High Dielectric Constant, Low Loss Additive Manufacturing Materials for RF/Microwave Applications

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IMAPS New England
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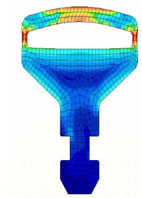
Why? Additive Manufacturing and Rapid Prototyping

3D Printing and Additive Manufacturing Enables Rapid Design Iteration



Design → Model → ***Build***

Experimentally Evaluate Part

Tweak Model and/or Re-design

Loop iterations are limited by time to build, but 3D printing enables rapid build and rapid iterations

But current applications that benefit from this design process are limited by the materials

Aerospace & Aviation parts – light weight, low cost materials, such as seat buckles
Medical & Dental – dental and orthopedic implants, visual aids from scanned parts
Manufacturing (Mechanical Parts) – alternative to injection molding
Bio-manufacturing – printing cells & tissue (more experimental with low modulus materials)

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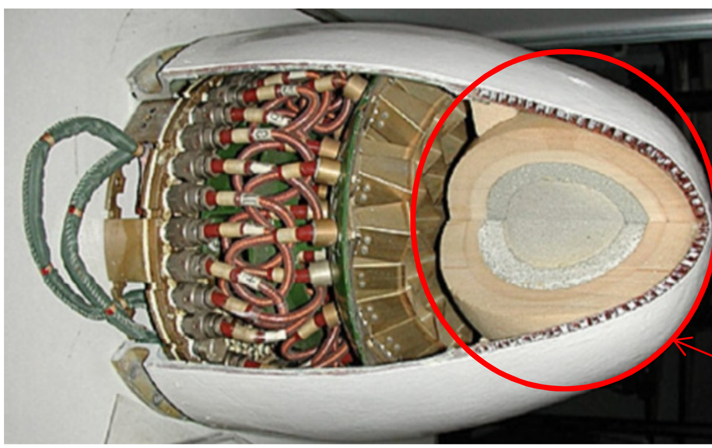
Pictures: http://annals.fih.upt.ro/pdf-full/2011/ANNALS-2011-4-27.pdf
Information: Piazza, Merissa and Alexander, Serena, "Additive Manufacturing: A Summary of the Literature" (2015). *Urban Publications.* Paper 1319.

Hi k applications at GHz frequencies

- Applications that use high k materials
  - *Embedded passive components (R, L, C) – 2.5D geometry*
  - *Waveguides – 3D geometry is more can be challenging to manufacture*
  - *Gradient index lenses – complex geometries often requiring multi-material interfaces*
- Current waveguide manufacturing techniques and limitations
  - *Typical Materials: brass, copper, silver, aluminum, or any metal that has low bulk resistivity*
  - *Dielectric materials have been used a waveguides for mm wave frequencies, where metal is not a good conductor*
- Forming could be greatly simplified if the right materials are available via additive manufacturing tools

Approximately 1m



Guided Missile Head
http://www.ausairpower.net/APA-Fullback.html

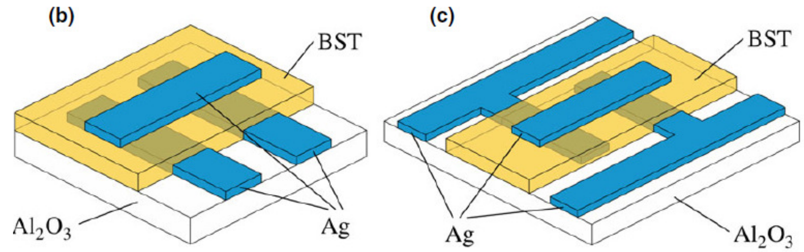
Lens on tip of guided Missile

Can same technology be placed on a bullet tip?
High k material and fine 3D geometry are required

Printed High Frequency Devices

- Recent advancements show possibility of high k 2.5D printing
- Materials for 3D printing are in development, but have not been implemented

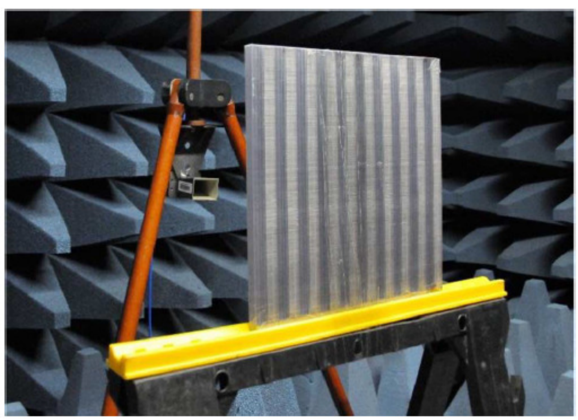
Ink Jet Printed varactor & phase shifter



A. Friederich, et. al. *Int. J. of App. Ceramic Tech.*, vol. 12, 2015.

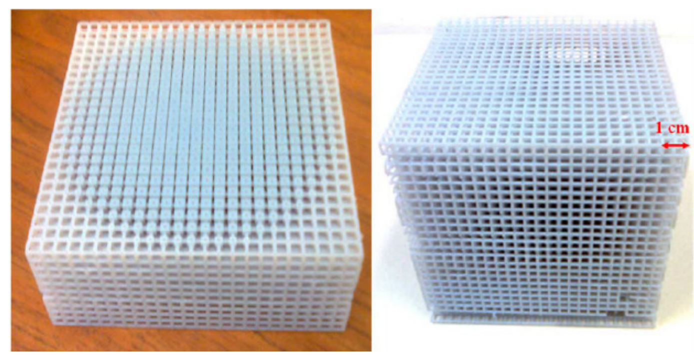
Engineered BST Ink with k=129

SLA Printed Radio/Microwave All-Dielectric Frequency Selective Surfaces, U. Texas, El Paso



J. Barton, et. Al., *IEEE Trans. on Ant. & Prop.*, vol. 63, 2015.

Luneburg Lens, U of Az, Polyjet Printer
(UV Curable polymer)
Fill fraction used for 3D Gradient



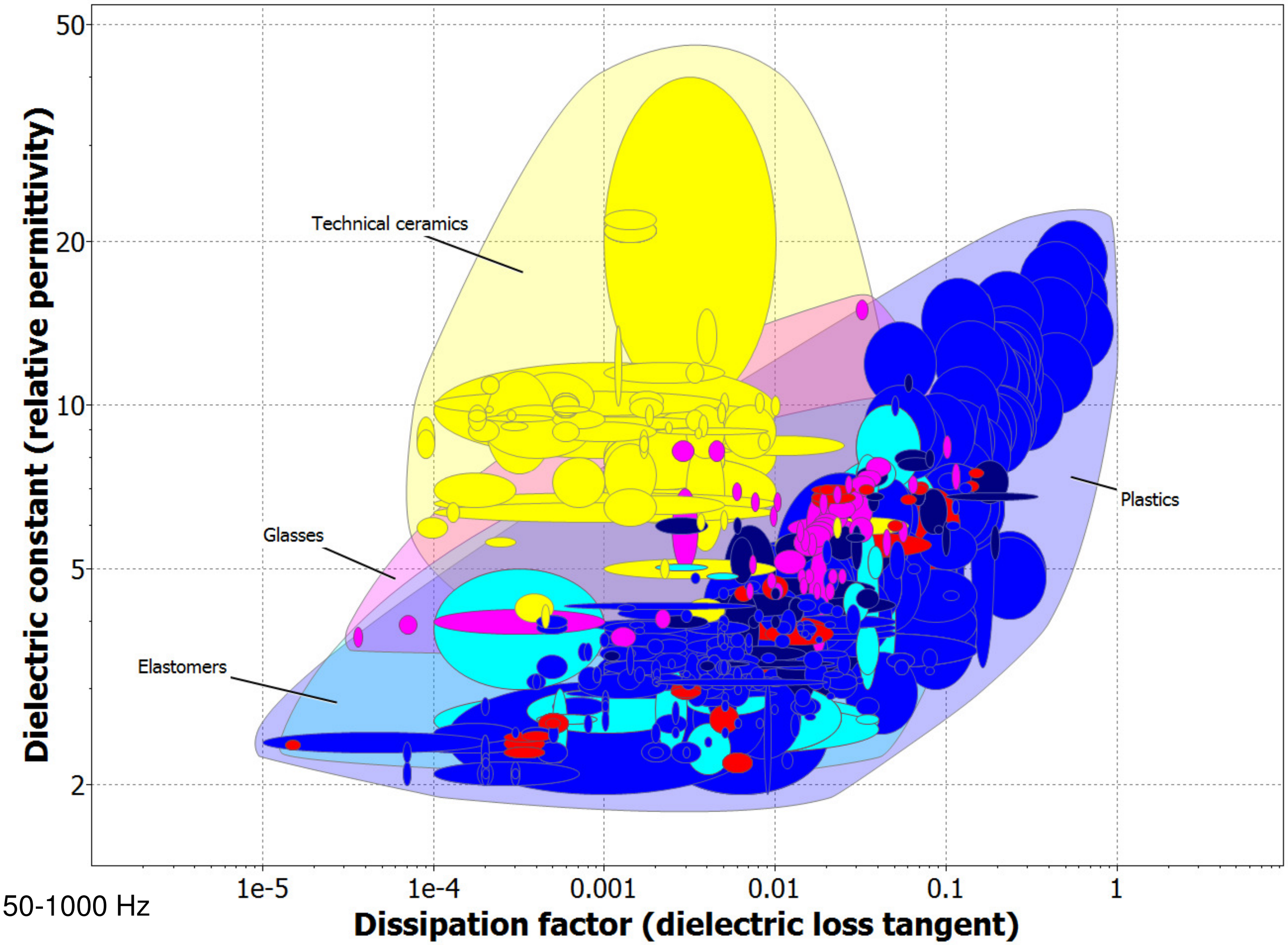
M. Liang, et. Al., *IEEE Trans. on Ant. & Prop.*, vol. 62, 2014.

