ADDITIVE MANUFACTURING AND CONFORMAL INTEGRATION OF RADIOFREQUENCY CONNECTORS AND BALUNS

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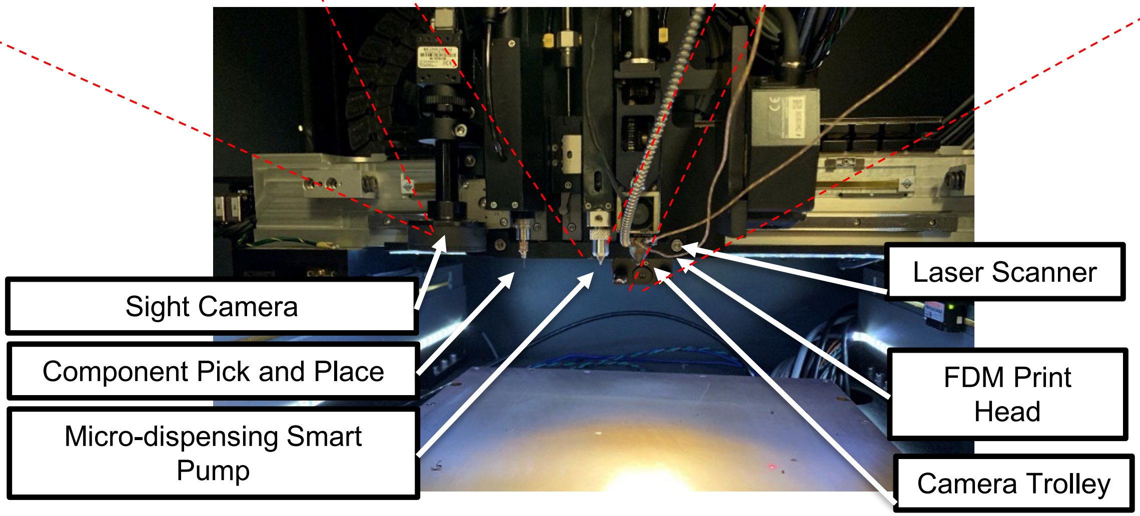
Background: Additive Manufacturing

- Smart pump for printing inks and pastes
- FDM for thermoplastics
- Pick-and-Place for placing bulk components
- Micro-milling for surface smoothing
- Positional accuracy ± 1 um
- Laser scanner
    - Conformal printing

[2]

