Ceramic Materials for 5G Wireless Communications

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History of Cellular Communication

- 1G: Introduced ~ 1982 – Full Analog System
- 2G: Launched ~1991 – First Use of Digital Signals/GPRS and EDGE Technologies
- 3G: Launched ~2001 – Faster data rates
- 4G (LTE): 2011 – Current technology. Networks Strained by Content Demand (700 MHz – 2.7 GHz)
- 5G: (Est 2019 – Early 2020s)
  - 3-5 GHz and mm-Wave (20-100 GHz)
  - Higher Data Rates ~10 times faster than 4G
  - Low Latency
    - No Delays (Latency) Between Transmit and Receive Signals – i.e. autonomous vehicles
  - Increased Connectivity
    - Internet of Things (IoT); Increased capacity

What are the Advantages of 5G?

System Capacity

- 1000 x Capacity / km^2
- >10 Gbps Peak
- 100 Mbps for Every User
- Spectrum Efficiency

Mission Critical

- Low Latency (< 1 mS)
- High Reliability (99.99999%)
- High Availability
- Reduce Cost per bit

Extreme Density

- Sporadic Access
- Energy Optimized (10 yr)
- Signaling Reduction
- 1000 X Connected Devices

Key Technology Pillars for 5G

- **Millimeter Waves**:
  - Large Swaths of Unused Spectrum Above 10 GHz (28 GHz and 39 GHz being examined most closely)
  - Plenty of Bandwidth for High Data Rates
  - Higher Frequency = Shorter Distances; Huge Increases in Number of Base Stations
  - Filtering and Switching Technologies Different at Higher Frequencies (No BAW)
- **Massive MIMO**:
  - Antenna Array at Each Base Station to Direct Beam Due to Destructive Interference
  - Large Number of Users Served Simultaneously
  - mm-Wave Frequencies Miniaturizing Antennas
- **Full Duplexing (TDD):**
  - Transmit and Receive at the Same Frequency (But at Different Times)
  - Requires Efficient Switching Mechanism

Where Do Ceramics Play?

- **Dielectric Materials for Dielectric Resonators (Filters, Dielectric Resonator Antennas etc.)**
  - 3-6 GHz (High Frequency Extension of Current TM and TE Mode Microwave Dielectrics)
  - mm-Waves
    - Low Dielectric Constant, Low Loss Tangent, Temperature Stable Materials
    - Ultra-high Qf Product Materials
- **Magnetic Materials for High Frequency Isolators and Circulators**
  - 3-6 GHz: Triplate or Stripline (Below Resonance Yttrium Iron Garnet-Based Materials)
  - mm-waves: Microstrip or SIW (High Magnetization Ni-Zn Ferrite and Li-Based Spinels)
    - Microstrip Technology to 28 GHz; Substrate Integrated Waveguides for Higher Frequencies
    - Competing with GaN Switches; Isolators Much Lower Loss
- **LTCC and Ultra-Low Sintering Ceramics**
  - Low Firing Temperature Key to Integration
  - Need to Broaden Range of Dielectric Constants
- **Substrates and Integrated Ceramic Systems**
  - Integrated Dielectric-magnetic – Semiconductor Materials

Dielectrics: What are Requirements?

- **Temperature Stable Low Dielectric Constant Materials**

  Frequencies above 10 GHz will drive need for temperature stable dielectric resonator materials with high Q and dielectric constants between 6 and 18. There is currently a lack of temperature compensated materials in this range.

- **Temperature Stable Ultra-High Q Materials with Dielectric Constants < 30**

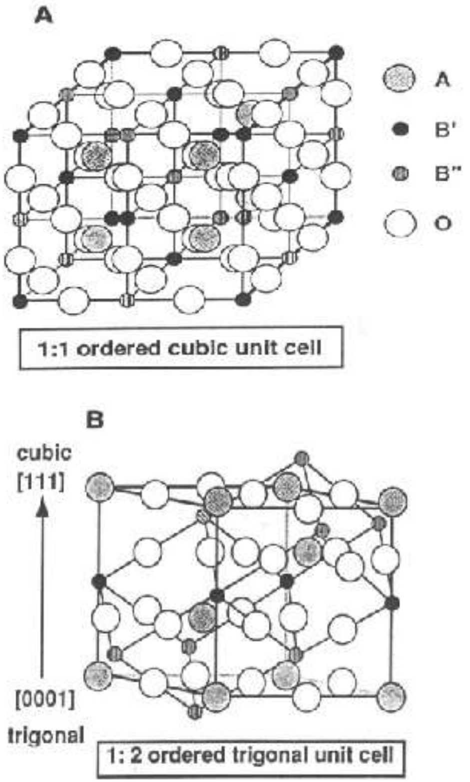
  Q decreases with frequency - The product of Qf or f/tan δ is roughly constant.   Therefore at higher f (28 GHz), need to have extremely high Q non dispersive materials to get usable loss tangents.

