Development of a Monolithic Ceramic Electrostatic Ion Thruster for Interplanetary SmallSat Missions

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Overview

- Background
- LTCC Technology
- The LTCC-ET
- Test Articles and Testing
- Lessons Learned, Future Work and Closing Thoughts
Research Background

• Context: +C3 ride share opportunities on the horizon are increasing (SLS EM1, SpaceX BFR, etc)

• Goal: To develop a propulsion system suited for interplanetary CubeSat missions

• Critical Requirements...
  – Low power
  – Compact
  – High Delta-V
Strategy

• Develop a new propulsion system architecture
  – High $I_{sp}$
    • Electrostatic RF design
  – Long thruster lifetime
    • Protect electrodes by embedding them in ceramic
  – Affordable $\rightarrow$ Scalable Manufacturing
    • Use a ‘PCB-like’ process to afford design complexity without increasing manufacturing complexity
  – High propellant density
    • ‘In the works’
Low Temperature Cofired Ceramic

• Process realizes monolithic structures
• Low dielectric loss tangent
• High temperature resilience
• Typically used as a substrate for multi-chip modules, MEMS, power devices
Low Temperature Cofired Ceramic
The LTCC-ET

• Embed RF antenna, screen electrodes, and cavities in a monolithic ceramic structure
  – Ceramic is durable to increase grid lifetime
• Design is tolerant to very high temperatures
  – Leakage current won’t show up until ~450°C
• Manufacturing process is scalable
• Additional complexity doesn’t add cost
LTCC-ET Layer Stackup

L1: Accelerating Electrodes
L2: Screen Electrodes
L3: Small Cavities
L4: Medium Cavities
L5: Large Cavities
L6: RF Antenna
L7: Ground Plane
LTCC-ET Stack Overview

Layer 1
Layer 2
Layer 3
Layer 4

Layer 5
Layer 6
Layer 7

Schematic

Plasma Cavity
Electrical and Mechanical Structure

CAD visualization of how the internal cavities in the LTCC-ET add up to form a propellant manifold, plasma cavity, and propellant outlet ports.

CAD model of the plasma cavity with ceramic removed and color added for visual clarity. The red structure is the RF antenna, the green structure is the Screen electrode, and the blue structures are the via post-wall.
LTCC-ET Fabrication

Layers 2 & 6

Layer 3

Layer 4

Layer 5
LTCC-ET Fabrication

Layers 2 & 6

Partially Completed Stack

Laminated Device before Firing

Finished Device
Final layout of 9k7 Module3 & 4

Stack orientation:
- 10mil → L1-1
- 10milx5 → L1-2
- 10mil → L2
- 10milx4 → L3-1
- 10milx4 → L3-2
- 10milx4 → L4-1
- 10milx4 → L4-2
- 10milx4 → L5-1
- 10milx4 → L5-2
- 5mil → L6
- 10mil → L7-1
- 10milx4 → L7-2
- 10mil → L7-3
- 10milx4 → L7-2
- 10mil → L7-3

Lamination:
- 3000psi
- 2500psi

Cofire paste:
- L2 top

Post paste:
- L7-1 top

Tape: 9k7(10mil)
Trace: LL612(Ag)
Vias: LL601(Ag)
Solderable pad and ground: Cofire LL617 and post fire 6277(Ag/Pd)
Setter: Alumina plate for 9k7
The LTCC-ET Test Articles
LTCC-ET Testing Goals

1. Ignite a plasma – COMPLETED!
2. Determine ignition power as a function of propellant flow rate
3. Characterize thrust as a function of accelerating grid voltage
Testing was conducted at the High-Power Plasma Propulsion and Diagnostics Laboratory at NASA’s Marshall Space Flight Center (MSFC) in Huntsville, Alabama in June 2018
Lessons Learned so Far

• We lit a Plasma the very first day we tried!
  – It takes 10’s of Watts to ignite a plasma, yikes!
• There is much more work to be done!
• Impedance matching is better than anticipated
• Plume exhaust ports are MUCH to large
• Power requirements are higher than needed because the pressure in the chamber is too low
• The gas distribution (manifold) is woefully inadequate to maintain reasonable chamber pressure
• Testing was hampered by under-spec’d RF connectors failing as the power requirements were significantly higher than anticipated
Future Work

• Improve gas distribution with branching feed network
• Improve antenna
• Reduce orifice size to increase cavity pressure
• Decrease power needs
• Incorporate multiple independent grids

Continuously branching feed network
Closing Thoughts

• The test articles were fabricated as a manufacturing experiment and were never designed for test (I never thought I would have the opportunity to test these articles).

• The LTCC-ET was designed over the course of a week due to a very narrow window of opportunity for fabrication; it works pretty well considering that fact.

• No modeling, simulation, or analytical work was done for the test articles (no time) so it isn’t surprising that performance is lackluster.
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