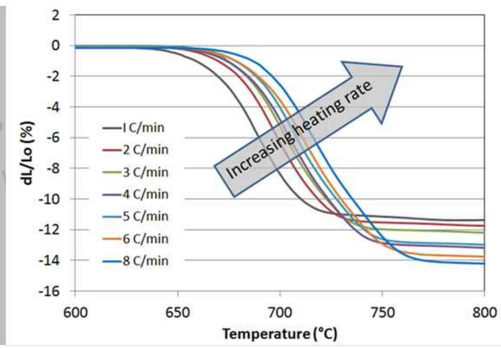
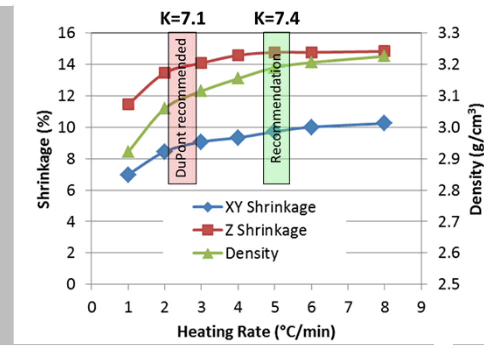
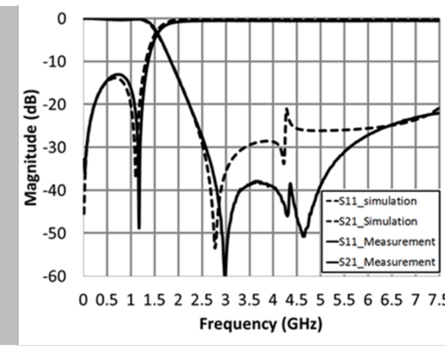
SAND2016-5900C

Exceptional service in the national interest

Sandia National Laboratories







Miniature Lowpass Filters in Low Loss 9k7 Low Temperature Co-fired Ceramics

Steve Dai and Lung-Hwa Hsieh

Sandia National Laboratories, Albuquerque, New Mexico, USA

MMA2016, Seoul, Korea, Jul 3 - 6, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is 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. SAND NO. 2011-XXXXP

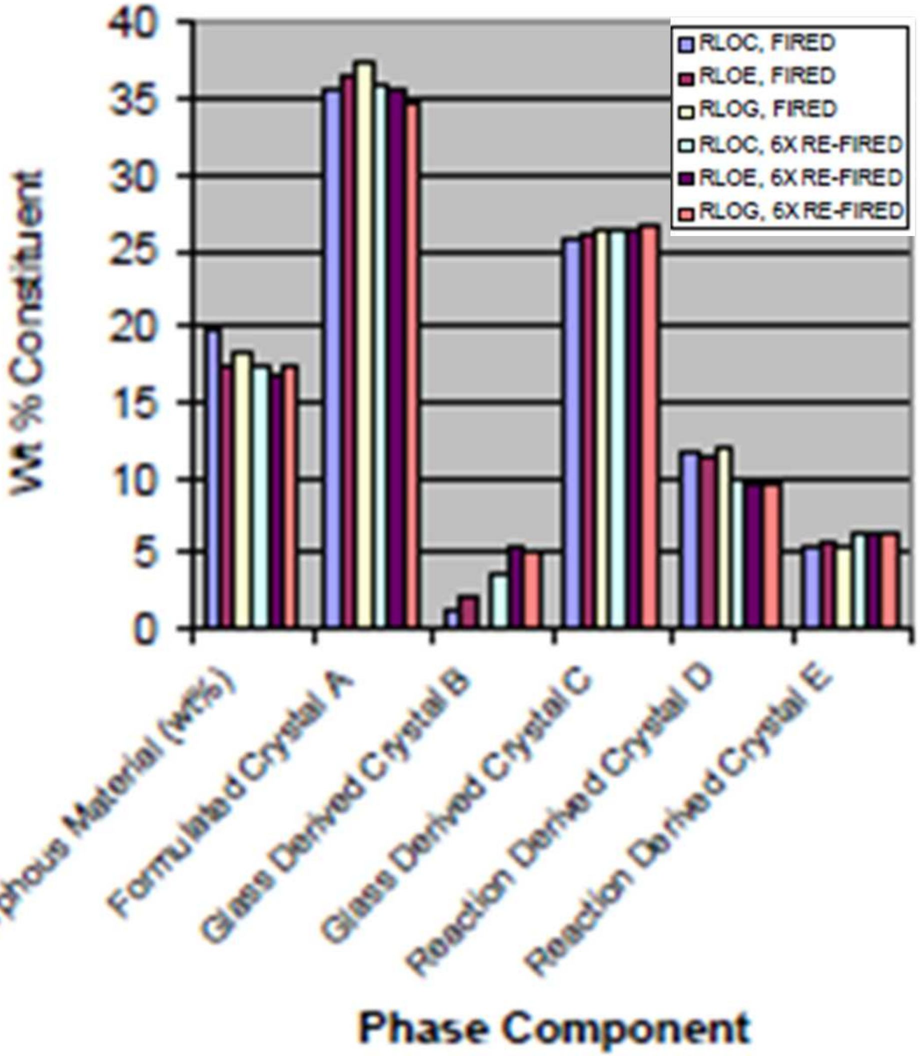
Outline

- Pb-free Low Loss 9k7 LTCC
  - Densification and crystallization
  - Optimized process conditions
- Low Pass Filters (LPF) in multilayer 9k7 LTCC
  - LPF in 4-layer LTCC
  - Miniaturized LPF in 8-layer LTCC
- Summary

Crystallization in 9k7 LTCC

$$\frac{1}{Q} = \sum \frac{V_i}{Q_i} \approx \frac{V_{glass}}{350} + \frac{V_{cryst.}}{1500} + \frac{V_{Al_2O_3}}{10000}$$

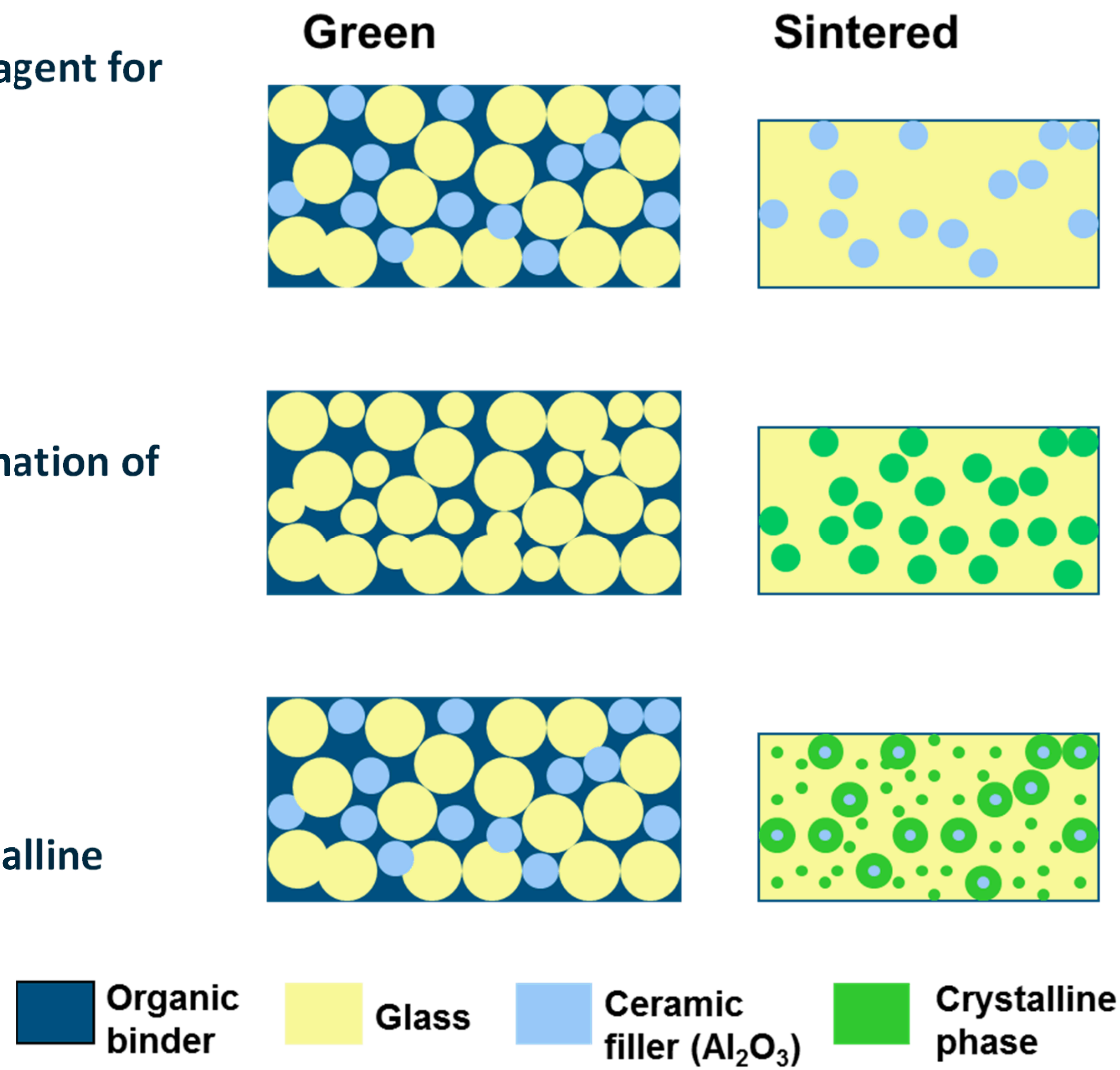
- Low loss achieved via multiple crystallization
  - Ceramic filler = formulated crystal A
  - Glass derived crystals, B and C
  - Reaction derived crystals, D and E
- Role of glass in 9k7
  - Densification via viscous sintering
  - Diffusion controlled multiple crystallization, takes time
- Ramp rate (530-850 ^{o}C) critical