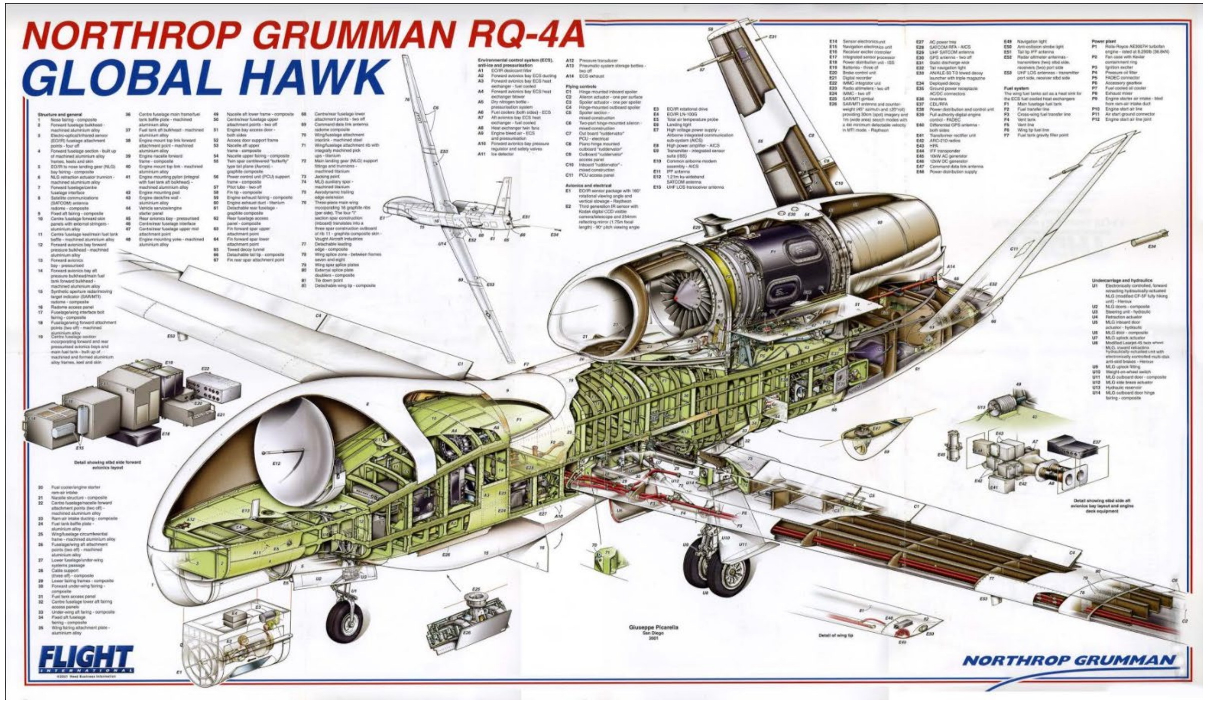


Background: Beamforming

Phased Arrays

High performance but expensive. [3]

