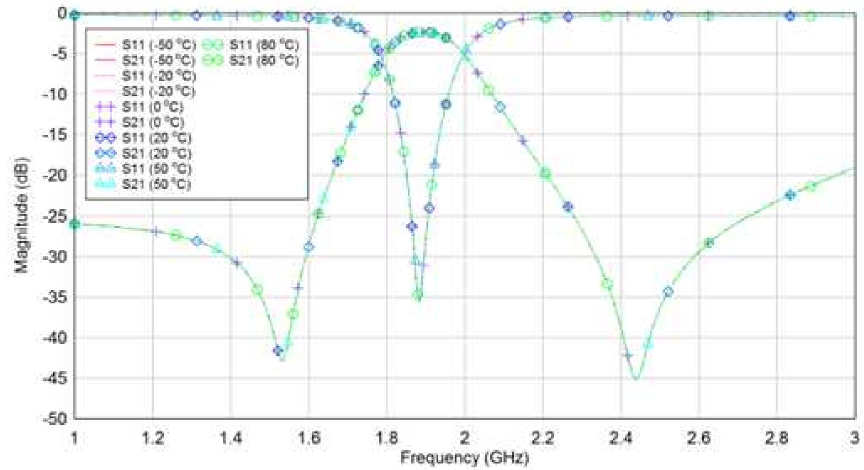
$0\tau_f$ Demo: design of a S-band filter

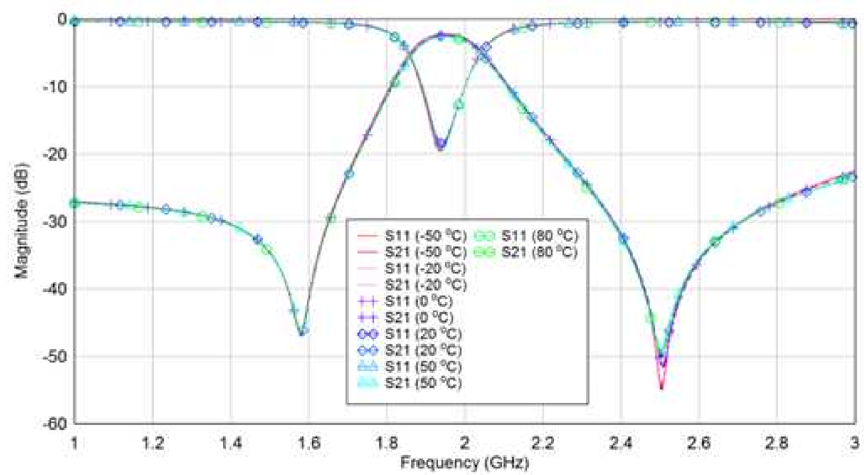




Simulation (20 µm STO30)