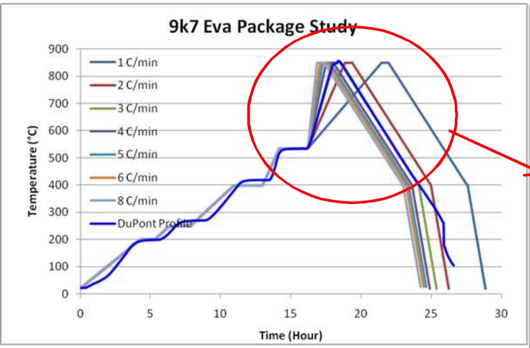
* K.M. Nair, et al, Advances in Electroceramic Materials II, Volume 221. Wiley, Dec 7, 2010.

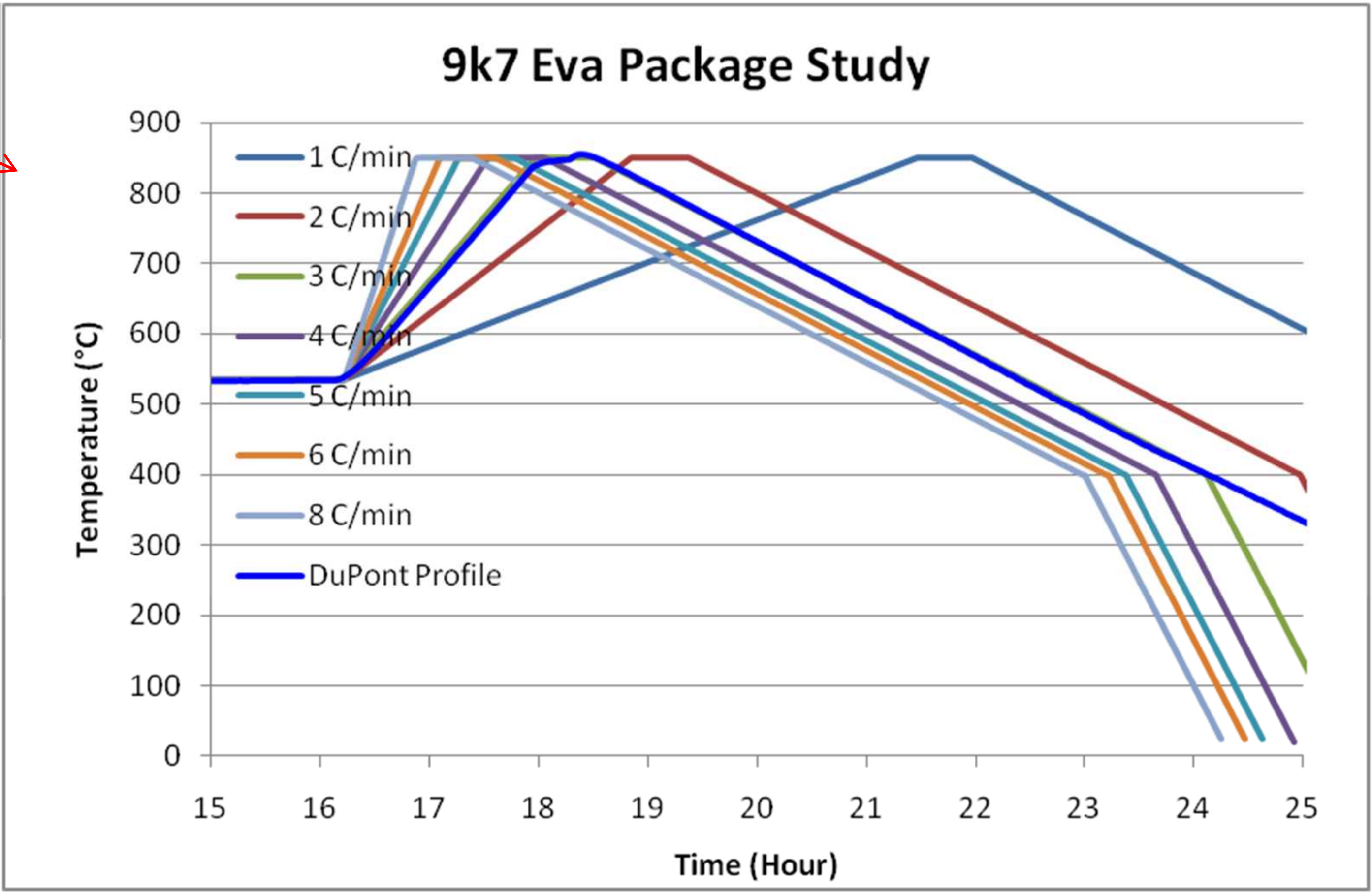
LTCC Base Dielectrics – a composite

- **Type 1:**
  - **Unreactive, glass as sintering agent for high density**
  - **Example: DuPont 951**
- **Type 2:**
  - **Sinter to full density**
  - **Re-crystallizeable, partial formation of crystalline high Q phases**
  - **Example: Ferro A6**
- **Type 3:**
  - **Sinter to high density**
  - **Reactive, forming high Q crystalline phases**
  - **Example: 9k7**