Rapid Prototyping Capabilities

- Four machines
  - 3D Systems Viper (Stereolithography)
    - Epoxy resin material
  - Objet Connex260 (Polyjet Printer)
    - Multi-material printer
  - Stratasys Titan (Fused Deposition Modeler)
    - Polycarbonate material
  - Stratasys Prodigy (Fused Deposition Modeler)
    - ABS material

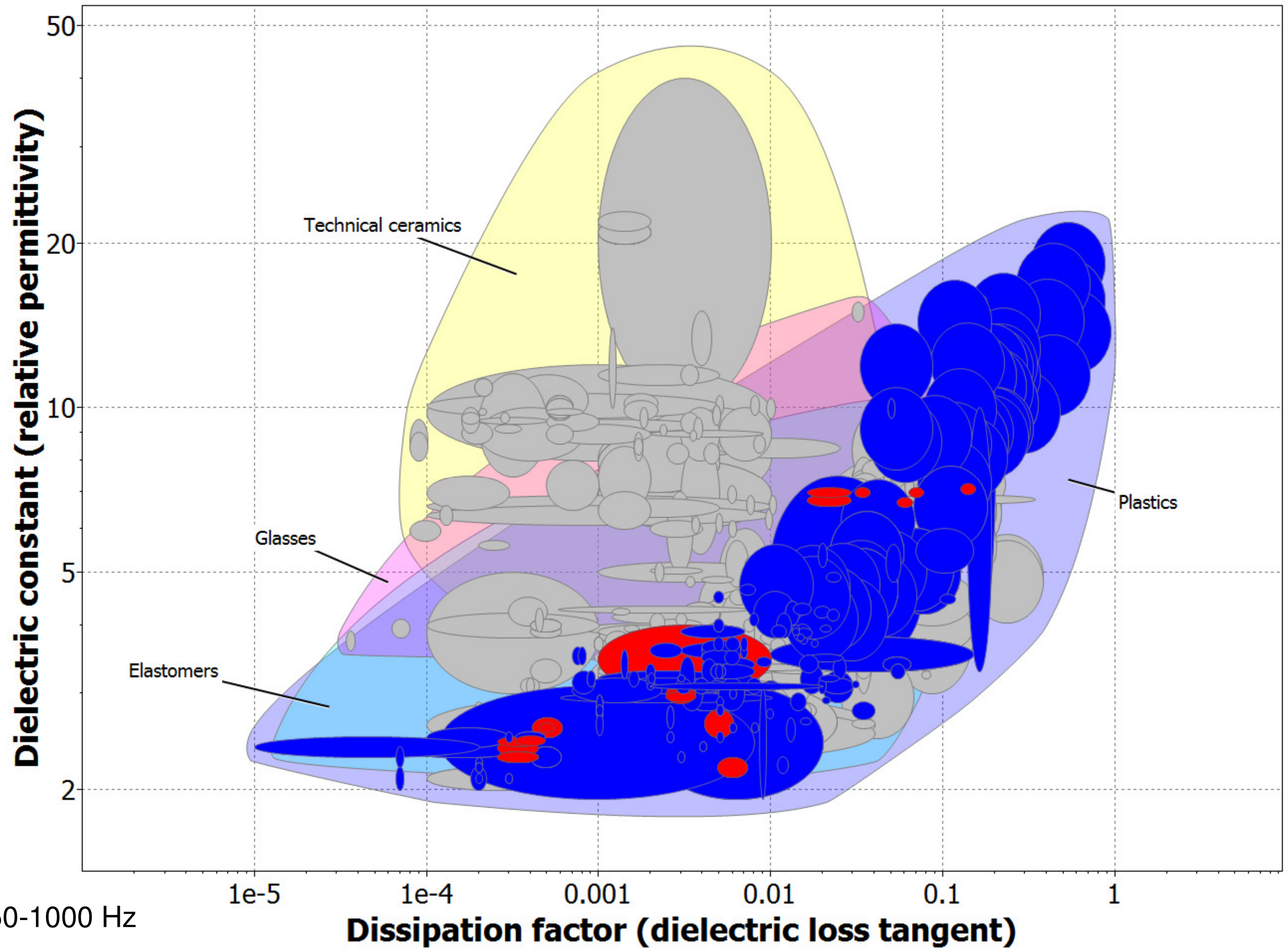
- Use universal STL file format for import of geometry from 3D modeling software
- Machines run unattended allowing greater throughput and quicker turn around time
- Post processing capabilities including painting, inserting threads (tapping or inserts) and final assembly

For miniature RF devices, need high k, low loss materials



Data taken at 50-1000 Hz

Which Materials Can be 3D Printed?



Data taken at 50-1000 Hz

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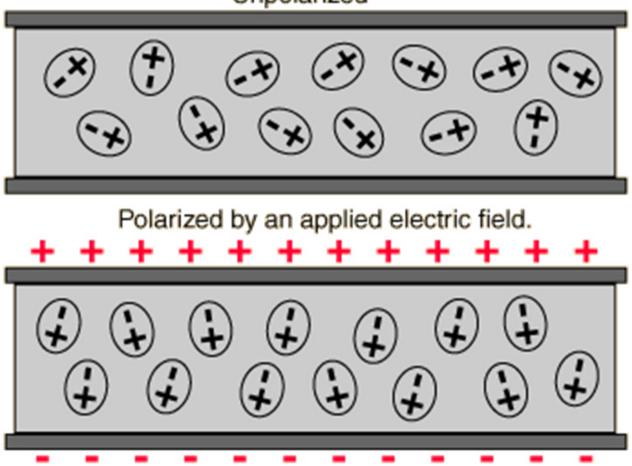
What are k and tan d from a molecular perspective?



Z. Dang, et. Al., *Prog. Mat Sci.*, vol. 57, 2012.

Relative dielectric permittivity

Loss Factor

Dielectric Constant (Permittivity)

$$k^*(\omega) = k'(\omega) + jk''(\omega)$$

ω is angular frequency

Loss Tangent:

$$\tan\delta(\omega) = k''(\omega)/k'(\omega)$$

Dielectric Constant (Permittivity) – the tendency for a material to polarize in an electric field

