Application Note: Nuvotronics PolyStrata® Power Combiners

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1. Introduction

This application note provides guidelines for the handling, mounting, and interconnection of Nuvotronics' power combiner products. For additional information please consult Nuvotronics Application note "General Guidelines for Handling PolyStrata Components"[1].

PolyStrata® technology is based on an additive manufacturing integration platform using a photolithography-based metal process that provides micron-level accuracy and precision in all three axes for unparalleled component repeatability. Power combiners designed with PolyStrata® Technology offer near-waveguide loss performance in a footprint similar to a softboard combiner. The designs covered by this document can handle up to approximately 80 Watts and can support graceful degradation, as described in Section 2.

2. Overview

Nuvotronics offers a family of power combiners in two different architectures: Wilkinson and Gysel:

- Wilkinson in-phase combiners are designed for EW applications. Graceful degradation is currently supported for 5W input amplifiers, an upgrade to 20W amplifiers is planned.
  - Four-way covering 6 -18 GHz with wire bond inputs and coax combined port.
  - Four-way covering 18 - 40 GHz with wire-bond inputs and coax combined port.
- Gysel combiners are designed for SatCom applications. Graceful degradation is supported for 20W input amplifiers.
  - Two-way covering 37.5 – 42.5 GHz combiner and two-way combiner with directional coupler for sampling output power, with wire bond inputs and waveguide combined port, designed for quadrature combining (90-degree difference between input ports).
  - Four-way covering 27.5 - 31 GHz and 47.2 – 52.4 GHz with wire bond inputs and waveguide (input ports are all in phase).

3. Technical Details

PolyStrata parts are high-performance components that can be handled and assembled using standard microelectronics industry methods. These RF devices are constructed by using an additive manufacturing process using copper for conductors and using primarily air as a dielectric.

High-power isolation resistors (Smiths Diamond RF Resistives® Family[2]) are included in all Nuvotronics high-power combiner products and are assembled inside a small pocket with a factory-attached lid.

> **IMPORTANT**: Release holes (openings in the coax outer jacket) are present on all PolyStrata components as they are required for our fabrication process. They do not affect RF attenuation or characteristic impedance, but two issues need to be considered by power combiner users. A small amount of RF signal will radiate outside the combiner through the release holes, so the combiner should be enclosed with a metal lid or RF absorptive material. At next level assembly, care must be taken to avoid transferring attachment material into the combiner through the release holes.

3.1. Wilkinson Combiners

The Wilkinson power combiner architecture is used on Nuvotronics wideband combiners. Figure 1 shows the most basic Wilkinson structure, where port 1 is the combined port, ports 2 and 3 are the input ports and a single isolation resistor is connected across the input paths. Our two-way combiners typically have two isolation resistors, and our four-way combiners have up to have six isolation resistors. Characteristic impedances of line segments vary throughout our combiner networks to form wideband impedance transformations.

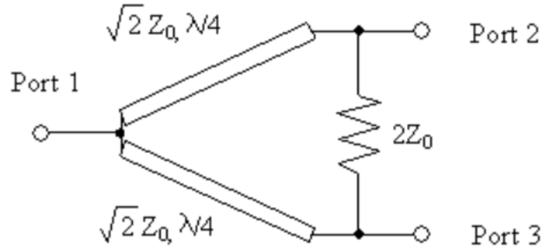

Figure 1: Wilkinson two-way combiner simplified architecture

3.1.1. Four-Way Wilkinson Combiner, 6-18 GHz (PSX12Q12W)

The PSX12Q12W is a four-way combiner covering 6 to 18 GHz, shown in Figure 2. It is designed to be wire-bonded directly to power amplifier MMICs. The combined (output) port accommodates a pin launch to an external coax connector (not included). Screw holes sized for #2 screws (or metric M2) and alignment features sized for 1mm diameter pins are provided for precise mounting to a substrate. Input ports are all in phase with respect to the output port; SSPA designers can use their own four-way divider design or use a second PSX12Q12W as a power divider.

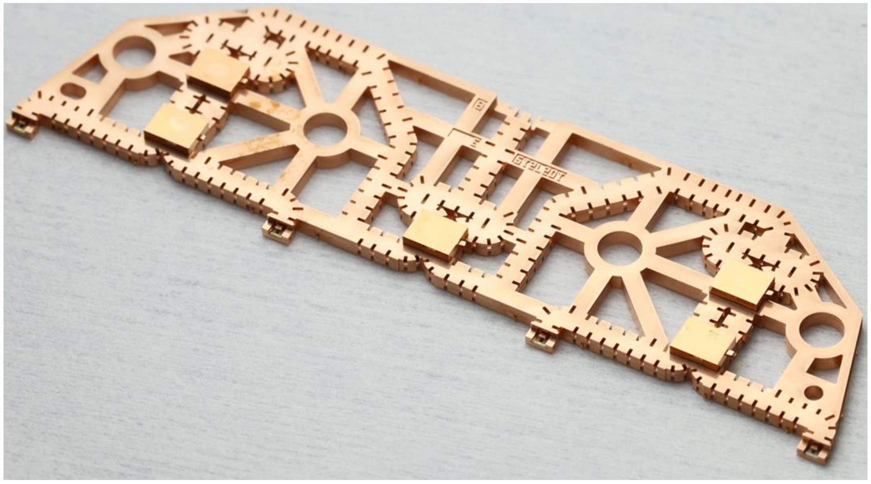

Figure 2: Wilkinson 6-18 GHz, Four-Way Combiner (PSX12Q12W)

3.1.2. Four-Way Wilkinson Combiner, 18-40 GHz (PSX29Q22W)

The PSX29Q22W is a four-way combiner covering 18 to 40 GHz, shown in Figure 3. It is designed to be wire-bonded directly to the power amplifier MMICs. The combined (output) port accommodates a pin launch to an external coax connector (not included). Screw holes sized for #2 screws (or metric M2) and alignment features sized for 1mm diameter pins are provided for precise mounting to a substrate. Input ports are all in phase with respect to the output port; SSPA designers can use their own four-way divider design or use a second PSX29Q22W as a power divider.

