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Radial Combiners Based on Printed Circuit Board Manufacturing with Ball Grid Array Integration (FY23 Progress Report)

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Radial Combiners Based on Printed Circuit Board Manufacturing with Ball Grid Array Integration (FY23 Progress Report)

Rick Kindt, Code 5310.1

I. ABSTRACT

This NRL memorandum report provides details on FY23 technical progress developing a wideband radial combiner based on printed circuit board (PCB) manufacturing technology. This planar PCB-based combiner circuit is intended for integration with wideband planar antenna array apertures – integration that will be accomplished using ball grid array (BGA) technology. Background work leading up to this development, progress through FY23, as well as future directions are all reported below (NOT a final report).

II. INTRODUCTION

NRL researchers are interested in developing cost-effective, fully-planar, low-profile, wideband phased antenna array systems. Studies on wideband antenna apertures have been ongoing at NRL for many years, most notably directed towards developing the Planar Ultrawideband Modular Antenna (PUMA) array technology. These low-profile printed antenna apertures are based on PCB manufacturing technology and are fully planar. A planned future milestone will be the planar integration of PUMA apertures with wideband chipsets for controlling phased array antenna apertures. This integration also requires a beamforming circuit, preferably also in a planar form factor and based on cost-effective PCB manufacturing technology. Currently, the accepted state of the art in wideband beamforming circuits is the Wilkinson power divider/combiner. In order for typical Wilkinson-based power combiners/dividers to work over wide bandwidths, the circuits must employ multiple stages and thus become increasingly difficult to manufacture in a compact space as bandwidths increase. To keep within the footprint of the array aperture, it becomes necessary to create multi-layer designs that use a prohibitively large number of printed circuit board layers, creating potential challenges for via aspect ratios. Wideband planar printed apertures such as the PUMA also require multiple printed circuit board layers and challenging via aspect ratios, hence a direct integration of the PUMA with Wilkinson-based power combiners becomes doubly challenging. As such, a large part of this base program is geared towards effective interfacing techniques, e.g., interfaces based on ball grid array (BGA) patterns, that could be used to integrate complex planar circuits, with individual circuits potentially built using different technologies (Low-Temperature Co-fired Ceramics (LTCC) vs PCB vs 3D printing), that might otherwise be too challenging for direct integration (blind/buried vias, prohibitive via aspect ratios, excessive numbers of material layers, etc.).

In recent work, an alternative to power splitting / corporate feed Wilkinson-based combiners was demonstrated for wide bandwidths [1]. For an earlier NRL base program, radial combiners, previously limited to narrowband operation, were designed and partially demonstrated for operation over a 6:1 frequency bandwidth. Researchers at The University of Massachusetts (UMass), Amherst, in collaboration with NRL researchers, developed a 32-port combiner circuit that could operate over 3.5 GHz to 21 GHz. The part was specifically designed to be compatible with planar-printed PUMA apertures operating at the same frequencies. Because the radial combiner is based on LTCC manufacturing and the PUMA is based on PCB manufacturing, it would require an advanced interface technique to integrate the two. Thus both the PUMA apertures and radial combiners have been designed and developed with BGA-compatible interfaces. However, the input/outputs of the radial combiner (ports in a circle) and the PUMA array aperture (ports in a regular square grid) do not match up. Thus, it is also necessary to include an interposer circuit to route the circular ports of the combiner to the square grid ports of the planar array. Interposer circuits can be designed and built as a PCB, same as the PUMA aperture, thus it may be possible to directly integrate these circuit designs. The combiner circuit is LTCC-based, so direct integration would not be possible, therefore, this project takes a first look at extending the radial combiner design to PCB manufacturing. If three circuits (combiner, interposer, antenna aperture) can be based on the same manufacturing approach (PCB construction), in the future it may be possible to produce them as a fully-integrated design. Future work will also explore extending these wideband aperture/combiner designs to Ka-band frequencies (45 GHz).

Manuscript approved December 26, 2023.

III. BACKGROUND – WIDEBAND RADIAL COMBINERS

For a previous NRL base program developing wideband circuits for decoy applications, collaborators at UMass Amherst designed and built (with Kyocera International) an LTCC-based radial combiner for operation from roughly 3.5 GHz to 21 GHz - a 6:1 fractional frequency bandwidth. As well as having the potential for performing with near ideal loss and isolation numbers, the circuit is very compact, such that two planar combiner circuits, each having 32 array ports, can easily fit (without dilation) side-by-side behind a dual-polarized 8x8 phased antenna array aperture (32 ports in each polarization) that is ideally sampled for scanning operation up to 21 GHz. The circuit design, as well as a photo of a manufactured piece of hardware, appear in Figure 1. This was the first design iteration on a BGA-based radial combiner circuit, and objectively, Kyocera was not entirely happy with the quality of the build. The final size of the circuit was not predicted as accurately as expected, soldermask layers were inadvertently not included with the design data, and the BGA attachment did not carry out as accurately as was hoped. Therefore, because it was deemed too difficult to directly test this first build of the 21 GHz radial combiners, it was decided to repeat the build and incorporate lessons learned from the first attempt at manufacturing this circuit. Nonetheless, the experimental build showed that such a circuit can be successfully built. The footprint is 1.75”x1.75” and features 8 layers. The via diameters for the array ports have an OD=0.004”, which is normal for LTCC processing, but is much smaller than used in common printed circuit board manufacturing practices.

