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A Cathode Support Structure for Use in a Magnetron Oscillator Experiment

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Abstract

A Low Temperature Cofired Ceramic (LTCC) material system has been used to develop a protype field emission cathode structure for use in an experimental magnetron oscillator. The structure is designed for used with 30 Gated Field Emission Array (GFEA) die electrically connected through silver metal traces and electrical vias. To approximate a cylinder, the cathode structure (48 mm long and 13.7 mm in diameter) is comprised of 10 faceted plates which cover the GFEA dies. Slits in the facet plates allow electron injection. The GFEA die (3 mm x 8 mm) are placed in axial columns of 3 and spaced azimuthally around a cylindrical support structure in a staggered configuration resulting in 10 azimuthal locations. LTCC manufacturing techniques were developed in order to fabricate the newly designed cathode with 7 layers wrapped to form the cylinder with electrical traces and vias. Two different cathode wrapping techniques and two different via filling techniques were studied and compared. Two different facet plate manufacturing techniques were studied. Finally, four different support stand configurations for firing the cylindrical structure were also compared with a square post stand having the best circularity and linearity measurements of the fired structure.

Introduction

Magnetrons are microwave oscillators used in radar, communications, industrial heating, and home use for microwave ovens (1,2). Magnetrons comprise an electron source (cathode), a radio frequency (RF) slow-wave circuit (anode), and an applied magnetic field perpendicular to the electric field between the cathode and anode. Injected electrons from the cathode spin around the cylindrical cathode because of the crossed electric and magnetic fields. Traditional magnetron cathodes use thermionic emission in which a conductive material is heated to a high

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enough temperature to generate electron emission (1). This process, while robust and widely used, offers no control of emission as a function of position or time. It allows for ion back-bombardment, which can damage the cathode and keep it in a heated emitting state (3). Because magnetrons are free running oscillators, phase locking requires external equipment which is expensive at high power. Therefore, there is a need for an internal injection locking method to control magnetron phase (4).

This work discusses the development of a new cathode structure which uses Gated Field Emission Arrays (GFEAs) (5,6,7,8) to replace the traditional thermionic cathodes. GFEAs can be modulated in time and addressed spatially using numerous devices spaced out around the device (3). This paper describes the development of such a cathode structure using DuPont 951 Low Temperature Co-fired Ceramic (LTCC) (9) to connect and support GFEA die in a configuration which allows the structure to replace a helical shaped thermionic cathode used in the L3Harris Technologies industrial CWM75KW magnetron (10). We present background information on magnetrons and then the detailed structure design and fabrication techniques followed by fabrication results.

Magnetron Approach

The experimental approach utilizes the CWM75KW industrial magnetron from L3Harris Technologies. This magnetron is strapped and has 10 anode cavities to provide a resonant frequency for the primary oscillation mode between 900-915 MHz. The magnetron typically operates with a cathode voltage of -17 kV, a current of 5 A, and a magnetic field of 1800 G. At these conditions the magnetron can generate 75 kW of RF power with nearly 90% efficiency. The magnetron uses a helically shaped wire cathode. The cylinder surface formed by the helix is 13.7 mm (0.54 in) in diameter and 48 mm (1.89 in) in length. Current is driven through this wire to generate thermionic emission, and electrons are accelerated from the wire by the electric field generated between the anode and cathode. For this project, the helical cathode has been replaced by a 10-sided faceted cathode, as shown in the drawing in Figure 1. The anode, which is a 10- cavity circuit, is 80 mm (3.15 in) in length, 13.64 mm (0.537 in) from the facet plate flat to flat, and 8.64 mm (0.34 in) in inner diameter. The cylindrical emission area, however, is still 13.7 mm (0.54 in) from facet plate edge to edge (outer diameter) and 48 mm (1.89 in) in length. The anode circuit is fabricated from copper and includes water cooling channels. In this drawing, the faceted cathode is seen in place of the helical cathode with 10-sides to match the cavity geometry and to approximate a cylinder. Slits in the facet plates allow the electron injection into the interaction region. These “hop funnel” structures (11) protect the GFEAs placed below from ion back-bombardment.

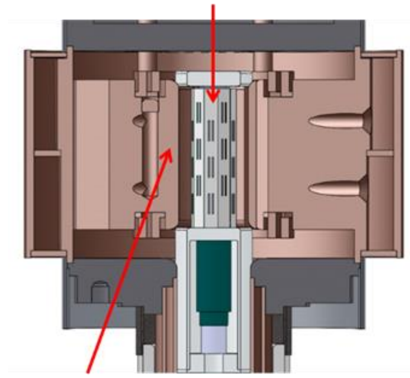

Figure 1. Cross-sectional drawing of the magnetron structure showing the anode and the 10-sided faceted cathode with slits. The slits in each facet are at the locations of the GFEA die.

In this new structure, DuPont 951 Low Temperature Co-fired Ceramic (LTCC) was used for the structure along with several types of silver paste. Our group has used LTCC extensively in vacuum systems for a variety of experiments. Pressure measurement in three different vacuum test systems have achieved pressure of <10^{-8} Torr when using various LTCC structures and silver pastes. These results show negligible outgassing compared to operations when the LTCC is not present, so the material has acceptable vacuum compatibility. Experiments have also been performed up to 400C to test LTCC and silver paste compatibility. While there was no evidence of issues with the LTCC outgassing, some silver paste would evaporate. This issue can be remedied in our magnetron design by ensuring encapsulation with a layer of LTCC which prevents the contamination or by selection of alternative pastes.

The new cathode structure described here uses a modulated cathode comprised of GFEAs (3). These emitters generate electrons from field emission and are described by Fowler-Nordheim tunneling. Because these devices can be micro-fabricated into addressable arrays, these cathodes can emit electrons at specific locations and times rather than continuously (thermionic emission). The new cathode offers several advantages over the traditional cathode. The field emitters can be turned off and on using the relatively low (<60 V) gate voltage. Spatial modulation may improve performance by injecting electrons at optimal locations to minimize startup times and increase efficiency. Lastly, the temporal modulation could control the electron spoke formation and allow for phase-locking (3,4).

Shown in Figure 2a is a pictorial representation of the GFEA die, and shown in Figure 2b is a microscope image of an actual GFEA die used in the project. These 2.5 mm wide by 8 mm long die are placed axially along the cathode structure with 3 die per facet plate structure for a total of 30 GFEA die for the entire cathode structure. These GFEAs are fabricated using the process described here (8,12). Each die has 2 elements to match the 2 slits in the facet plates. Electrons are then extracted through these slits.