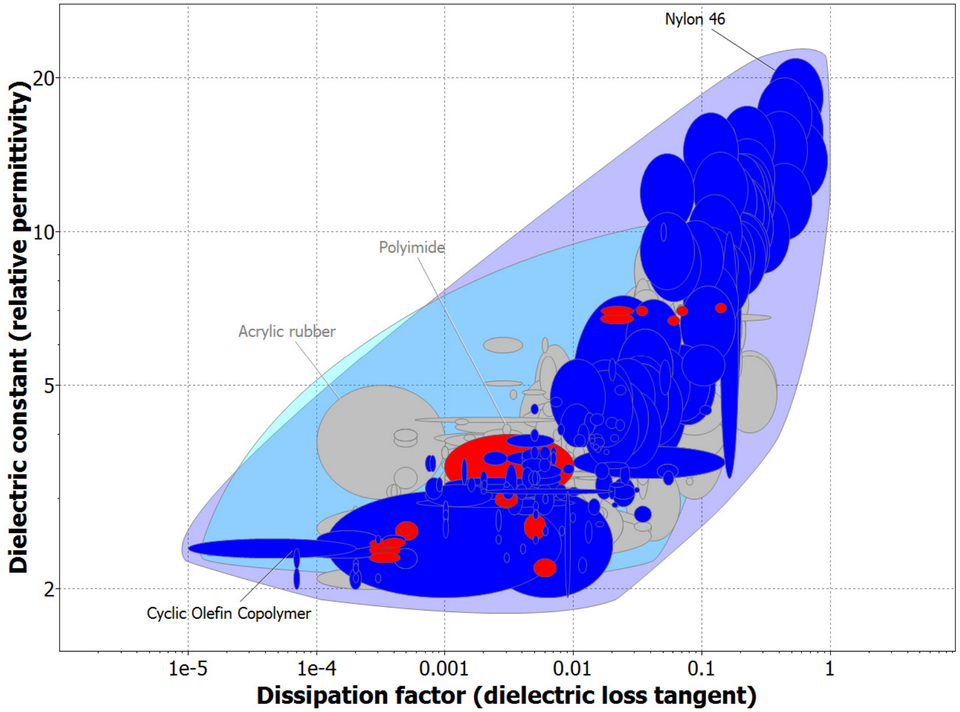
Loss Tangent – the ratio of the apparent power consumed by a material to the real power consumed

Loss is minimized when the time it takes for a for the ***dipole moment*** of a molecule *reaches equilibrium* with the electric field ***quickly***

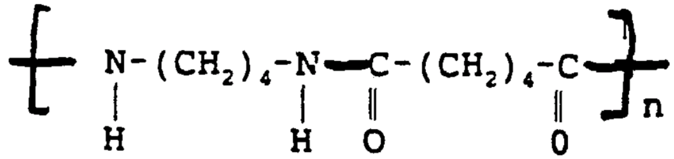
A material with NO LOSS would switch polarization in sync with the applied electric field

MOLECULAR CONFIGURATION and **FREQUENCY** play a huge role

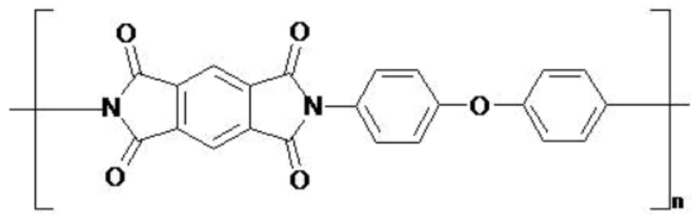
Molecular Structure of Polymers
k and tanδ



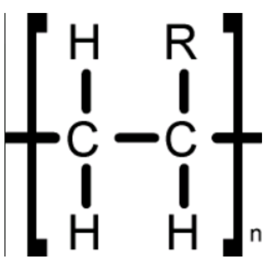
polytetramethylene adipamide (Nylon 46), high k and high tanδ



polyimide, mod k and mod tanδ

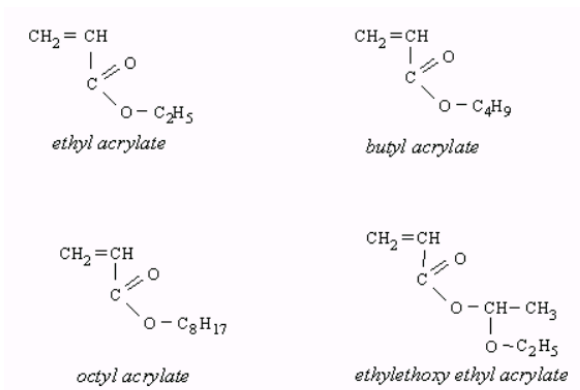


Polyolefin,
low k and low tanδ



R=ethylene for above graph

Acrylic rubbers, mod k and low tanδ



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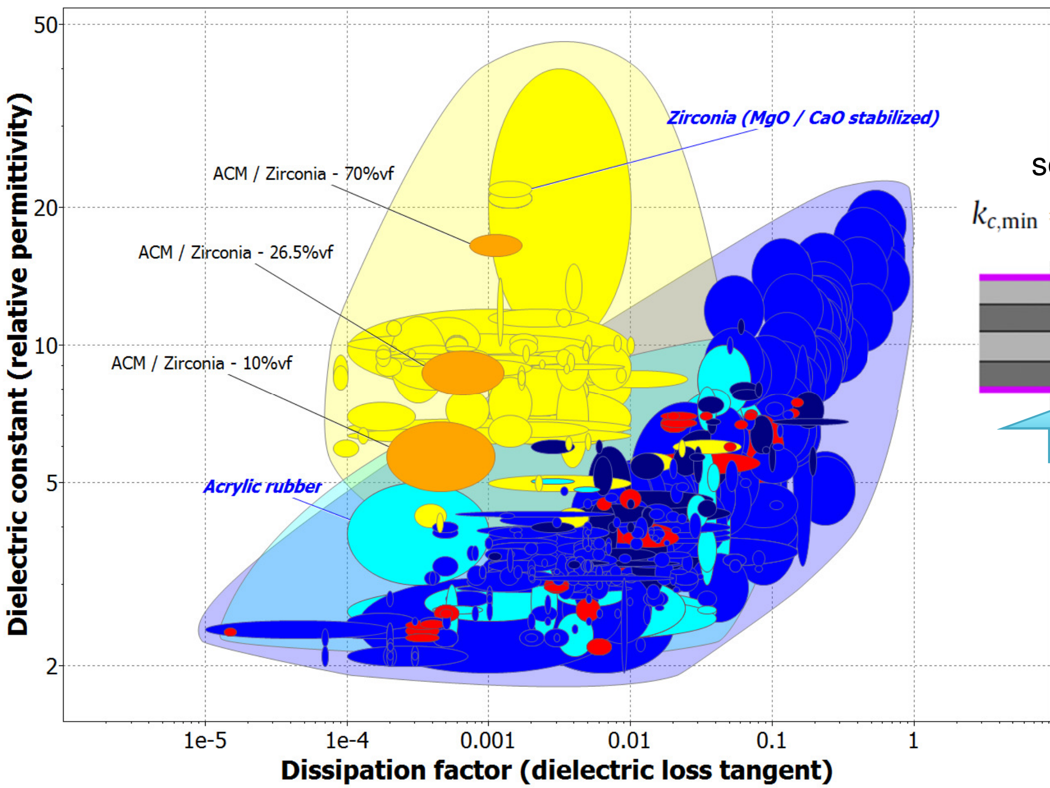
Typical Materials Design Strategy: Composites



Wagner Theoretical Limits

series

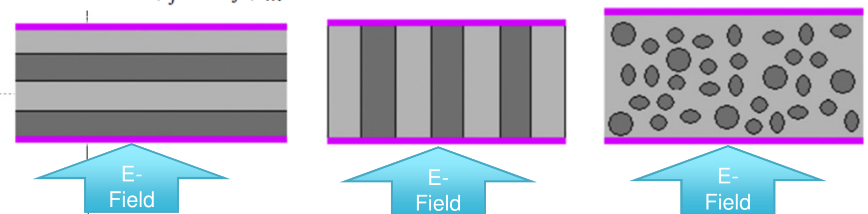
$$k_{c,\min} = \frac{k_m k_f}{k_m \phi_f + k_f \phi_m}$$

parallel

$$k_{c,\max} = k_m \phi_m + k_f \phi_f$$

Particles in a matrix

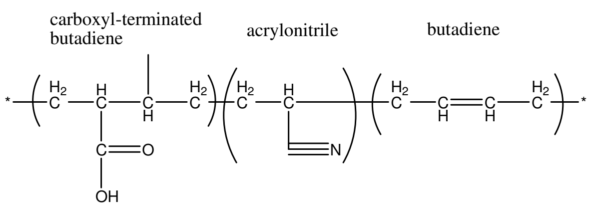
$$k_{c,\min} \leqslant k_c \leqslant k_{c,\max}$$