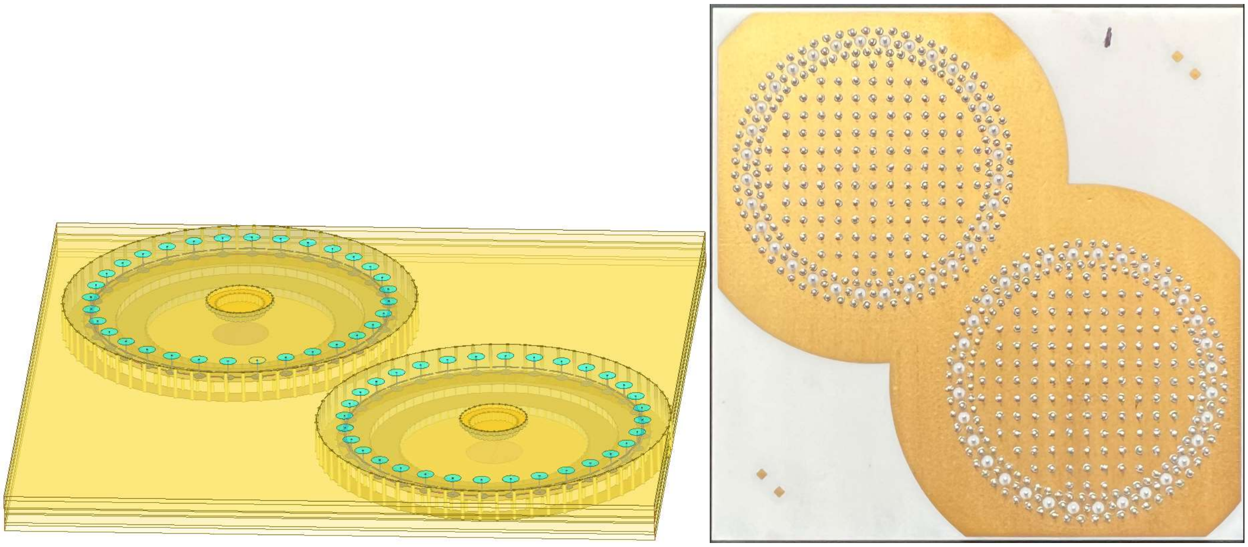

Figure 1. An LTCC-based radial combiner build, two 32-way combiners, one for each polarization. Dimensions are 1.75”x1.75”.

Though the combiner circuits can and should be tested individually for basic performance tests, ultimately, these combiner circuits are intended for integrated testing with a matching planar phased antenna array aperture of a commensurate size. Specifically, this radial combiner was designed to integrate with a PUMA aperture operating at the same frequencies, i.e., from 3.5 GHz to 21 GHz. One such PUMA aperture is shown in Figure 2. The PUMA aperture is 8x8 in size, having 64 total elements, 32 ports in each polarization. The overall aperture footprint is just 1.78”x1.78”, nearly the same size as the radial combiner circuits shown in Figure 1. Thus, the combiner circuits can fit compactly behind the PUMA aperture as an additional planar layer. However, the typical PUMA aperture is connectorized with commercial standard coaxial connectors. Therefore, in order to achieve integration with the BGA-based combiner circuit shown in Figure 1, a PUMA aperture must also be designed with a matching BGA interface. As a step in the direction of this kind of integration, a PUMA designed and manufactured with a BGA interface is shown in Figure 3. In separate work under this same base program, the BGA-based PUMA apertures were tested with standard coaxial interfaces [2]. One of the BGA-based PUMA apertures integrated with a coaxial test circuit is shown at the bottom of Figure 3.

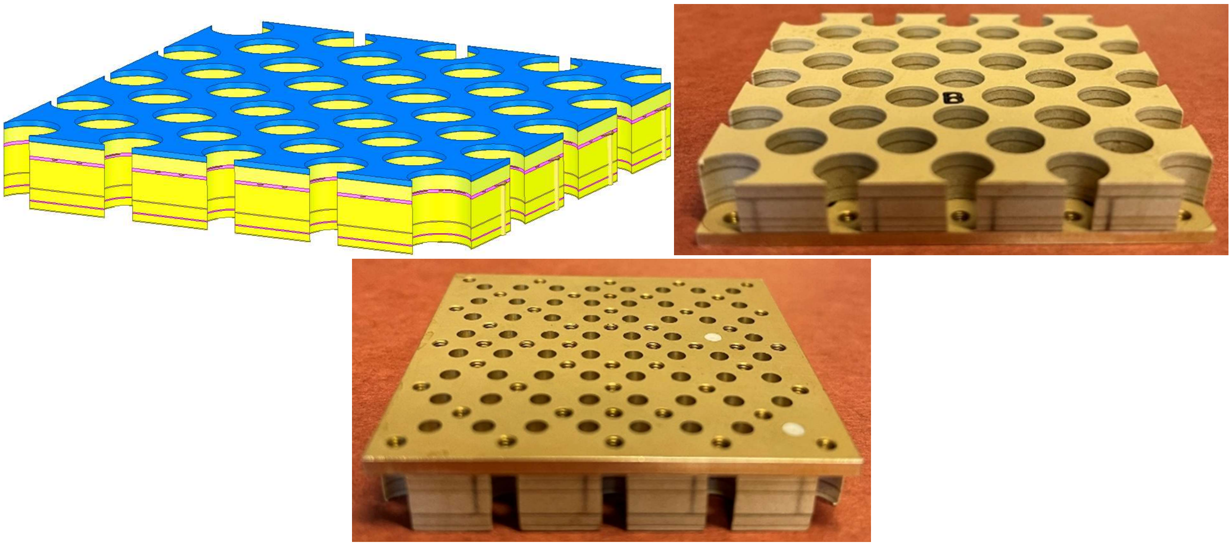

Figure 2. A PCB-based Planar Ultra-wideband Modular Antenna (PUMA) array with 64 elements – 32 in each polarization. Dimensions are 1.78”x1.78”. The aperture is backed with commercial standard coaxial ports.

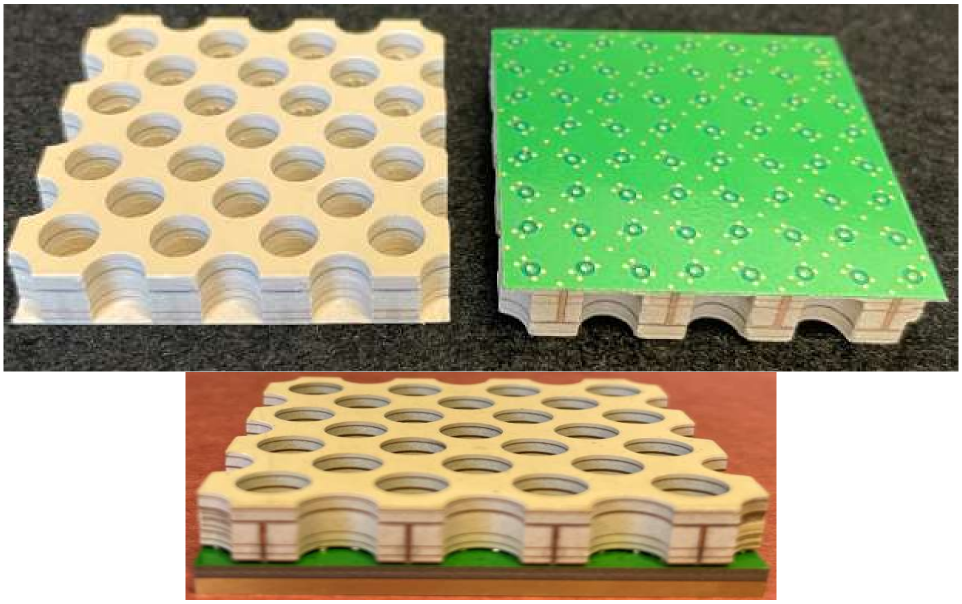

Figure 3. A PCB-based Planar Ultra-wideband Modular Antenna (PUMA) array designed and developed with a BGA compatible backing.