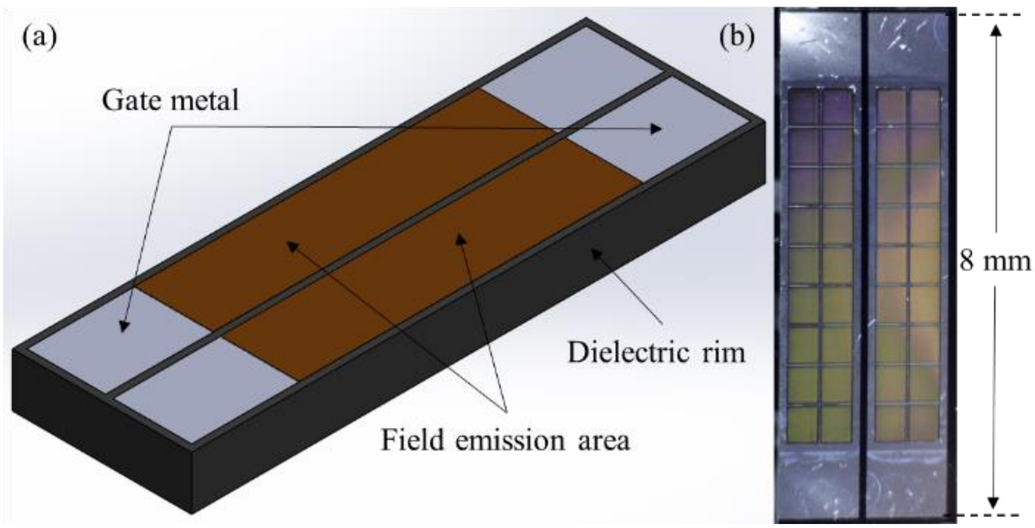

Figure 2. (a) Gated vacuum field emitter diagram and (b) photograph of a die provided by Akinwande [12]. Each GFEA die is divided into 2 sections to allow spatial addressing. Each addressable section is subdivided into a mesh to improve emission uniformity.

Design

The new cathode that replaces the old thermionic emission cathode has a GFEA die on every side of the cylindrical structure with facet plates that protect the die. The die are electrically addressed by an RF stripline circuit (13), which is an impedance matched transmission line that is sandwiched between two ground planes. Figure 3a shows a diagram of a basic stripline which is comprised of a ground plane, dielectric layer, transmission line (trace), another dielectric layer, and another ground plane. The addressable cathode structure approach uses different elements of the 30 die to emit electrons at different points in time (3,4). By creating a “barber pole” type transmission line, an RF drive signal applied to the line will propagate around the cylinder applying a drive signal to the GFEA gate electrodes at different times resulting in a phase difference among the drive locations. The structure is designed such that each emitter element of the GFEA is turned on 25% of the time as there are 4 phase elements. Because the

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magnetron has 5 electron spokes, 5 locations are turned on simultaneously spaced azimuthally around the cathode. Then these elements turn off as the next elements turn on as described in prior work [3,4].

The physical characteristics of the stripline (H, T, and W dimensions) and material properties directly relate to the electrical properties of the stripline particularly the characteristic impedance. Figure 3b shows a diagram of the stripline with the die that will be used for the cathode structure. For the cathode structure, die rests on top of the second ground plane, and an electrical via is used to complete the transmission line to die connection. This via passes through a hole in the top ground plane (via clearance hole) that must be large enough to prevent shorting between the ground plane and the via. The via to die connection is formed using a silver paste to create a conducting jumper. This jumper is applied by hand once the die is connected to the structure and is shown in Figure 3b, colored yellow for clarity. Because each die has two emission areas, each die requires two electrical connections, one on each side as shown in Figure 3b. For the cathode structure, these connections are above and below each die.

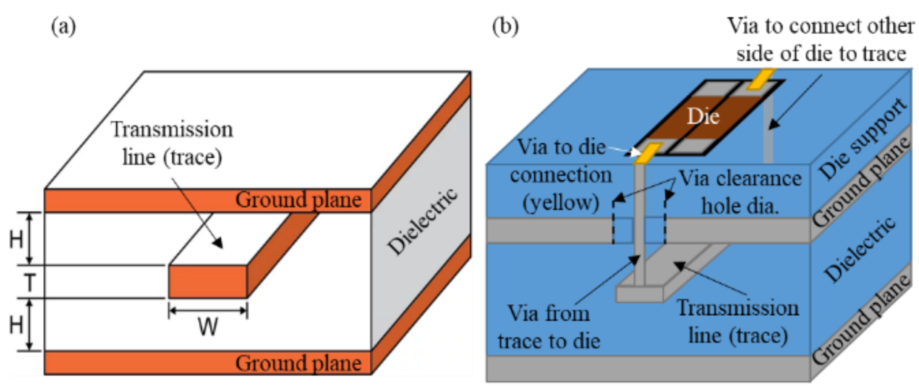

Figure 3. (a) Basic stripline (13) and (b) cathode structure stripline with die diagram. The central transmission line trace carries the RF signal and the dimensions of the structure determine the characteristic impedance. For the cathode structure shown in (b), a metal via connects to the trace to provide the RF signal to the gate of the GFEA die. A jumper connects the via to the die conductor metal.

This cathode structure is comprised of a number of structural layers as shown in Figure. 4. The new cathode structure has 7 layers including (working outward radially): an internal first ground plane (L1, Figure 4a), a dielectric layer with a stripline trace (L2, Figure 4b), another dielectric layer with a second ground plane (L3&4, Figure 4c), die support layers with die slots (L5-7, Figure 4d), and finally facet plates with die placed in the slots of the cathode structure (Figure 4e) to complete the full cathode assembly. To connect to all the vias, the trace layer needs to spiral around the cathode structure in a "barber pole" style, as shown in Figure 4b.

The new cathode specifications and dimensional constraints are based upon the L3Harris Technologies magnetron (10). The stripline characteristics are such that each azimuthal revolution of the traces will result in an RF signal that will be 90° out of phase from the previous die. This phase delay will cause all three of the die aligned vertically to emit at the same time at 5 different azimuthal locations. The transmission line (for the stripline) starts from the bottom of the cathode where the line splits into five traces and then spirals around the cathode. Each of the five sublines connect to six die each (totaling 30 die) through holes in the top (outer) ground plane. The five sublines then merge back together and terminate into a 50 Ω resistor. The RF drive signal connects to the transmission line through a coaxial wire attached onto the bottom of the cathode structure.