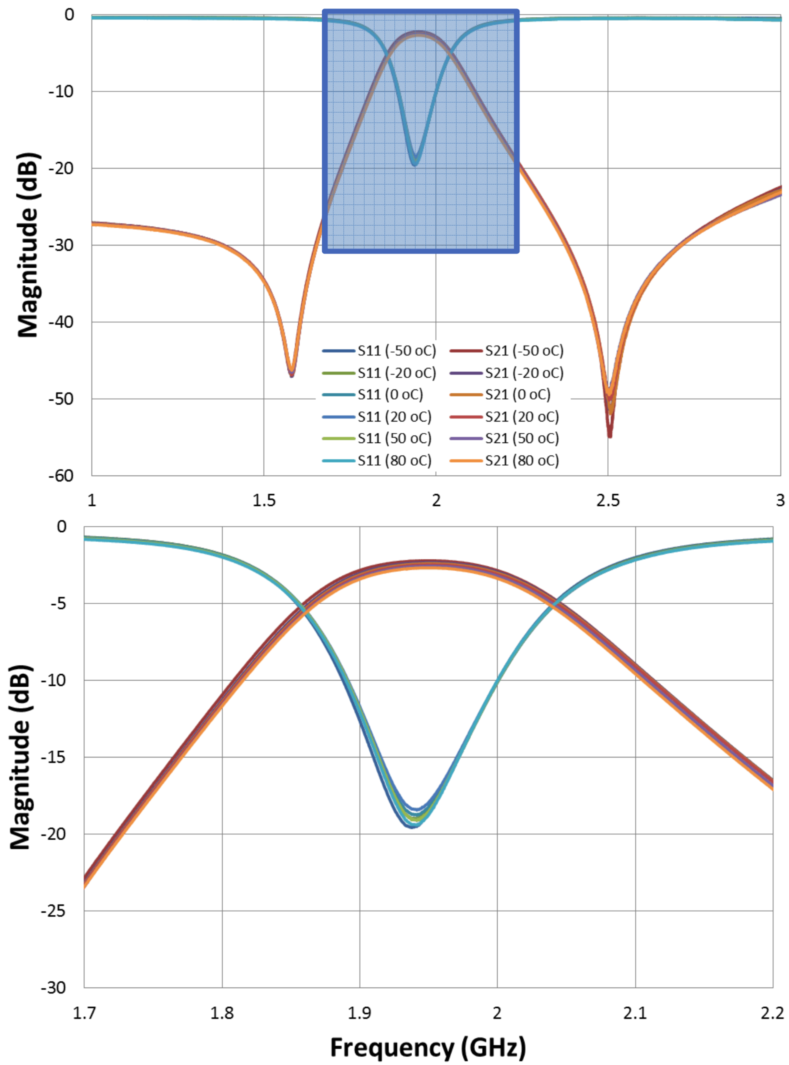


Measurement (τ_f = 1.8 ppm/ºC)