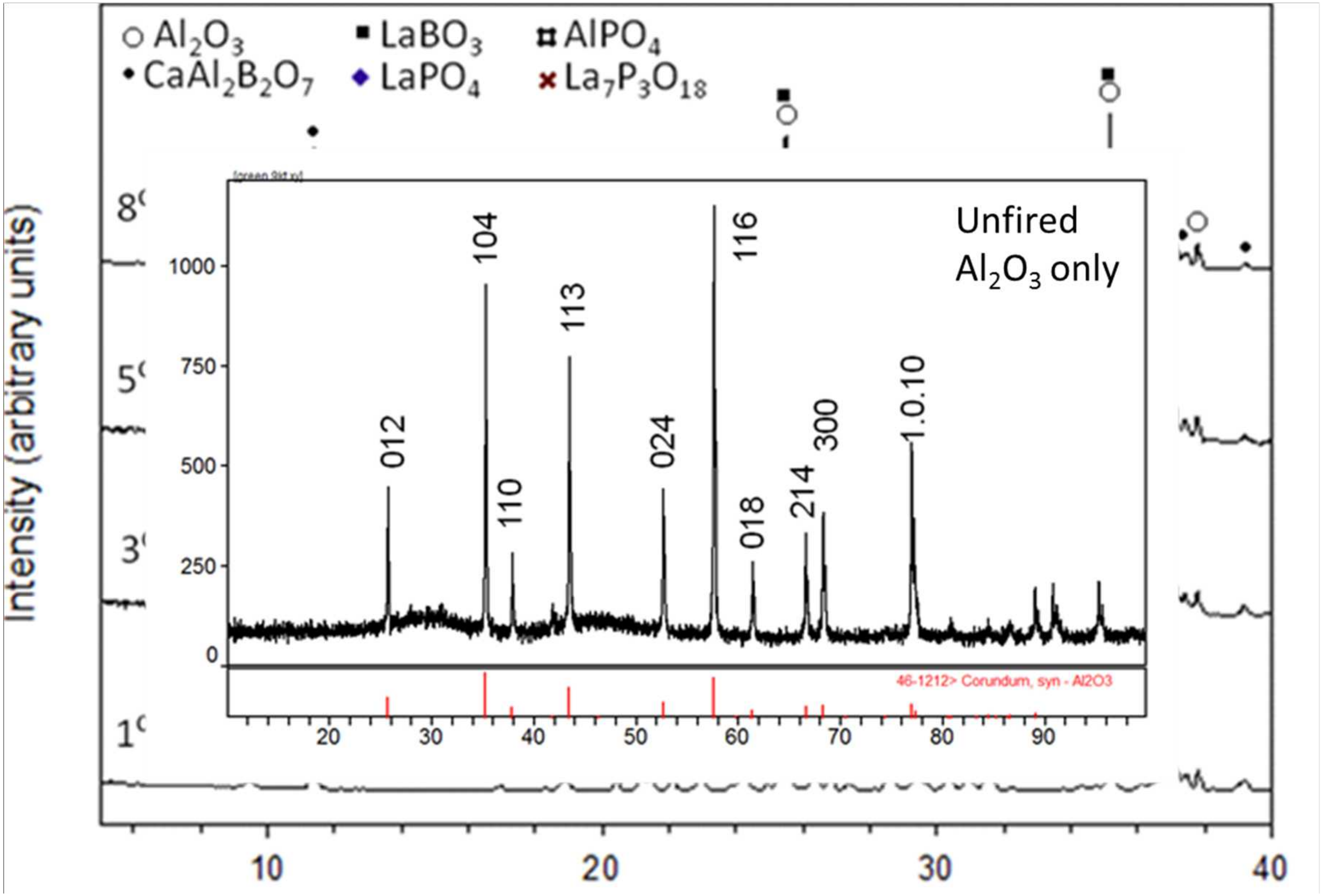
Ramp Rate





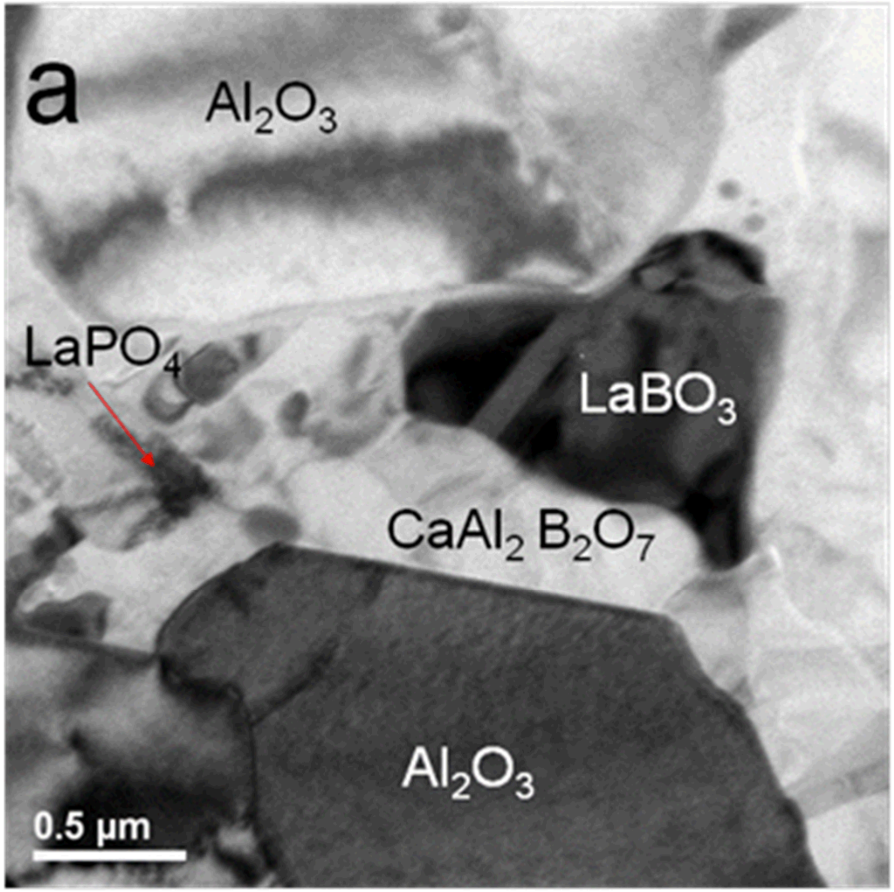
- DuPont recommended ramp rate ~ 2.45° C/min
- Ramp rate in current study: 1 – 8° C/min