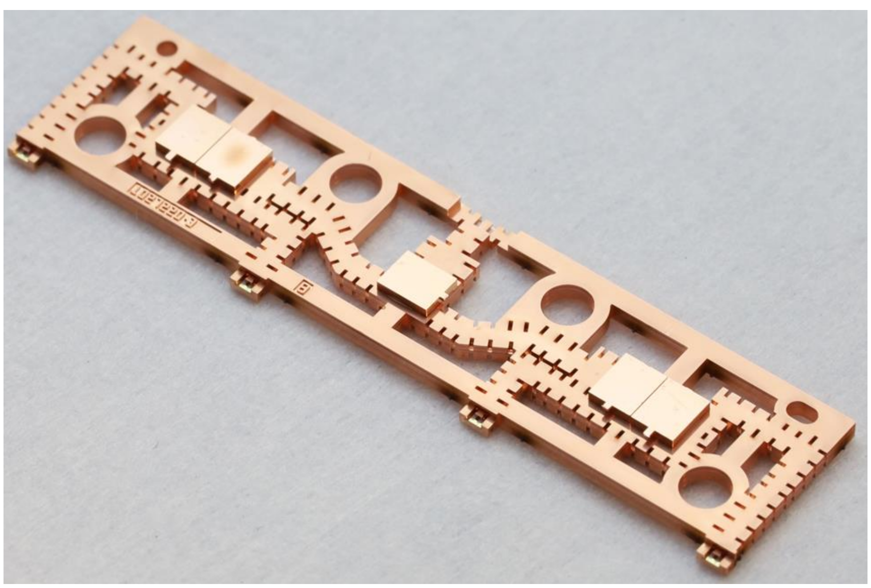

Figure 3: Wilkinson 18-40 GHz, Four-Way Combiner (PSX29Q22W)

3.2. Gysel Combiners

The two-way Gysel architecture (as shown in Figure 4) is used in Nuvotronics SatCom combiners. It comprises a ring of 1.5 wavelengths at center frequency, with shunt isolation terminations at two nodes. Four-way SatCom combiners are realized by cascading two-way Gysel combiners with fifty-ohm routing in between them.

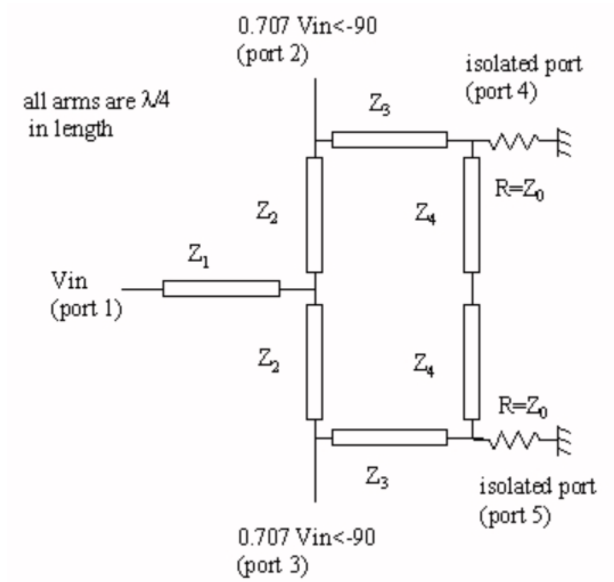

Figure 4: Gysel two-way combiner simplified architecture

3.2.1. Two-Way Gysel Quadrature Combiner, 37.5-42.5 GHz (PSX40D05W)

The PSX40D05W is a two-way combiner covering 37.5-42.5 GHz, shown in Figure 5. Input ports are designed to be wire-bonded directly to power amplifier MMICs. The combined (output) port is also designed for wire bonding. Screw holes sized for #0 screws (or metric M1.6) and alignment features sized for 1mm diameter pins are provided for precise mounting to a substrate. Input ports have been designed to have a 90-degree (quadrature) phase difference. Nuvotronics recommends pairing two PSX20D05W combiners, one used as a power divider, when combining two amplifiers to maintain correct phasing.

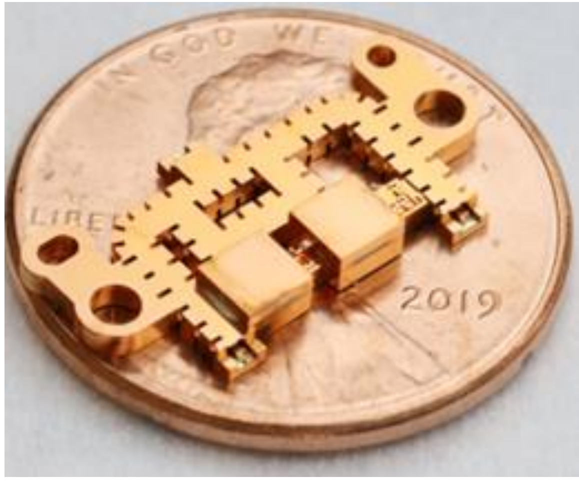

Figure 5: Gysel Two-Way Combiner, 37.5-42.5 GHz (PSX40D05W)

3.2.2. Two-Way Gysel Quadrature Combiner with Integrated 20dB Directional Coupler, 37.5-42.5 GHz (PSX40D05V2W)

The PSX40D05V2W is a two-way combiner covering 37.5-42.5 GHz, shown in Figure 6. Input ports are designed to be wire-bonded directly to power amplifier MMIC. The combined (output) port is compatible with standard rectangular waveguide that launches from the ground plane side of the part. The waveguide is back-shorted on top of the combiner output with a lid. The waveguide lid, terminating resistors, and resistor lids come pre-assembled on the combiner part. Screw holes sized for #0 screws (or metric M1.6) and alignment features sized for 1mm diameter pins are provided for precise mounting to a substrate. A 20 dB directional coupler is integrated into the combiner, with a wire bond interface. The coupled port is configured for use in monitoring output power (as opposed to reflected power) and may be left in an open-circuit condition without performance penalty. The opposite port of the directional coupler is internally terminated. Input ports have been designed to have a 90-degree (quadrature) phase difference. Nuvotronics recommends pairing the PSX40D05V2W combiner with the PSX20D05W (combiner without directional coupler) as a power divider when combining two amplifiers to maintain correct phasing.