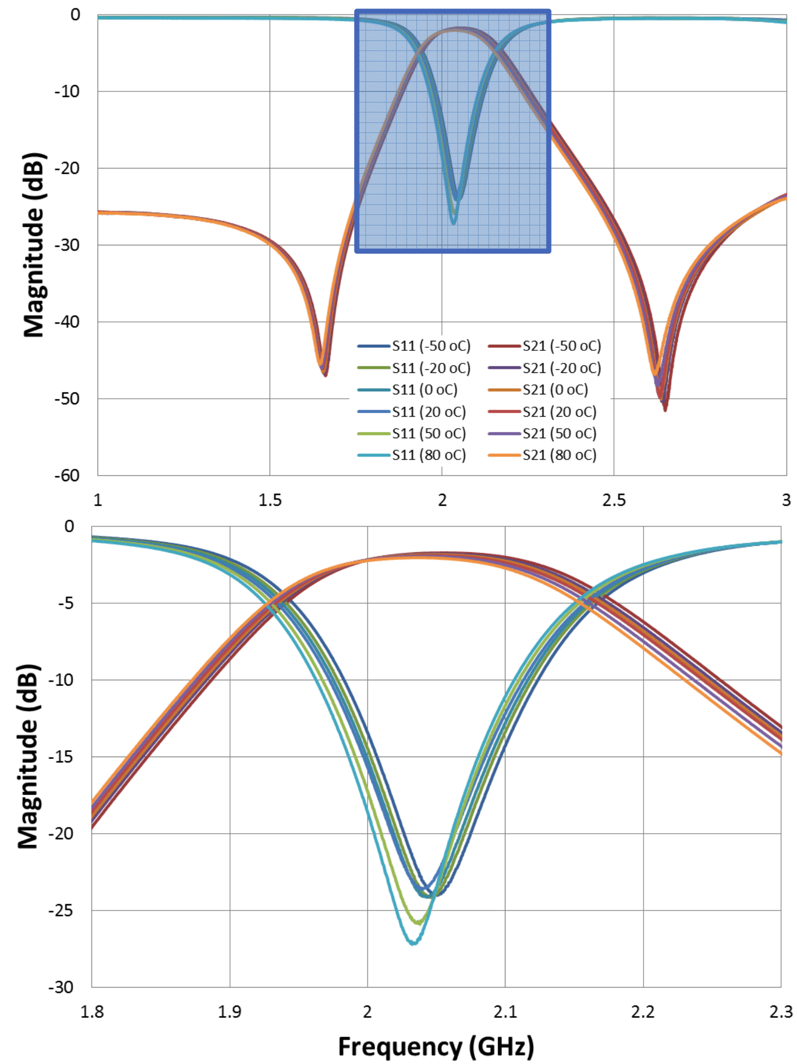


$0\tau_f$ Demo: filter measurement

With 20 µm STO30, τ_f = 1.8 ppm/ºC



Without STO, τ_f = -71.2 ppm/ºC



Summary

- **SL resonators with a near $0\tau_f$ have been demonstrated by locally integrating a τ_f compensating material in a multilayer LTCC package**

- **Placing STO materials next to the SL is essential for τ_f compensation, due to the EM energy concentration in the STO layers**

- **S-band filter with $0\tau_f$ has been demonstrated**

Acknowledgement

- **The authors thank Adrian Wagner, Tom Chavez , Dennis De Smet and Shelley Williams for help in LTCC fabrication and measurement**

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Thank You!

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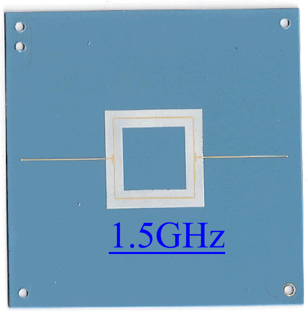
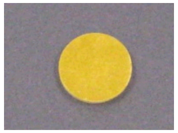
Characterization of τ_f and τ_ε

- **Test vehicle; 4 layer LTCC panel**



- **Test setup**



- Test method
  - Resonant frequency, f_r, from reflection coefficient, S11
  - Temperature range -50 to 80°C
  - $$\tau_f = \frac{1}{f_r}\frac{\Delta f}{\Delta T}$$

Properties of compensating materials

Composition		Temperature (°C)						τ_ε (ppm/°C)
		-50	-20	0	20	50	80	
Dielectric constant	951	7.82	7.84	7.86	7.88	7.91	7.94	118
	Base	7.70	7.74	7.76	7.79	7.83	7.89	190
	STO10	9.58	9.57	9.57	9.57	9.57	9.59	10
	STO20	12.49	12.35	12.28	12.22	12.15	12.10	-240
	STO25	14.34	14.12	13.99	13.88	13.75	13.66	-379
	STO30	16.46	16.10	15.92	15.76	15.57	15.39	-525

- τ_ε changes from positive to negative as STO increases
- STO20, STO25 and STO30 are promising for τ_f compensation. STO10 not considered
- Dielectric constant increases as STO increases → lower f_r

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ε_{eff} of Heterogeneous Multilayer Dielectric

$$\frac{1}{C} = \frac{1}{\pi}\int_0^{\infty} \frac{[\tilde{f}(\beta)/Q]^2}{\beta}\frac{1}{Y}d\beta$$

$\beta = 2\pi/\lambda_g$: propagation constant, Q: SL charge

$$\varepsilon_{eff} = \frac{C}{C_o}$$

$$\frac{\tilde{f}(\beta)}{Q} = \frac{8}{5}\frac{\sin(\beta w/2)}{\beta w/2} + \frac{12}{5(\beta w/2)^2}\left[\cos(\beta w/2) - \frac{2\sin(\beta w/2)}{\beta w/2} + \left(\frac{\sin(\beta w/4)}{\beta w/4}\right)^2\right]$$

