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Bandpass Filters With Localized Temperature Compensation in LTCC

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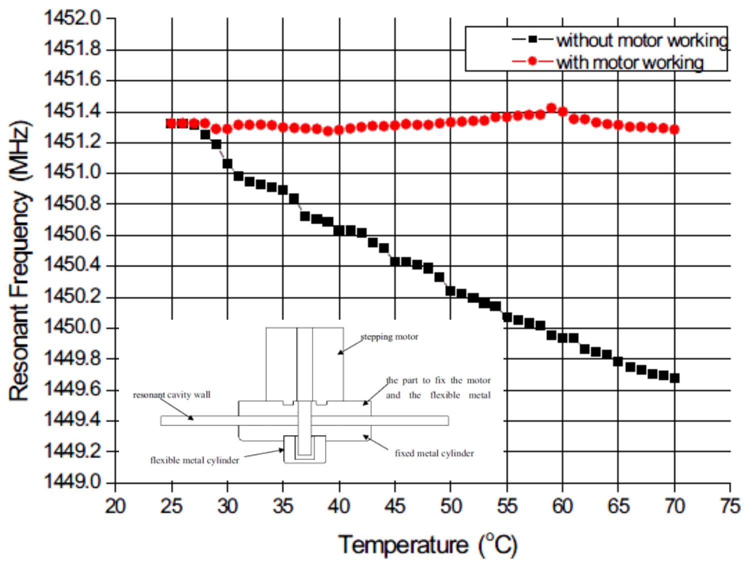
Outline

- **Introduction**
  - Temperature coefficient of resonant frequency, τ_f
  - τ_f compensation
- **τ_f compensating materials**
  - Formulation, processing, and characterization
  - Cofireability with LTCC
- **Stripline resonator study**
- **Demo of $0\tau_f$ bandpass filter**
- **Summary**

Temperature Compensated Filters

Mechanically tuned resonant cavity

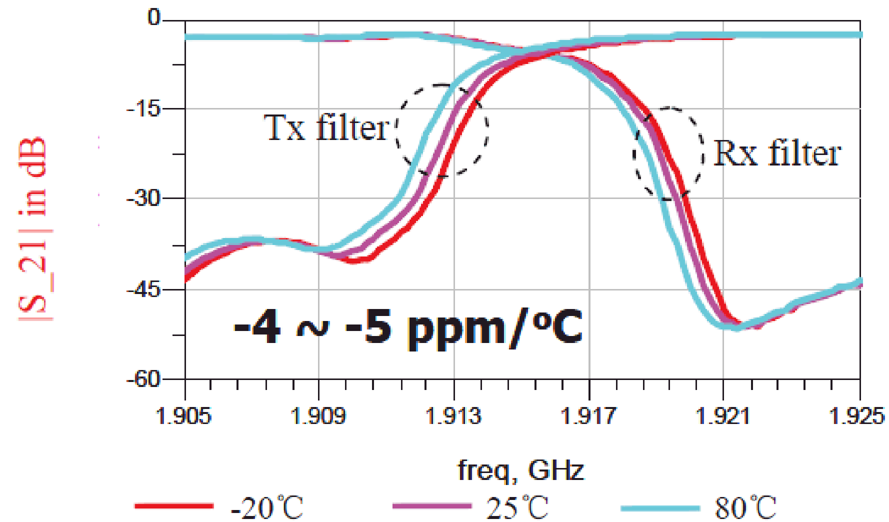
Pan and Sui, 2009

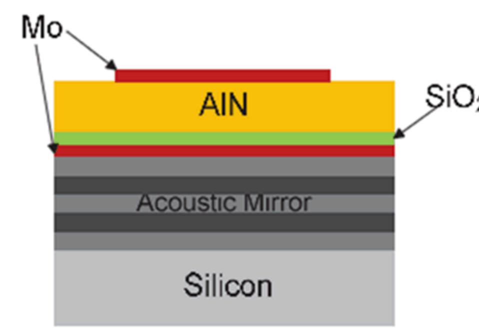


- **The resonant frequency tuned by a step motor controlled moving metal plate**
- **τ_f reduced to 2.2 ppm/°C from the uncompensated -26 ppm/°C**

BAW filter with SiO_2 integration

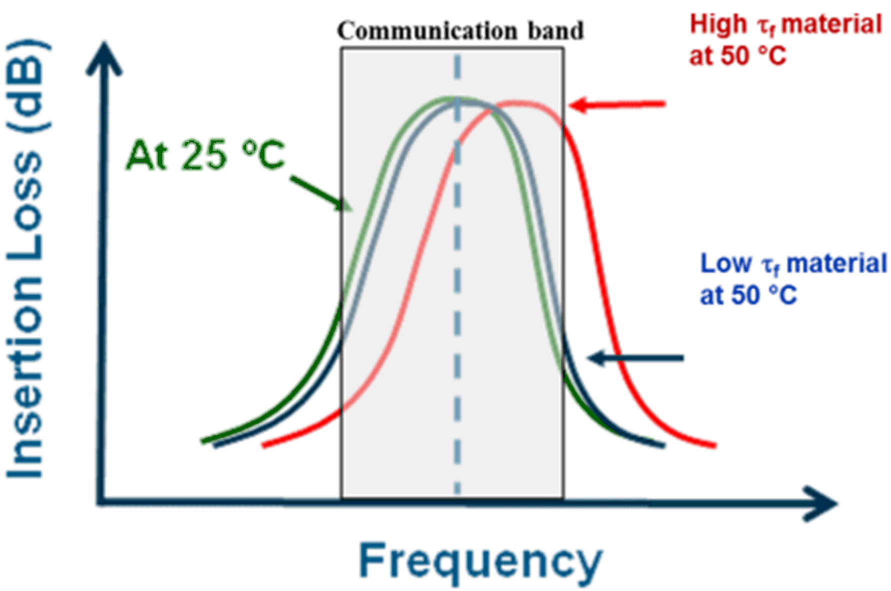
Hu, Zhou, Pang and Zhang, IEEE, 2011





- **τ_f of AlN (<0 ppm/°C) is compensated by SiO2 (τ_f >0 ppm/°C**

Why τ_f is Important?



Example:

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

Δf ~ 6 MHz (-50 to 80 °C)

Shannon-Hartley

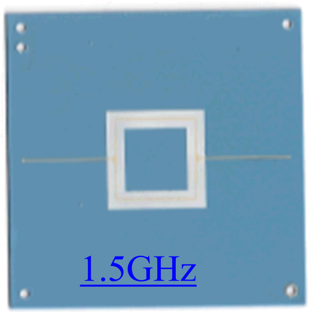
$$C = B \log_2(1+S/N)$$

C: channel capacity
B: bandwidth
S/N: signal/noise ratio

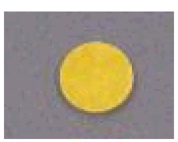
- **Critical dielectric properties for RF/MW applications: ε, Q and τ_f**
- **Low τ_f is needed:**
  - For filtering and frequency generation circuits
  - Efficient use of wireless bandwidth
  - To eliminate costly temperature compensation mechanisms