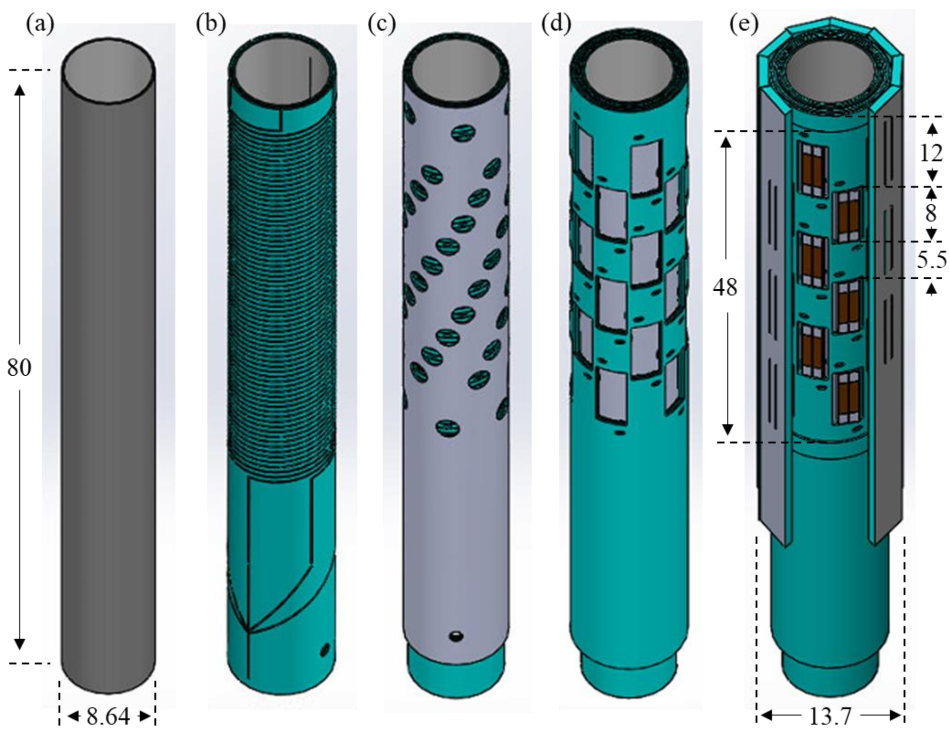

Figure 4. Cathode layers radially: (a) first ground plane, (b) dielectric with stripline barber pole trace divided into 5 separate lines, (c) dielectric with second ground plane and openings for vias, (d) die support layer with openings for die placement, and (e) facet plates with electron extraction slits and with uncovered die. All dimensions are mm.

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To accommodate the stripline (transmission line) and internal electrical connections, the seven individual layers of LTCC are rolled up into a tube shape starting from the inner layer 1 to the outer layer 7 as seen in Figure 4. There is a silver paste layer on the inside of layer 1 (0.005" or 5 mil thick) that acts as the first ground plane. Layer 2 (10 mil) has the stripline screen-printed onto the outside, creating a 15 mil LTCC separation (dielectric) from the first ground plane to the transmission line. Layer 3 (10 mil) has a screen-printed jumper on the inside, to connect the transmission line (outside layer 2) across the seam on layer 2. This layer 3 has vias cut out of the LTCC to start the transmission line to die connection (layers 3 to 7). Figure 5 shows three-dimensional and two-dimensional cross-sectional views of the cathode structure design without die, spacers, or facet plates.

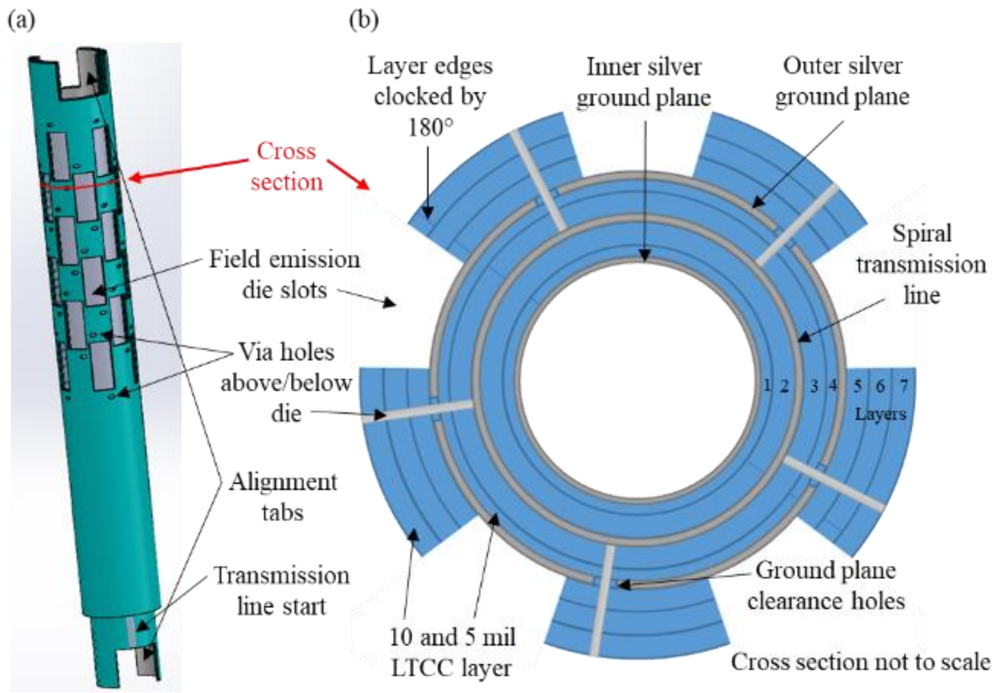

Figure 5. (a) 3-D cathode structure showing slots for die and via holes with the silver ground planes seen at the inside of each slot and (b) 2-D cross section of the cathode structure showing the various LTCC and trace layers as well as the slots for the GFEA die (not shown).

Layer 4 (5 mil) has a silver paste layer on the outside to act as the second ground plane. Once again, another 15-mil gap (layers 3 and 4) forms the transmission line (layer 2) to the second ground plane. This layer 4 also has vias cut out of the LTCC to allow for the transmission line to die connection. Because of the vias, the ground plane has holes (ground plane clearance holes) to prevent shorting between the ground plane and the vias. The two ground planes

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are connected by a single via (ground via), away from the others, from layers 1 to 4. Layers 5, 6, and 7 are primarily used for structural support and to form the slots for the GFEA die which are intended to be flush with the top layer 7. The spacers are used to separate the die from the facet plates which are attached to the exterior of the cathode structure using ceramic epoxy, as shown in Figure 6. The backside of each die is coated with a silver paint, and then when the die is placed in its slot, additional silver paint is used to make the electrical connection from the die backside to the ground plane. The facet plates act as hop funnels that direct the electrons emitted from the die into the magnetron interaction space (11). Besides increasing uniformity of electron emission, these hop funnels also protect the die from ion back-bombardment, which over time could destroy the die. Hop funnels operate by reaching a steady-state balance between secondary electron emission and primary electron impact from the GFEAs. As such, the hop funnels operate at unity gain (100% effective transmission) with the correct operating voltage. For this design roughly 500 V is needed across the funnel. In addition, the charge redistribution which occurs in the funnel greatly homogenizes the electron beam. This effect results in a uniform emission even when the electron source is not uniform or when the funnel is not well-aligned to the electron course.

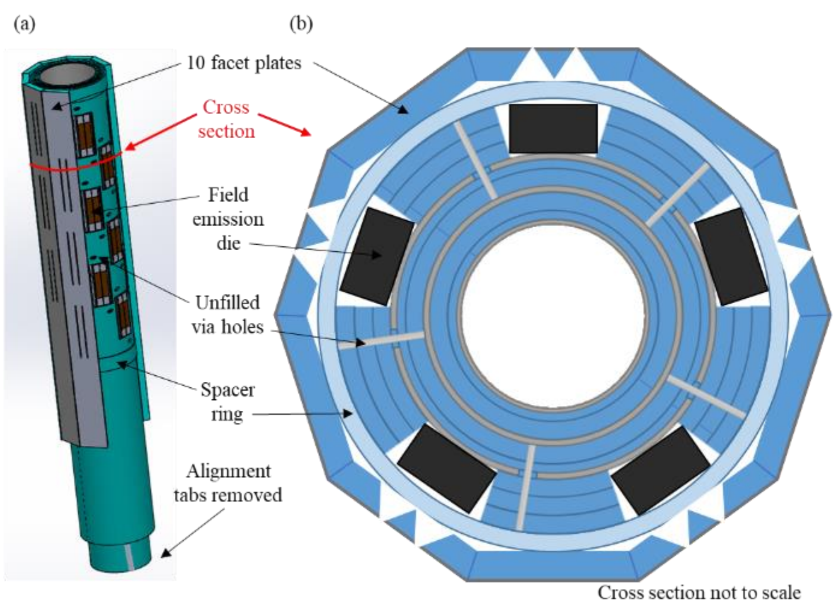

Figure 6. (a) 3-D cathode structure and (b) 2-D cross section of the entire assembly showing the GFEA die and facet plates in place. Note that at this cross section 5 die locations are shown.