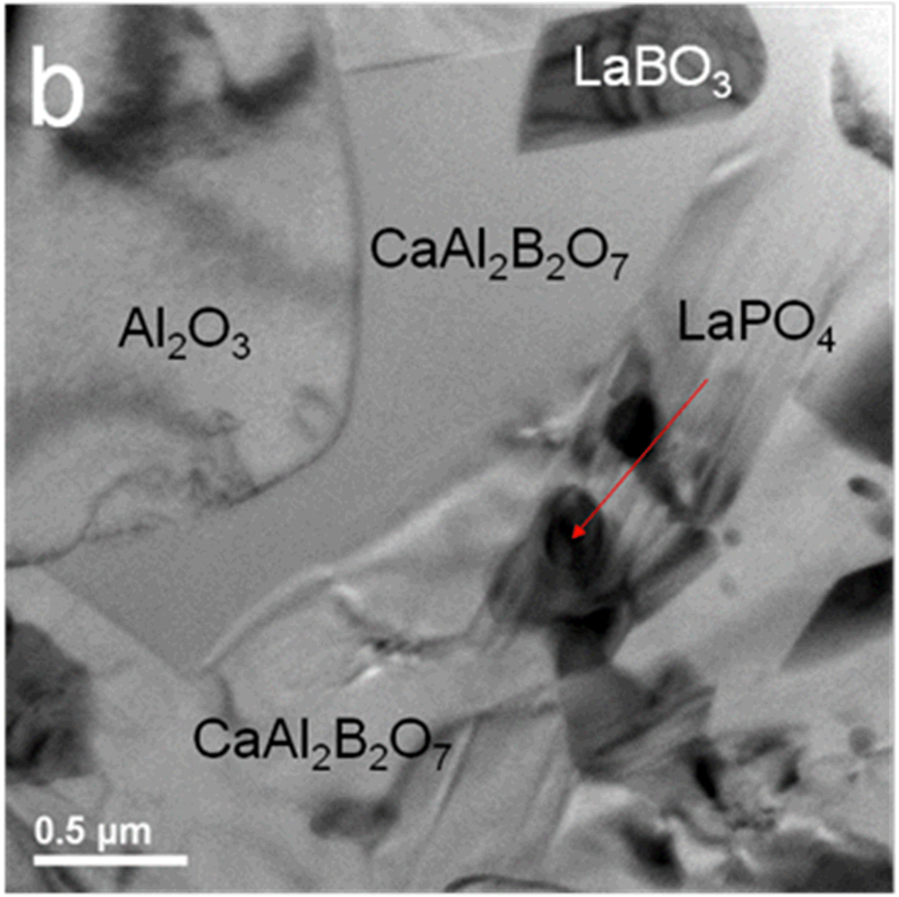
Crystallization in 9k7 LTCC -- XRD



- Both self-derived and reaction-derived crystalline phases

Crystallization in 9k7 LTCC -- TEM





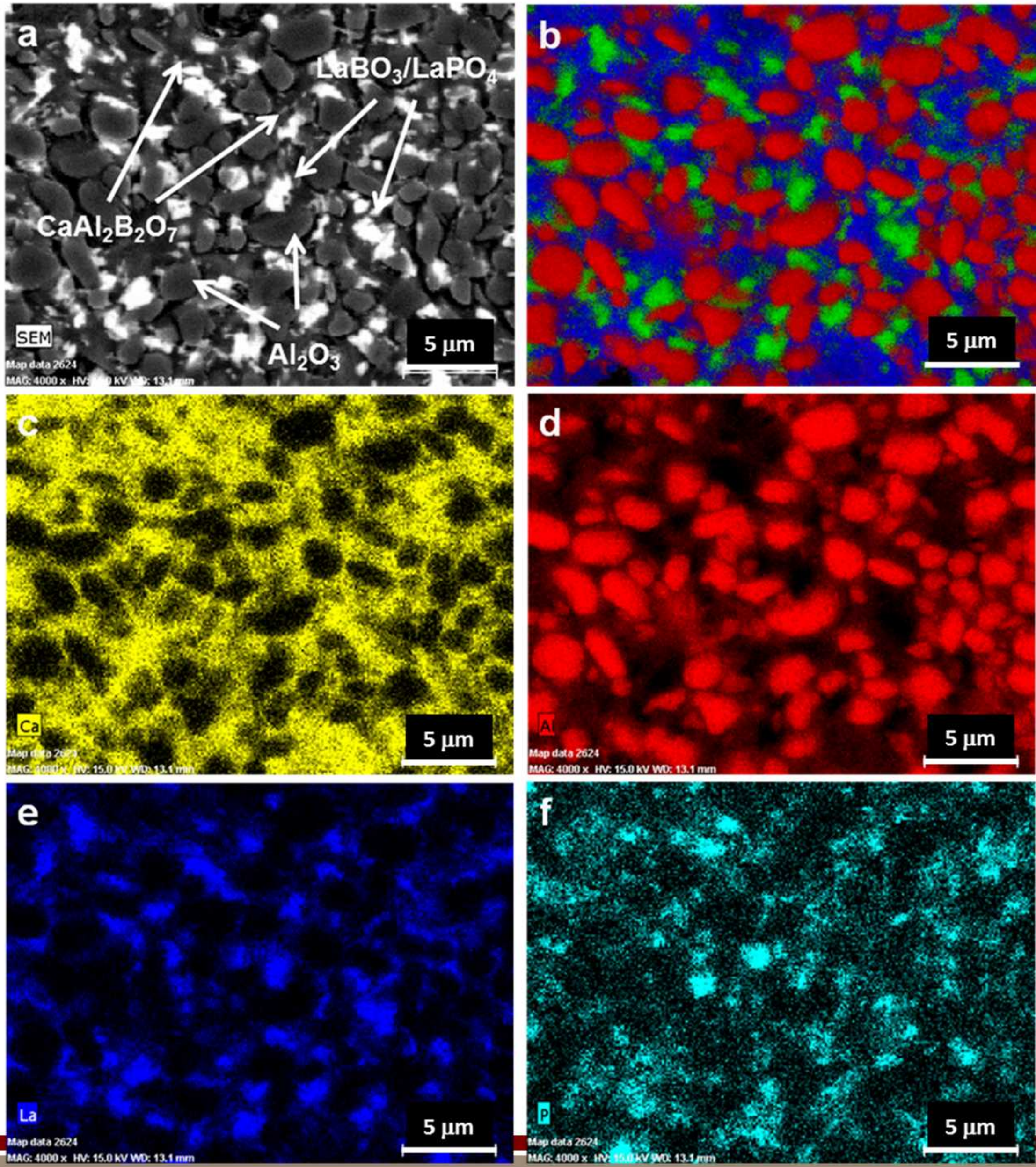
- Al_2O_3 filler
- Continuous reaction-derived $CaAl_2B_2O_7$ phase around Al_2O_3 filler
- Isolated self-derived $LaBO_3$ and $LaPO_4$ crystals, away from Al_2O_3

Crystallization in 9k7 LTCC -- SEM

- Phase map from an automated multivariate statistical analysis technique*
  - Red = Al_2O_3
  - Blue = $CaAl_2B_2O_7$
  - Green = $LaBO_3/LaPO_4$

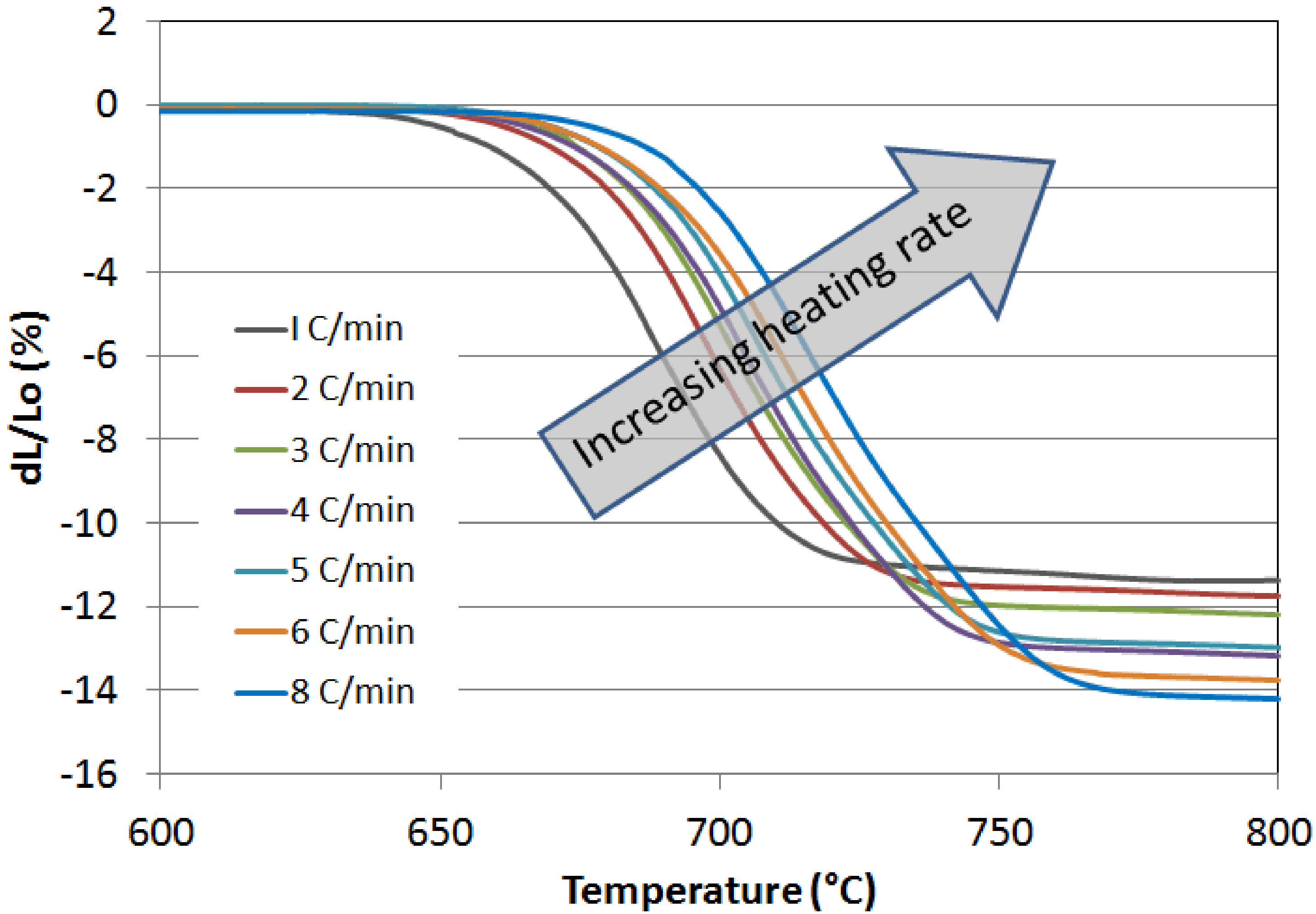
- Continuous reaction derived $CaAl_2B_2O_7$ phase