It should be noted that – much as should be expected – the outputs of the radial combiner shown in Figure 1 are arrayed in a perfect circle, with the BGA interface pattern matching this radial layout. However, the outputs of a typical 8x8 array and the subsequent BGA pattern for signal interface follow a regular 8x8 square grid. Therefore, it is necessary to employ an intermediary circuit for routing the square lattice outputs of the planar PUMA array to the radial inputs of the combiner circuits. A circuit designed for routing the radial ports of the combiner to the regular square lattice of the phased antenna array is shown in Figure 4. This interposer circuit consists of two layers of stripline circuitry – one layer for each polarization of the array. The interposer circuit can be realized with either LTCC or PCB manufacturing technology. If BGAs are used to interface the three planar circuits (array aperture, interposer, radial combiner), the manufacturing choice for the interposer circuit does not necessarily matter. However, in the future, it will be desirable that all three planar circuits can be made with the same manufacturing approach, such that – if possible – two or more of the planar circuits might be directly integrated. In any case, a planned approach for interfacing the combiner-interposer-array using two layers of BGAs is shown in Figure 5. This proposed integration suggests that even if the various planar circuits cannot be directly integrated, integration via a BGA-based interface can potentially be done in a very compact, low-profile way. The combined planar circuits, as shown in Figure 5, would constitute a low-profile, planar aperture with dual/orthogonal polarizations, similar to a horn antenna with an opening equivalent to the planar aperture antenna footprint.

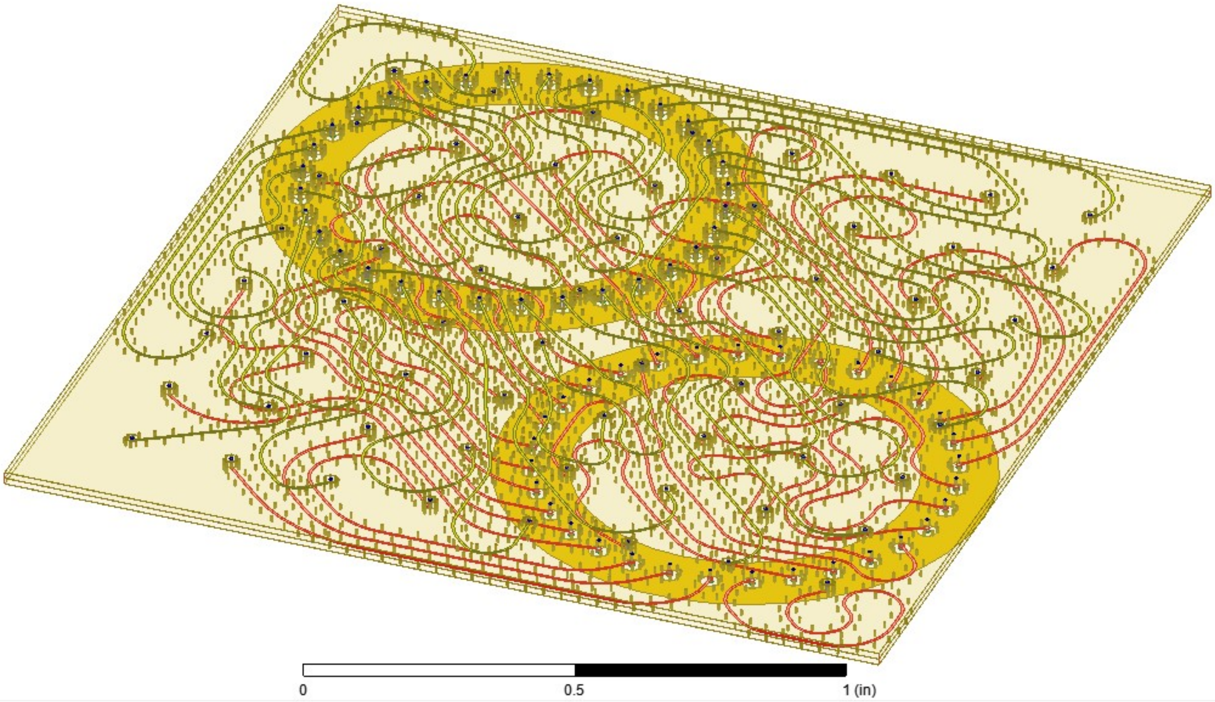

Figure 4. A PCB-based interposer circuit to route radial outputs to a typical square grid for planar antenna arrays. Dimensions are 1.75”x1.75”

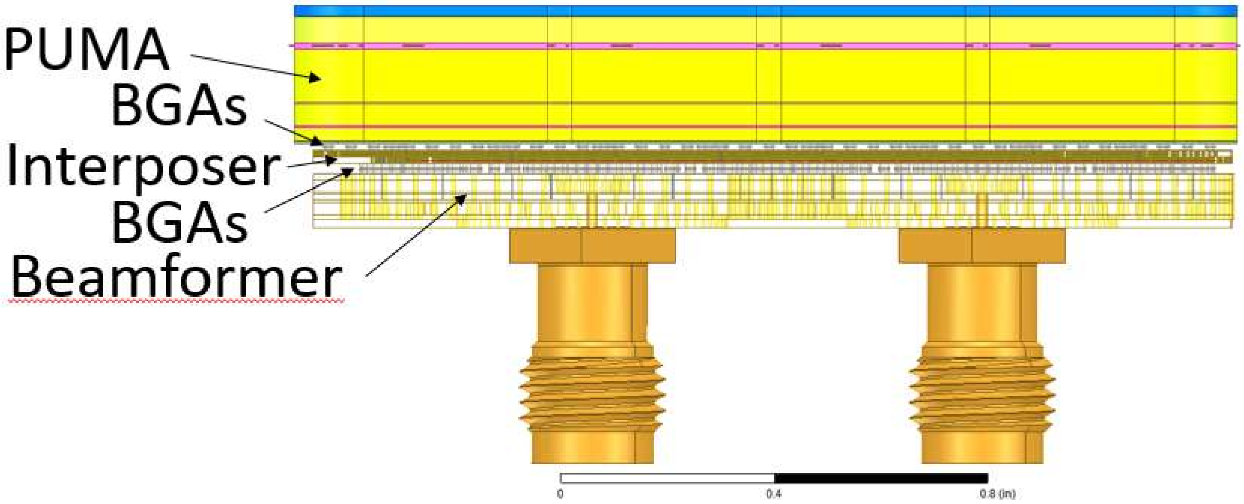

Figure 5. Proposed BGA integration of a planar PUMA aperture with a radial combiner (beamformer) using an intermediary layer of planar interposer circuit between two layers of BGA interfaces.