Z. Dang, et. Al., *Prog. Mat Sci.*, vol. 57, 2012.

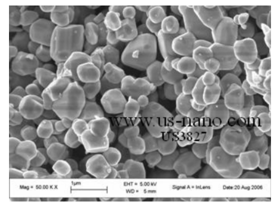
Designing PMC Materials

MATRIX



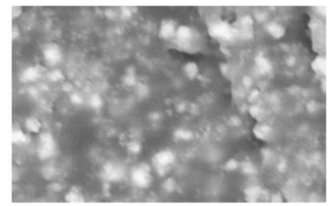
x% Polymer

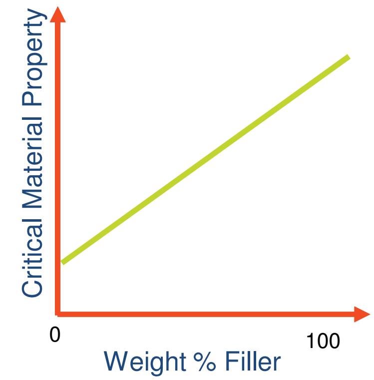
FILLER



(1-x)% Particles

PMC





For a PMC:

Permittivity of all components; Permittivity of interfaces; DC Conductivity; Permittivity in a vacuum

$$k^*_{\text{eff}} = k^*(\omega) + \sum_i k^*_{MW,i}(\omega) + j\left(\frac{\sigma_{DC}}{\omega k_0}\right)$$

$$= \left(k'(\omega) + \sum_i k'_{MW,i}(\omega)\right) + j\left(k''(\omega) + \sum_i k''_{MW,i}(\omega) + \frac{\sigma_{DC}}{\omega k_0}\right)$$

$$k'(\omega) \rightarrow k_\infty + \frac{k_s - k_\infty}{1 + \omega^2\tau^2} \qquad k''(\omega) \rightarrow \frac{(k_s - k_\infty)\omega\tau}{1 + \omega^2\tau^2}$$

Dipole relaxation time

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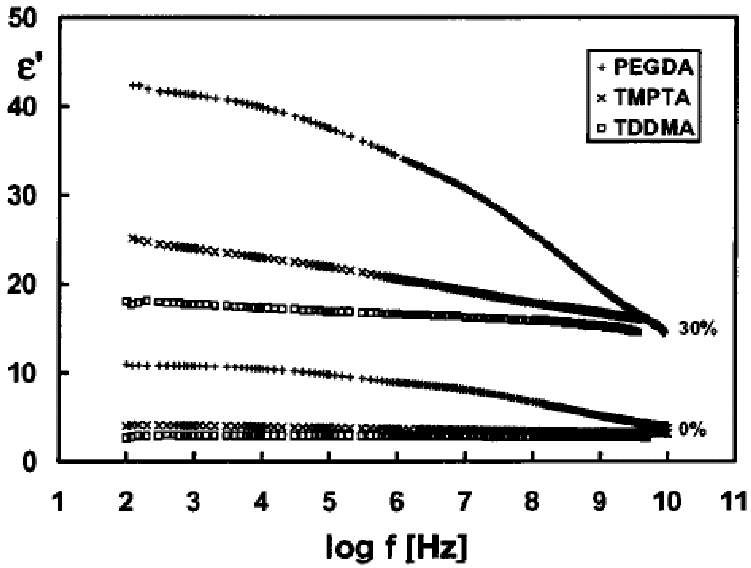
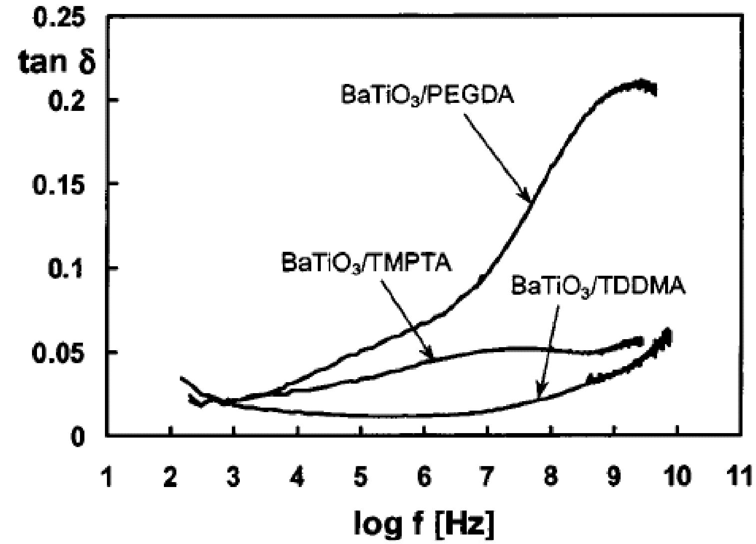
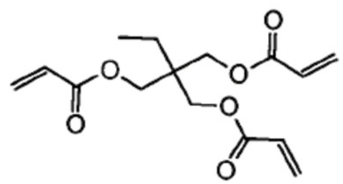
Z. Dang, et. Al., *Prog. Mat Sci.*, vol. 57, 2012.

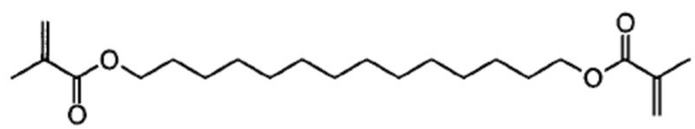
Choosing a Matrix Material



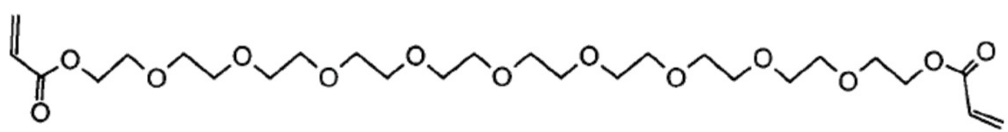




Trimethylolpropane triacrylate
(TMPTA)



1,14-Tetradecanediol dimethacrylate
(TDDMA)



Poly(ethylene glycol) diacrylate
(PEGDA)