Table of Potential Low Dielectric Constant Materials

Material	ε'	Qf > 50000	τ_F near 0	Comments
Cordierite	4-5	112500	No	Skyworks RFC D4
Eucryptite $LiAlSiO_4$	5.3	80000	+8	Li a challenge Corning ware crystal
Li_2MgSiO_4	5.6	80000	+8	
Forsterite + Cordierite	6.0	No	-60 to -100	Skyworks RFC D6 (modified)
Forsterite (Mg_2SiO_4)	6.6	No	-60 to -100	Skyworks RFC D6
Willemite (Zn_2SiO_4)	6.6-7.5	147000	-22	Attempts to synthesize high Q material unsuccessful
Celsian $(Sr,Ba)Al_2Si_2O_8$	7.2	77000	-22	Radome material
Spinel ($MgAl_2O_4$)	8.5	105000	-63	Spinel a commodity material
Alumina (Al_2O_3)	10.0	634000	-40	Electrical Grade alumina a commodity material

Ultra-Low Loss Tangent Dielectric Materials

- **Highest Q "Super Q" Materials Have Qf Products Greater Than 80000 at 2 GHz**
- **Barium-Based Perovskites Containing Tantalum, Tungsten or Niobium**
  - ABO_3 Formula:
    - A site: 12 Coordinate Ba
    - B site: 6 Coordinate Zn,Co,Ti,Nb,Ta
  - Disordered
    - Random occupation of B-sites
  - 1:1 Ordered (Ba_2MgWO_6)
    - Rock Salt Structure B-site occupation
  - 2:1 Ordered ($Ba_3ZnTa_2O_9$)
    - Layered B-site occupation
- **Antiphase Domain Boundaries Problematic**
- **Industry Standard "High Q" Material**
  - $Ba_3ZnTa_2O_9$
  - Skyworks RF Ceramics 29XX Series Material. Qf > 90000



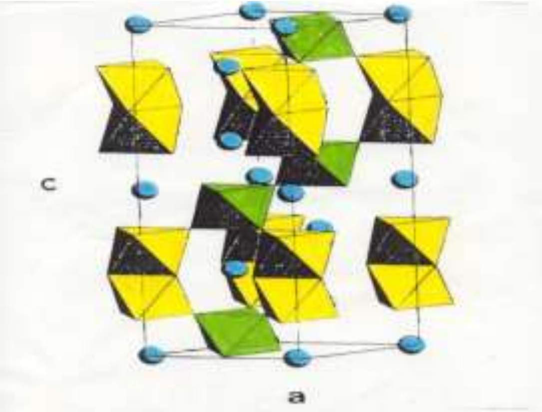
Davies et. al (1997)

Hexagonal Perovskite Additions Enhance Q in Perovskite Niobates and Tantalates

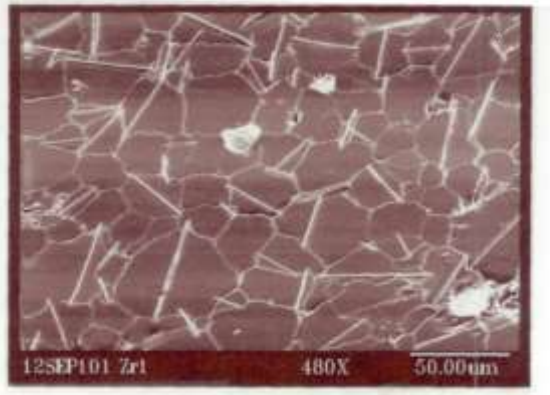
- Approach is to add materials forming hexagonal perovskites so that cation vacancies can remove excess positive charge at grain boundaries