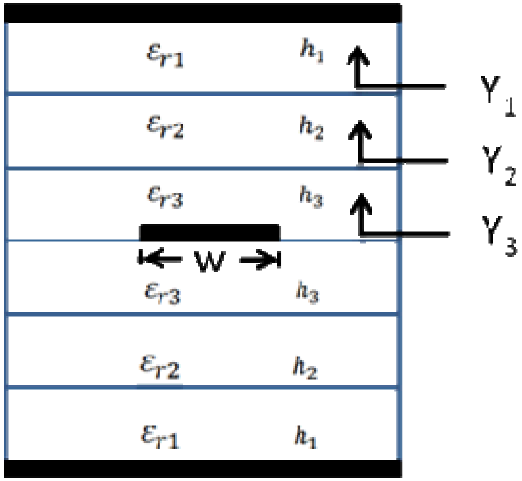
Fourier transform of the charge density distribution

$$Y_1 = \varepsilon_o \varepsilon_{r1} \coth(\beta h_1)$$

$$Y_2 = \varepsilon_o \varepsilon_{r2} \frac{Y_1 + \varepsilon_o \varepsilon_{r2} \tanh(\beta h_2)}{\varepsilon_o \varepsilon_{r2} + Y_1 \tanh(\beta h_2)}$$

$$Y_3 = \varepsilon_o \varepsilon_{r3} \frac{Y_2 + \varepsilon_o \varepsilon_{r3} \tanh(\beta h_3)}{\varepsilon_o \varepsilon_{r3} + Y_2 \tanh(\beta h_3)}$$

Y_1, Y_2, Y_3 are transverse transmission line admittance



$$Y = 2\varepsilon_o \varepsilon_{r3} \frac{Y_2 + \varepsilon_o \varepsilon_{r3} \tanh(\beta h_3)}{\varepsilon_o \varepsilon_{r3} + Y_2 \tanh(\beta h_3)}$$

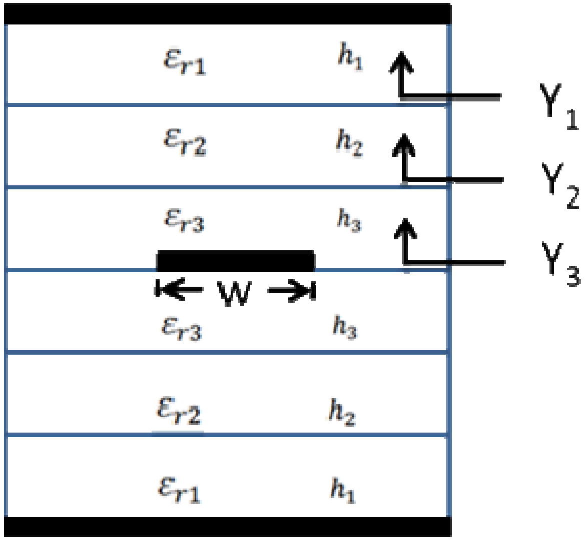
ε_{eff} and f_r

$$\frac{1}{C_o} = \frac{1}{\pi}\int_0^{\infty} \frac{\left[\frac{\tilde{f}(\beta)}{Q}\right]^2}{\beta} \frac{1}{Y_o} d\beta$$