R. Popielarz, et. Al., *Macromolecules.*, vol. 34, 2011.

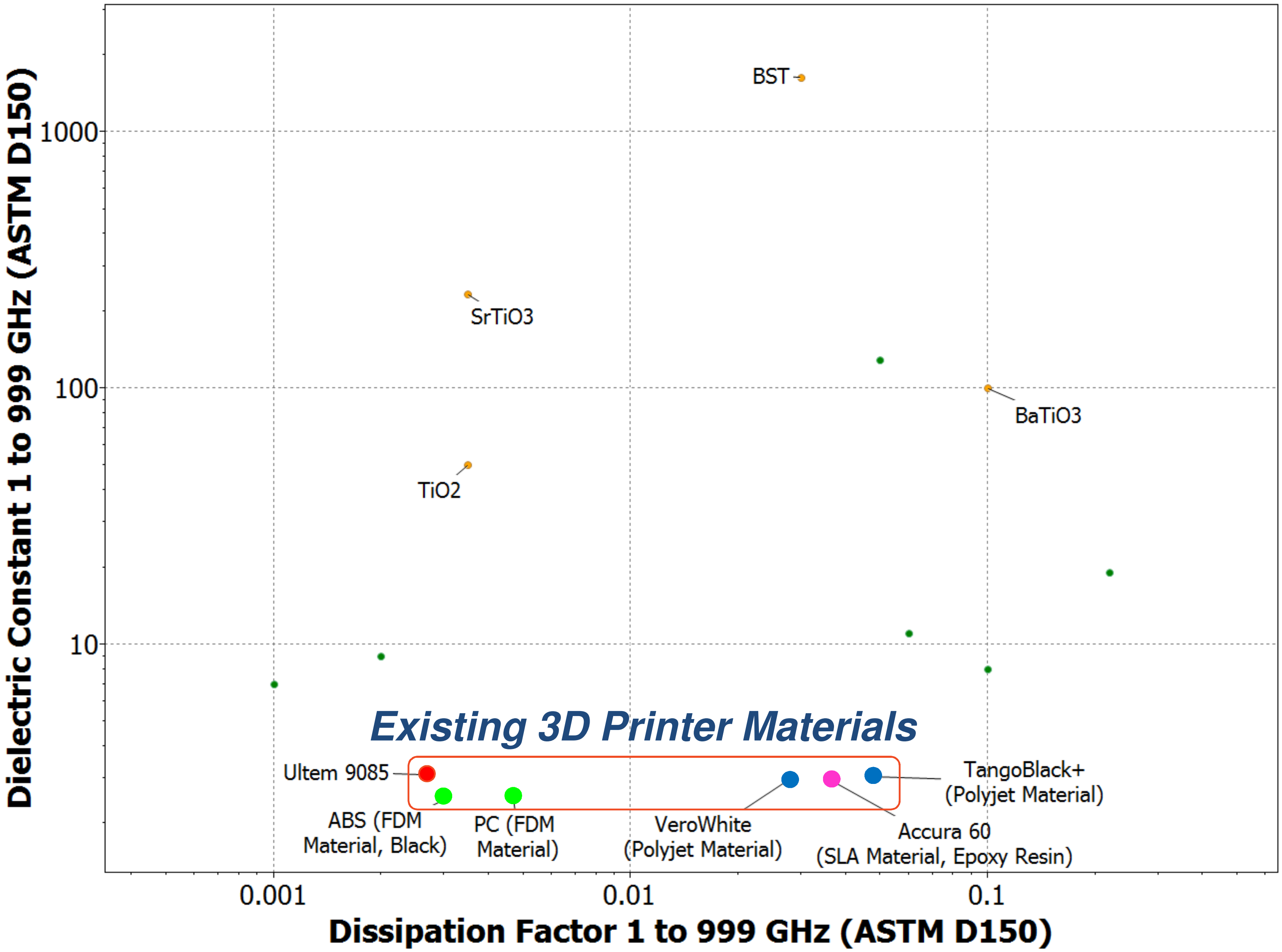
Choosing a filler and processing method

Filler	Advantage	Major Challenges
Metal	Small amounts can significantly boost dielectric constant	Increases conductivity and loss Dielectric becomes a conductor at high volume fraction
Ceramic	Natural high k, low loss dielectrics	Affects both mechanical and electrical properties → Processability is lost at high concentrations
Carbon		Particles tend to agglomerate, lowering percolation threshold
Organics	Mixing and dispersion may be simple, fewer agglomerates	High k organics are loss (more conductive) At high frequency, dielectric constant drops significantly

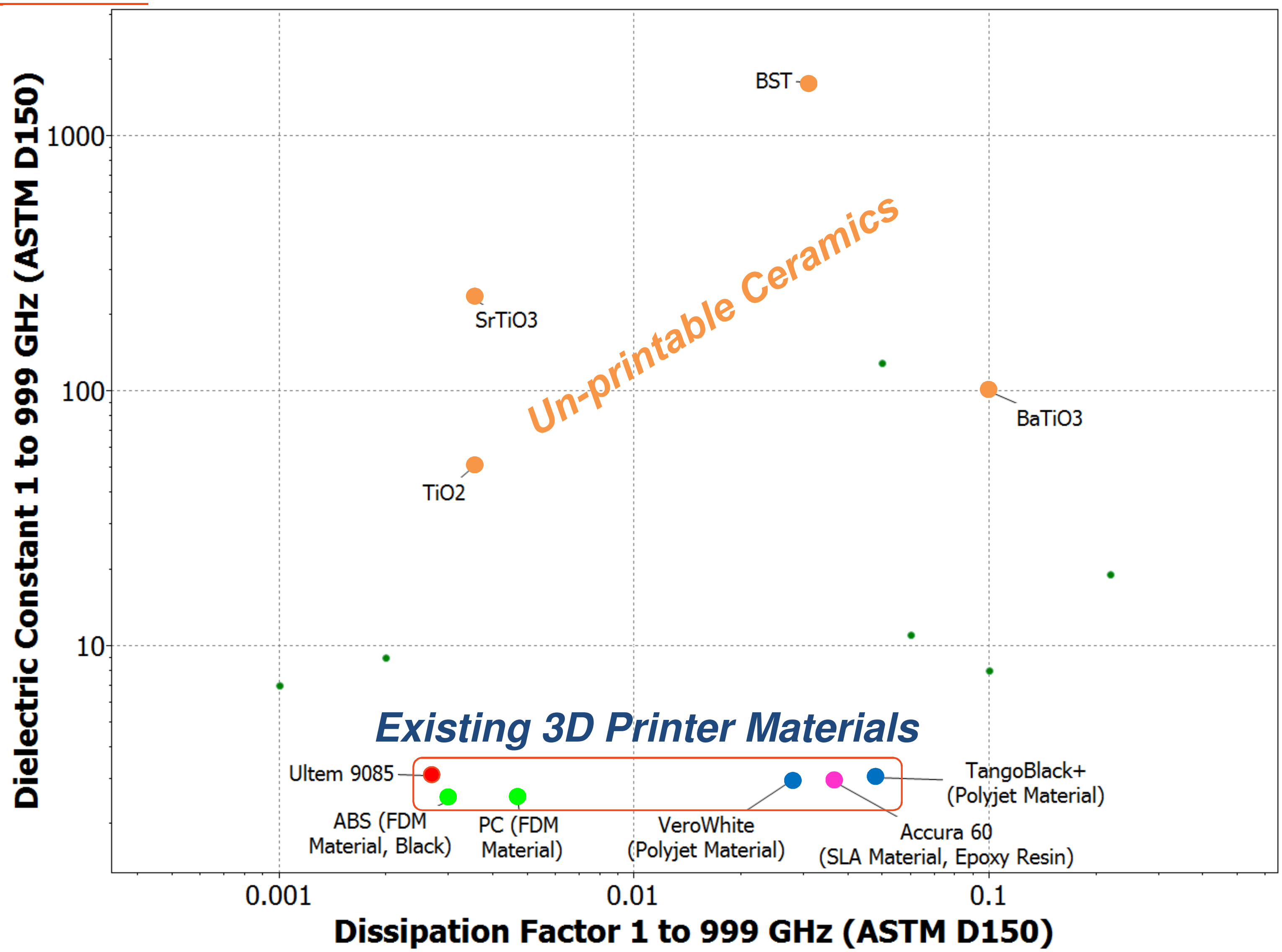
- Direct compounding – particles tend to agglomerate, surface treatment, such as functionalization only works sometimes

- Melt Compounding

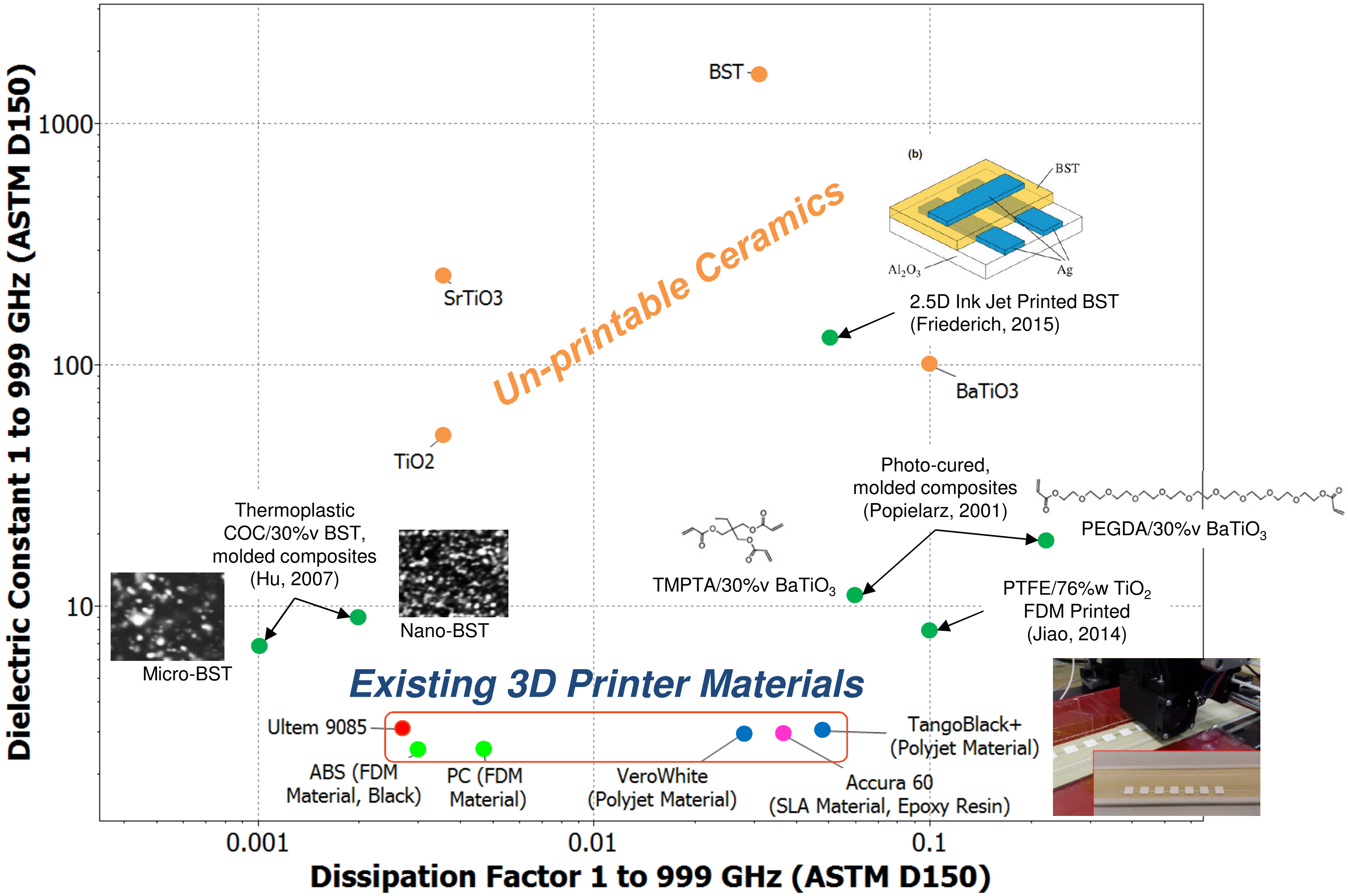
What's out there already?