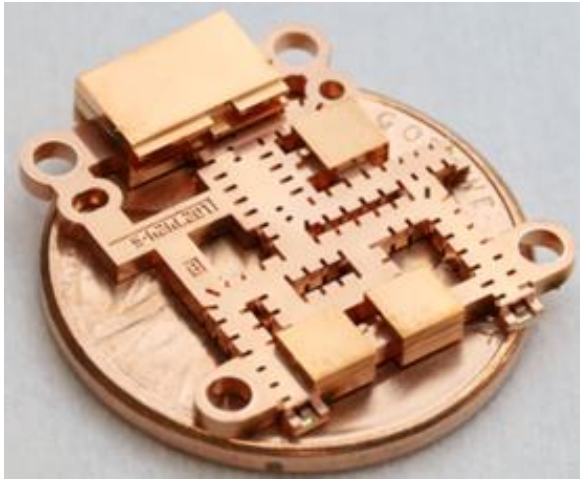

Figure 6: Gysel Two-Way Combiner with Integrated 20dB Directional Coupler (PSX40D05V2W)

3.2.3. Four-Way Gysel Combiners (PSX29Q03W and PSX50Q05W)

Nuvotronics four-way Gysel combiners include PSX29Q03W, 27.5 to 31 GHz design (see Figure 7) and PSX50Q05W, 47.2 to 52.4 GHz design (see Figure 8). These parts are designed to be wire bonded directly to power amplifier MMICs. The combined (output) port is compatible with standard rectangular waveguide that launches from the ground plane side of the part. The waveguide is back-shorted on top of the combiner output with a lid. The waveguide lid, terminating resistors, and resistor lids come pre-assembled on the combiner part. Screw holes sized for #2 screws (or metric M2) and alignment features sized for 1mm diameter pins are provided for precise mounting to a substrate. Input ports are all in phase with respect to the output port; SSPA designers can use their own four-way divider design or use a second PSX29Q03W or PSX50Q05W as a power divider.

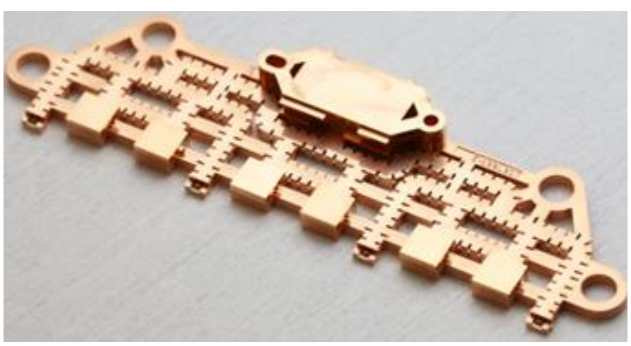

Figure 7: Gysel 27.5-31 GHz, four-way Combiner (PSX29Q03W)

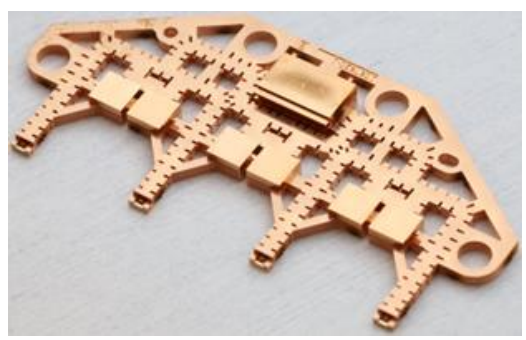

Figure 8: Gysel 47.2-52.4 GHz, four-way Combiner (PSX50Q05W)

4. Mounting Considerations

Combiners discussed in this application note are designed to be integrated with high power amplifiers. If amplifiers fail or operate out of phase, a significant amount of heat will be dissipated in the combiner's isolation resistors. The combiners are designed with high thermal conductivity materials that efficiently dissipate heat from the resistors to the surrounding PolyStrata copper ground structure. Mounting the combiner properly to a good heat sink is critical.

Every combiner part contains alignment hole & slot features to ensure optimal alignment to the end application substrate. Corrosion-resistant stainless steel dowel pins are typically press-fit into the next assembly substrate. Alternatively, gauge pins may also be used for a slip fit design where the pins are removed after assembly.

In the case of gauge pins, the hole in the end-use substrate is typically designed as a tight clearance slip fit and the pin removed after the combiner is bolted and/or bonded down to the housing. However, there are two things related to gauge pins that make them more difficult than dowel pins. Gauge pins are typically not offered in corrosion-resistant stainless steel so these pins should be used for temporary alignment only and removed after assembly. Also, gauge pins are typically fabricated 2 inches long, so these pins need to be cut shorter for ease of use.

There are several different methods to mount Nuvotronics combiners to a heat sink:

- Screws for a removable configuration
- Directly applied sintered silver or paste epoxy dots
- Custom preformed layer of sintered silver or conductive epoxy, cured within a holding fixture
- Solder (possible but not recommended)

4.1. Mounting with Screws

To avoid overheating, it is highly recommended to use a conductive interface such as Indium Corporation's Heat Spring® foil between the ground plane of the combiner and the heat sink in the end application. Heat Spring has very low electrical resistivity (<10 µohm-cm) and high thermal conductivity (86 W/m-K) properties, thus making it a good interface material for high power RF devices. It is a compliant foil made from high purity indium that plastically deforms when screw-clamped between two substrates. It is patterned with small dimples that help take up small mismatches between surfaces to improve electrical and thermal properties of the joint. Heat Spring is typically offered in 0.004" (100µm) and 0.006" (150µm) thicknesses and can be easily laser cut, stamped or knife cut to desired shapes. Refer to the application note from Indium Corporation[3] for more details on handling and use of Heat Spring foil.

1. Cut or stamp the Heat Spring foil to the desired shape. Cubic Nuvotronics can assist with design of Heat Spring foil preforms. The Heat Spring foil can be cut with integrated alignment hole and slot features to assist with accurate placement onto the heat sink. This

is particularly important for combiner parts with a waveguide combined port to ensure optimum waveguide opening alignment.

2. Place the foil down onto the heat sink.
3. Use screws to attach the combiner on top of the foil (see Figure 9). Screw pressure will provide a robust thermal and electrical ground. Screws should be installed "finger tight" first and then torque to spec. Washers up to 0.188" (4.8mm) outside diameter are recommended to help distribute the fastener load and prevent damage to the combiner surface. Typical torque values for the recommended combiner mounting screws are shown in Table 1 below.