- Isolated self-derived $LaBO_3$ and $LaPO_4$ crystals



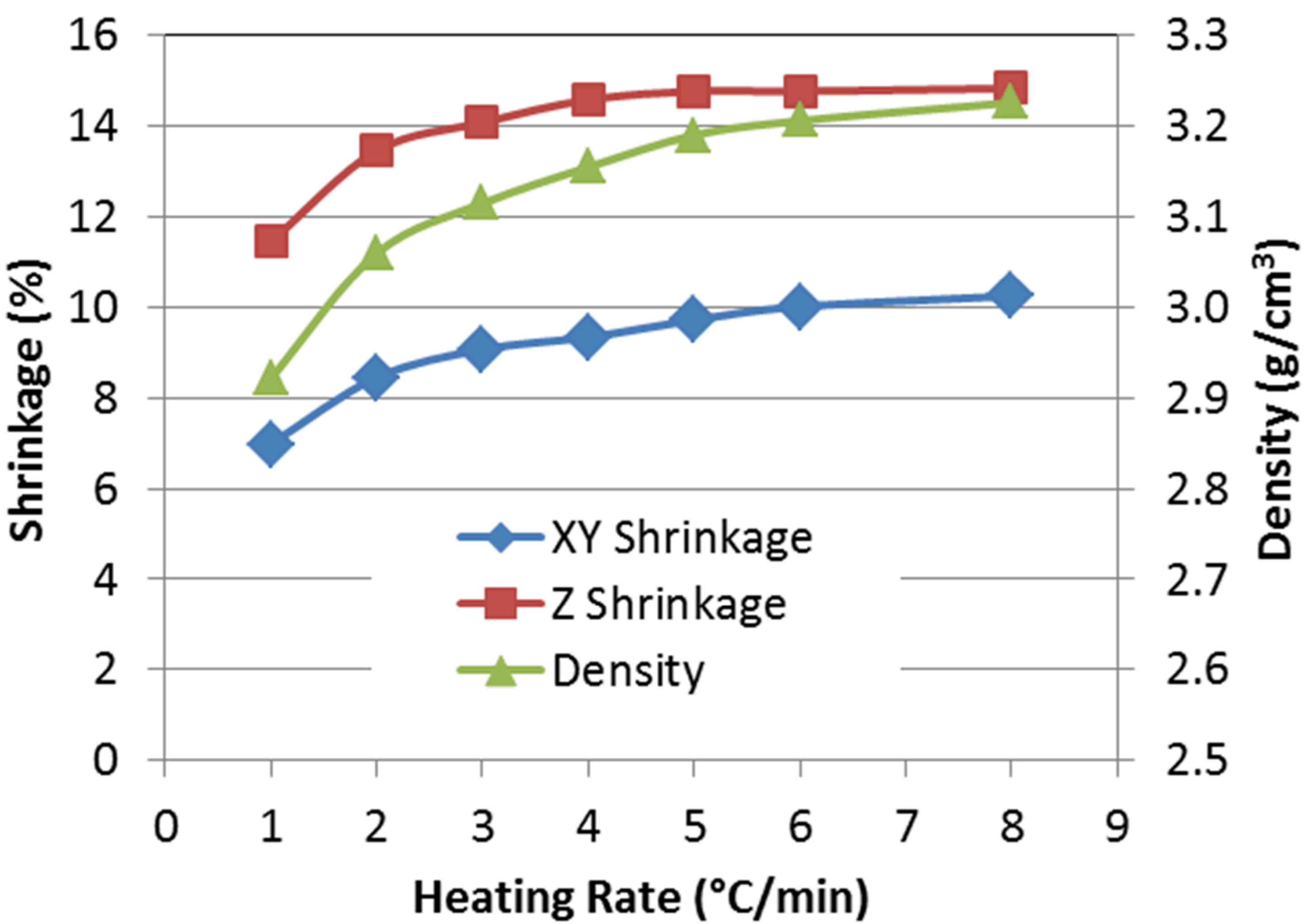
*Kotula, et al, *Microsc. Microanal.* **9**, 1-17 (2003)

9k7 Dilatometry – Z Shrinkage



- Ramp-rate dependent shrinkage
- Higher ramp rate → more shrinkage

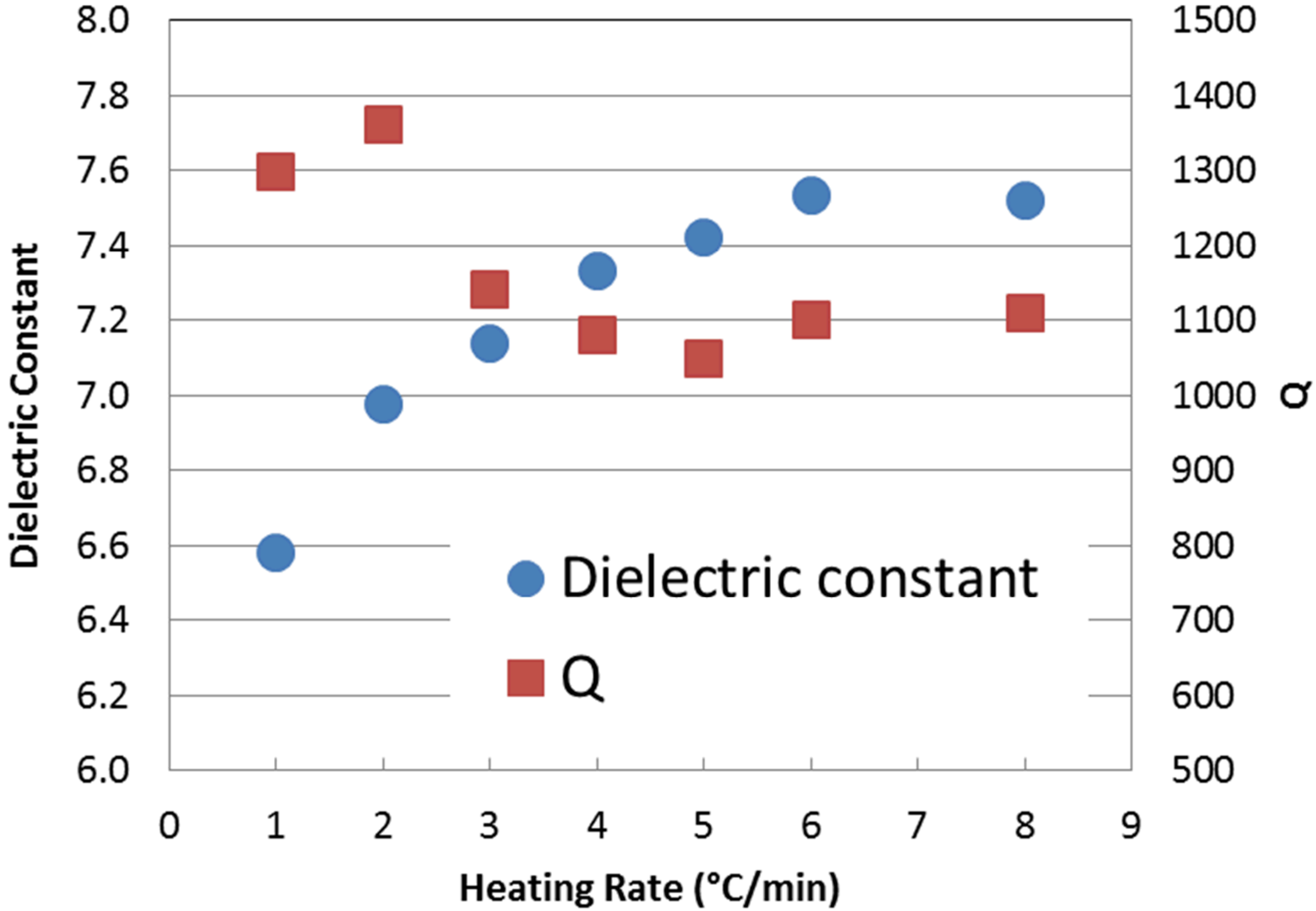
Shrinkage



- Both XY&Z shrinkage and density increase as ramp rate increases
- Z reaches plateau while XY and density increase slightly beyond 5 ^{o}C/min

Dielectric Properties (9.5 GHz)