Fabrication

All of the techniques discussed in this section will directly correspond to manufacturing steps for producing the multilayered cathode structure. The processing techniques are grouped as (a) LTCC rolling/wrapping, (b) via filling, (c) machining/facet plates, and (d) firing techniques. The major cathode structure manufacturing process consists of:

- All seven layers of LTCC are cut and cleaned and conductive paste is applied to the layer surfaces and vias (via filling). These vias complete the transmission line to die connection.
- All seven LTCC layers are rolled onto the jig (LTCC wrapping) and then laminated into the cathode structure.
- The electron hop funnels (facet plates) that protect the die and increase uniformity of the emission source are manufactured.
- The cathode structure (firing technique) and facet plates are placed into a furnace where they are fired.

LTCC Rolling

Two techniques were studied for rolling the LTCC into the cylindrical structures: layer by layer and layer by group. The layer by layer technique is the process of wrapping one layer on the jig at a time and then laminating after all seven layers have been wrapped. Layer 1 is wrapped and bonded to the jig using poly 2-ethyl-2-oxazoline (PEOX). PEOX is a glue that is used to bond LTCC layers in the green state with minimal lamination pressure. Layer 2 is laid out flat, and PEOX is applied to the surface, near the edge used to align with layer 1. The jig with layer 1 is then placed on layer 2, using the alignment tabs to align, and held down until the PEOX dries (~30 seconds) as shown in Figure 7.

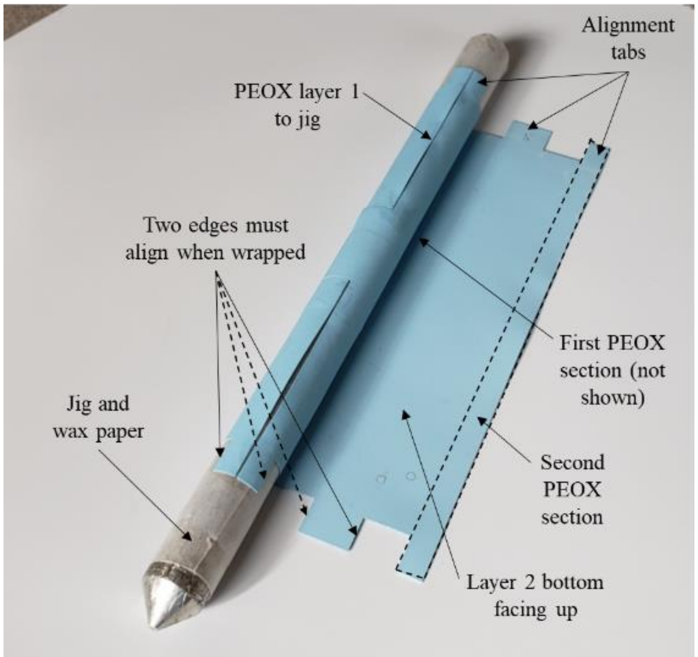

Figure 7. Layer by layer technique: layer 1 has been completely wrapped around the jig and layer 2 is about to be wrapped. The jig is covered with wax paper to prevent sticking. Alignment tabs help with alignment during wrapping, and PEOX holds the structure together prior to lamination.

More PEOX is applied to the other surface near the edge of layer 2 and then the jig is rolled, wrapping layer 2 onto the jig. The process is then repeated for all the remaining layers. Finally, the spacer strips are rolled on using PEOX, and the cathode structure is placed in the isostatic press to be laminated. In the lamination process for DuPont 951 series, LTCC is pressed under 20.7 MPa (3 Ksi) at 70°C (158°F) for 10 min (14).

The layer by group technique involves gluing multiple layers together flat and then wrapping the whole group in one or multiple rolls. Layers 1 to 4 are overlapped about halfway on top of each other, using the fiducial marks and tabs to align. Then all four layers are glued together using a minimal amount of PEOX. This layer 1 to 4 strip is shown in Figure 8. Once the PEOX dries, the layers create an almost continuous layer that can be rolled altogether at one time without gluing layer 1 to the jig. Layer 5 is then aligned using the fiducial marks and rolled on using the layer by layer technique previously discussed.

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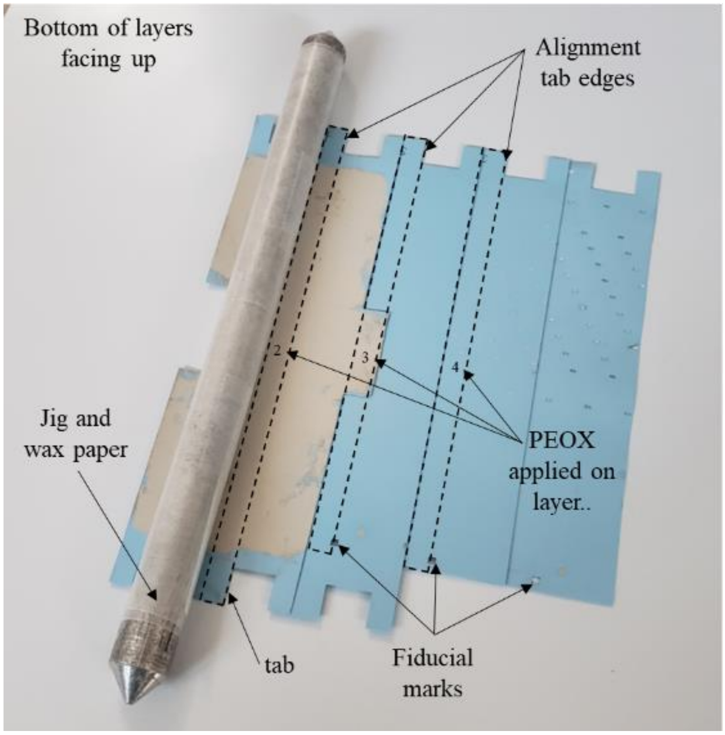

Figure 8. Layer by group technique: layers 1 to 4 have been glued together with PEOX and are about to be wrapped around the jig which is covered with wax paper to prevent sticking. Fiducial marks help with alignment during wrapping, and PEOX holds the structure together prior to lamination.

At this point the cathode structure is placed in the isostatic press where it is laminated at half the normal pressure, 10.35 MPa (1.5 Ksi) at 70°C (158°F) for 10 min. After lamination, layers 1 to 5 are securely bonded together which makes rolling layers 6 and 7 using the layer by layer technique very easy. Finally, the spacer strips are rolled on using PEOX, and the cathode structure is placed in the isostatic press to be laminated at half pressure for a second time. Laminating the cathode in stages, also known as progressive lamination, adds to the structural integrity of the cathode (15).