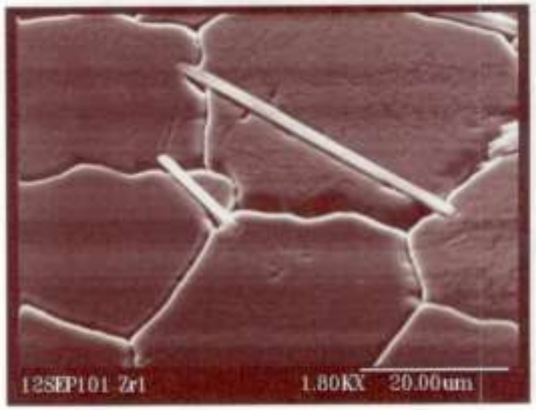
- $Ba_8(Zn,Co)Nb_6O_{24}$ (816) is added to enhance Q

- 8-layer hexagonal perovskites isostructural with $Ba_4LiTa_3O_{12}$ (Negas and Roth) and $Ba_8NiTa_6O_{24}$ (Abakumov)

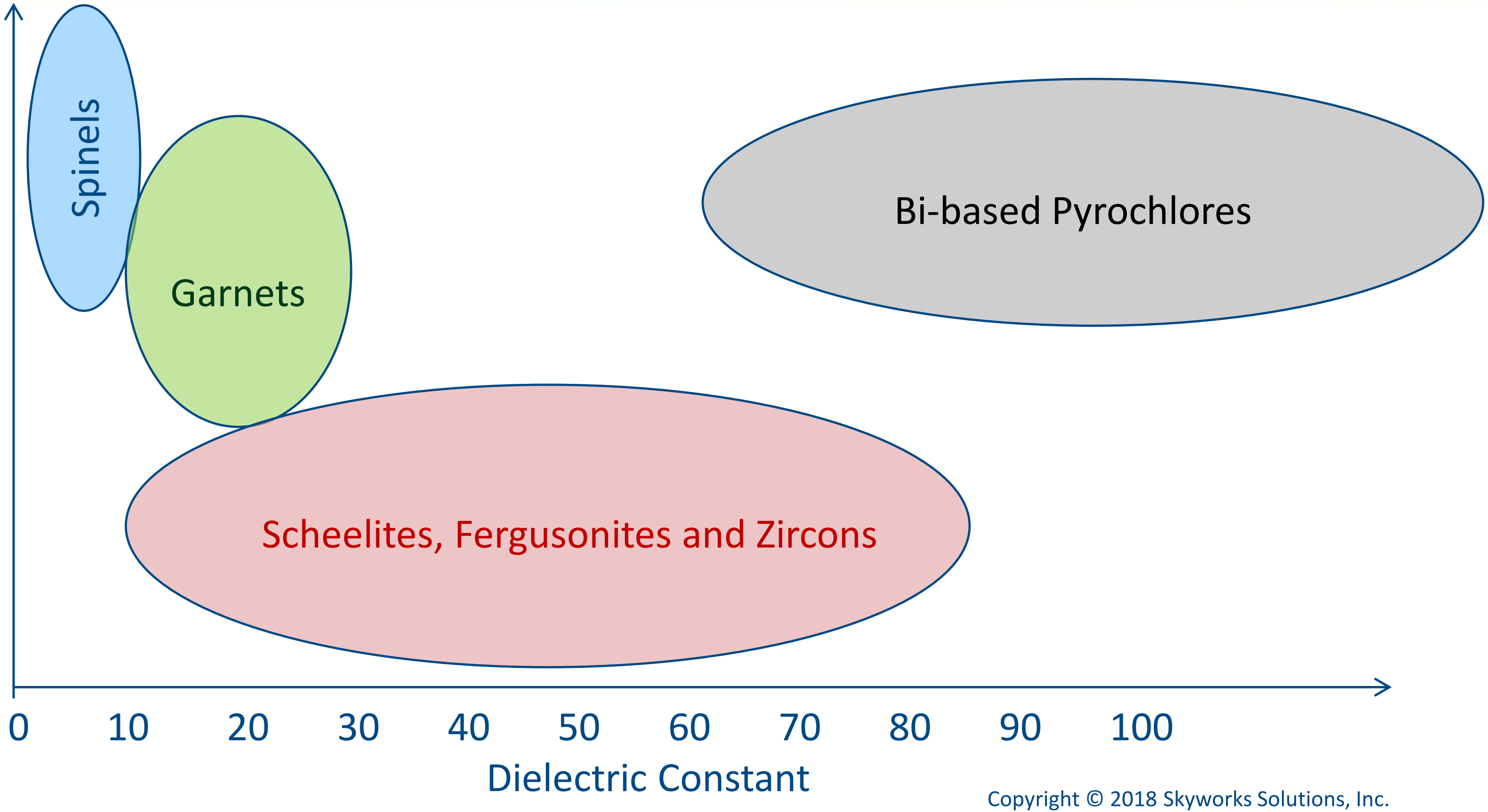


Abakumov, Van Tendeloo, Scheglov, Shpanchenko and Antipov (1996)