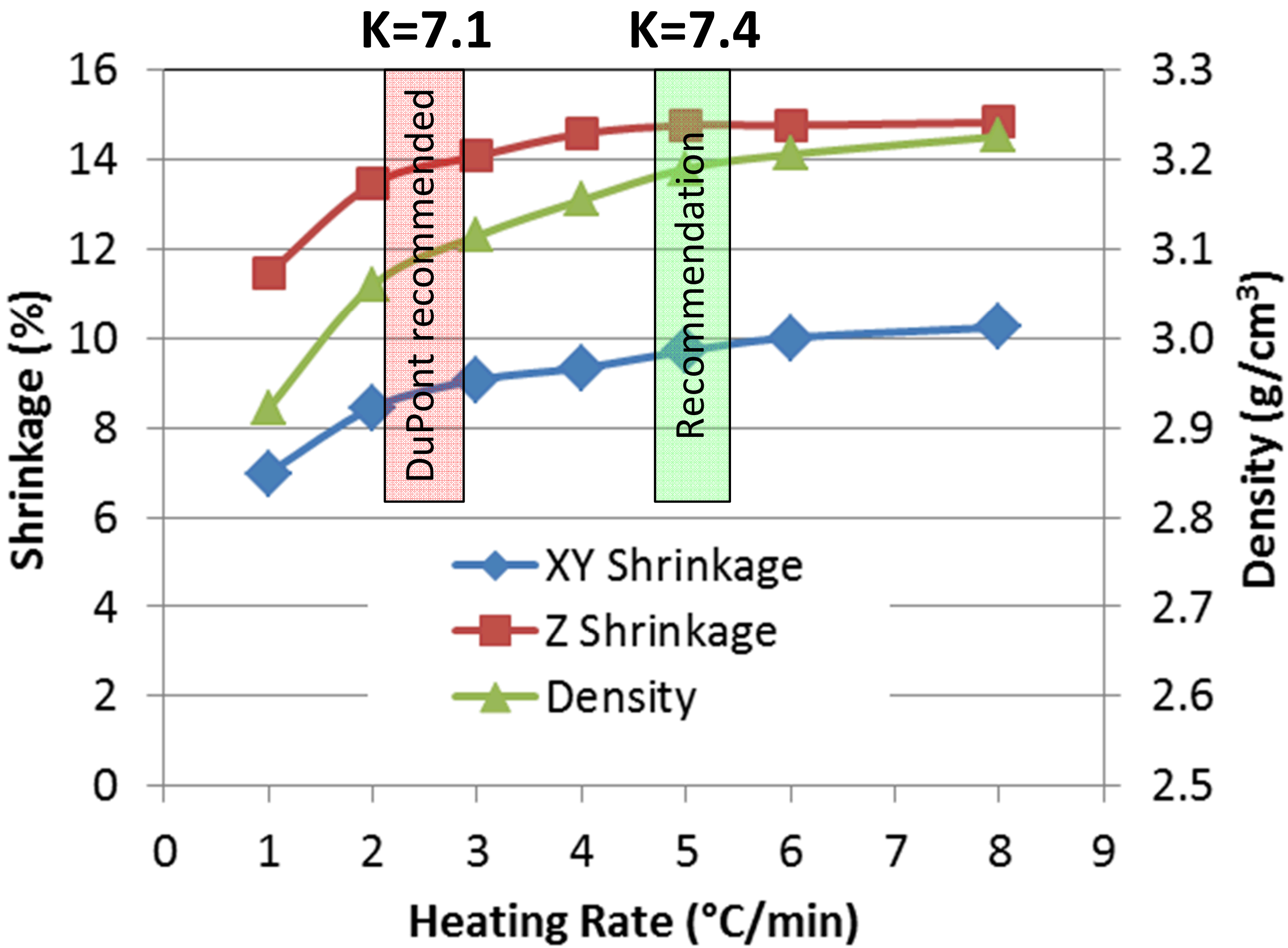
Sandia National Laboratories



- Split cavity with resonant frequency 10 GHz
- Data validated by Deepu Nair of DuPont

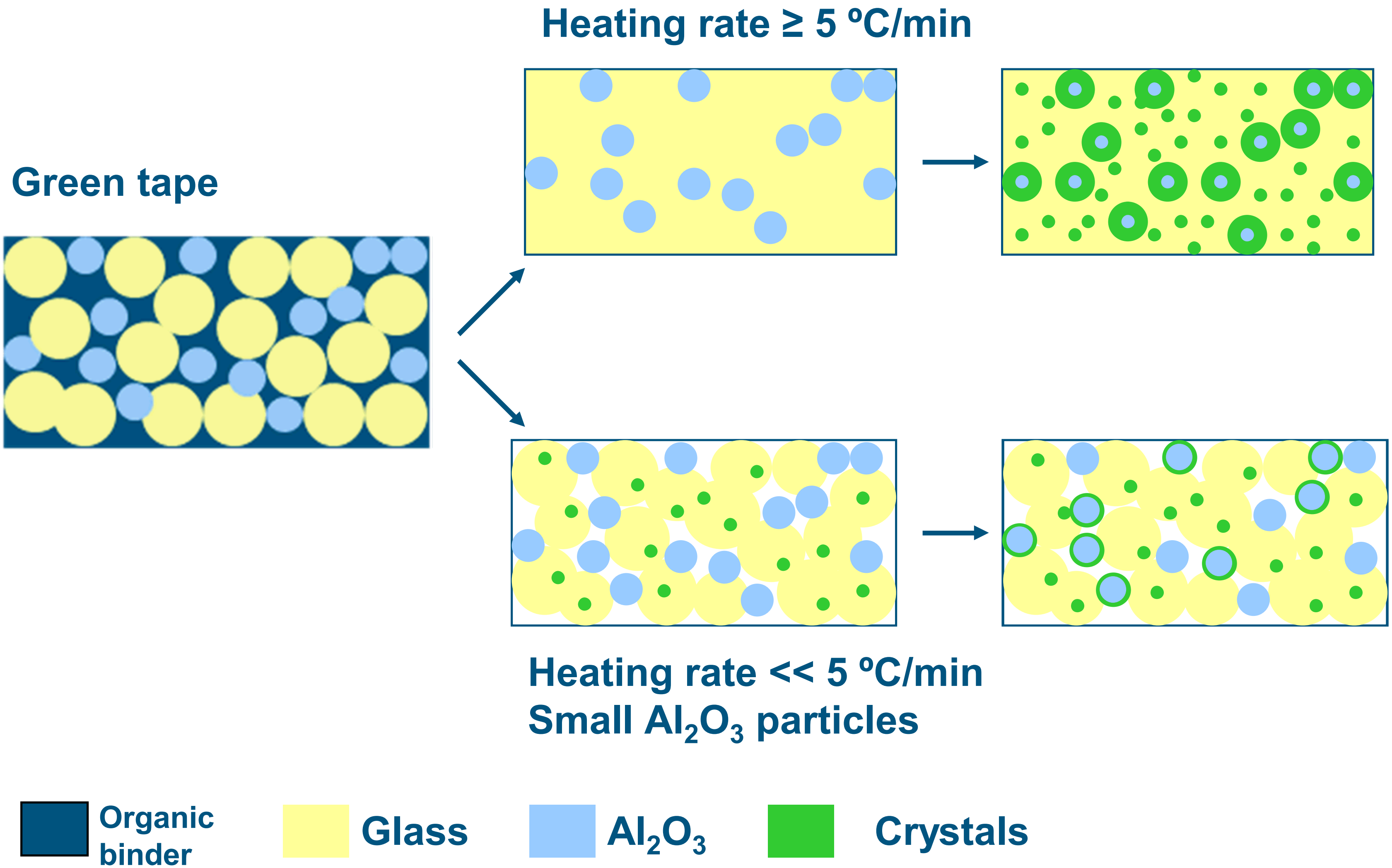
- ε increases as density increases
- Q > 1000

Process Window of 9k7



Steve Dai, "Densification and Crystallization in Crystallizable Low Temperature Co-fired Ceramics", J Mater Sci, 47, 4579–4584, 2012

Densification vs Crystallization – ramp rate



- Enough high ramp rate → densification 1st, crystallization 2nd

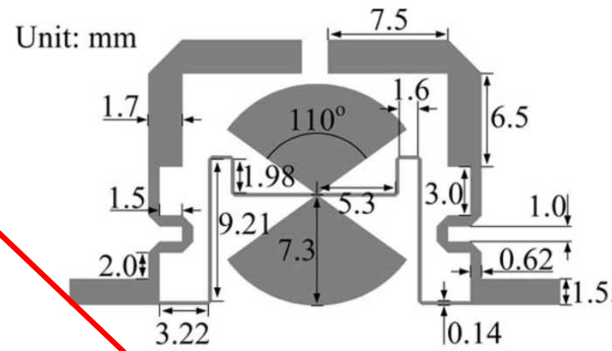
LPF: single dielectric board

- Single layer Arlon DiClad 880
  - h = 0.508 mm
  - ε = 2.2
  - tanδ = 0.0009
- Wide stopband, **IL ~ 1.5 dB**
- Size: 2.5 x 1.9 x 0.51 mm → vol ~ 2.42 mm^3
- Hard to integrate

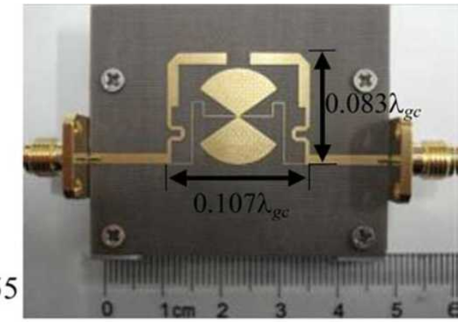
IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 23, NO. 8, AUGUST 2013