Note that in order to have electrical continuity along the stripline, it is necessary for the traces to connect across the gap which forms in the LTCC when it is wound into a cylinder. To accomplish this connection, the traces are fabricated on both the inner and outer layers of the LTCC region containing the traces. For the outer layer, only a short "jumper" section of silver paste is used. This layer is mechanically clocked relative to the inner layer so that the jumper connects the trace across the seam in the LTCC.

Via Filling

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Two via filling techniques are described: flat fill and pneumatic fill. The flat fill techniques fills all the vias one layer at a time in a flat layout before the layer is rolled. The LTCC sheets are shipped on a white non-stick mylar paper that is required for this technique. An LTCC cathode structure layer is placed on top of the non-sticky side of the white mylar paper, which should then be placed on a flat surface. Next, a via stencil is placed on top of the LTCC layer, as shown in Figure 9. These stencils were made using a laser cutter to cut out only the via patterns for each layer; thus layers 3 to 7 have their own unique stencil. Once the via holes on the layer and stencil are aligned, silver paste is pushed across the stencil with a squeegee, pushing paste through the stencil into the vias on the LTCC layer.

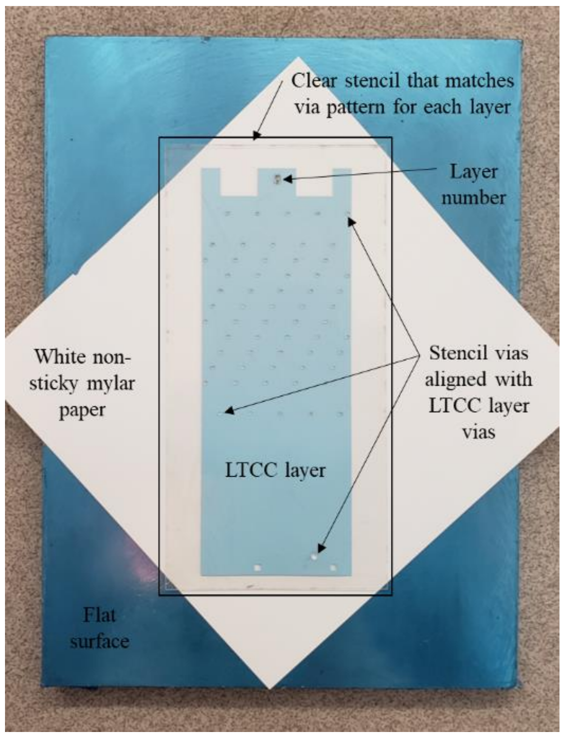

Figure 9. Flat fill technique: Stencil is placed on top of layer 3 which is placed on top of non-sticky mylar; then paste is squeegeed across the stencil.

After all the vias are filled, the stencil is carefully removed and the LTCC layer plus mylar paper are placed into the heater (mylar paper down) to dry for a specific temperature and time. The temperatures and times specified in Table 1 correspond to the silver paste that was used to fill the vias. The times and temperatures for the Ferro 903-A (16), DuPont 6145 (17), and DuPont 6141 (18) were taken from the literature and confirmed through testing. Testing comprised of filling the vias on a 10-mil thick LTCC layer (layer 3) and a 5-mil thick LTCC layer (layer 4) for all three silver pastes using the flat fill technique previously discussed. All three of the silver pastes dried completely, adhering to the inside of the vias for both LTCC layer thicknesses, confirming that the drying temperatures and times are correct.

Table 1. Drying temperatures and times for three different silver pastes used for the via filling process.

Silver Paste	Temperature (°C, °F)	Time (minutes)
Ferro 903-A (conductor)	70, 158	30
DuPont 6145 (conductor)	110, 230	10
DuPont 6141 (via fill)	110, 230	5

After the silver paste has dried, the LTCC layer and mylar paper are removed from the heater. The mylar paper is removed from the layer (sliding or rolling motion). Occasionally, a small amount of silver paste residue will be left on the mylar paper. Place the LTCC layer (side that was touching the mylar paper face up) back into the heater at the same temperature previously used for 5 minutes. Remove the LTCC layer from the heater and allow to cool for another 5 minutes before rolling or processing.

In the pneumatic pump technique, each via tube-like structure is filled after the cathode has been wrapped and laminated. This technique can be used with either the layer by layer or the layer by group LTCC wrapping techniques. After wrapping layers 1 to 5 on the jig and laminating, the vias are filled using a pneumatic pump. The silver paste is loaded into a large syringe that is attached to the pump. The cathode is placed horizontally on a 3-D printed stand, shown in Figure 10. Using an SRA-105 pneumatic pump, pressurized air is applied to the rear of the syringe which pushes paste out of a custom 200 µm (0.008 in) diameter nozzle. The syringe is guided by hand to place the nozzle at the top (opening) of each via. The pump is activated by pressing a button that opens the pressure valve for approximately one second. By adjusting the pressure, the entire via can be filled with one push of the button.

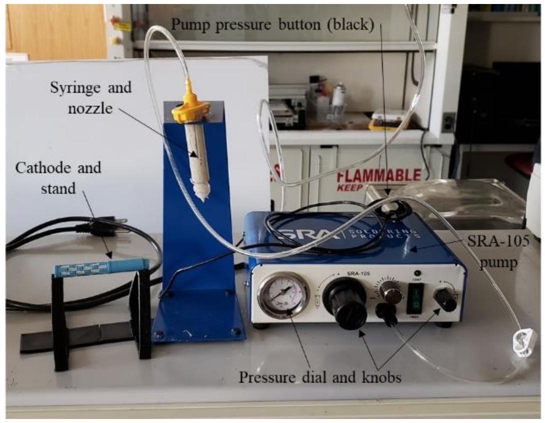

Figure 10. Photograph of the pneumatic pump setup showing the pump, syringe and nozzle, and a cathode structure on a support stand (lower left).

The required pressure for the Ferro 903-A/DuPont 6145 paste was ~0.21 MPa (30 psi), and the pressure for the DuPont 6141 was ~0.55 MPa (80 psi). These pressure differences are due to the differences in paste viscosity. The Ferro 903-A and DuPont 6145 paste have a viscosity of ~200 and ~160 PaS, respectively while the DuPont 6141 has a viscosity of ~2100 PaS. Because the pressure could be easily adjusted with the turn of a knob, these pressures were determined with a trial and error approach. After all 60 of the vias are filled, the cathode is placed in the heater at ~70°C (158°F) for 10 min, regardless of the paste used. This process dries the paste enough that layers 6 and 7 can be wrapped and that the whole cathode to be laminated for the last time.