Characterization of τ_f and τ_ε

Test vehicle

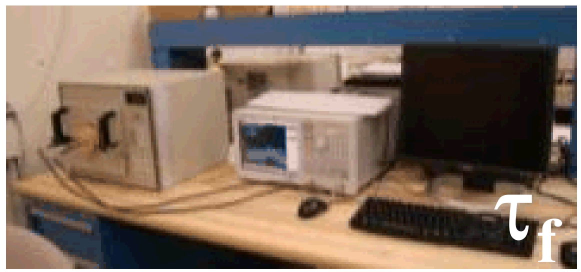


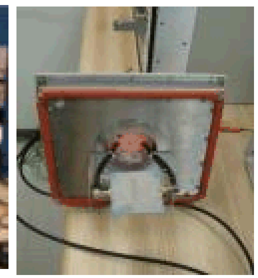
resonator



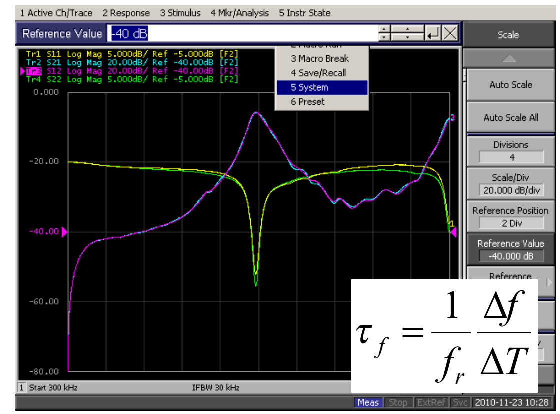
Sintered Pellet with Au electrode

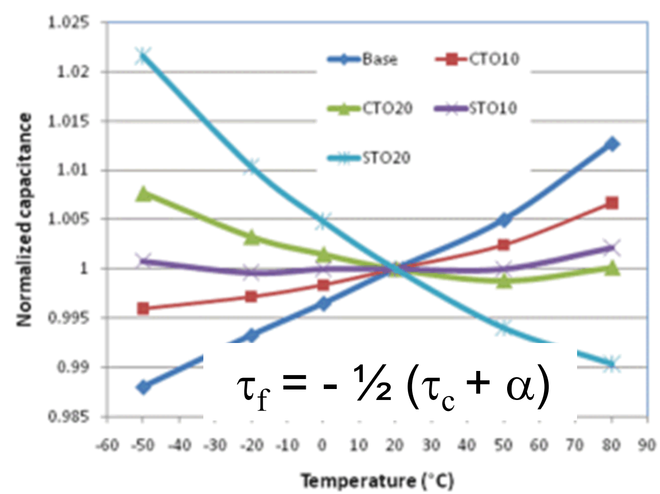
Test Setup
(-50 to 80°C)





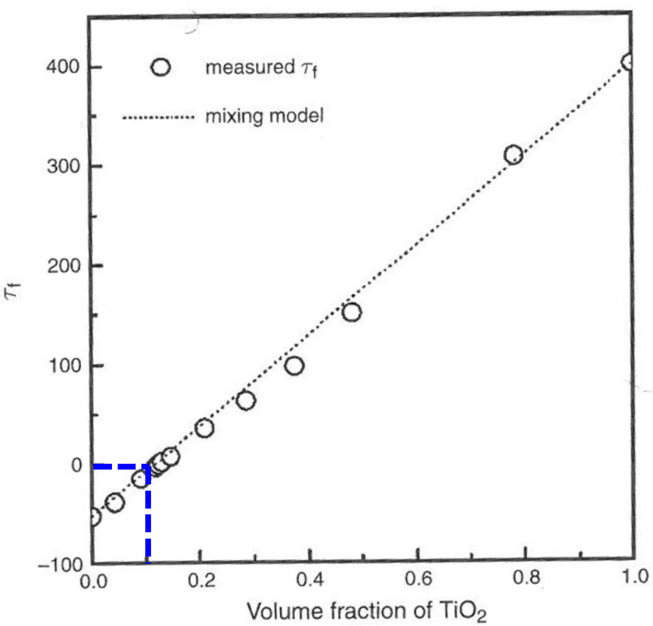
Test Results



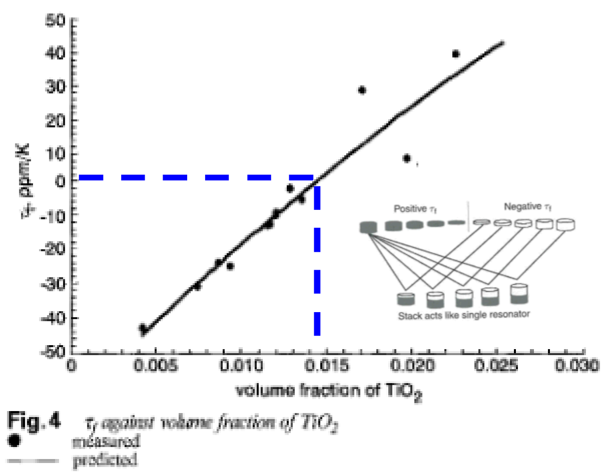


τ_f Compensated Dielectrics

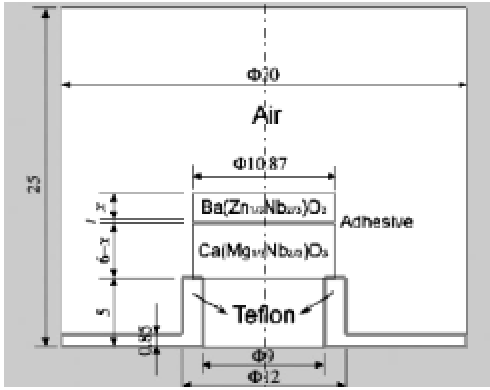
- Solid solution of dielectric ceramics with <u>opposite</u> τ_f
  - Microwave dielectrics
- Stack of alternating layers of <u>opposite</u> τ_f materials
  - Sequential sintering of Al_2O_3/TiO_2
  - Adhesively bonded structure



$(1-x)CaWO_4 – x\ TiO_2$
S. H. Yoon et al 2007



Al_2O_3-TiO_2-Al_2O_3-TiO_2 …
N. Alford, 2000



Adhesive-Bonded $Ca(Mg_{1/3}Nb_{2/3})O_3/Ba(Zn_{1/3}Nb_{2/3})O_3$ Layered Dielectric Resonators L. Li and X. M. Chen, 2006.

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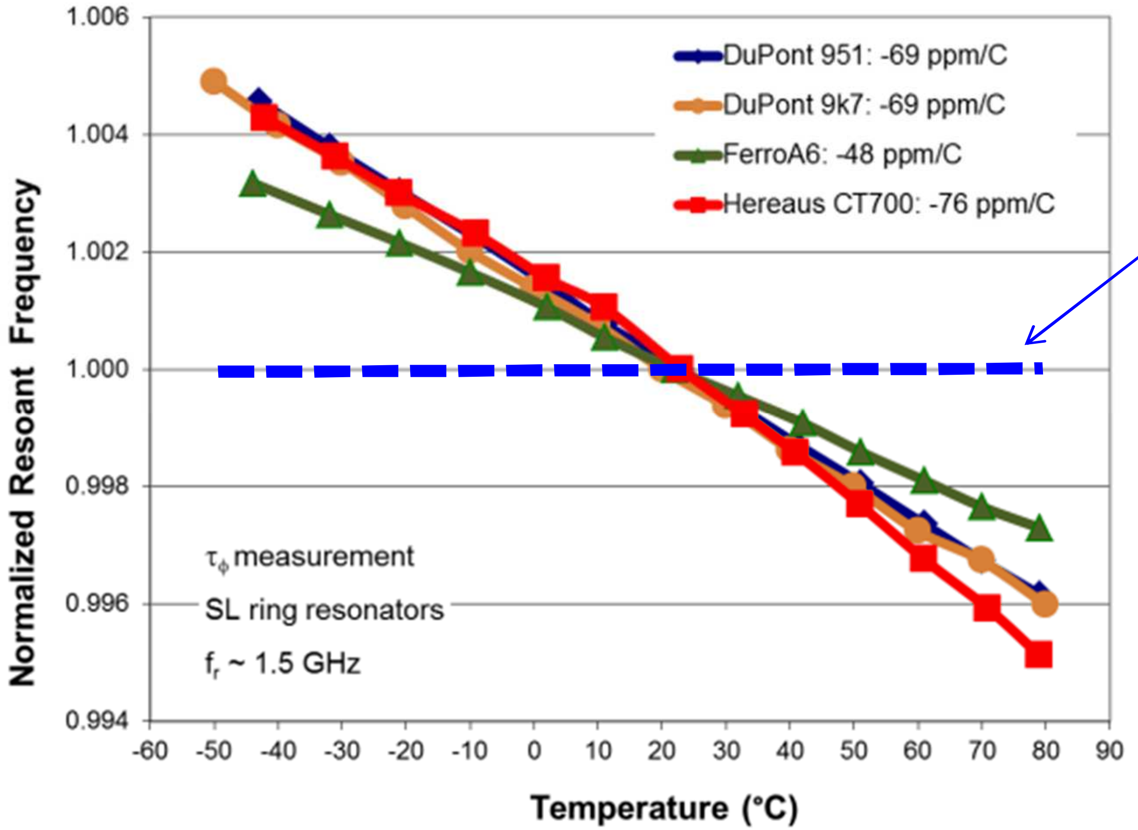
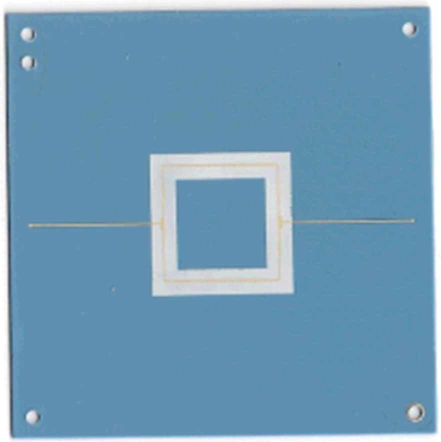
τ_f of Commercial LTCCs