IV. RADIAL COMBINER BASED ON PRINTED CIRCUIT BOARD TECHNOLOGY

As mentioned above, direct integration of all three circuit types – the planar antenna aperture, interposer circuit, and radial combiner – would require the three circuits be constructed using the same manufacturing approach. At present, the high dielectric constant of LTCC materials make them generally unsuitable for design and construction of PUMA apertures. However, all three circuit types could potentially be done with multi-layer printed circuit board construction. In order to prepare for the eventuality of a complete, fully-planar integration of all three circuit components, in FY23 we began looking at possible PCB designs for the radial combiner. The combiner design for LTCC cannot be directly ported to PCB manufacturing. The primary challenge is that the LTCC design is not scalable from the perspective of PCB manufacturing. LTCC allows for very small via aspect ratios, whereas PCB manufacturing have stringent limitations on via diameters relative to panel thicknesses. Though the first attempt at a fully-PCB version of the radial combiner requires some compromises, a workable design solution was eventually achieved. Figure 6 shows the notional stack-up of the PCB-based radial combiner design for operation from 3.5 GHz to 21 GHz. The design is constructed from Panasonic Megtron 6 (R5755K) core material bonded with R-5670 bond-ply. The critical via diameters have been set to OD=0.0118" and having an aspect ratio of less than 4.5:1. Smaller diameter vias are compatible with PCB manufacturing, but as designed, this will allow for the PCB-based combiner to be (potentially) scaled to higher frequencies (e.g., Ka-band, 40 GHz). The design requires 4 cores of Megtron 6 material and three layers of bond ply.

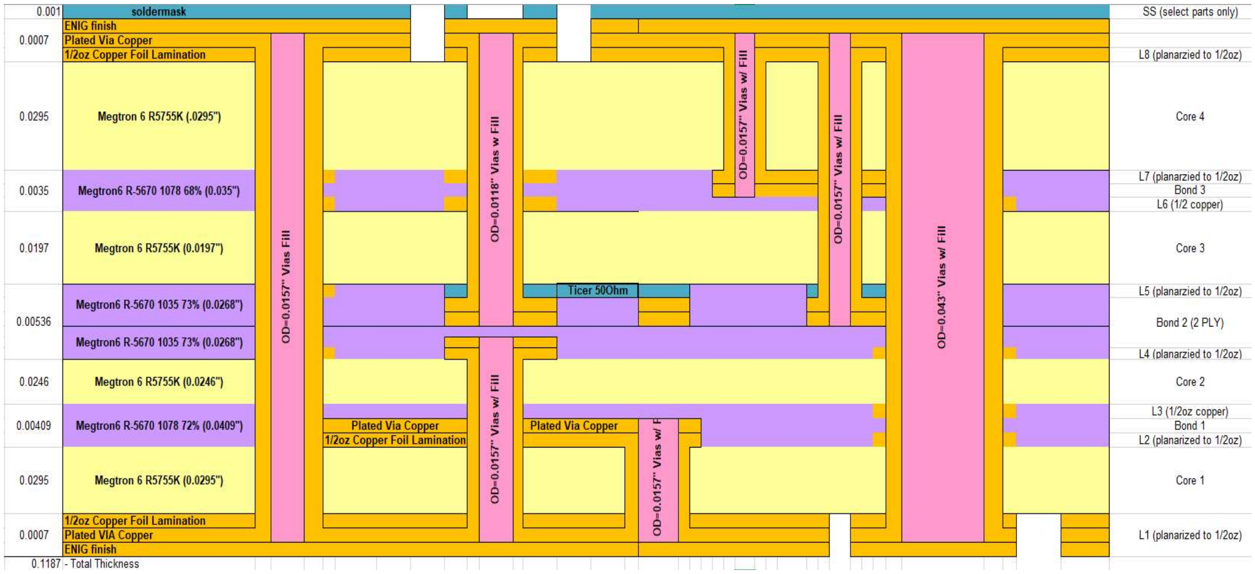

Figure 6. Radial combiner design stack-up based on standard printed circuit board manufacturing.

As with the LTCC-based combiner, the PCB-based radial combiner is designed to place two 32-port circuits in a planar layout below an 8x8, 64-element dual-polarized 21 GHz PUMA aperture. One difference between the LTCC and PCB-based designs of critical importance is the difference in material dielectric constant. Ferro A6 (LTCC) has a dielectric constant near to 5.6, whereas Megtron 6 is closer to 3.6. From a design and manufacturing perspective, this means that the Megtron 6 combiner must be notably larger in size to operate at the same frequencies. Hence, the Megtron 6 design, shown in is roughly 2.3 inches square compared to the 1.75 inches square for the LTCC design. Future PCB-based designs could be attempted using materials with a higher dielectric constant, but Megtron 6 was deemed a good choice for this initial design attempt.

For the initial design of the PCB-based radial combiner, construction will be done in two ways. Some parts will be produced with a soldermask in place on the radial output side of the circuit for BGA attachment to an interposer circuit (Figure 7). The remaining parts will be produced with bare metal for direct solder attachment of commercial RF coaxial connectors (see Figure 8). This approach to testing allows for direct evaluation of the circuits as well as testing of the BGA interfacing approach. A commercial SMPS connector was selected that fits within the pitch of the radial ports, as demonstrated in Figure 9.