Facet Plate Manufacturing

Two techniques were studied for fabricating the slits in the facet plates: laser milling and mechanical milling. Both techniques require the same initial starting block of LTCC. This block is made by laminating five rectangles with area 76.2 mm by 127 mm (3 in by 5 in) of 10-mil thick LTCC together under 20.7 MPa (3 ksi) at 70°C (158°F) for 10 min. This will give a block of LTCC that has enough area to cut out all ten facet plates with a thickness (~1.2 mm) that will shrink once fired to the desired 1 mm. The laser technique uses an M-300 Universal laser to cut the desired geometry of the facet plates. The aforementioned block of LTCC is placed into the laser setup where the facet plate outline is cut twice. Both cuts are applied to the slots and outline of the facet plates to achieve the desired 'V' shape slots and angled edges of ~36°. The laser milling process works by focusing the beam at a single point (focal point). Normal (single sheet) LTCC cutting operations cut at this focal point to give close to vertical edges (perpendicular to cutting bed). By raising and lowering the laser height (Z-height), the vertical cut becomes a slanted cut, in theory, as shown in Figure 11.

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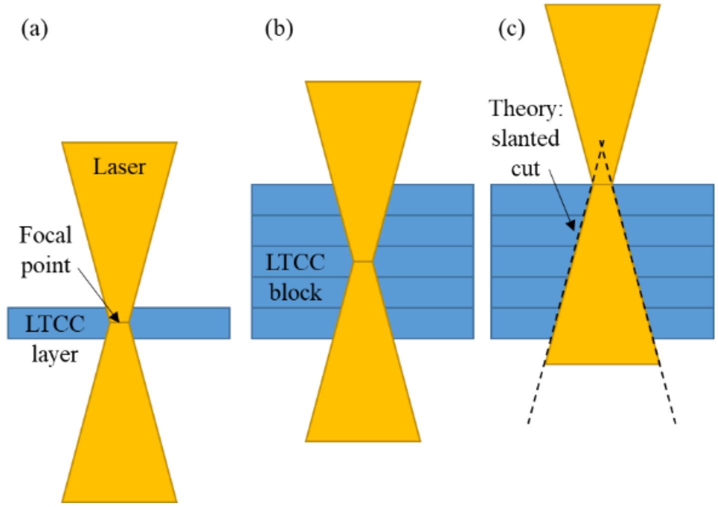

Figure 11. Laser milling techniques for (a) Normal Z-height, (b) cut 1, and (c) cut 2 to form tapered slits for the hop funnels in the facet plates.

In actuality, changing the Z-height vaporizes and weakens different portions of the block of LTCC along this slanted line. The first cut lowers the material, raising the focal point to remove the middle portion of the slot. Then, the second cut raises the focal point more to remove a larger portion of the top of the slot. After the second cut, the facet plates slightly resemble the 'V' shape but often require additional scraping with a drill bit or end mill to remove residual material. Figure 12 shows the LTCC block with the facet plates being cut out using the laser technique.

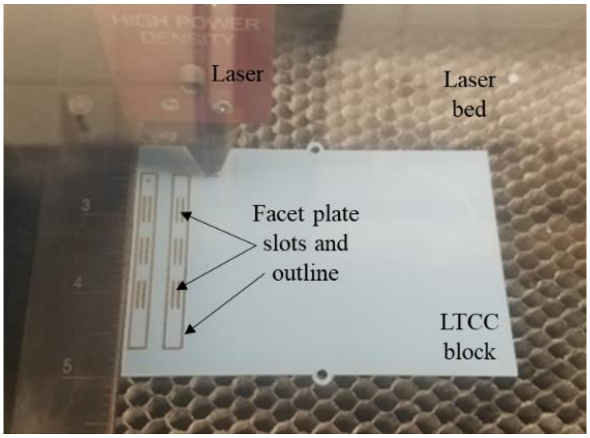

Figure 12. Photograph of LTCC facet plate structure during milling of the slits and formation of the facet plates. An LTCC block is placed on the bed; then the laser cuts the facet plate slots and outlines the plates.

The mill technique uses a Bungard PCB mill to cut the desired geometry of the facet plates. The LTCC block, previously discussed, is taped to a millable substrate (usually clear plastic) and placed on the vacuum chuck on the

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mill bed and secured using the vacuum. Like the laser technique, this mill technique also requires two cuts. The first cut uses a 60° 'V' tip end mill to cut out the 'V' shaped slots in the facet plates. Slow and shallow passes should be taken when cutting the slots to avoid breaking the center point. The second cut uses a 40° 'V' tip end mill to cut out the outline of the facet plates. The taper in the edges of the facet plates are needed to allow assembly into a cylindrical structure to prevent gaps at the joints. Figure 13 shows the depth of the angled end mills for each cut during the mill technique.

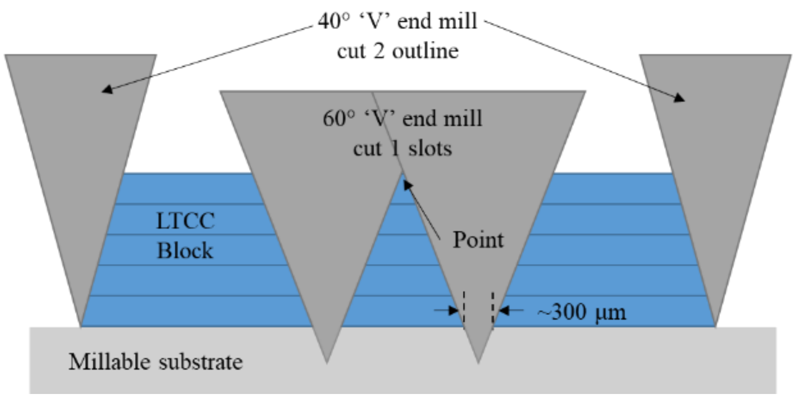

Figure 13. Mill cutting cross-sectional diagram of the facet plate.

Firing structure

Four different techniques were implemented and tested for the firing structure. The LTCC and silver pastes react differently to the high furnace temperatures which can cause the cathode to warp or even crack. Most of the warping can be resolved by slow ramp rates during the firing profile, shown in Figure 14. The rest of the warping can be corrected by using techniques that physically prevent warping during firing.

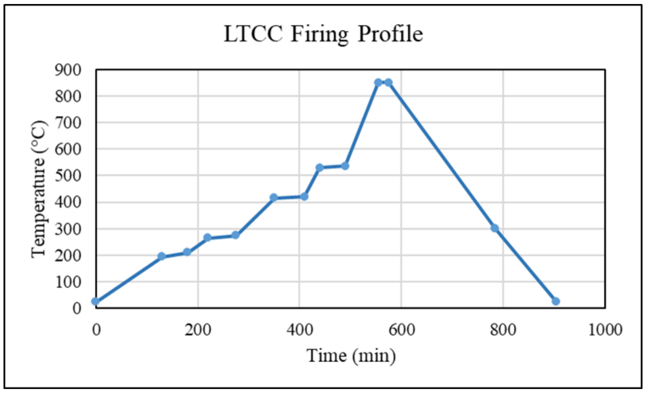

Figure 14. LTCC Firing profile (9)

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The first technique was horizontal, which means that the cathode was laid down horizontally in the furnace. The second technique used circular caps placed on both ends of the cathode. These caps are comprised of two stacked circle layers of LTCC. The first layers have a large OD to hold the cathode upright, and the second layers are the same OD as the ID of the cathode. They are sprayed with boron nitride to prevent sticking; and they shrink at the same rate as the cathode which helps maintain circularity. The third technique used a stand which the cathode would slide over and stand upright in the furnace. The stand consists of a post and base block to keep the post upright. The post was designed with long rectangular layers of LTCC that, when laminated and fired flat, would shrink to a post having a cross-sectional area of a square. Firing flat allowed for the post to be linear (as linear as the floor of the furnace), and the square cross-sectional area allowed for circular support from the four corners of the square. A large rectangular base was attached to the bottom of the square post. The fourth technique combined the caps and stand to create "caps with stand". The cathode would slide over the stand post, and then a cap would be placed on top of the cathode structure. These firing techniques are shown in Figure 15.