Temperature stable dielectric
τ_f = 0 ppm/°C

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

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**

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Candidates for τ_f Adjustment

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

device (τ_f) — **material** (τ_ε, α)

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

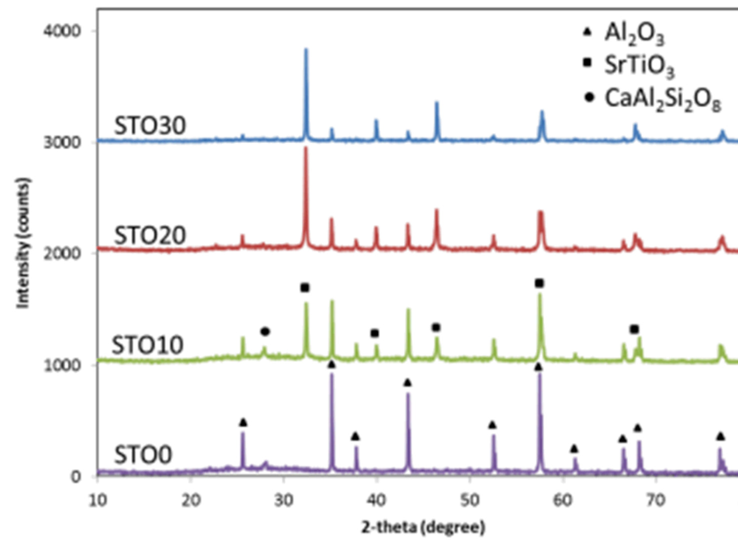
Materials	Density (g/cm^3)	ε	τ_ε (ppm/°C)	τ_f (ppm/°C)	Sintering Temp (°C)
TiO_2	4.23	85	-750	370	~ 1200
$CaTiO_3$	3.98	180	-1850	920	~ 1400
$SrTiO_3$	5.13	300	-3000	1500	~ 1550
Al_2O_3	4.00	9.6	105	-60	~ 1600
V-glass	2.77	7.3	N/A	N/A	Tg= 625°C

τ_f Adjuster Formulation, Property and Microstructure

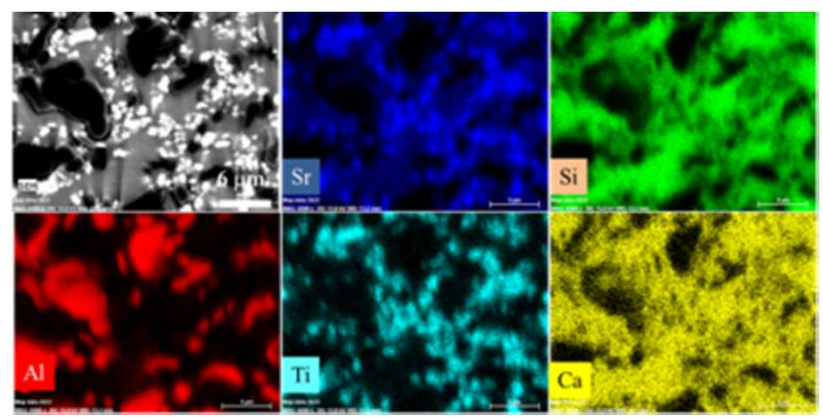
Composition	V-glass (wt%)	Al_2O_3 (wt%)	TiO_2 (wt%)	$CaTiO_3$ (wt%)	$SrTiO_3$ (wt%)	Total wt%
CMB base	55	45				100
CMB TO15	55	30	15			100
CMB TO30	55	15	30			100
CMB CTO10	55	35		10		100
CMB CTO20	55	25		20		100
CMB STO10	55	35			10	100
CMB STO20	55	25			20	100
CMB STO25	55	20			25	100
CMB STO30	55	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/ºC)	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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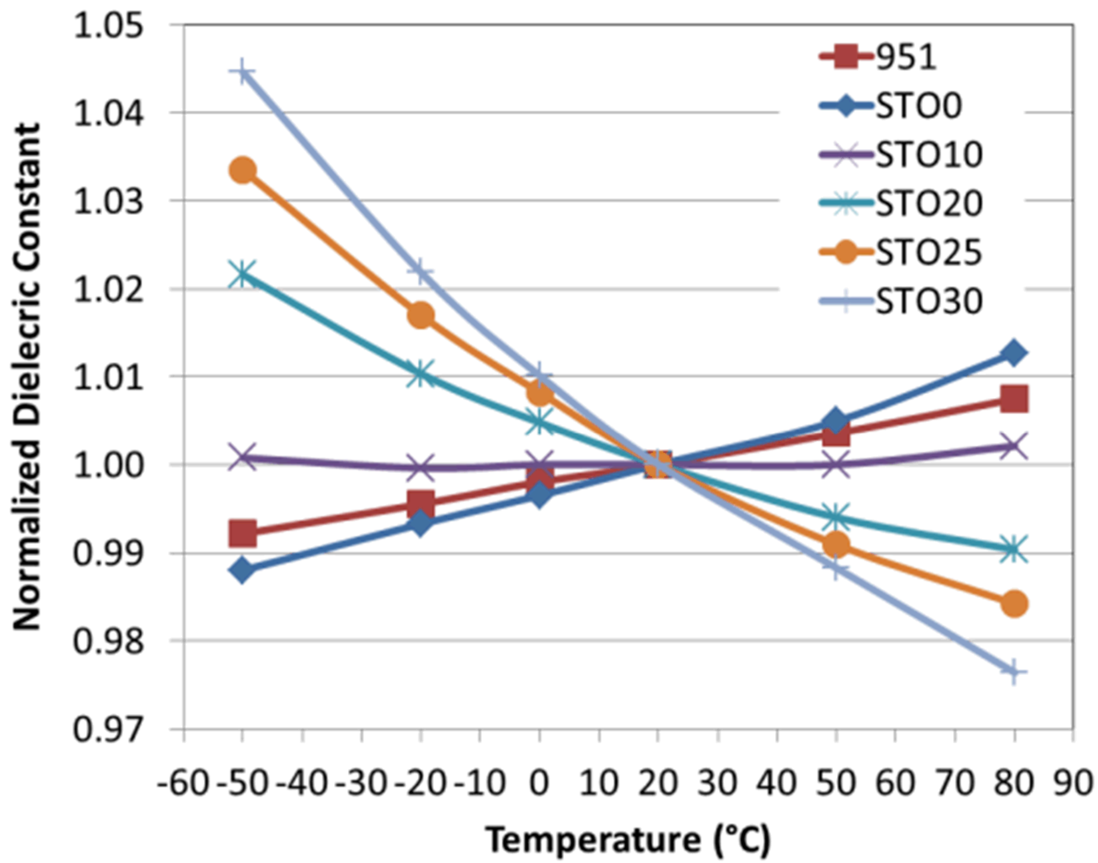
τ_ε of Compensating Materials