Design of Miniaturized Microstrip LPF and Wideband BPF With Ultra-Wide Stopband

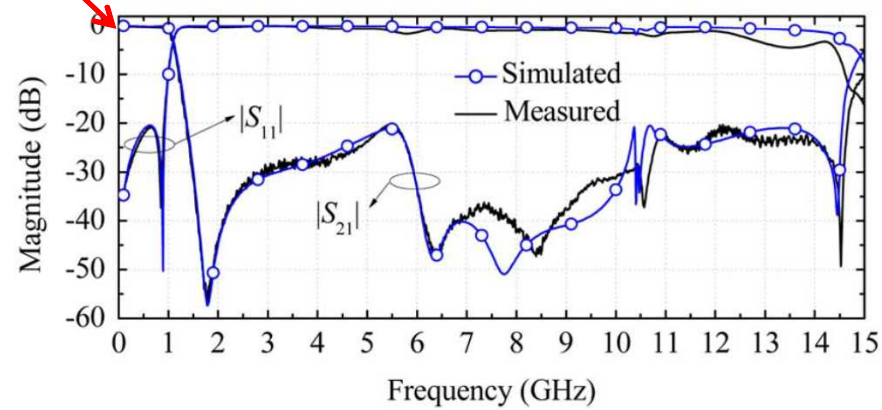
Jin Xu, Yu-Xue Ji, Wen Wu, *Senior Member, IEEE*, and Chen Miao, *Member, IEEE*



(a)



(b)



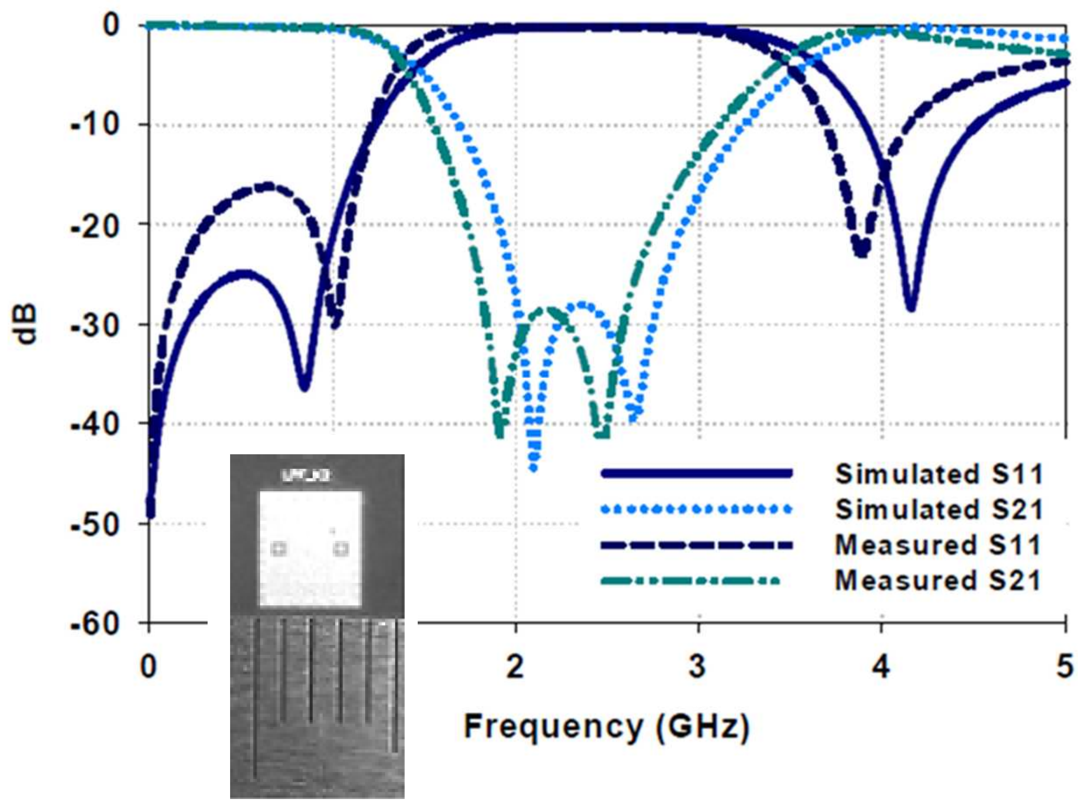
(c)

LPF: Multilayer LTCC

- 5 layer DuPont 951 LTCC
  - Combination of 5 mil and 10 mil green tapes
- Size: 3.5 × 4 × 0.33 mm
- Limited stopband

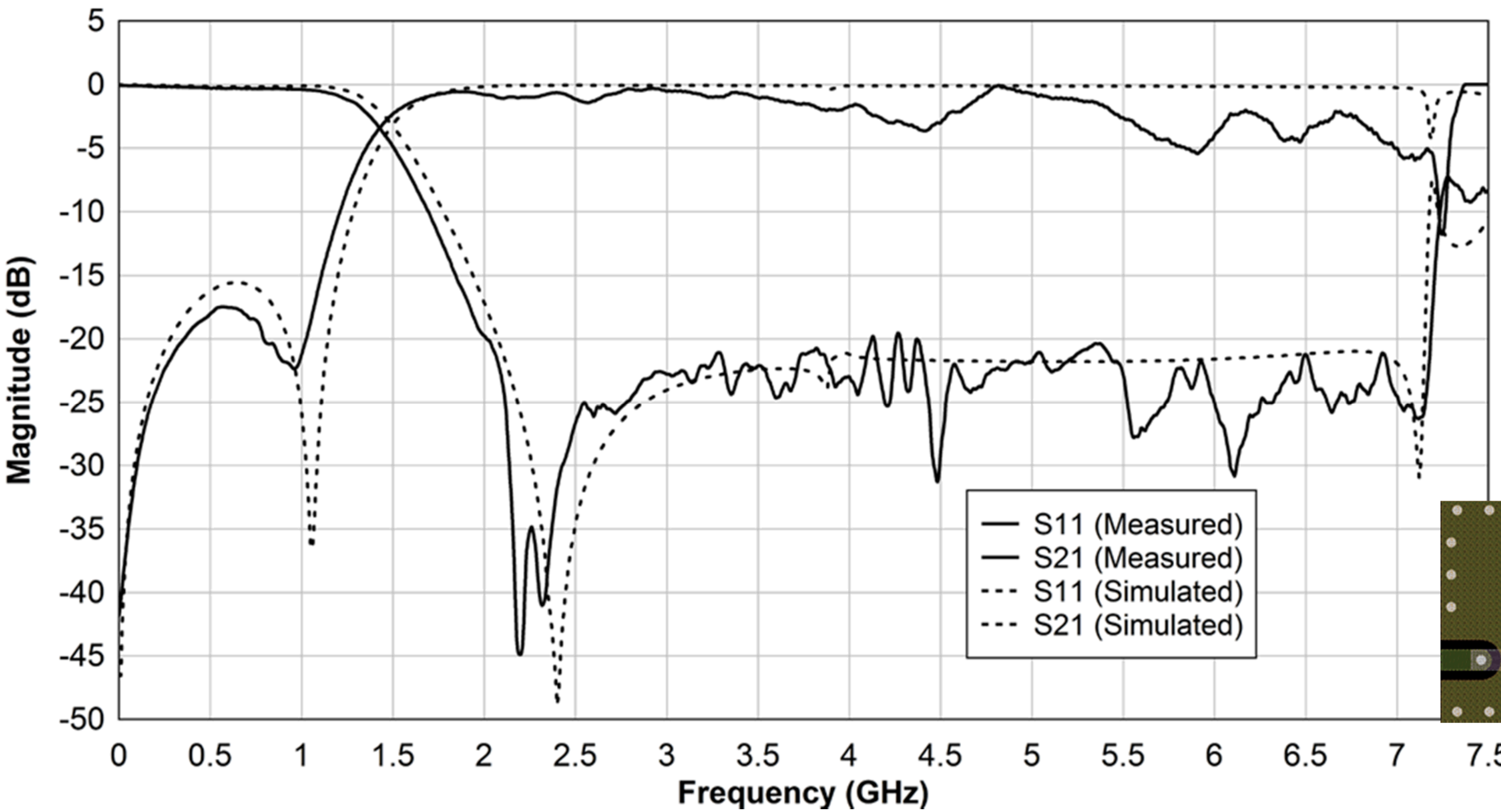
Stacked Lowpass Filter using LTCC Technology

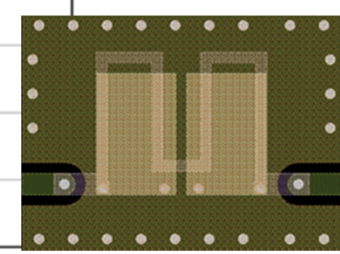
Kyoungkeun Kim, Yuseon Kim, Hyeonsik Na, Jahyeon Lee, Sooman Park, Yeongseog Lim
Dept. Electronics Engineering, Chonnam National University, Gwang-ju, Korea
relmk3@empal.com



LPF: 4-layer 9k7 LTCC

- Size: 7.5 × 5.5 × 0.85 mm
- Wide stopband to 7.1 GHz (below 19.5 dB)
- Excellent agreement: measured and simulated S-parameters