$$Y_{30} = \varepsilon_o coth[\beta(h_1 + h_2 + h_3)]$$

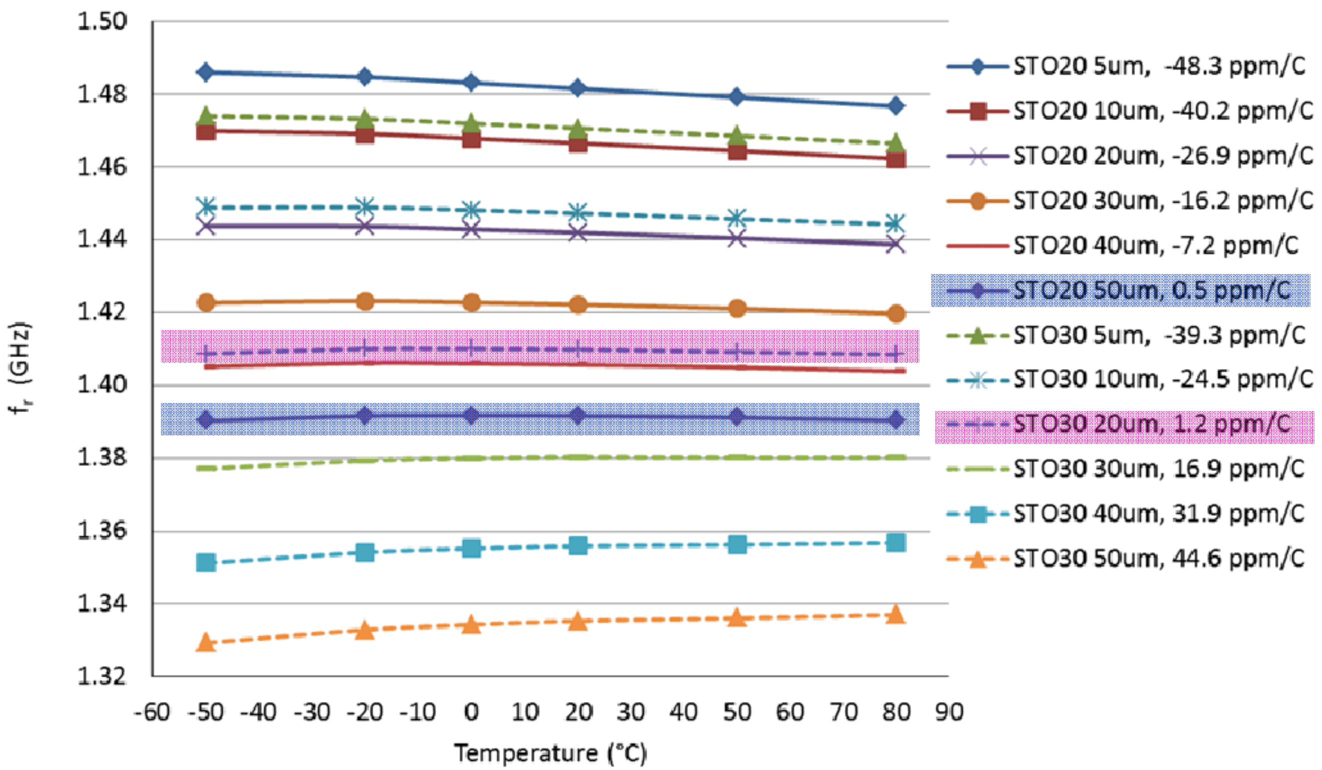
$$\boldsymbol{Y_o = 2Y_{30} = 2\varepsilon_o coth[\beta(h_1 + h_2 + h_3)]}$$

$$\varepsilon_{eff} = \frac{C}{C_o}$$



Method of Momentum EM simulation → f_r

Effect of Composition and Thickness for Case 1



- f_r
  - STO20 shows 0 τ_f at 50 μm
  - STO30 shows 0 τ_f at 20 μm
- τ_f compensation
  - Scales to wt% of STO
  - Scales to thickness