Table 1: Suggested torque values for combiner screws

SCREW	TORQUE, in-oz (cN-m)
#0	19 (14)
#2	57 (40)

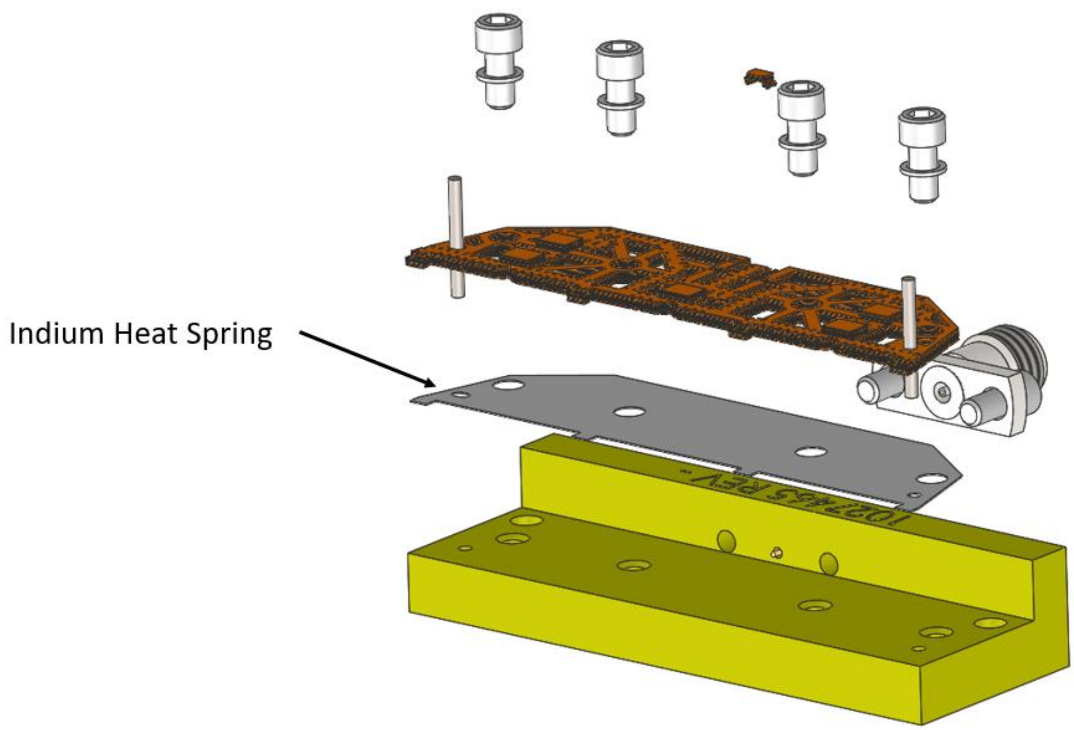

Figure 9: Mounting a PSX12Q12W combiner with Indium Heat Spring® interface

CAUTION: If a reworkable joint is desired, it is recommended to not exceed 130°C during assembly processing or operation. Indium reflows at 157°C. If a 150°C stage temperature is used for the successive wire bonding operation, the Heat Spring foil may partially reflow.

4.2. Mounting with Directly Applied Sintered Silver or Paste Epoxy

Combiners can be permanently attached to a heat sink using a conductive silver paste epoxy such as Henkel 84-1LMIT1 or, for higher conductivity, sintered silver such as Namics H9890-6. This can be accomplished using auto or manual dispense, jetting or stencil methods.

> **IMPORTANT:** It is recommended to apply conductive paste across the entire ground plane only in regions that are sufficiently away from release holes. A typical paste epoxy or sintered silver dot diameter or bead width is about 350 microns (0.014”) x about 0.13mm (0.005”) tall, if applied using an approximately 0.010” diameter syringe tip. Dots applied using a stencil can be made a little smaller with thickness controlled by the stencil thickness used. A 350-micron dot or bead width is small enough to allow epoxy to be centered between release holes along coax lines with ample clearance to release holes. This yields minimal risk of epoxy squeezing out and pushing up into release holes. Suggested dot patterns are available upon request.

1. Place sintered silver or epoxy dots across the entire surface, approximately centered between release holes as shown in Figure 10.
2. Flip the part over and place it onto the end application substrate using pin alignment.
3. Apply gentle pressure to squeeze out the epoxy dots.
4. (Optional) Screws may be installed while the epoxy is wet prior to oven cure. Alternatively, screws may be installed after epoxy cure.
5. Cure the epoxy.

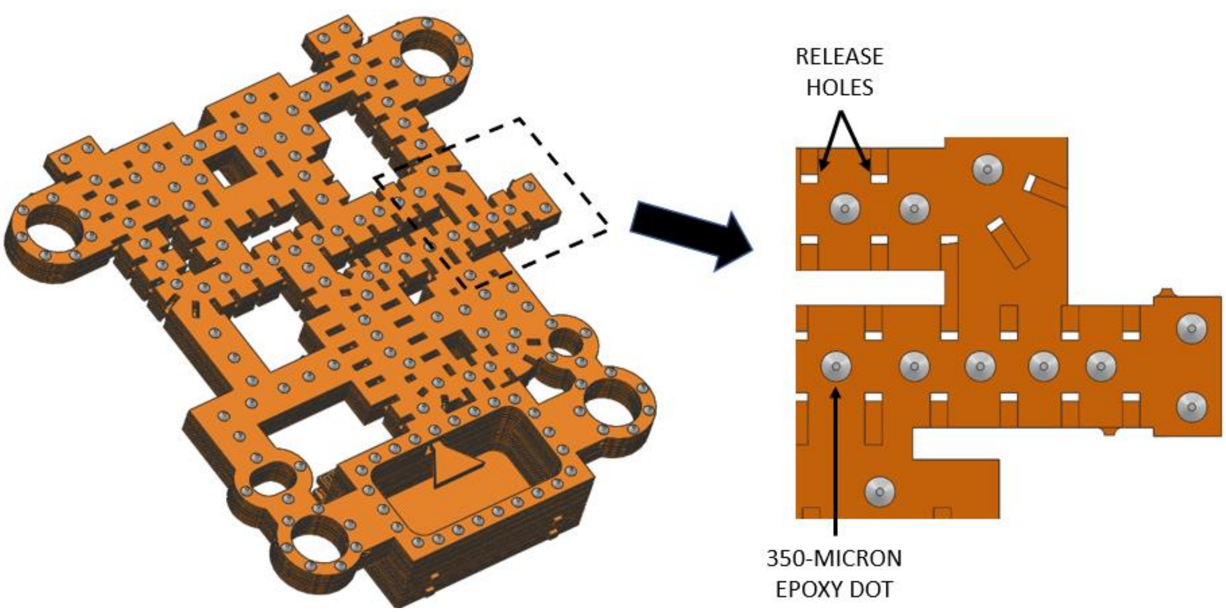

Figure 10: Example conductive epoxy dot pattern applied to bottom of PSX40D05V2W

4.3. Mounting with Preform Epoxy or Sintered-Silver Film

Nuvotronics commonly uses Henkel 5025E conductive film preforms to attach PolyStrata parts to substrates. Film preforms are easier to assemble than pastes because they can be handled without concern of epoxy smearing. However, constant pressure is typically required during oven cure of the preform, and this requires a custom mounting fixture set.