What’s out there already?



What’s out there already?



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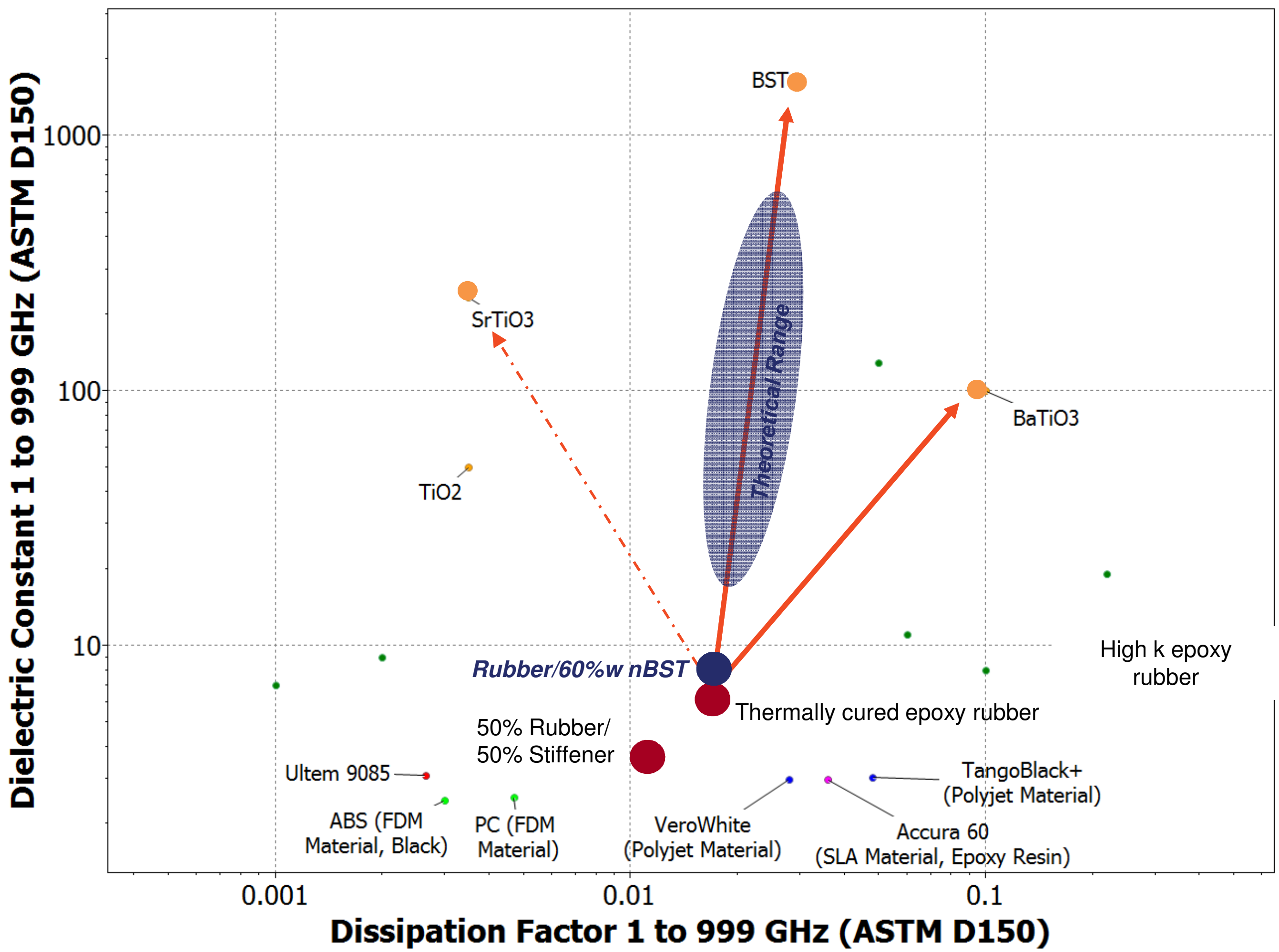
Draper's 1st attempt



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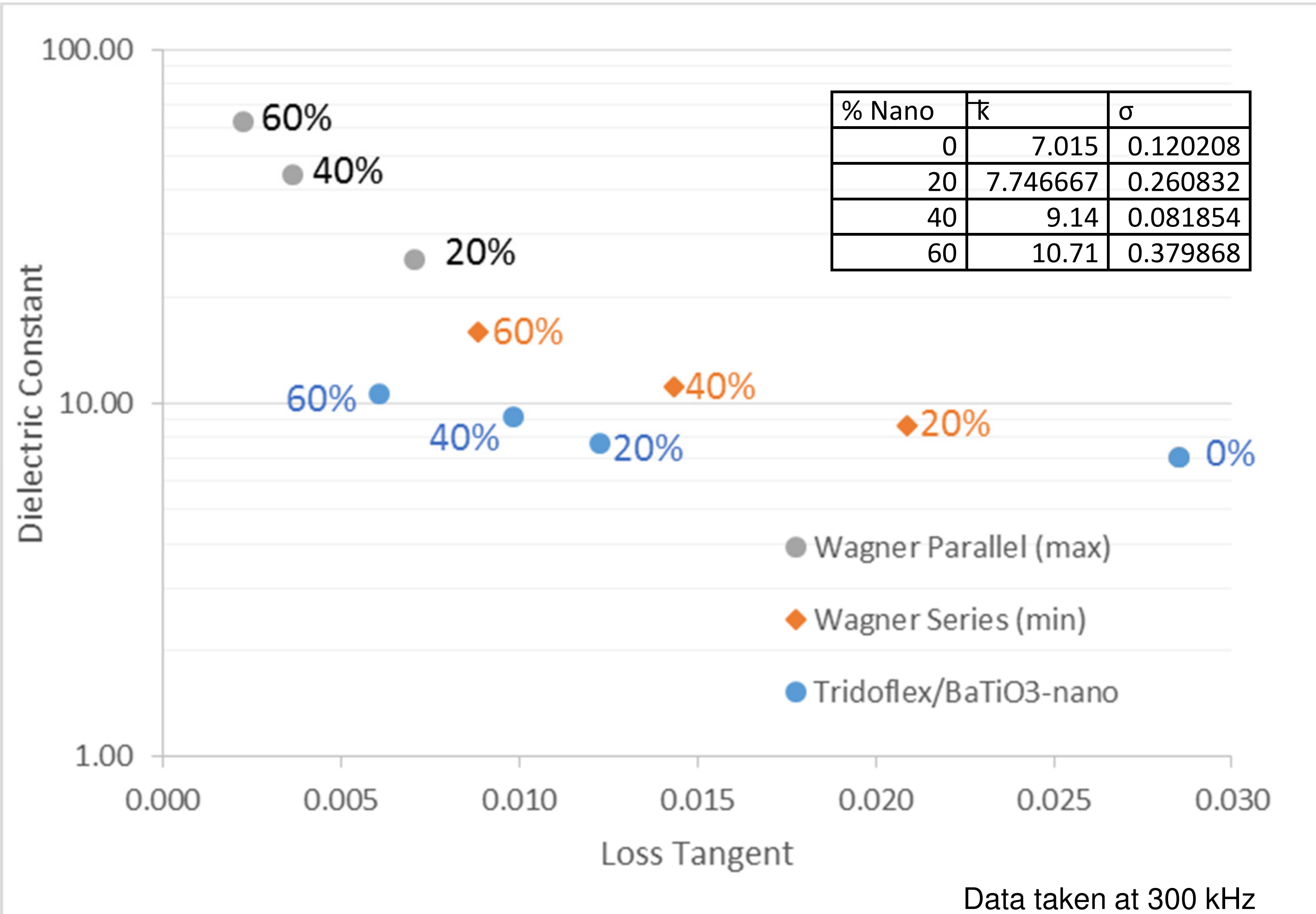
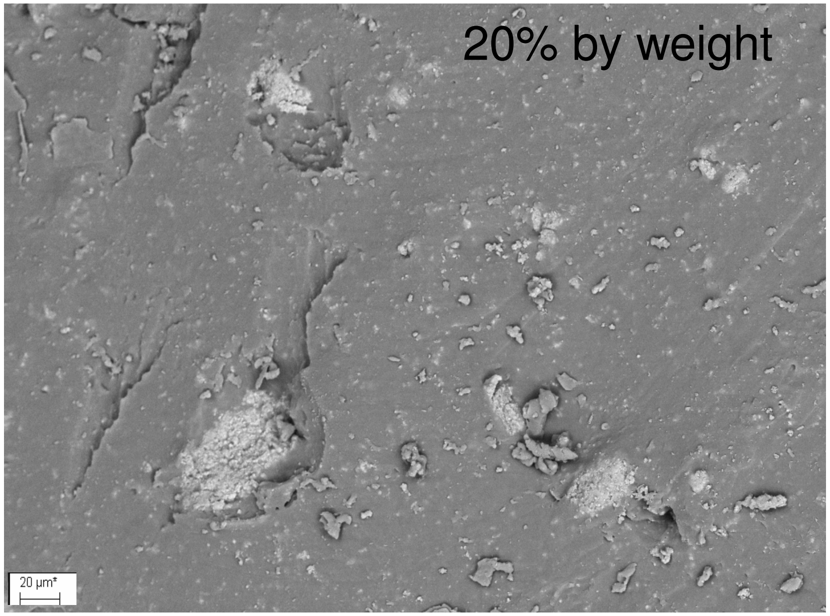
footer