- 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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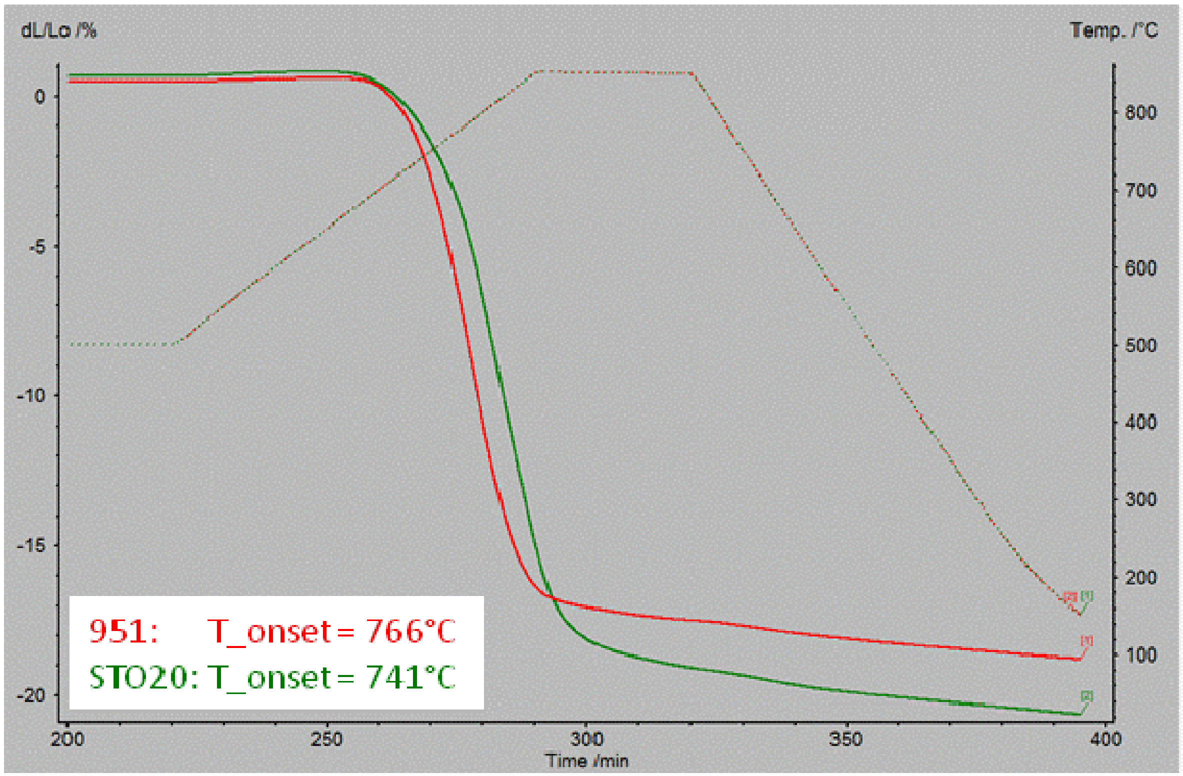
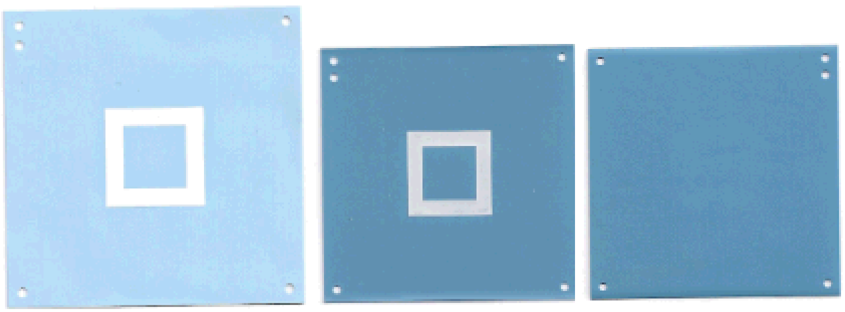
STO20 Cofireability - dilatometry

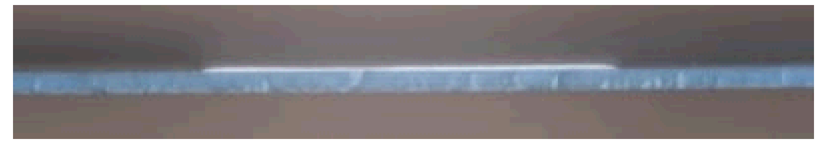


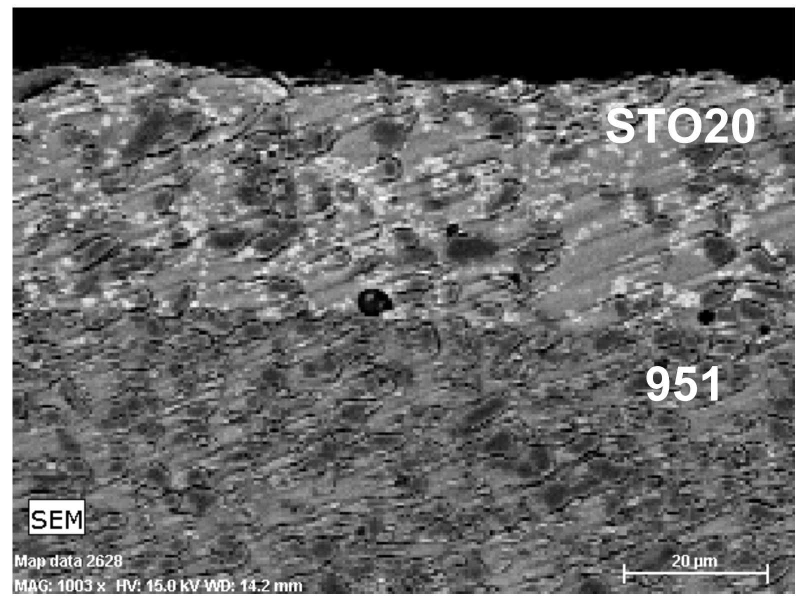
- **The temperatures for the onset of STO20 and 951 shrinkage are closely matched**