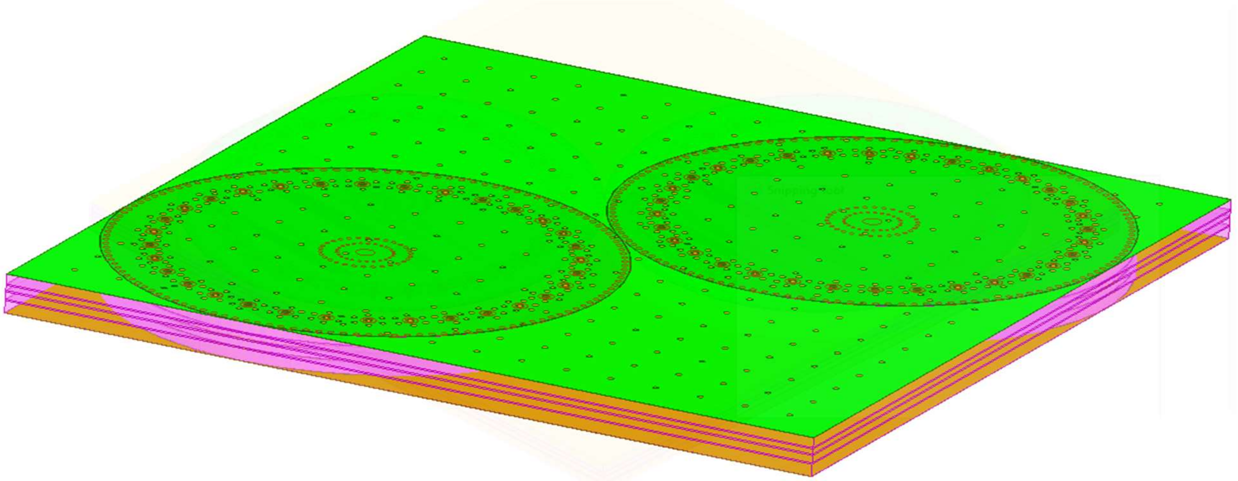

Figure 7. Some PCB-based radial combiners will be produced with soldermask in place for BGA ball attachment.

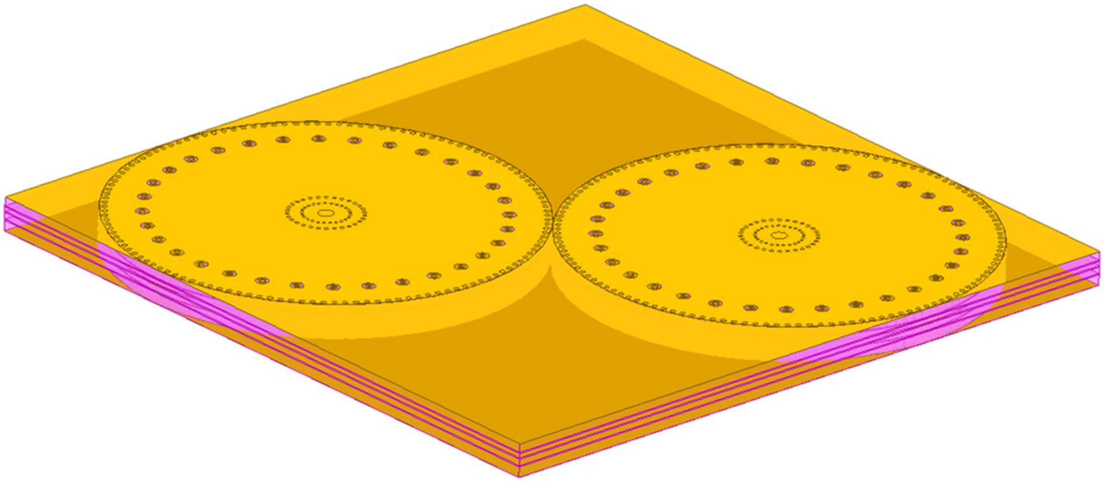

Figure 8. The PCB-based (Megtron 6) radial combiner. Dimensions are roughly 2.3” square.

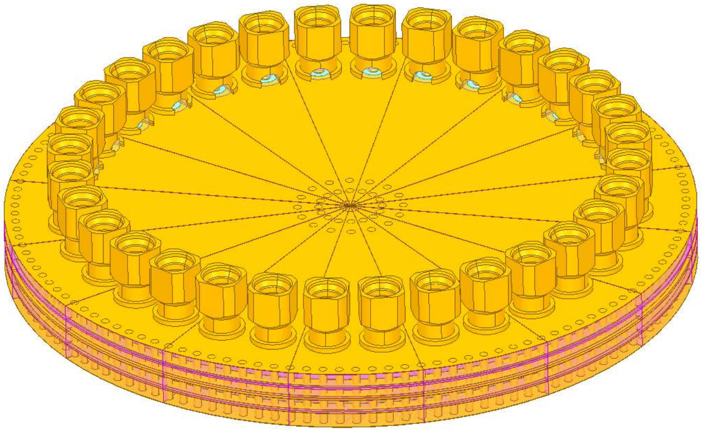

Figure 9. A PCB-based radial combiner circuit with the proposed SMPS surface mount connectors in place, demonstrating proper fitment.

The radial combiner circuit is predicted to perform over the bandwidth shown in Figure 10. The return loss at the common port of the 32-way radial combiner was designed to remain below -10dB levels from roughly 3.5 GHz to 21 GHz. With wide bandwidth designs such as this, there is always a tradeoff in tuning. Often lower return loss and/or wider bandwidths can be tuned with the design, but these gains come at the compromise of larger circuit footprints or worse port isolation. Port isolation for the same circuit is shown in Figure 11. It was attempted to minimize the circuit size given the chosen materials and available core thicknesses, while maintain return loss at or below -10dB and simultaneously maintaining isolation across all array ports at -15dB or better levels. These constraints proved to be challenging to work with, but a design that came close to meeting all tuning parameters was eventually achieved. A functional design was completed and submitted for manufacture in the last quarter of 2023.

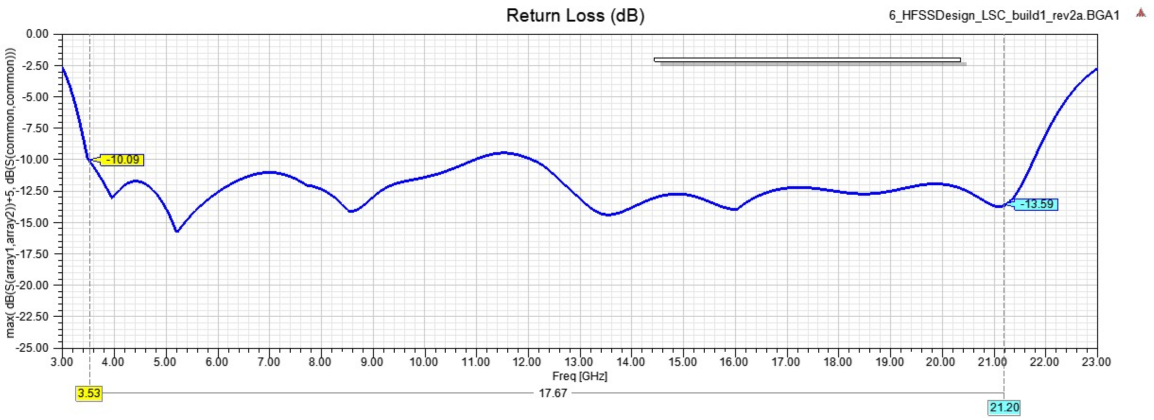

Figure 10. Common port return loss (dB), as designed, for the 32-way radial combiner (target of -10dB).