Tridoflex + BaTiO3 fillers



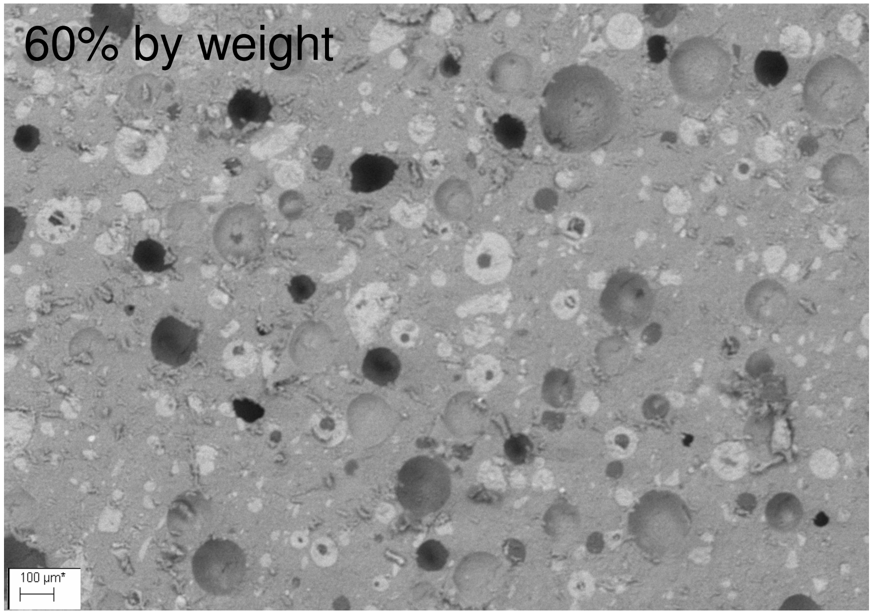
% Nano	$\bar{k}$	σ
0	7.015	0.120208
20	7.746667	0.260832
40	9.14	0.081854
60	10.71	0.379868

Issues found with BaTiO3 Composites



Particle agglomeration

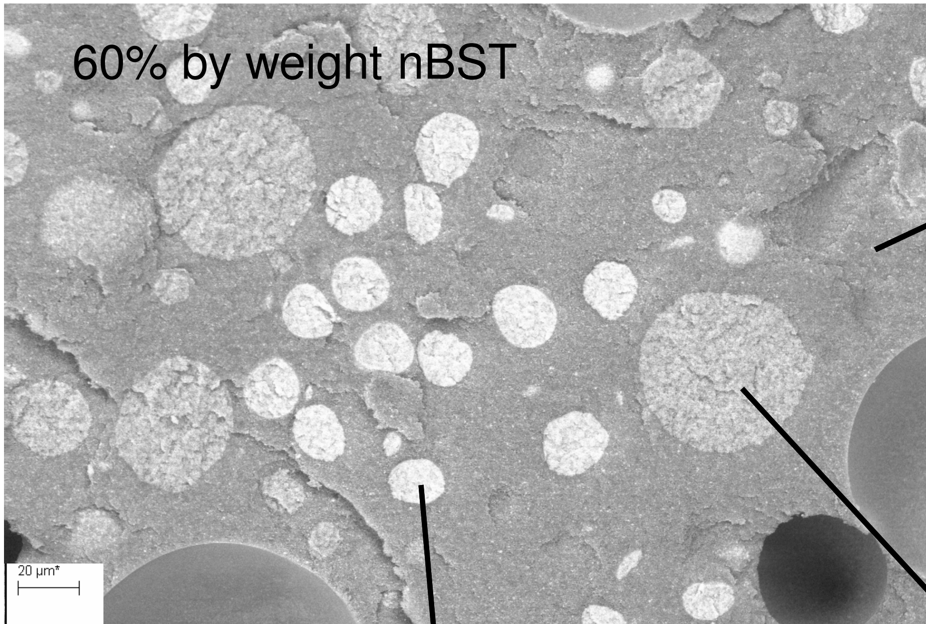
Possible solutions:
Functionalizing particles
Furnace treatment prior to mixing
Ultrasonic mixing