STO20 Cofireability – printed layer on 951

Green | Sintered front | Sintered backside

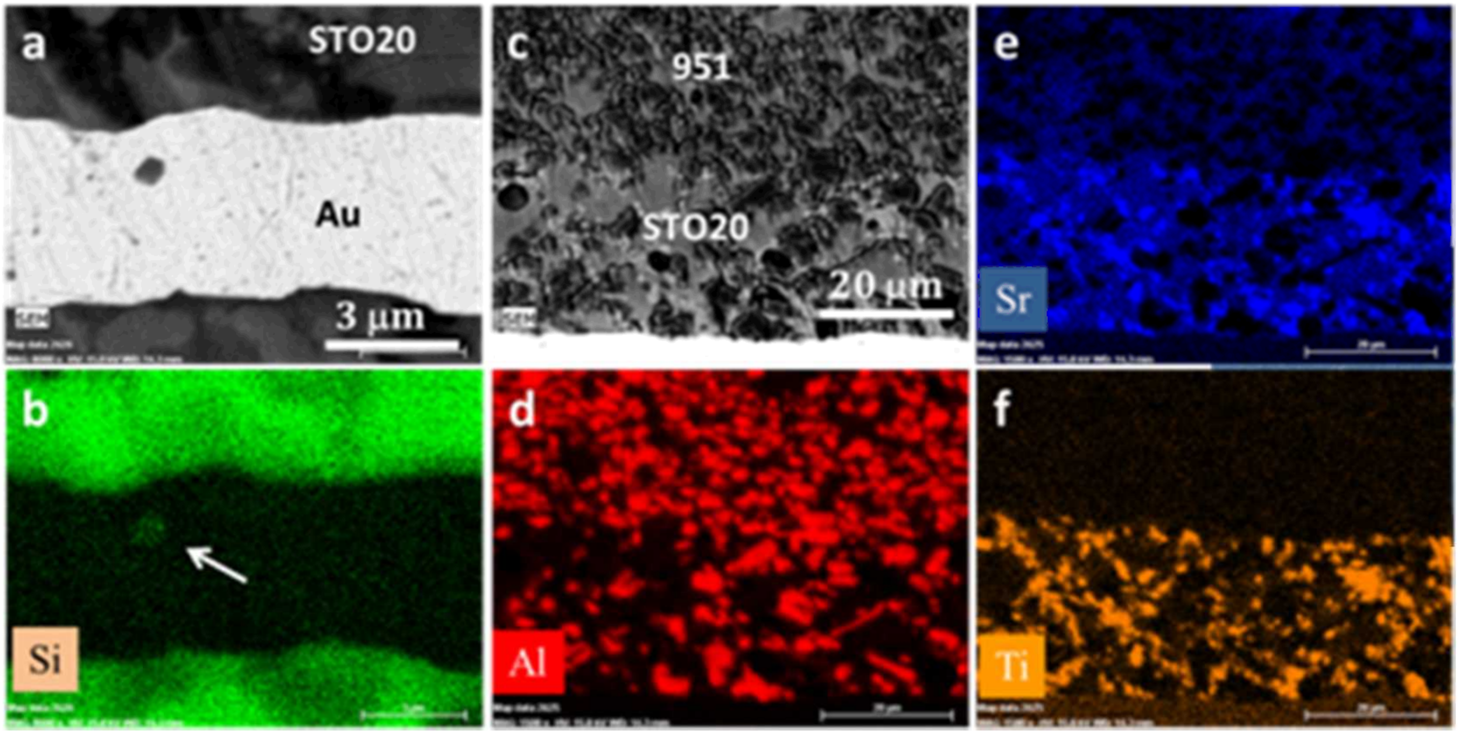


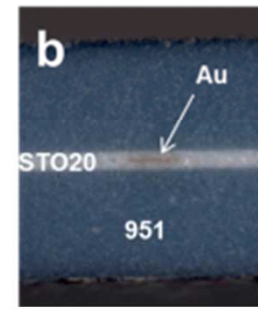




- **No deformation of cofired printed STO layer on a 10 mil 951 tape**
- **Both optical and SEM images show a clean STO20/951 interface, suggesting no or minimal reaction or inter-diffusion**

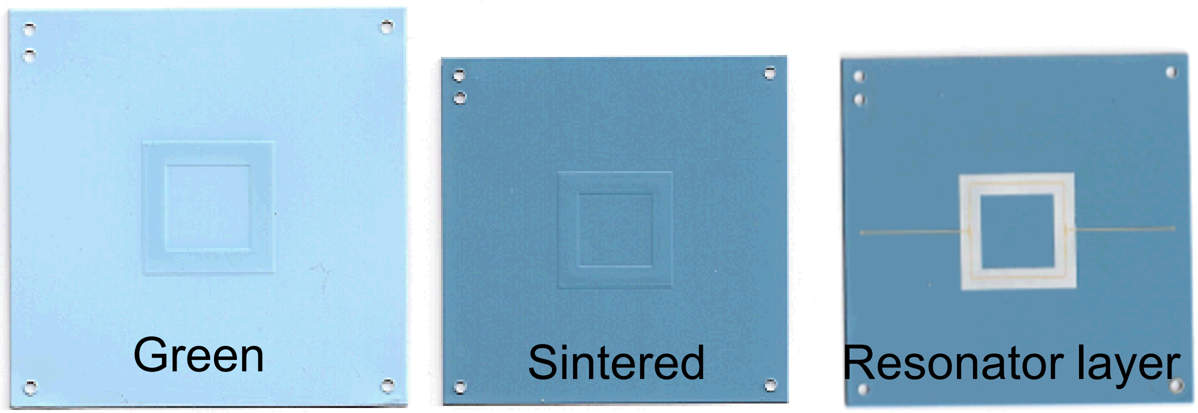
Cofireability - microstructure

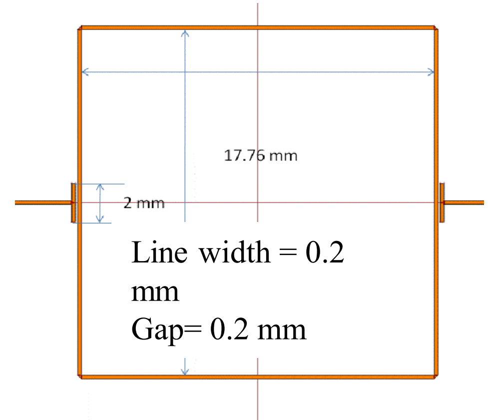




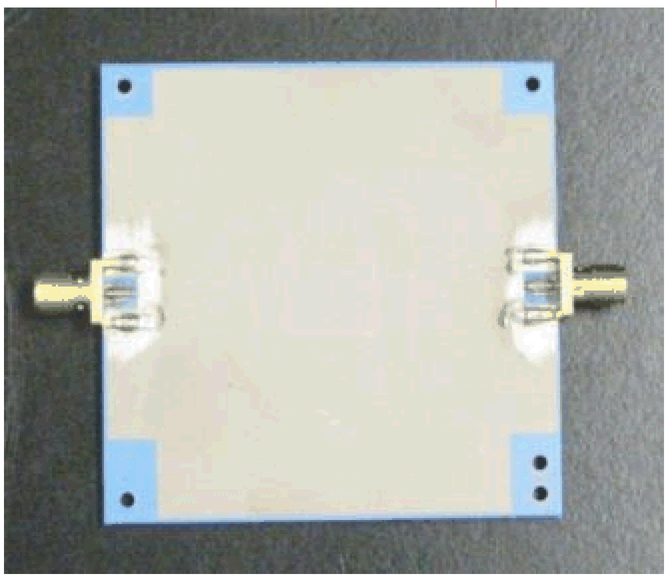
- STO20 layers in a 4-layer 951 panel also sintered flat
- No inter-diffusion from SEM pictures: preserve STO20 properties