Figure 11 shows an illustration of a custom mounting fixture set. A base fixture holds the end application substrate (housing, PCB, or similar) in position. A bridge fixture screw mounts to the base fixture. The bridge fixture has stainless steel spring plungers threaded into it. The ball nose ends of the spring plungers touch down against a flat pressure plate which in turn applies the down force to the PolyStrata part/preform/substrate material sandwich. The pressure plate should have relief pockets to avoid contacting the lids (resistor, waveguide) on the combiner part.

CAUTION: Do not apply pressure on top of the combiner lids!

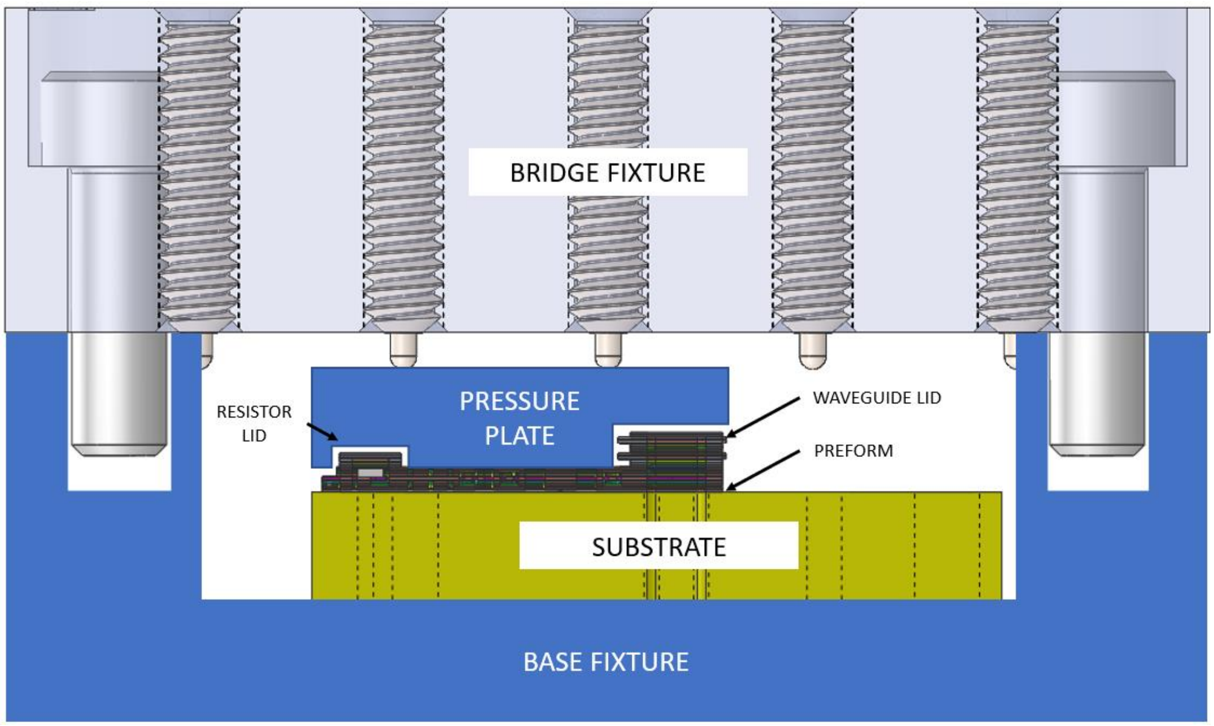

Figure 11: Illustration of a custom mounting fixture set to apply continuous pressure on film epoxy during oven cure with pockets in pressure plate to clear lids.

The spring plungers should be distributed approximately evenly over the area of the pressure plate and PolyStrata part. Use the preform manufacturer's datasheet to obtain the curing pressure recommendation. Calculate the plunger quantity and number of turns of each plunger to achieve the recommended pressure. Pressure is calculated as total force divided by attach area. The attach area of the combiner part can be obtained from the 3D model (provided upon request).

Cubic Nuvotronics can assist with design of custom pressure cure fixtures and epoxy preforms.

4.4. Mounting with Solder

Solder is not recommended but may be used with a few caveats.

PolyStrata parts are necessarily designed with small holes, called “release holes”, that go through the ground walls of the part and into the RF coax structures. Release holes enable removal of resist material from internal coax volumes to provide the air dielectric that make PolyStrata parts uniquely high performing. During reflow, solder can wick uncontrolled across the copper ground plane. Because release holes do not have solder stops, solder can also wick into the RF coax space and potentially degrade the performance of the combiner. For additional information please consult Nuvotronics Application note “General Guidelines for Handling PolyStrata Components.”[1]

In addition, care must be taken with bare copper PolyStrata parts to sufficiently deoxidize the copper prior to soldering.

5. RF Interconnects

RF output interconnects depend on which combiner is being considered.

5.1. Waveguide RF Output (Gysel Combiners)

A typical packaging embodiment of the PSX40D05V2W combiner part in an end application is shown in Figure 12. Models and drawings of generic end application packaging environments for all combiner products are available upon request. Additionally, Cubic Nuvotronics can assist with end application packaging design of its combiner products.

The end application substrate may be a machined housing or type of circuit board. Threaded mounting holes, alignment holes and WR22 waveguide slot features are designed into the substrate. The alignment holes and pins should be used to precisely align the WR22 waveguide port in the combiner part to the waveguide port in the end application substrate. The interface material coupled with the mounting screws force intimate electrical and thermal contact between the ground plane of the combiner, including the WR22 waveguide port, to the mating features in the substrate. A COTS waveguide adapter aligns and screw mounts to the opposite side of the substrate.