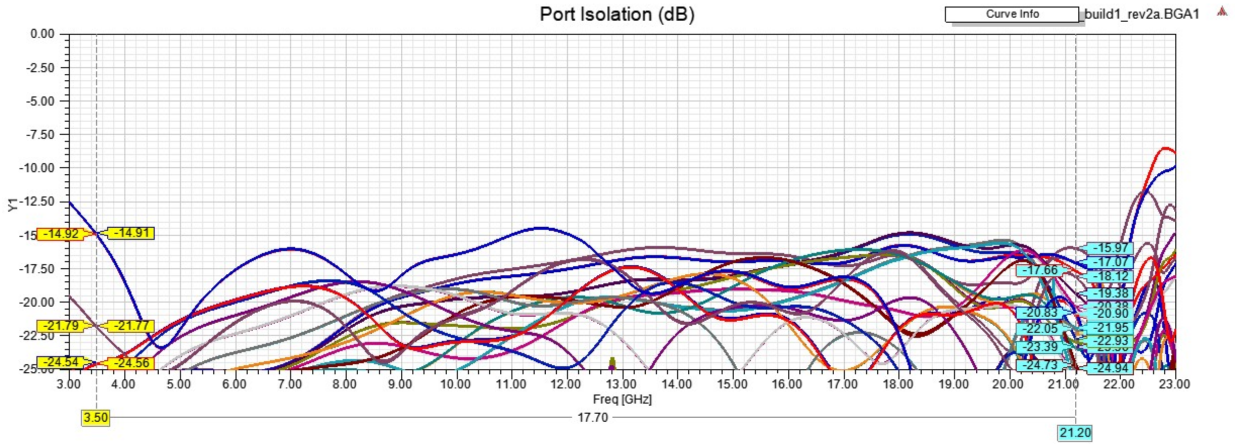

Figure 11. Port isolation (dB), as designed, for the 32-way radial combiner (target of -15dB).

Additional hardware was also designed for testing both the radial combiners as well as the BGA interfaces on the circuits. Figure 12 shows a coaxial through testing piece that was designed for attachment (via BGA interface) to the radial combiner. The material stack-up for this through circuit design is shown in Figure 13. Once attached to the array ports of the radial combiner, a robust and removable/reusable coaxial port interface can be hard contacted to the radial combiner using standard fasteners and fuzz button electrical interconnects. The design for the coaxial port interfaces are shown in Figure 14. As with the combiner itself, these parts were designed and purchased in late 2023.

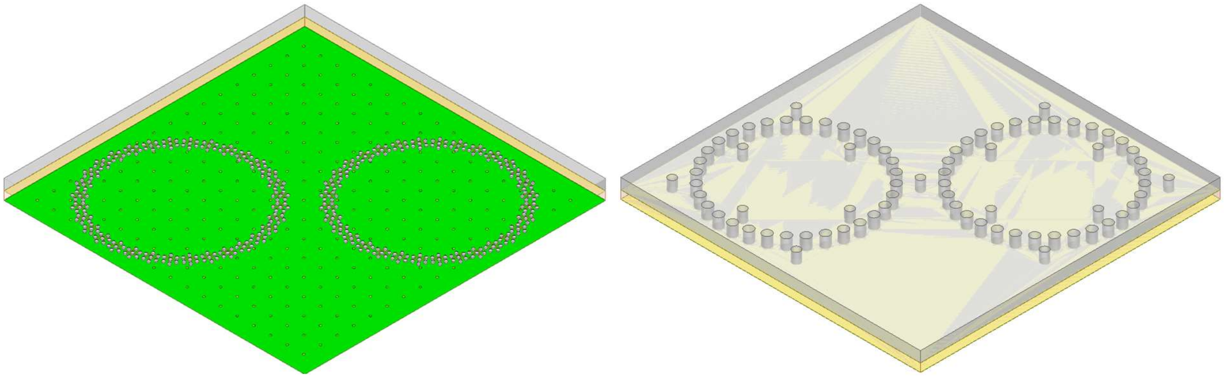

Figure 12. Coaxial through circuit for testing the array ports of the radial combiner – requires BGA attachment for testing.

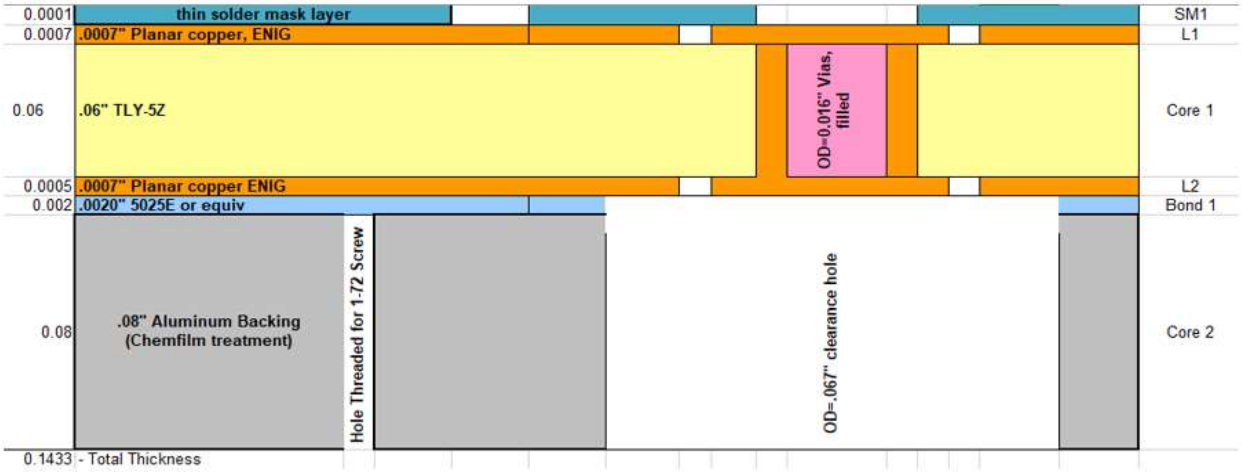

Figure 13. Material stack-up for the coaxial through testing circuit.