LTCC Material Systems for Higher Dielectric Constants

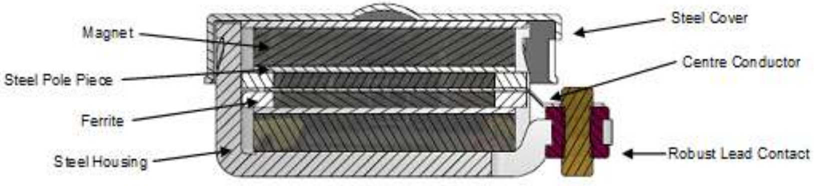


Ceramic vs. Polymeric Materials for mm-Wave applications

	Polymers (or Ceramic Filled Polymers)	Ceramics
Advantages	- Easily conformal - Low Dielectric Constants easily achievable - Established technology (FR4 and Rogers) - Low temperature processes to directly integrate with other components	- Low dielectric loss - Can be designed with excellent thermal stability of dielectric properties - Good thermal management - Large range of dielectric constants available - Relative ease of metallization - Magnetic Properties - Absorber Properties - Incorporated as filler in polymeric substrates
Disadvantages	- High Dielectric Loss - Poor thermal stability of dielectric constant - Poor thermal management (thermal conductivity) - Limited range of dielectric constants available - Limited range of materials for metallization - Limited mechanical stability in thin sections	- Difficult for conformal shapes (Planar processing technology favored) - Specialty materials more expensive - LTCC established technology (planar) but with limited range of dielectric constants - Tricky to directly integrate with other components (Co-fire process)

Co-Fired Assemblies

- Co-Fired Assemblies: Co-fire certain combinations of ferrite and dielectric material, where the ‘green’ dielectric sleeve is sintered around the fired ferrite rod
- Eliminates lossy glue at interface
- In a stripline junction circulator, the ferrite (and dielectric) is the filler between the conductor and the ground plane. Improving the contact surface between the ferrite and the ground plane improves insertion loss
- Thick film sliver applied to co-fired assemblies further improves insertion loss. Improved contact with removal of air gaps, rough surfaces



Old Method

Co-fired

Next Level Integration

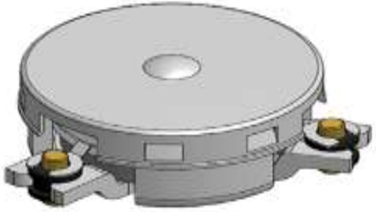
- **Using Co-Fire Process, We Can Embed Ferrite Material in a Dielectric Tile and Metalize Both the Circulator Circuit and Ground Plane**

- **Thin Ferrite Disc is Easier to Magnetise Uniformly**

- **Dielectric Area Available for the Addition of Other Components**
  - e.g. Coupler, Switch and Load
  - More space if TTHiE is used
  - Insertion loss of added components improved due to lower dielectric loss and better temperature stability of the dielectric relative to polymers or semiconductors

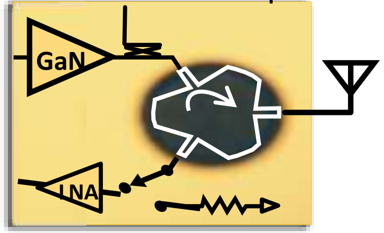
- **New “Co-Fire” Materials and Material Combinations an Enabling Technology**

Current Product



Next Generation

Circulator-Integrated Substrate Concept



Conclusions

- 5G Systems Expected to be Deployed by ~2020
  - Technology Still Needs to be Determined
  - Dielectric Materials Should be Key Ceramic Materials for 5G
  - Low Dielectric Constant Materials
  - Ultra-Low Loss Tangent Materials
  - LTCC Type Materials for Co-Firing; Low Temperature Firing Ceramics will be Enabling Technology
- Technology "Battles" Need to be Resolved
  - Isolators vs. GaN Switches
  - LTCC (Ceramic) vs. Polymer for Substrates, MIMO Antennas
  - Ferrite based circulator vs. semiconductor based circulator for full duplexing