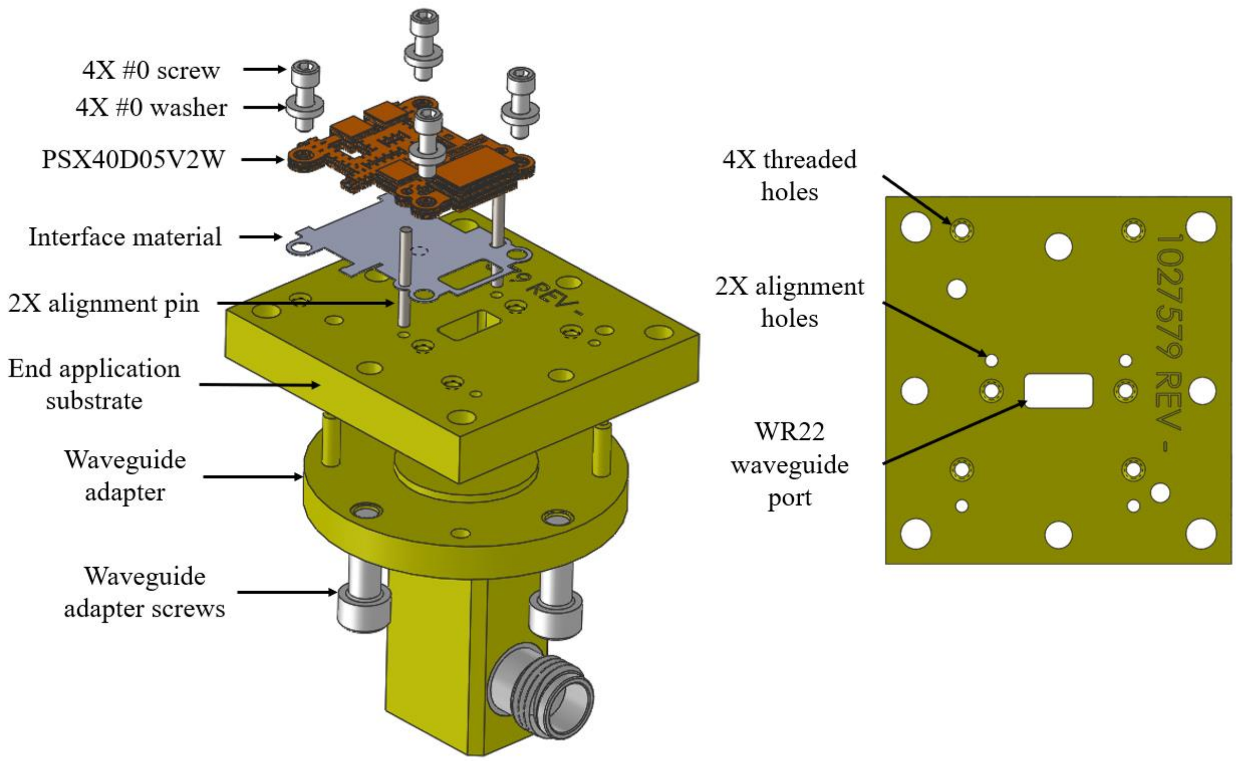

Figure 12. A lid over the entire combiner part may be designed into the end application to help with isolation and to reduce EMI.

Every combiner part contains clearance holes for screw mounting to the end use substrate. See Section 4.1 for more information.

5.2. Coaxial RF Output Connectors (Wilkinson Power Combiners)

PSX12Q12W and PSX29Q22W parts are designed to accept a coaxial pin at the combined port. The PSX12Q12W is designed for a 0.015" diameter launch pin. The PSX29Q22W interfaces to a 0.012" diameter pin. Figure 13 is a cross section through the combined port (left) along with a top view (right). Critical dimensions are provided.