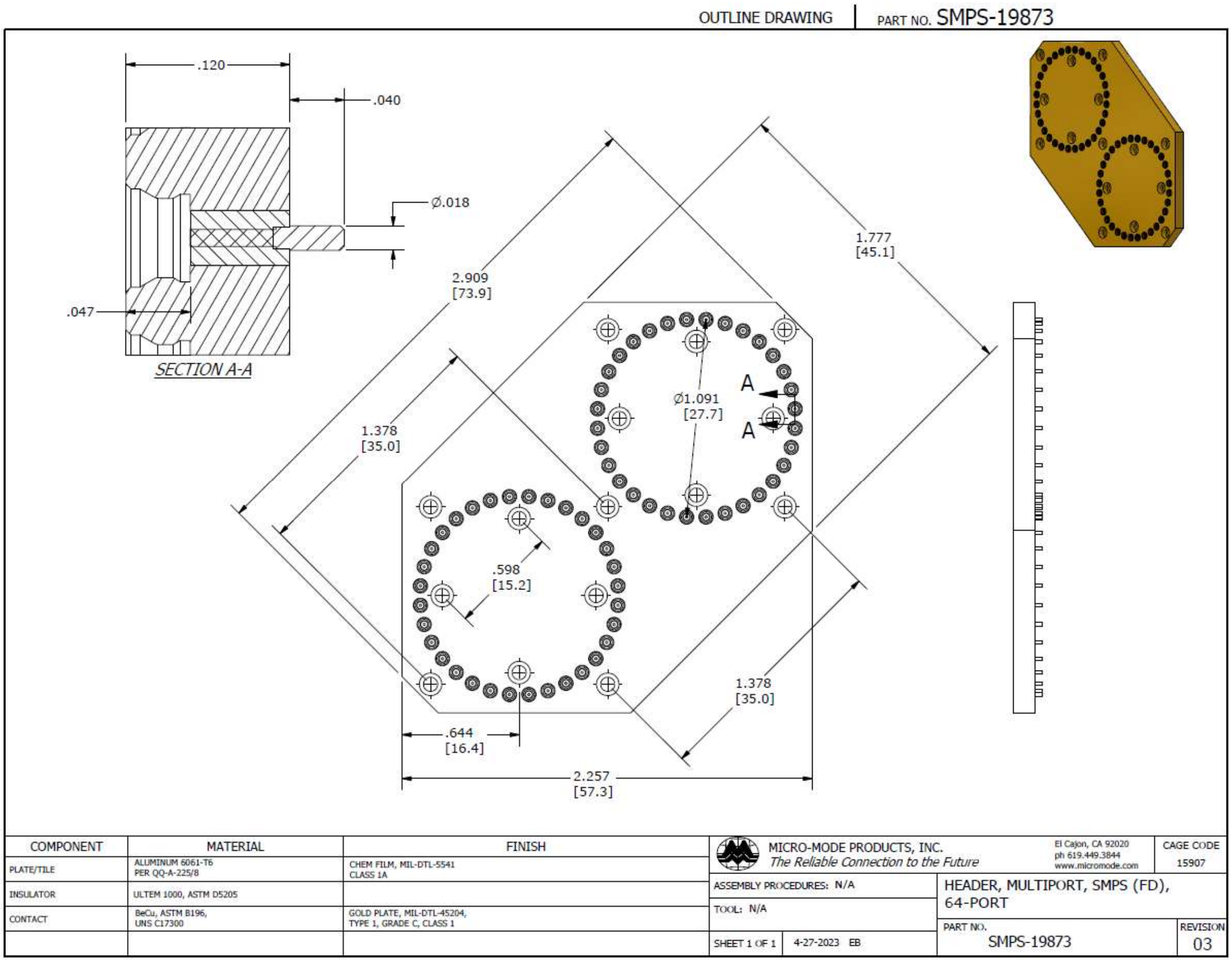

Figure 14. Detachable feed port for testing the array outputs of the PCB-based radial combiner.

For any of these testing applications based on the 8x8 PUMA apertures, having 32 ports in each polarization, the array aperture layout remains the same and will be the regular square grid spaced optimally for scanning operation at a high frequency of 21 GHz. However, because the size of the PCB-based combiner circuit is different than the LTCC-based design (as would likely be the case for any redesign of the combiner circuit), the array outputs of the radial combiners (LTCC vs PCB) are not in the same location. Therefore, the interface to work with them must be adapted for each new design of the radial combiner, such that it was necessary to also design a new interposer circuit for the PCB radial combiner. This new interposer design is shown in Figure 15.

The remainder of the PCB-based radial combiner study will proceed as follows. The LTCC-based build of the 3.5 GHz to 21 GHz combiner will be repeated with the soldermask applied correctly. This will be tested as a baseline for performance comparison with the PCB-based design. The first build of the PCB-based combiner has been submitted for manufacture. Upon completion, some units with no soldermask will be populated with solder-on connectors for direct testing. Other units with soldermask will be fitted with BGA balls and interfaced with coaxial-through testing circuits. Still other units with soldermask will be connected to BGA-based PUMA apertures with the proposed interposer design. Simultaneously, it will be considered if part if not all of the three-part PCB-based circuits can be directly integrated, e.g., the interposer directly integrated with the PUMA aperture or the combiner circuit.