SL Resonator Panels

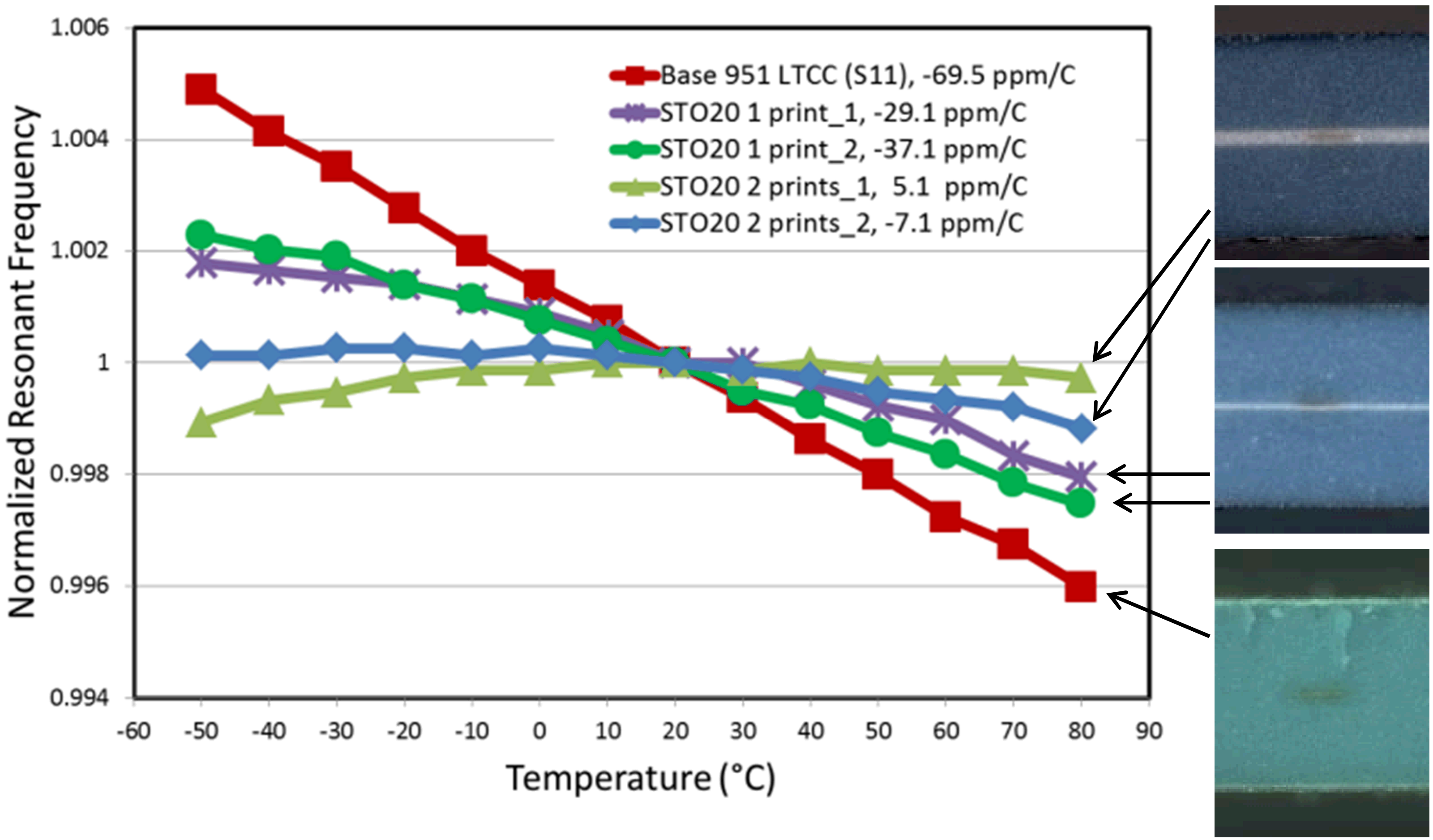




- **Standard LTCC fabricated with 951 matching conductors**
- **4 layers of 10 mil 951 tape. 50 Ω lines. f_r = 1.5 GHz**
- **No localized deformation, indicating no sintering mismatch**
- **Embedded STO shown as “embossed” feature on the non-contact side during lamination**



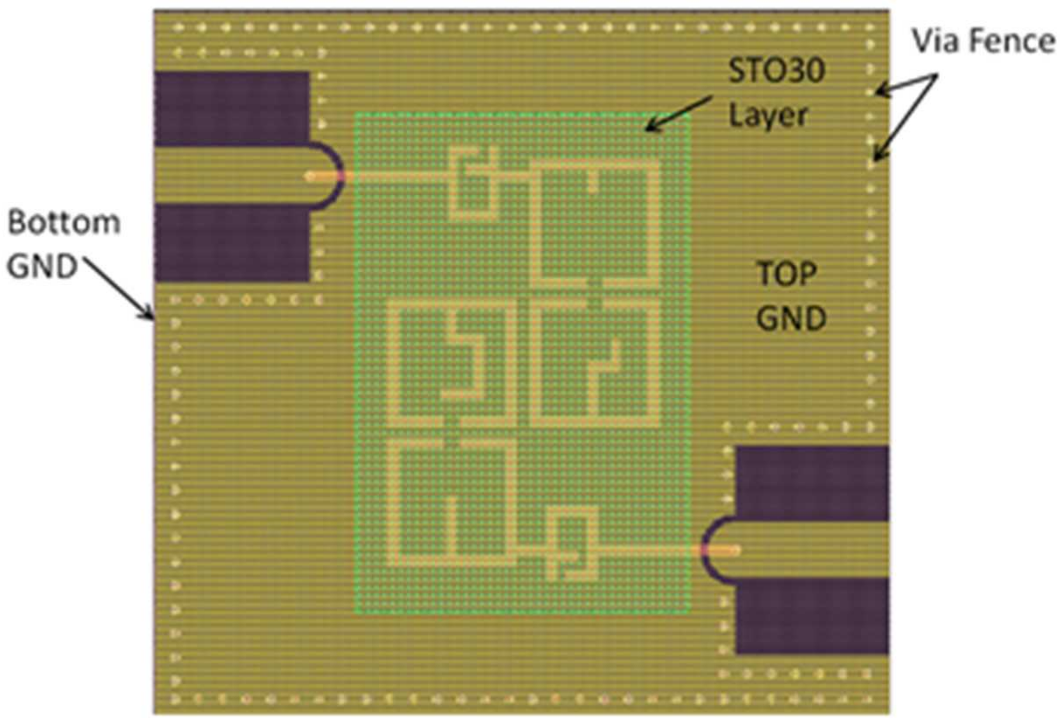
τ_f Results for STO20

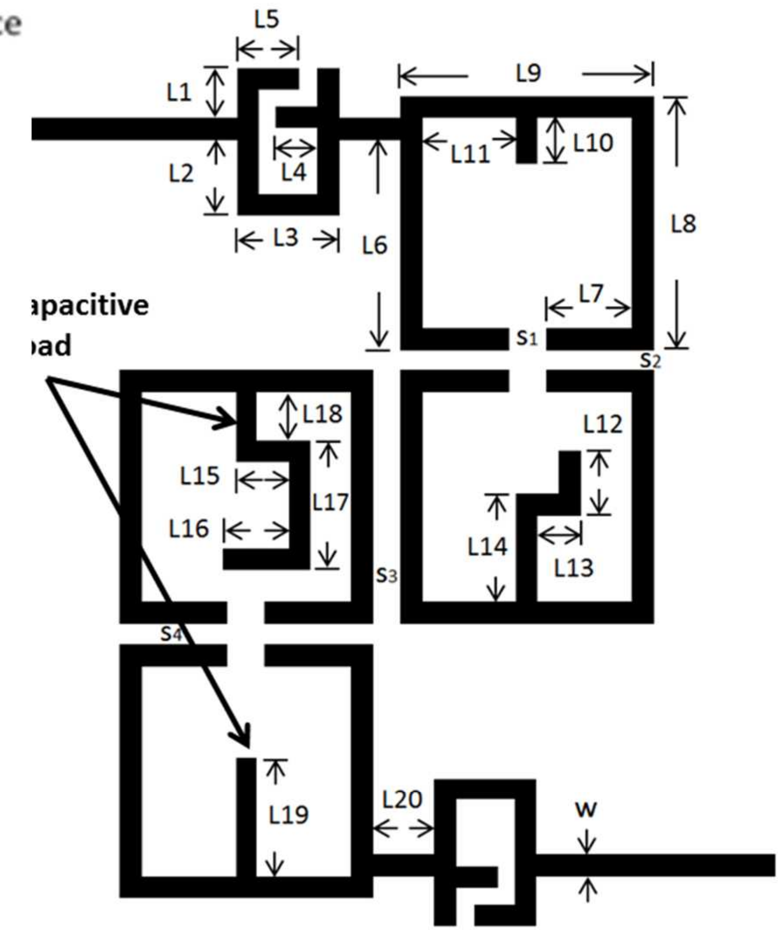


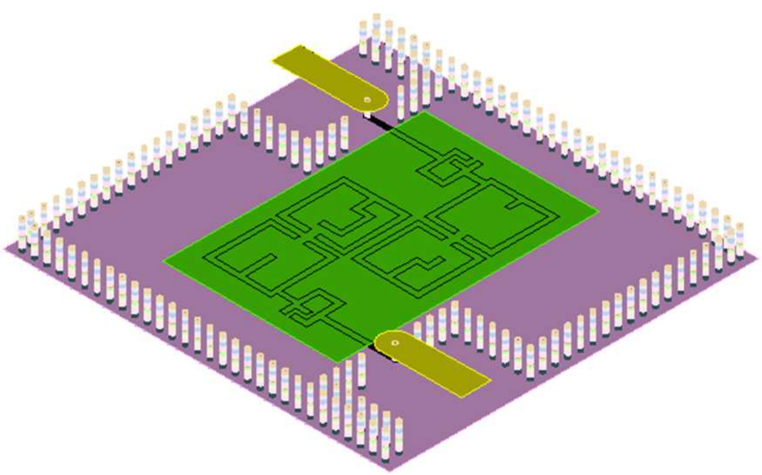
- **A true, near zero or zero τ_f is achievable**
- **Variation of τ_f, possibly by varying the STO20 thickness**