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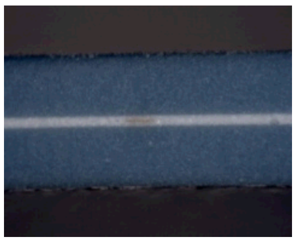
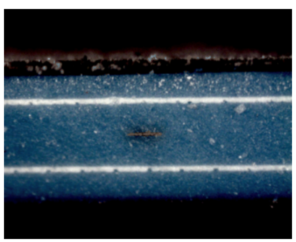
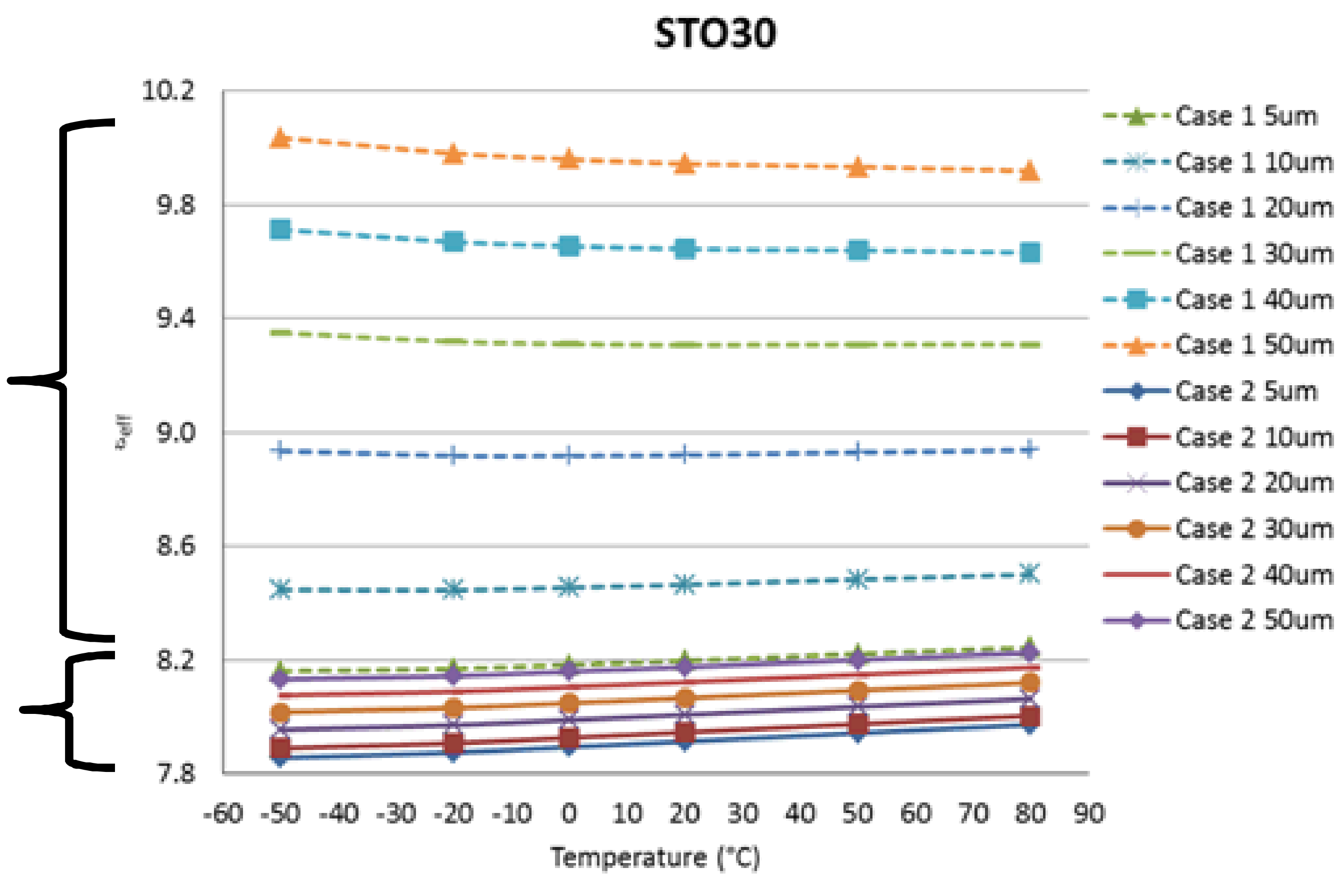
Effect of Configuration: ε_{eff}

Case 1



Case 2





- **Case 1**
  - **Increases of ε_{eff} significant**
  - **A crossover in slope**
- **Case 2**
  - **Change of ε_{eff} minimal**
  - **SL sees much less STO**