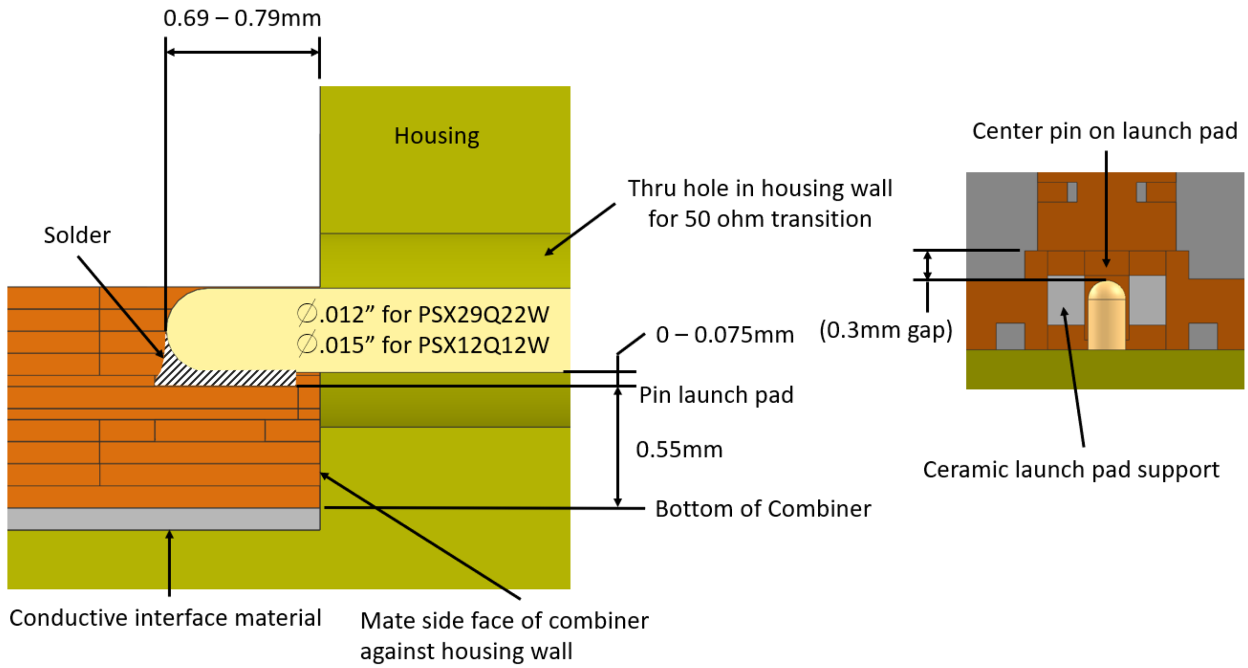

Figure 13: PSX12Q12W and PSX29Q22W Combined Port Launch Design

The launch pin should be designed to be centered over the launch pad. Design in a small gap (up to 0.075mm) between the bottom of the pin and the launch pad to allow for assembly clearance. The pin should be centered in the housing hole and extend 0.69 to 0.79mm (0.027" to 0.031") beyond the housing wall to allow a sufficient overlap length with the combiner launch pad for interconnection. It is recommended to solder the pin to the combiner launch pad for optimum reliability. Use gentle force when touching down on the launch pad manually with solder wands. The launch pad is supported on the underside by a ceramic seat which may fracture if excessive down-force is applied. It may also be helpful to place the assembly on a hot plate at 100°C to elevate the temperature of the entire assembly during this soldering step.

An eight-step process for attaching the combiner to a coaxial pin is provided below.

1.Align and place Heat Spring foil to housing (see Figure 14).

2. Prior to mating the combiner to the housing, it is recommended to first apply conductive epoxy as shown to the side face of the combiner around the pin. This epoxy provides the ground between housing and combiner around the signal pin into the combiner part and should be applied sparingly – enough to contact the housing wall but not too much that epoxy significantly intrudes into the air coax region.

3. Place combiner to housing floor and slide the launch pad under the pin. Mate the combiner flush against the housing wall to ensure an epoxy bridge between housing wall and combiner pin launch region.

4. Screw the combiner down. The alignment pins may be used here to help hold the combiner part in position as the screws are installed. The epoxy can be cured at this point or curing can wait until the end of this process.

5. Solder the pin to the launch pad. The coaxial pin is designed to be lidded for a 50ohm transition. The lid is included with the combiner part and is installed by the user after the pin is soldered to the launch pad.

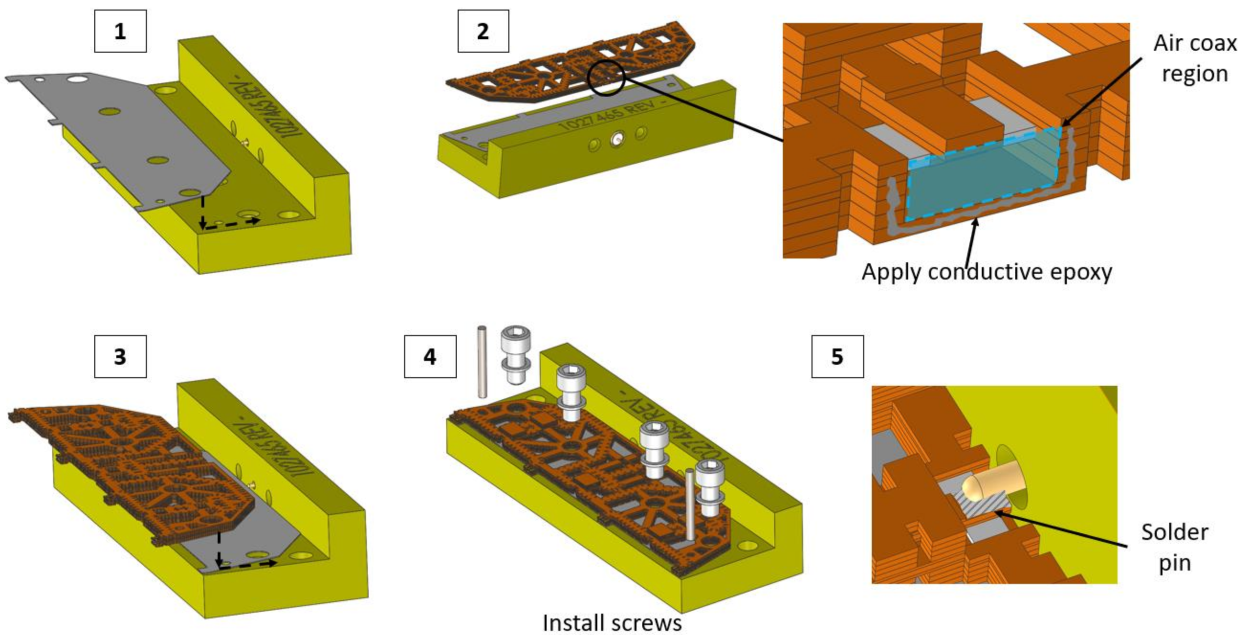

Figure 14: Coaxial Output Connection Assembly Steps 1 through 5

6. Sparingly apply epoxy in the areas shown in preparation for lid attach (see Figure 15).

7. Align and engage the nubs on the lid with the holes in the combiner part and seat the lid in the epoxy. The pre-applied epoxy paste should bridge from combiner part to lid to housing wall.