<u>Steve Dai</u>, "Localized Temperature Stability in Multilayer LTCC", J of Microelec and Elect Packaging, 8, 1-6, 2011

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







Total 8 10 mil layers

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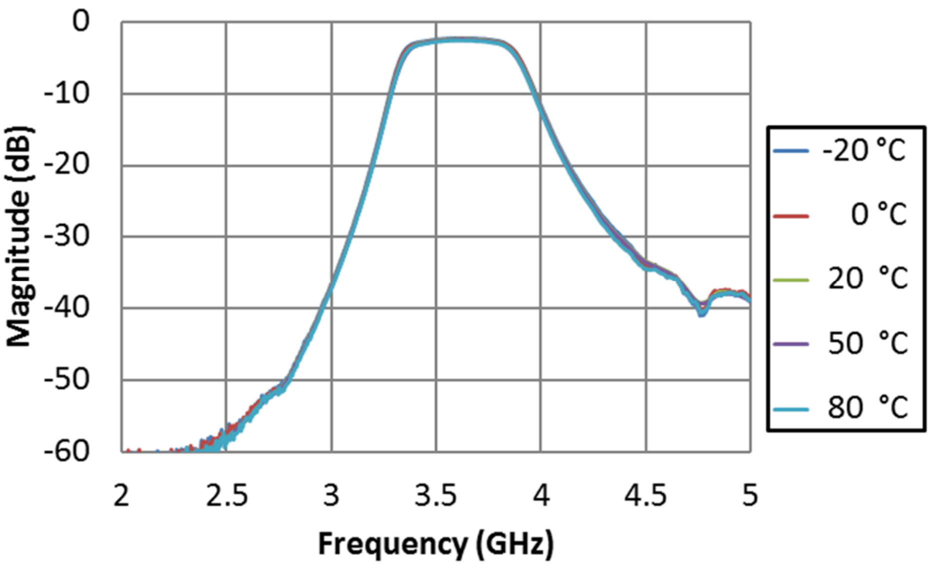
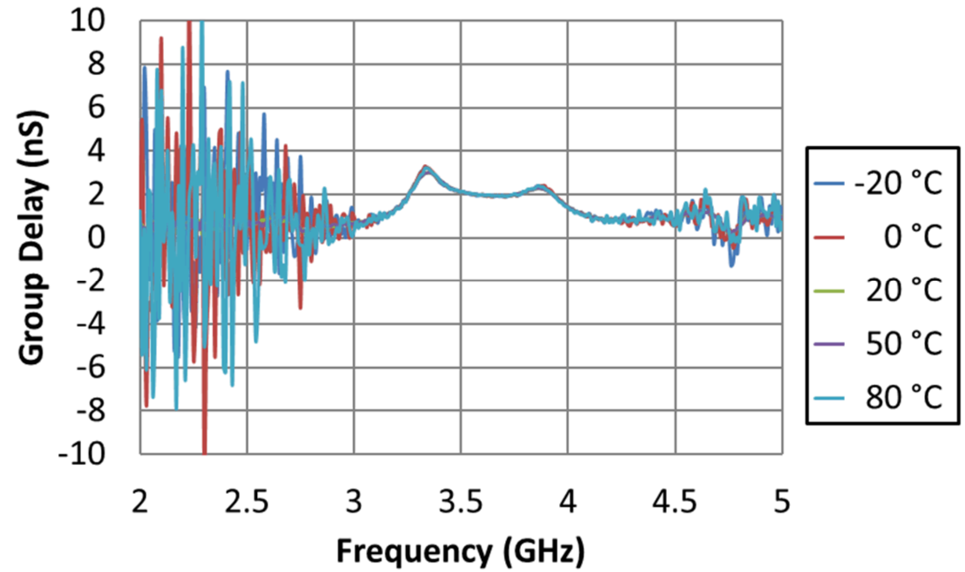
$0\tau_f$ Demo: filter performance



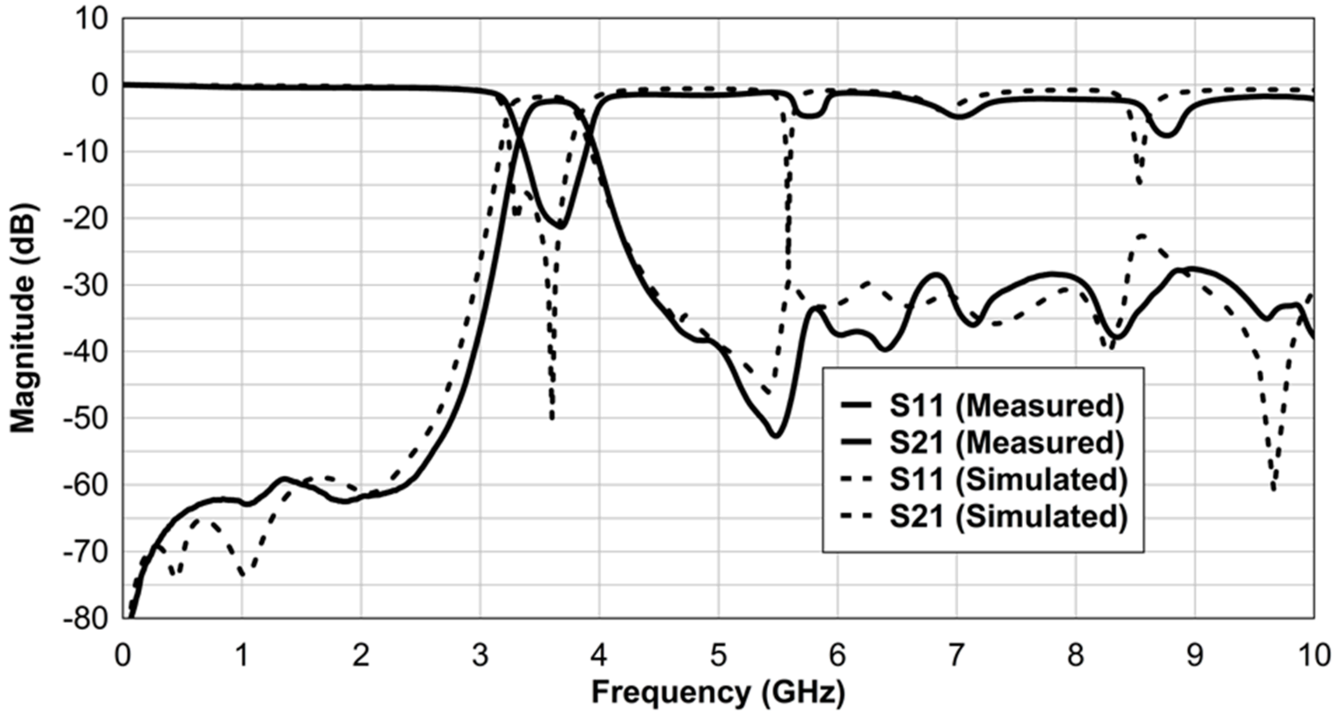


- τ_f = 0.7 ppm/°C over -20 to 80 °C
- insertion loss of the filter is 2.45 dB at 20 °C. The insertion loss variance over the temperature is 0.28 dB
- The maximum-difference group delay of the filter is 37pS

$$f_{center} = \frac{f_{L\_3dB} + f_{H\_3dB}}{2}$$

$$\tau_f = \frac{1}{f_{ro}} (\frac{\Delta f_r}{\Delta T}$$

$0\tau_f$ Demo: simulation versus measurement



- Agilent ADS EM simulator
- 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
- Excellent agreement between measurement and simulation

Summary

- τ_f compensating materials compatible to existing 951 LTCC have been successfully developed (patent pending)
- SL resonators with a near $0\tau_f$ have been demonstrated by locally integrating a τ_f compensating material in a multilayer LTCC package
- S-band filter with a near $0\tau_f$ has been demonstrated

Acknowledgement

This work is supported by the Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories, a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

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Thank You!