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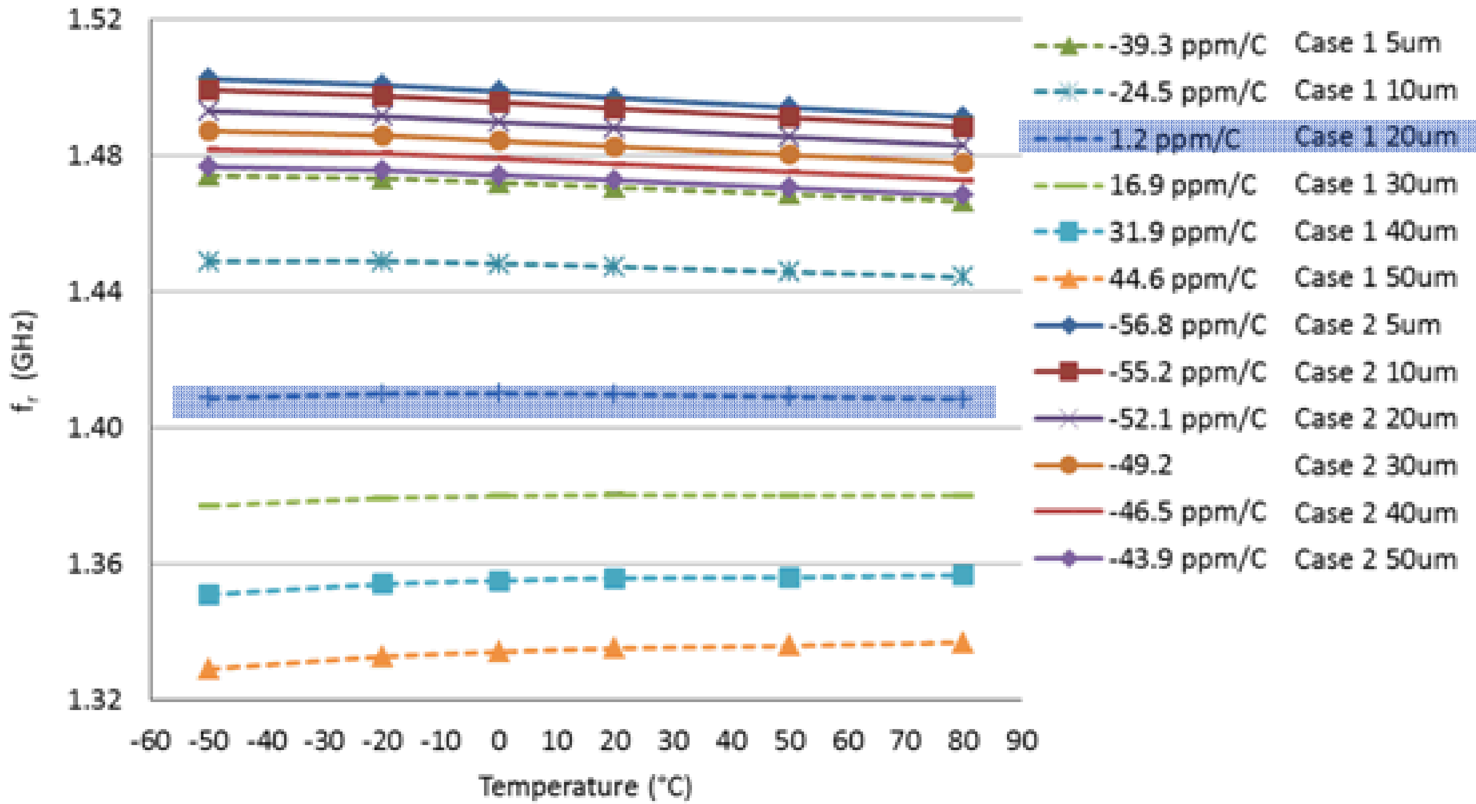
Localized $0\tau_f$

Simulation

Effect of Configuration: f_r



- f_r
  - STO30 shows 0 τ_f at 20 μm in case 1
  - Never reaches 0 τ_f in case 2

- τ_f compensation
  - Placement of STO is critical
  - Most effective when next to SL

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