Mechanically Steerable Dish

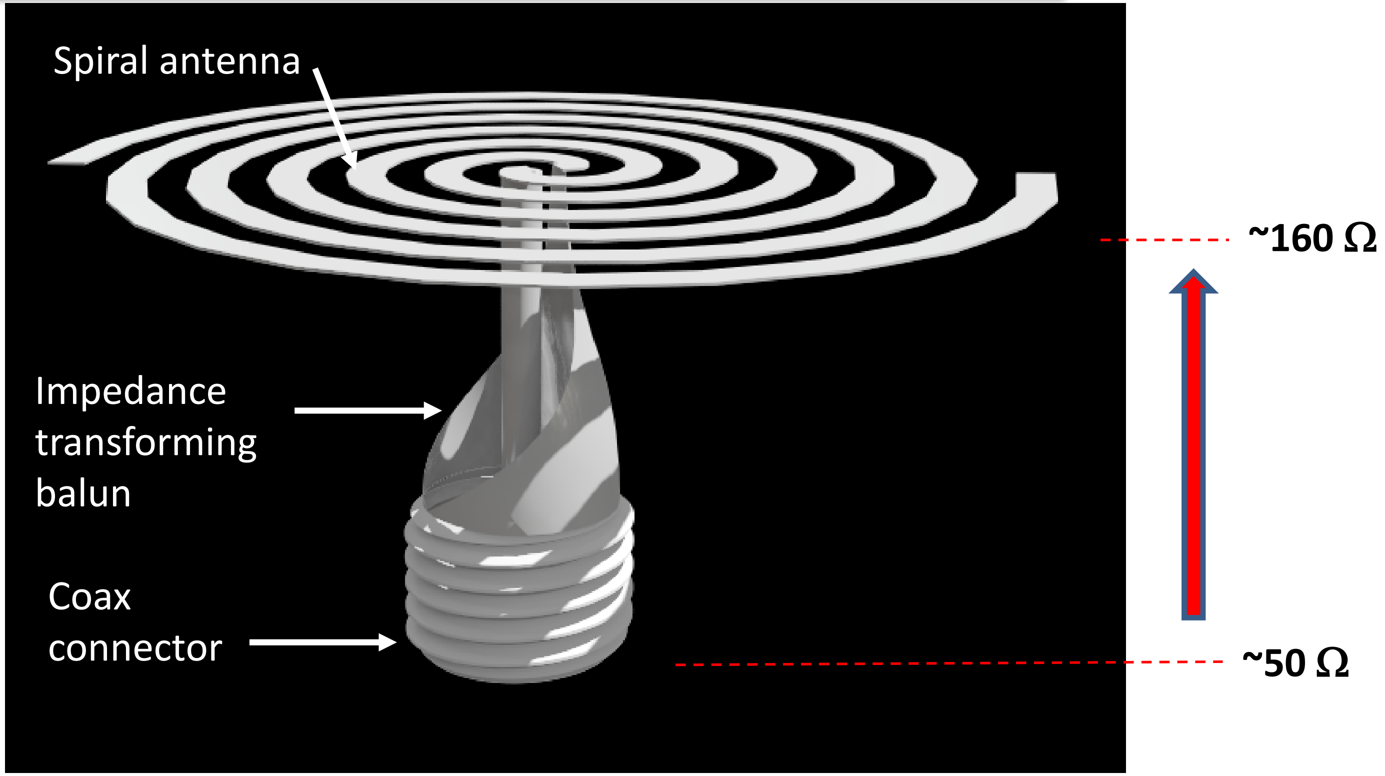


Less costly but slow, heavy and prone to breakdowns [4]

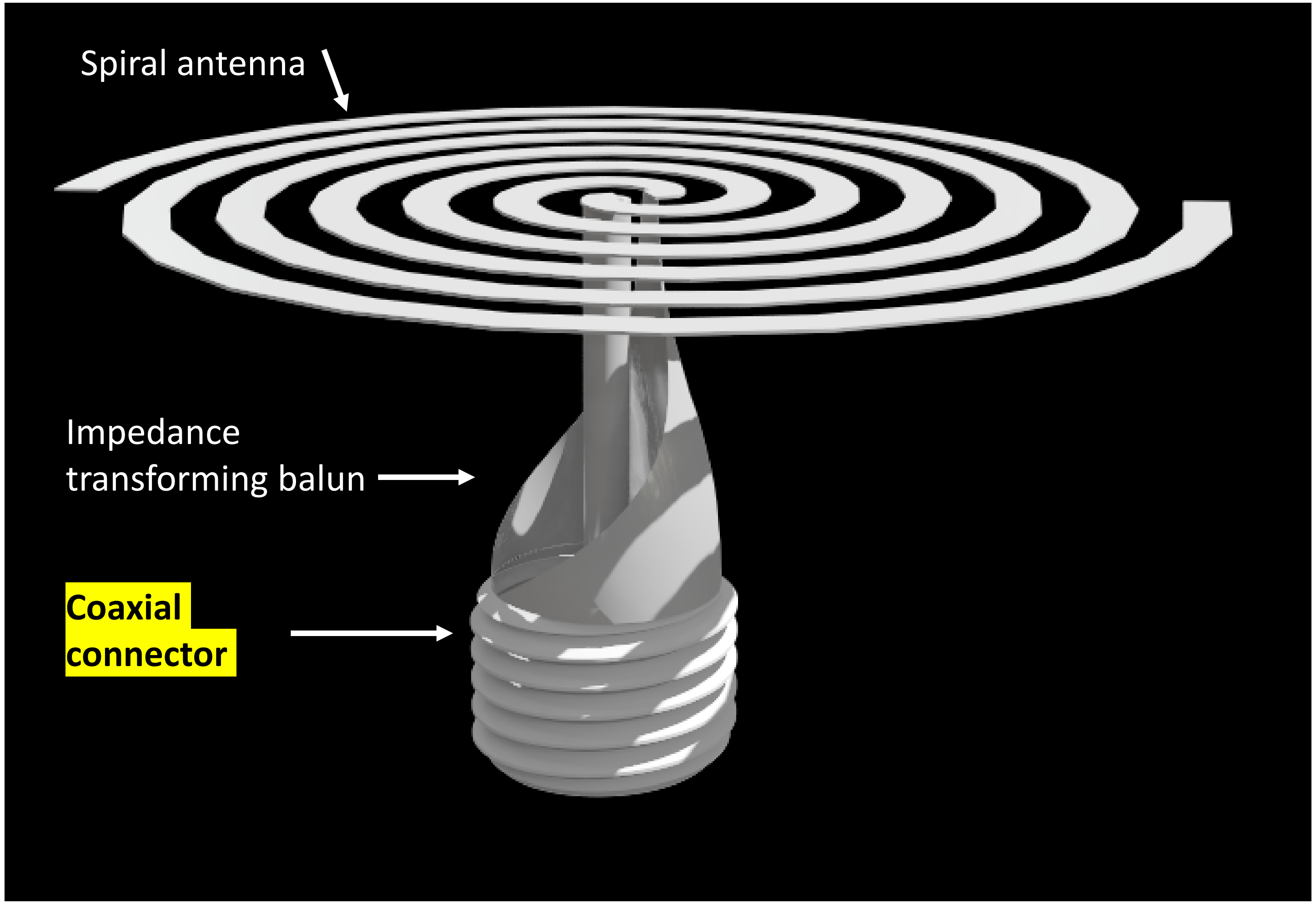
Feed Design for Conformal AM Printed Feeds