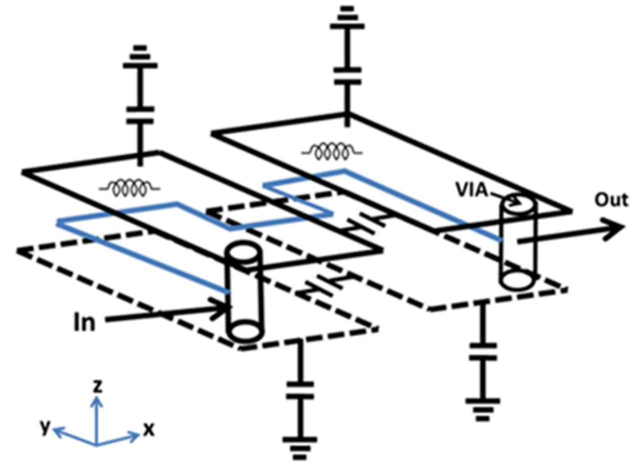


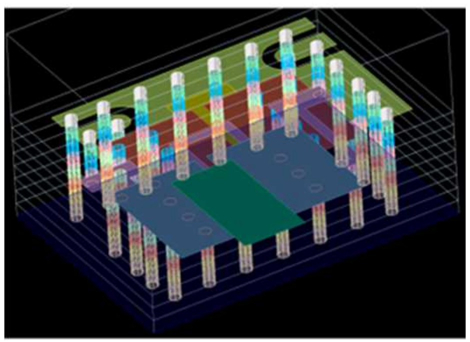


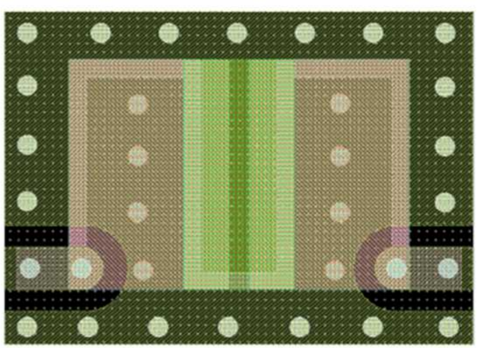
LPF: 8-layer 9k7 LTCC

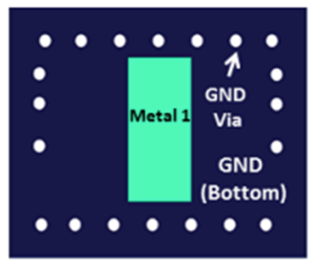
Sandia National Laboratories

- Size: 5.5 × 3.9 × 1.7 mm
- Standard LTCC processes
- Ramp rate 5 ^{o}C/min, ε = 7.4

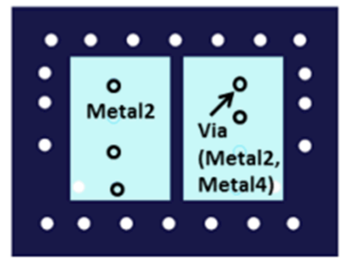




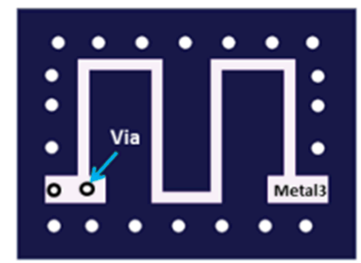




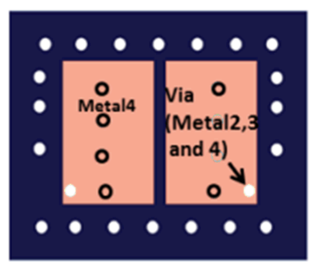
(a)



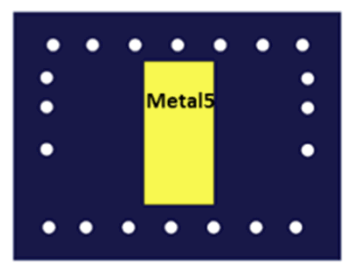
(b)



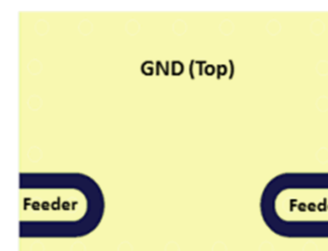
(c)



(d)



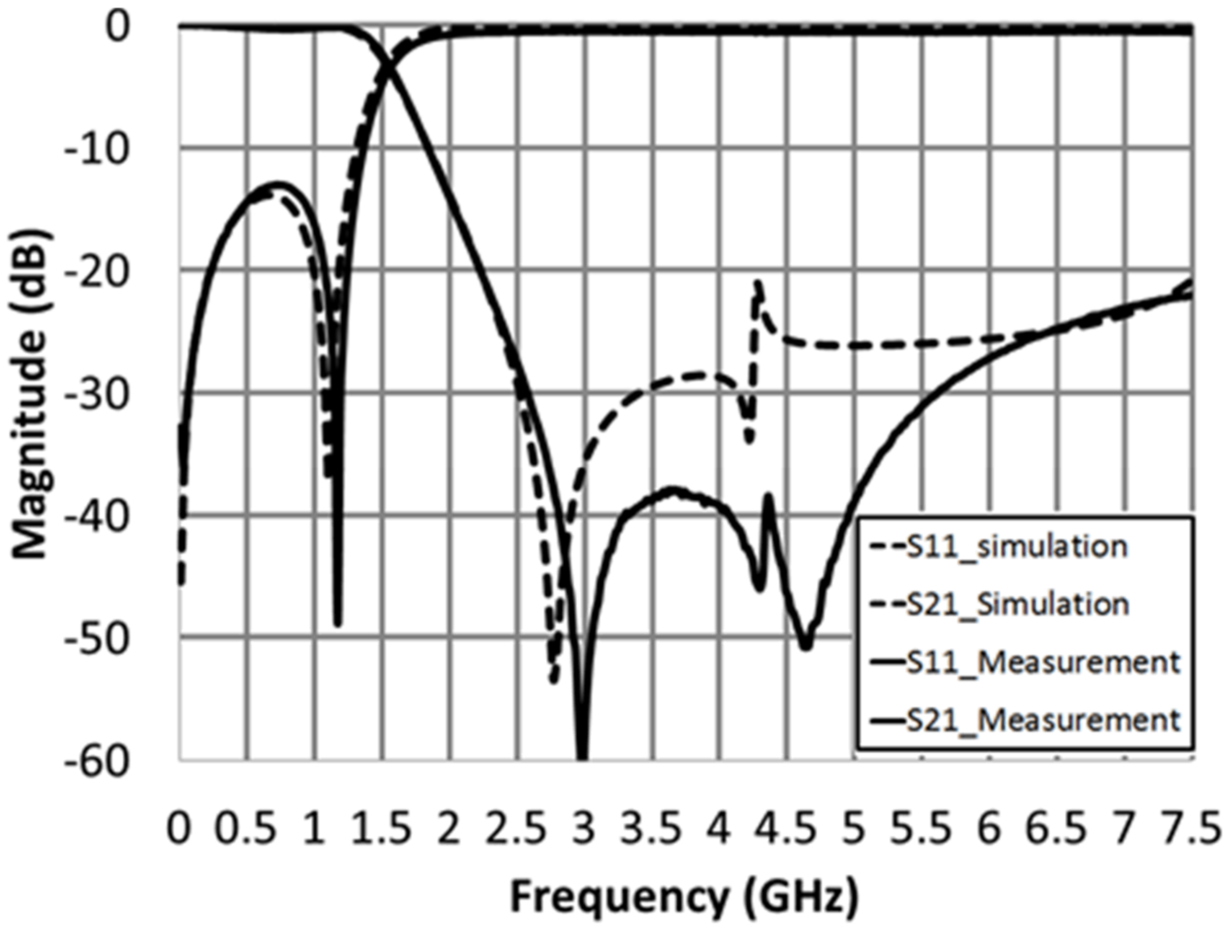
(e)



(f)

LPF: 8-layer 9k7 LTCC

- 3-dB passband from DC to 1.5 GHz. > 22 dB stopband rejection from 2.3 GHz to 7.5 GHz.
- Excellent agreement using ε = 7.4



Summary

- Competing densification and crystallization in 9k7 LTCC
- Optimization: densification followed by crystallization
  - → ramp rate 5 ºC/min
  - $\varepsilon = 7.4$
- LPF with broad stopband demonstrated. Good agreement simulation versus measurement assuming 7.4 dielectric constant