Backup slides

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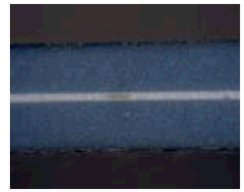
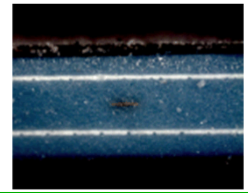
SL Resonators


STO compo-sition	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**
    - **0τ_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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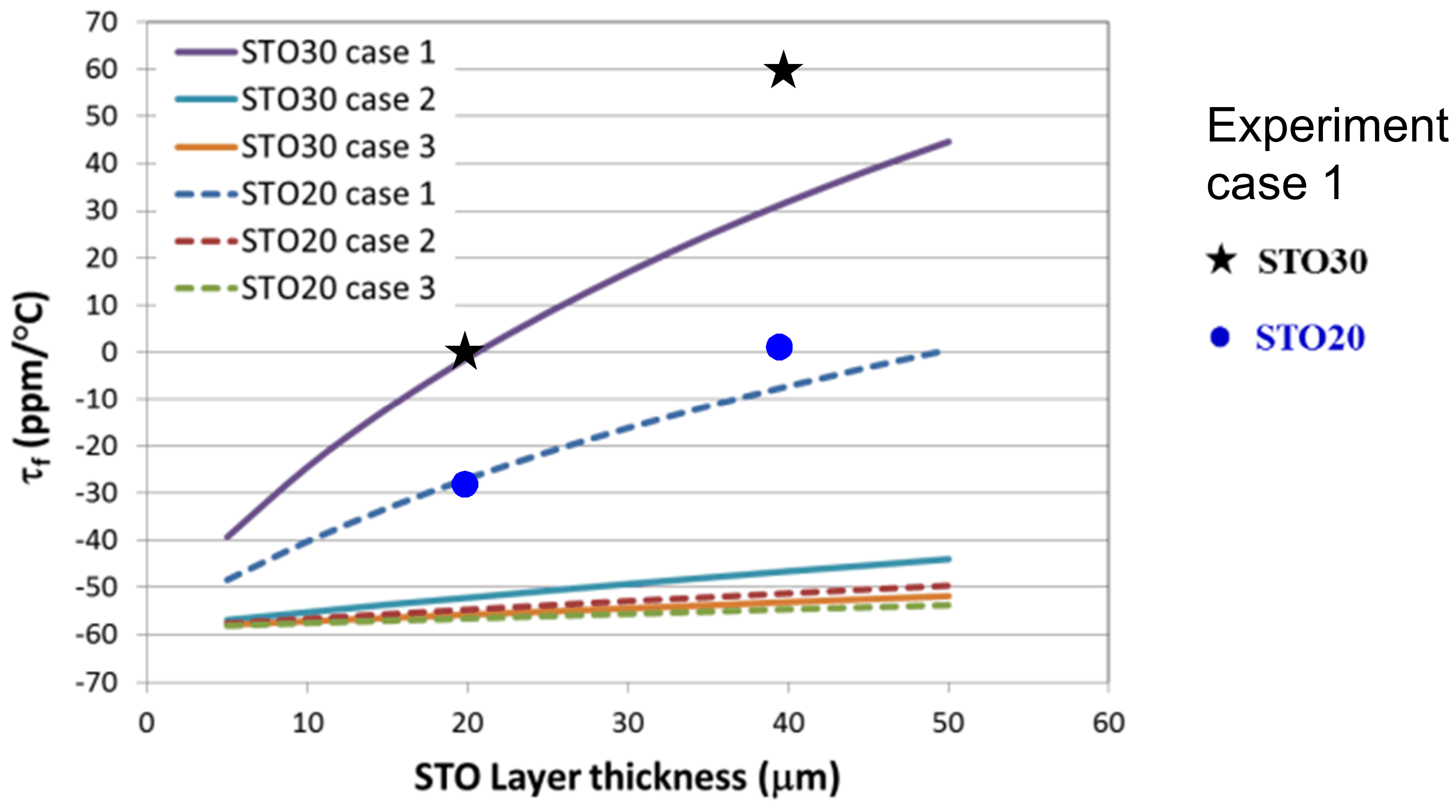
Experiment Versus Simulation



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

τ_f of a Dielectric Composite

- **Why the STO is effective only in case 1 (= next to the SL)?**

- **τ_f expressed as**

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

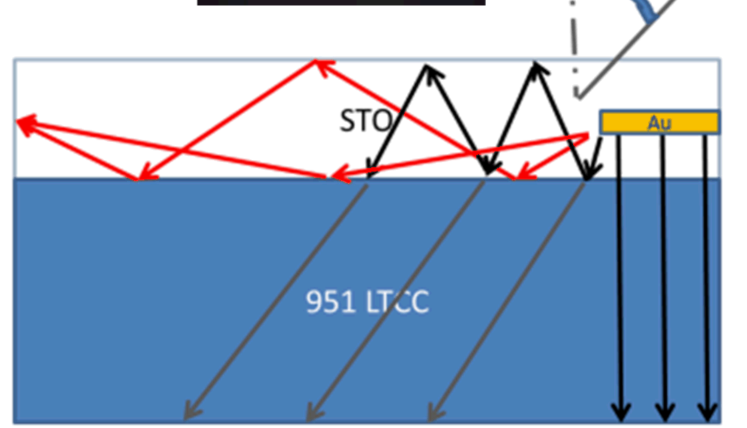
where P_i is defined as the energy filling factor, the fraction of total EM energy confined in dielectric phase i

- **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)**

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



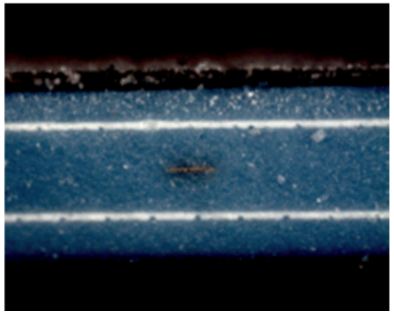
$\theta_c \geq 45°$, total internal reflection in STO

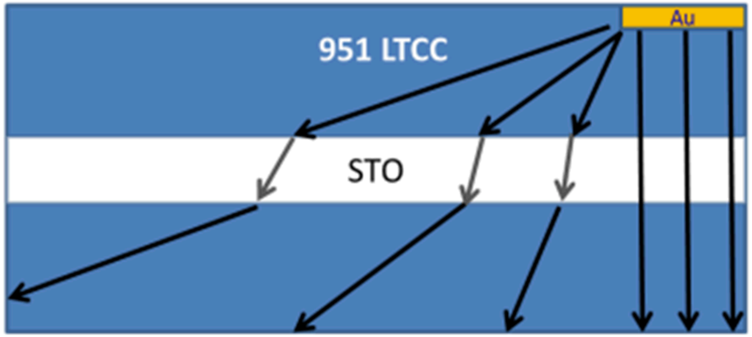
$\theta_c < 45°$, reflection/refraction at the STO-951 interfaces

Energy concentration in STO → effective τ_f compensation

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**





Steve Dai, "Localized Temperature Stability in Multilayer LTCC", submitted to J Am Ceram Soc