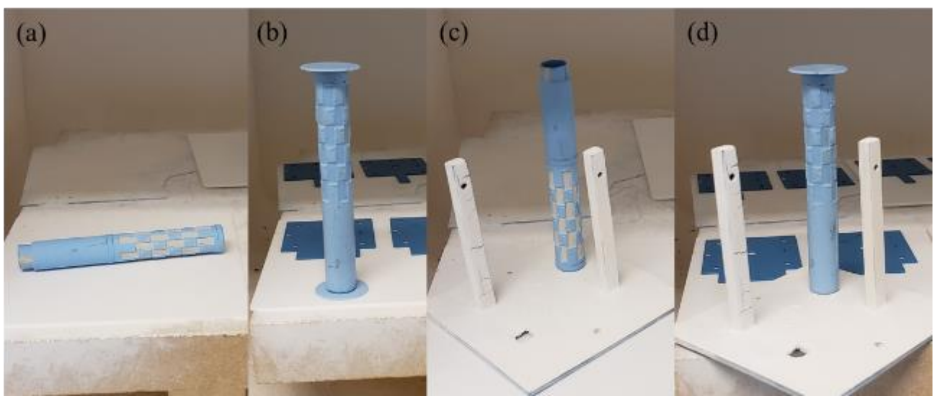

Figure 15. Cathode structure firing techniques showing the cylindrical cathode in the green state with four different techniques: (a) Horizontal, (b) caps, (c) stand, and (d) caps with stand.

Cathode Fabrication Technique Performance

Because the success of each technique was user (operator) dependent, a subjective scoring system was chosen to compare the LTCC wrapping, via filling, and facet plate processes for our lab's cathode structure optimization. Each of the technique's strengths will be addressed based on our optimization criteria rather than the scoring system. Two different factors relating to repeatability criteria will be discussed for each process. In addition, the ease and speed with which the techniques could be mastered are also considered. All the techniques discussed can obtain good

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results with a skilled operator, which is why some examples shown are technique independent. The purpose of this research was to determine which techniques were optimized for our cathode structure build.

The layer by group technique was more easily aligned because layers 1 to 4 are aligned flat as opposed to aligned rolled. The layer by group technique resulted in a tighter wrap because it requires fewer wraps which reduces the possibility of errors: four wraps (layers 1 to 4 group, 5, 6, and 7) as opposed to seven wraps (layers 1, 2, 3, 4, 5, 6, and 7). The layer by layer technique requires less training because it only used one wrapping technique (one layer at a time) as opposed to two (group roll and one layer at a time). The layer by group technique was faster because multiple layers were wrapped at one time as opposed to one layer at a time. Figure 16 shows examples of misaligned and aligned wraps.

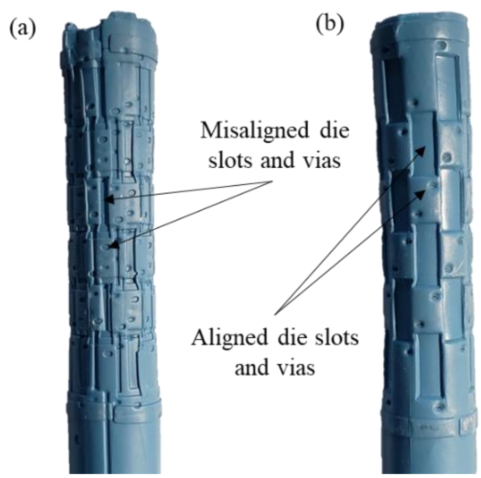

Figure 16. (a) Examples of not acceptable and (b) acceptable cathode wraps.

The flat fill technique is less likely to short because only layer misalignment causes shorts as opposed to overflow or leakage. The flat fill technique is more likely to fill the vias completely, which significantly increases the chance to connect the transmission line to the die (layers 3 to 7). The pneumatic pump technique requires less training because it consists of placing the nozzle in the via and pushing a button as opposed to aligning a template and then squeegeeing paste across. The pneumatic pump technique is faster because it fills the complete vias at one time as opposed to each layer of the vias as well as minimizing drying times. Figure 17 shows examples of incompletely and completely filled vias.

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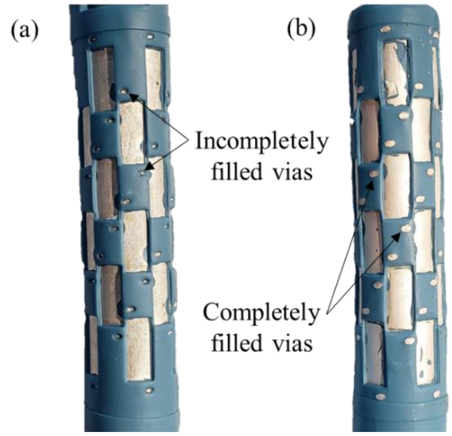

Figure 17. (a) Examples of incorrectly and (b) correctly filled vias.

The mill technique is more repeatable because it is a mechanically automatic technique as opposed to a human hand technique. The mill techniques can (visual inspection) produce smoother 'V' shaped slots. The laser technique requires less training because it consists of using the laser cutter as opposed to setting up and learning the mill software. The laser technique is faster because it cuts and scrapes (by hand) faster than the mill can remove the material. Figure 18 shows examples of facet plates using the laser and mill techniques with (a) the magnified image of the slit using the laser, (b) magnified image of the slit using the mill, (c) image of the entire facet plate using the laser, and (d) magnified image of the facet plate using the mill.

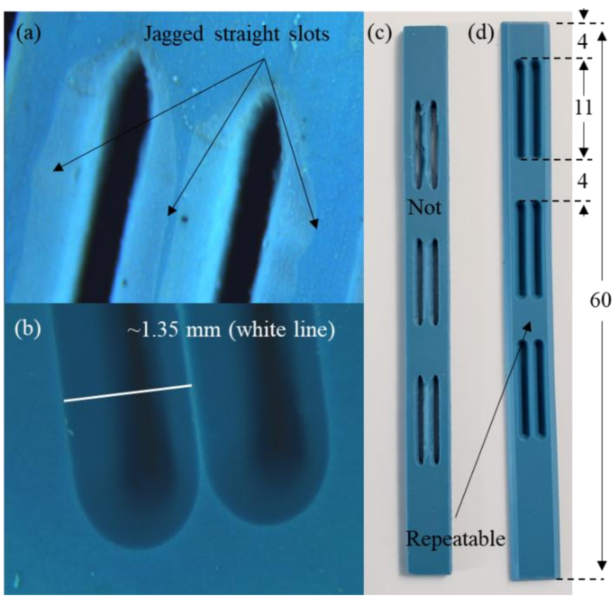

Figure 18. Images of the facet plates with (a) laser cut magnified image, (b) milled slits magnified image, (c) facet plate using laser cutting, and (d) milled facet plates. All dimensions are mm.