8. Cure the epoxy.

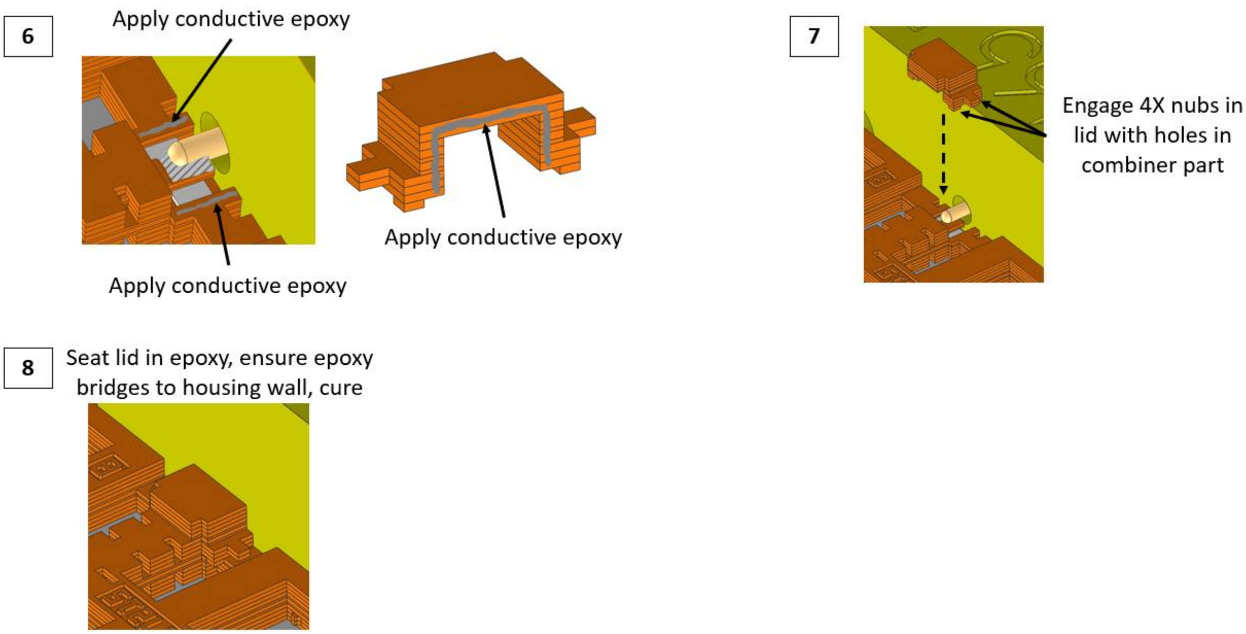

Figure 15: Coaxial Output Connection Assembly Steps 6 through 8

5.3. Amplifier Interconnects (Wire Bonding)

The design detail in this section should be treated as a guideline. There are many unique packaging embodiments and tolerances associated with chip and wire hybrids. Nuvotronics recommends the user perform their own RF simulations to ensure wire bond performance specifications are achieved in the end application.

The wire bond launch shown here is common for every combiner part. The wire bond launch is comprised of an integrated alumina chip with PolyStrata-defined copper ground-signal-ground (GSG) traces and a gold wire-bondable surface finish. The GSG launch is designed to be thermosonically bonded to gold interconnect wire.

Nuvotronics has performed RF simulation to tune the wire bond launch up to about 50 GHz operating frequency. Figure 16 provides details of the simulated wire bond transition design. Optimum RF performance might require modifying the wire bond geometry, depending on what the MMIC is expecting for wire bond inductance. Cubic Nuvotronics will provide an HFSS model of the interface upon request.

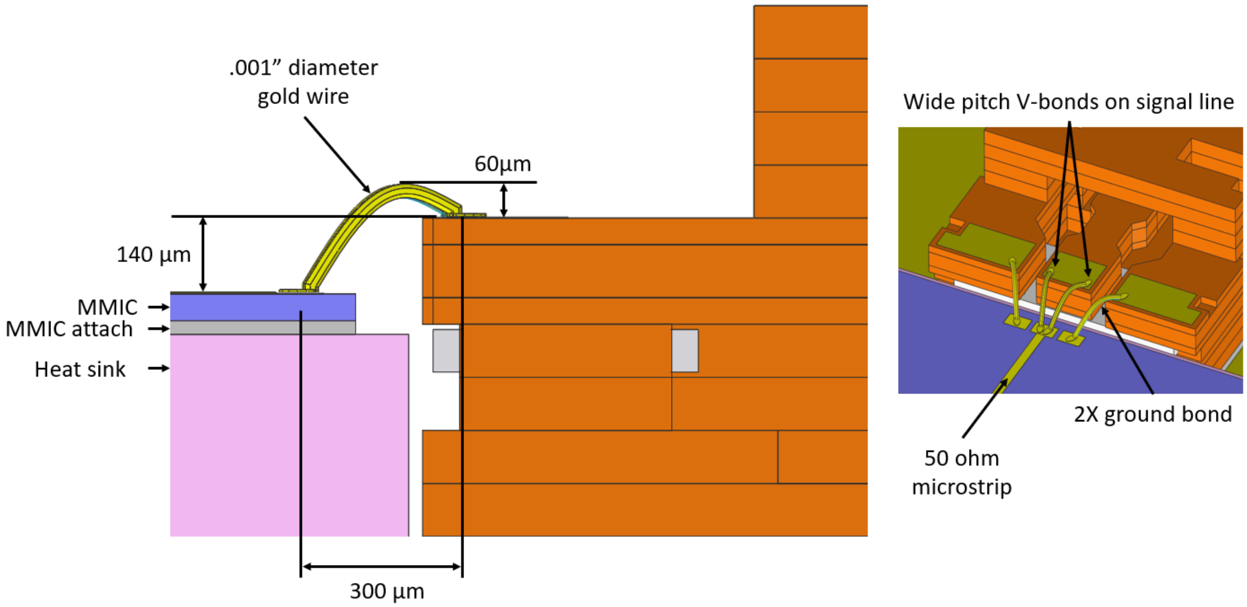

Figure 16: Wire bond transition design for operation up to 50 GHz

The simulated MMIC in the wire bond transition design has gold GSG pads and expects a 50-ohm interface inside the signal pad. The two ground pads each have through-vias that are tied to ground on the bottom side of the MMIC.

Two wires are bonded with a wide pitch to the signal line on the PolyStrata launch. The signal wires have a 60µm loop height and traverse 140µm down to the signal pad on the MMIC to roughly form a "V" shape when bonded. The bond pad to bond pad distance is 300µm. There is one ground wire per pad with the same loop height as the signal wires. The ground wire bond locations are biased to the inboard (signal) side on the PolyStrata launch. The inboard bias allows clearance of the wedge tool to the copper shield on both sides of the ground pads. Cubic Nuvotronics simulations show that the two ground bonds are optional at operating frequencies below 30 GHz.

6. References

1. "General Guidelines for Handling PolyStrata® Components", Cubic Mission & Performance Solutions, 3 November 2022, https://www.cubic.com/sites/default/files/2023-08/General%20Handling%20Guidelines.pdf

2. "Diamond RF Resistives® Family", Smiths Interconnect, https://www.smithsinterconnect.com/getattachment/fea9d43f-014a-4e60-9226-a1fcd888c2de/Diamond_RF-Resistives-Brochure.pdf

3. "Use of Heat Spring", Application Note, Indium Corporation, https://documents.indium.com/qdynamo/download.php?docid=5332

7. Revision Log

REV	DATE	ECN	COMMENT
-	04/10/24	ECN1008744	Initial Release
A	01/13/25	ECN1009313	Fix error in Figure 13