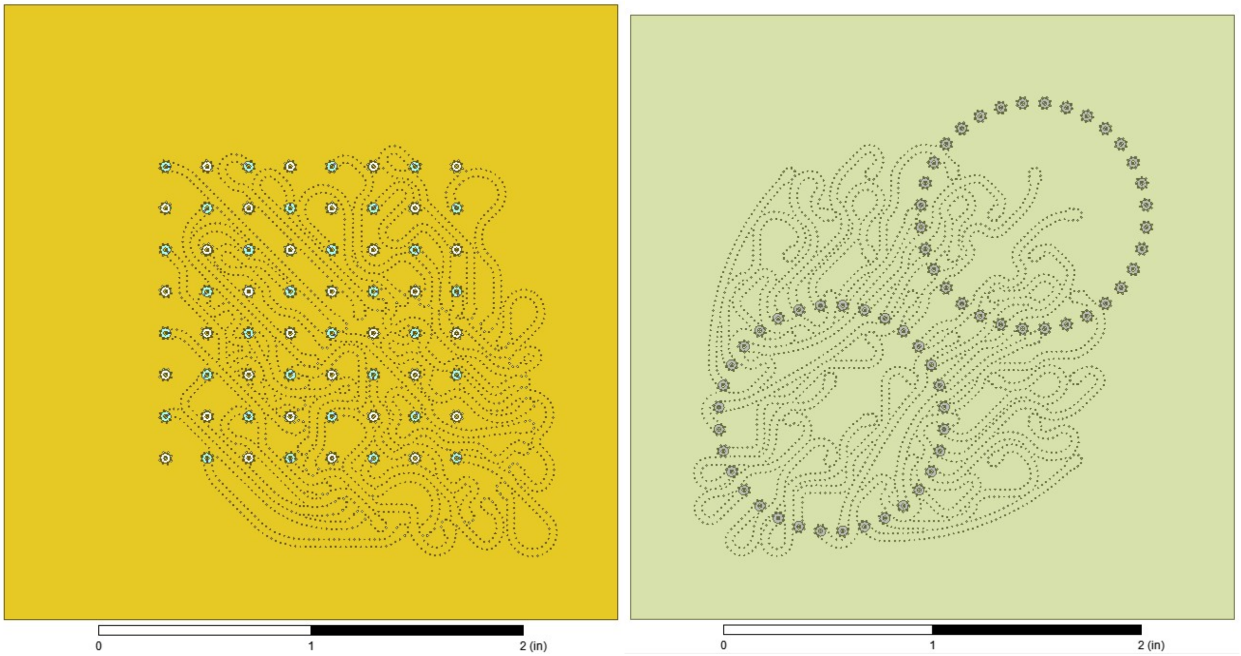

Figure 15. A new interposer design for the PCB-based radial combiner.

V. Future Development 45 GHz Antenna Aperture and Radial Combiner

In past work, a 6:1 bandwidth radial combiner (32-way) for operation at 7.5 GHz to 45 GHz was developed and produced using LTCC technology (see Figure 16). This work was carried out at a later date than the initial 21 GHz LTCC combiner design, and the resulting hardware was completed with a higher degree of precision/quality. To date, these circuits have not been tested. This work provides an opportunity of testing interfacing capabilities at higher frequencies and using smaller BGA balls (12mil vs. 16-20mil). A next step in this project will be to develop testing circuits (e.g., an interposer or a coaxial through testing circuit) to evaluate the performance of the combiner at 45 GHz.

Similarly, for the same project a 7.5 GHz to 45 GHz PUMA aperture was designed and tested (see Figure 16). These PUMA apertures were designed and built with precision RF coaxial connectors and validated to operate (roughly) as expected. As a next step for this project, new 45 GHz PUMA apertures can be re-designed with a BGA interface for future integration with the 45 GHz radial combiners.

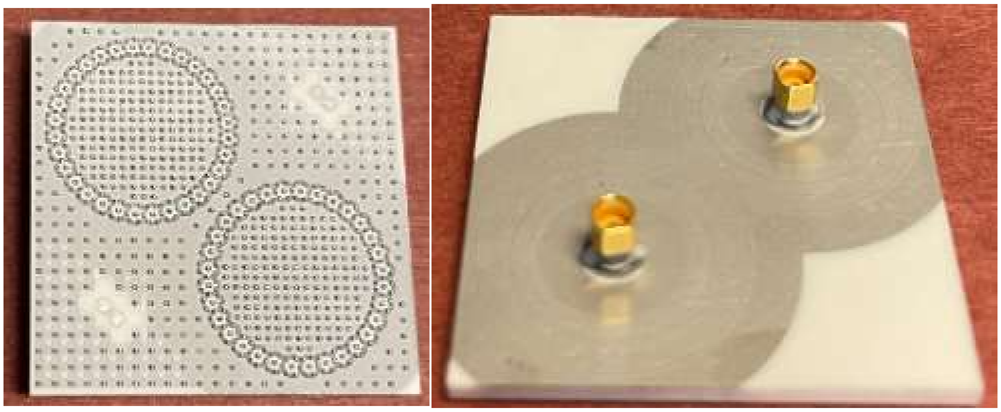

Figure 16. 45 GHz radial combiner based on LTCC technology.

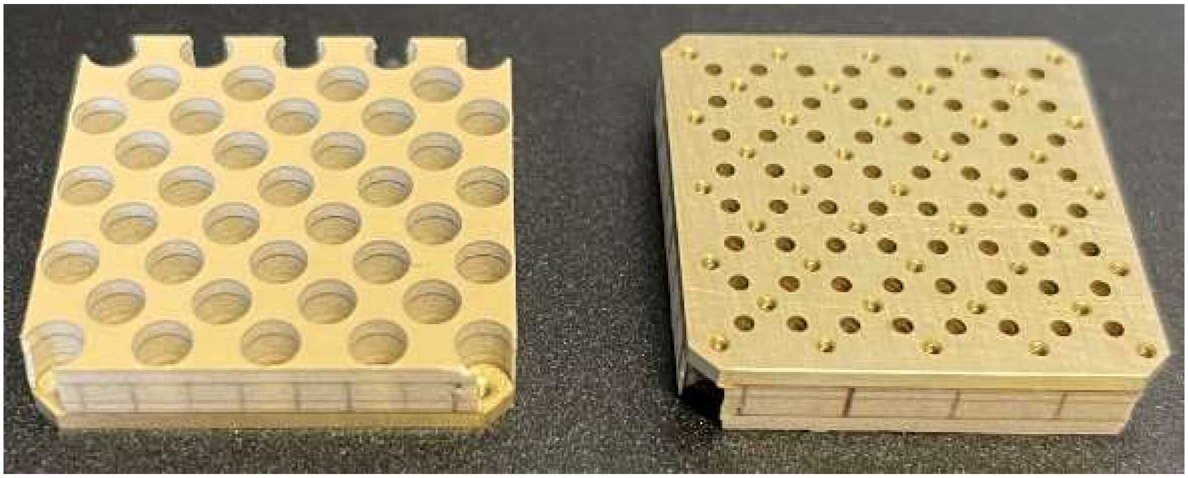

Figure 17. A 7.5 GHz to 45 GHz PUMA aperture (tested, but not BGA-based).

VI. CONCLUDING REMARKS

This report summarized the work to date on wideband radial combiners. Specifically, background was shared regarding the initial development of wideband radial combiners based on LTCC construction for a previous NRL base program. The projected path of this LTCC-based combiner research was explained, leading to the development of a radial combiner based on PCB technology. If it can be successfully demonstrated that each of the three circuit types based on PCB construction perform as intended and can be interfaced with BGA technology, then a next step could be the direct integration of all three circuit types in a single multi-layer build. In addition to the development plan at 21 GHz, progress to date was discussed for a similar effort at 45 GHz.

VII. REFERENCES

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[2] R. W. Kindt, S. Nunes, Miguel.Reynaga, and A. Piloto, "Ball Grid Array Integration of Wideband Planar Printed Array Apertures," presented at the IEEE Antennas and Propagation Society International Symposium, Portland, OR, 2023.