Because the outcomes of firing the structure were not user dependent, an objective scoring system was chosen to compare the better of the four techniques. The first metric was circularity because the facet plates and die must fit on the cathode and be a fixed distance from the anode. Circularity was determined by subtracting the maximum outer diameter (OD) from the minimum OD over three different spots along the cathode. The next metric is linearity because the cathode must be straight in the magnetron structure. Linearity was determined by measuring the displacement along the length of the cathode structure over three spots around the cathode. The three spot measurements were averaged for each cathode structure to give a total measurement for each structure. Each total measurement was calculated for two cathodes each and averaged to give circularity and linearity measurements for all four techniques shown in Table 2. The smallest deviation indicates the best technique.

Table 2. Objective scoring of firing techniques.

Parameters	**Horizontal**	**Caps**	**Stand**	**Caps with Stand**
Circularity (mm)	0.94	0.63	0.25	0.78
Linearity (mm)	0.30	1.92	0.24	1.06
Total (mm)	**1.24**	**2.55**	**0.49**	**1.84**

After analysis of the circularity and linearity metrics for each technique, the stand technique showed the best overall (combined) score (0.49) which makes the stand firing technique the best and most optimized for building tube-like structures. It has superior performance in both circularity and linearity. Figure 19 shows examples of (a) inadequate and (b) adequate circularity, as well as (c) inadequate and (d) adequate linearity.

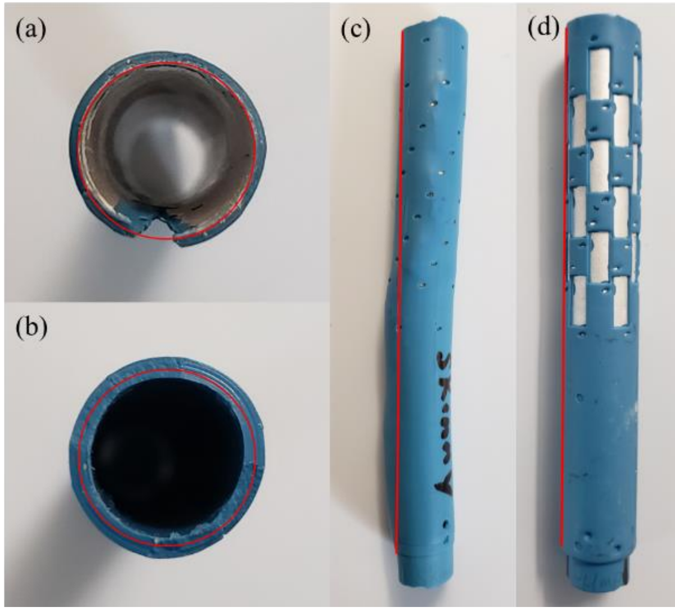

Figure 19. Examples of (a) inadequate circularity, (b) inadequate circularity, (c) inadequate linearity and (d) adequate linearity of fired cathode structures. Red circles and lines in the images are used for reference.

Testing required implementing the optimal techniques for each manufacturing process to fabricate the new field emission cathode structure. When comparing LTCC wrapping techniques, the layer by group technique was optimal because it was more easily aligned, lead to tighter wraps, and was faster than the layer by layer technique. When comparing via filling techniques, the flat fill technique was optimal because it was less likely to short electrically and more likely to connect from the stripline to the die than the pneumatic pump technique. When comparing facet plate techniques, the mill technique was optimal because it was more repeatable and had visibly smoother 'V' shaped slots than the laser technique. When comparing firing techniques, the stand technique was optimal because it had the lowest averaged circularity and linearity measurements compared to the other techniques.

By implementing all the optimal techniques previously discussed, the new cathode structure was fabricated as shown in Figure 20a and then tested. The first test verified with a multimeter that the vias were not shorted electrically to the ground layers. After verification, die were attached to the cathode (Figure 20b) and successfully electrically driven in a vacuum test chamber. A ceramic paste is used to cover the gap between the die and the edge of the LTCC slot. A silver paint is then painted across the paste to connect the via to the GFEA die gate metal. This proof-of-concept cathode structure proved that the cathode structure design and implementation can be used to connect and operate the GFEAs in a vacuum test chamber. Lastly, facet plates were adhered to the cathode (Figure

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20c) to achieve the final cathode structure. At this step, the facet plates would be coated with a thin film of aluminum and then the gaps between facets would be filled with a ceramic paste. Finally, a thin layer of silver paint would be coated over the ceramic to provide complete electrical connections to all of the facet plates and to ensure no insulating surface is exposed which could cause charging.

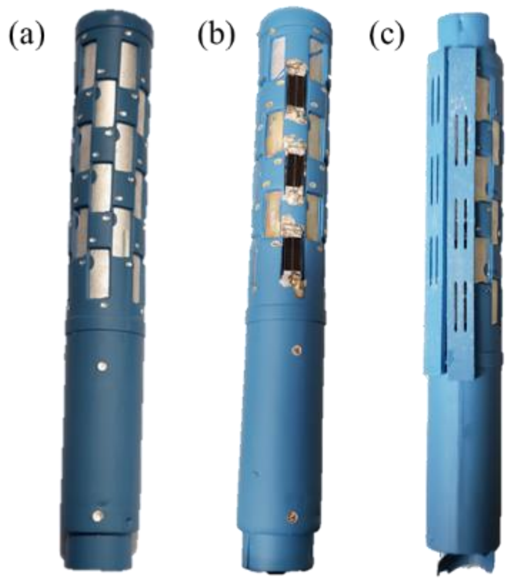

Figure 20. (a) Fired cathode structure (b) structure with actual GFEA die connected within the slots, and (c) with example facet plates covering the die locations. The seams between facet plates are not filled and the plates are not yet covered with aluminum. In (b) a ceramic paste is seen at the end of each die (top and bottom). This paste allows a thin line of hand dispensed silver paint to be drawn from the via to the GFEA die gate metal. The paste overs the gap between the die and the edge of the die slot so that the silver paint can be deposited and sop that the paint does not flow down along the edge of the die an electrically short the structure to the ground (die back side).

Conclusion

The LTCC material system is ideal for layered internal electrical structures that can be used in high vacuum such as the stripline that makes up the cathode structure. Through this research, multiple manufacturing techniques were compared and evaluated for their strengths and weaknesses. In this research, we demonstrated that a rolled LTCC device consisting of layers (one strip of LTCC per layer), vias, and embedded circuits could be fabricated. We also demonstrated that via filling could be performed with various pastes, even after the layers have been rolled. Additionally, we showed that a laser could be used to cut 'V' shaped slots into the surface of LTCC. Finally, we demonstrated that circularity and linearity of a rolled device could be maintained while being fired.

The best techniques for each process were compared and implemented to give the optimized cathode structure manufacturing process. This process was used to build proof-of-concept cathode structures that would not short electrically and would drive the field emission die in high vacuum (10^{-8} Torr). The step by step cathode manufacturing process and the complete research is discussed in greater detail in (19).

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