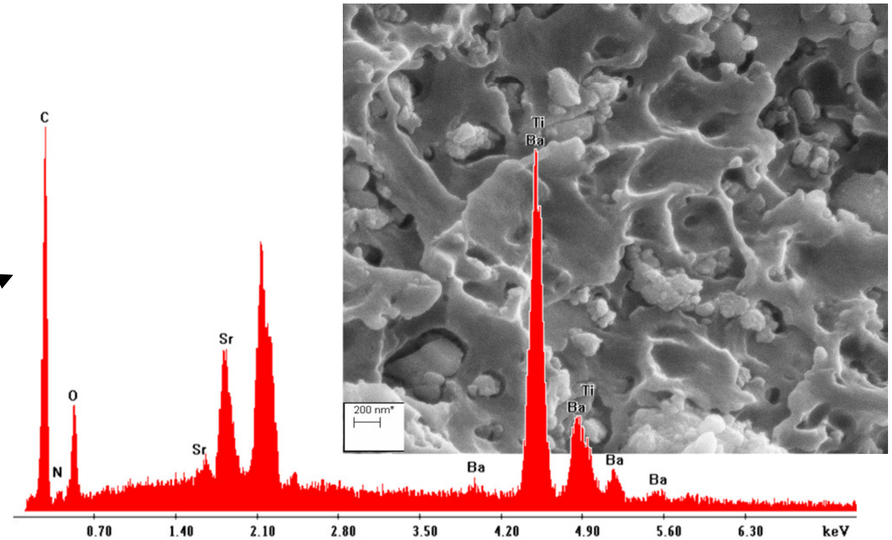


Air pockets/voids

Possible solutions:
Alternative mixing or compounding method
Vacuum degassing

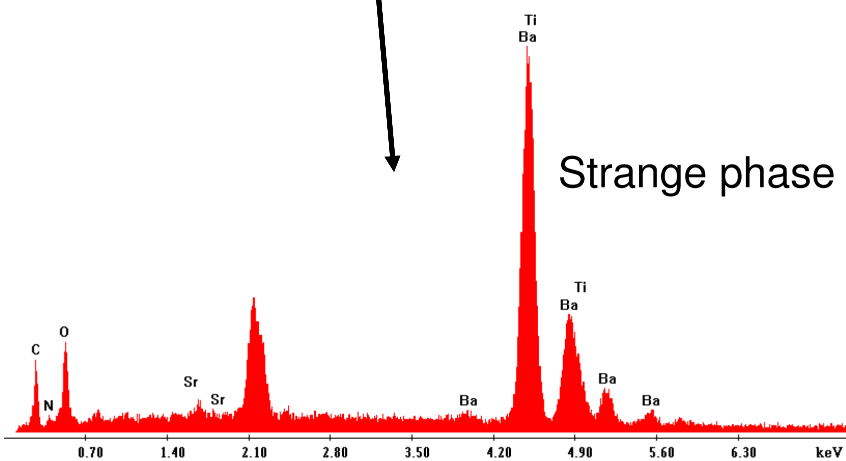
Unique issues with nBST Composites

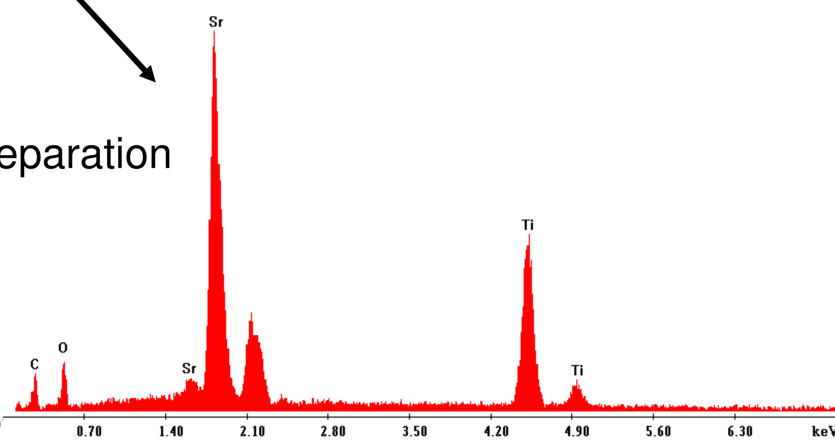




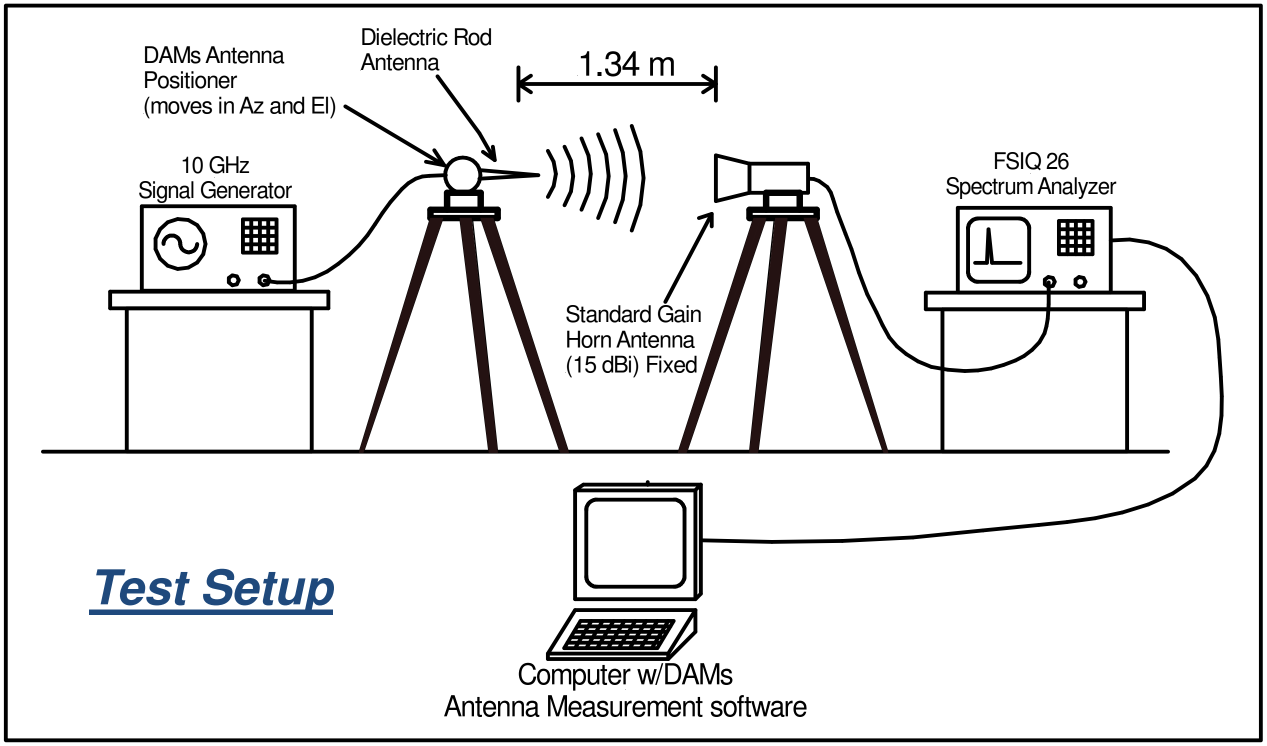
Good dispersion of BST

Strange phase separation





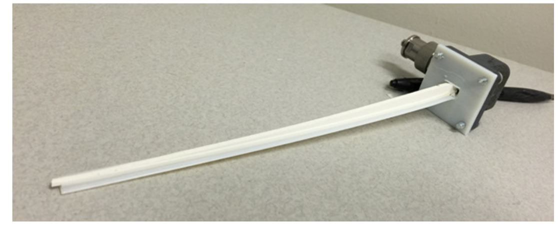
Single Material Demonstrator Results: Molded PMC Waveguide



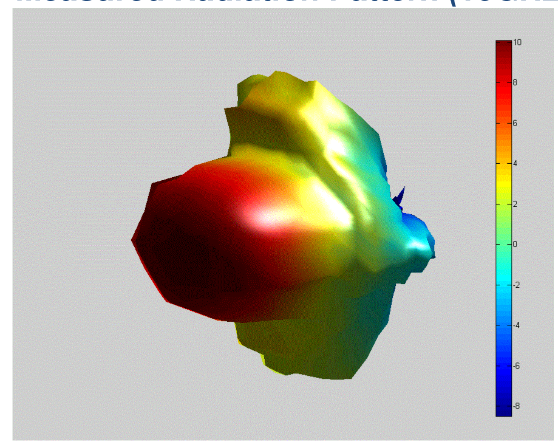
Created a mold-able material that can be used as a conformal dielectric antenna material

- *The material has predictable mm-wave radiation pattern with reasonable gain (10 dB)*
- *Modeled radiation pattern of material in CST to determine k and tan δ*
- *The stiffness and other mechanical properties can be tuned by changing the polymer matrix base*

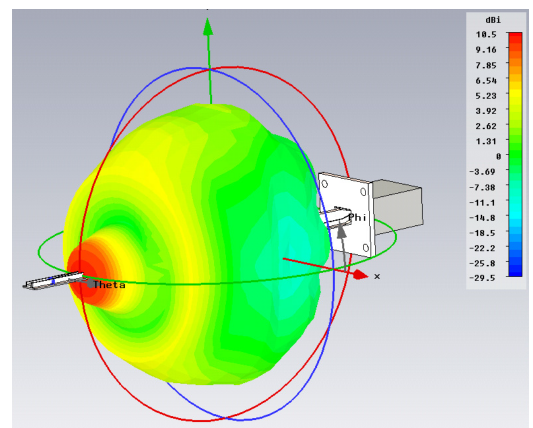
Dielectric Antenna



Measured Radiation Pattern (10GHZ)



Simuluated Radiation Pattern (10GHZ)



Conclusions

- Creating a high dielectric constant material with low loss that is also compatible with 3D printing tools would
  - *enable rapid design iteration for RF devices*
  - *access to geometries geometries that are inaccessible with conventional ceramic processing methods*

- PMCs are ideal candidates for FDM, SLA and Polyjet tools

- Nobody has yet to succeed in printing a 3D Geometry with $k > 10$ and $\tan\delta < 0.1$ above 1GHz
  - *Thermoplastic and photo-cured composites have been made that do exceed these values*

- We attempted to make our own material that could be converted into a printed material, but we did not exceed already published values

- Struggles include agglomeration, voids and ceramic phase separation
  - *We THINK all are solvable issues with adjustments to chemistry and mixing strategies*