Using hybrid additive manufacturing realize wideband feed antenna arrays that can be conformally integrated within a passive beamsteering lens.

- A completely integrated feed made using a single AM process and machine
- No need for soldering or bonding of many components
- Threaded SMA connector for mating to COTs adapters and cables
- Integrated wideband impedance transforming balun
- Wideband circularly polarized spiral antenna

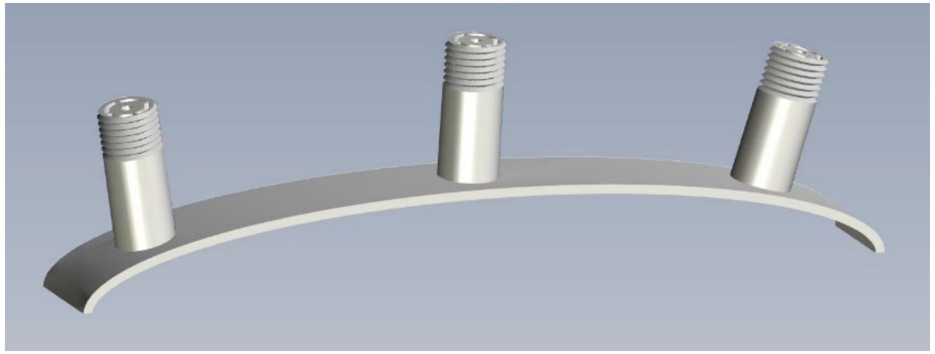


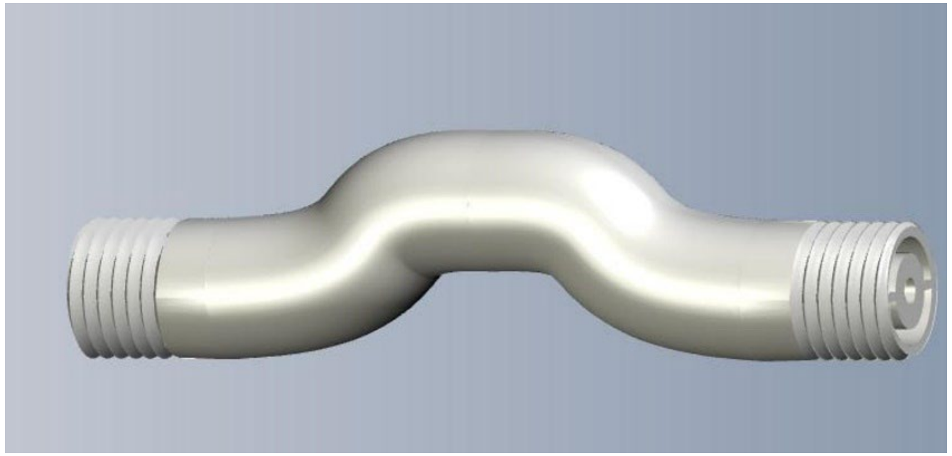
Feed Design for Conformal AM Printed Feeds



Design and Additive Manufacture of RF Connectors

- Method of transitioning from COTS RF connectors and adapters is required
- SMA connector was chosen to be modified for its high frequency operation
  - Advantage of mating with 3.5 mm and 2.92 mm connectors
- Seamlessly integrated into substrates
- Shaped into unusual geometries to address volume constraints





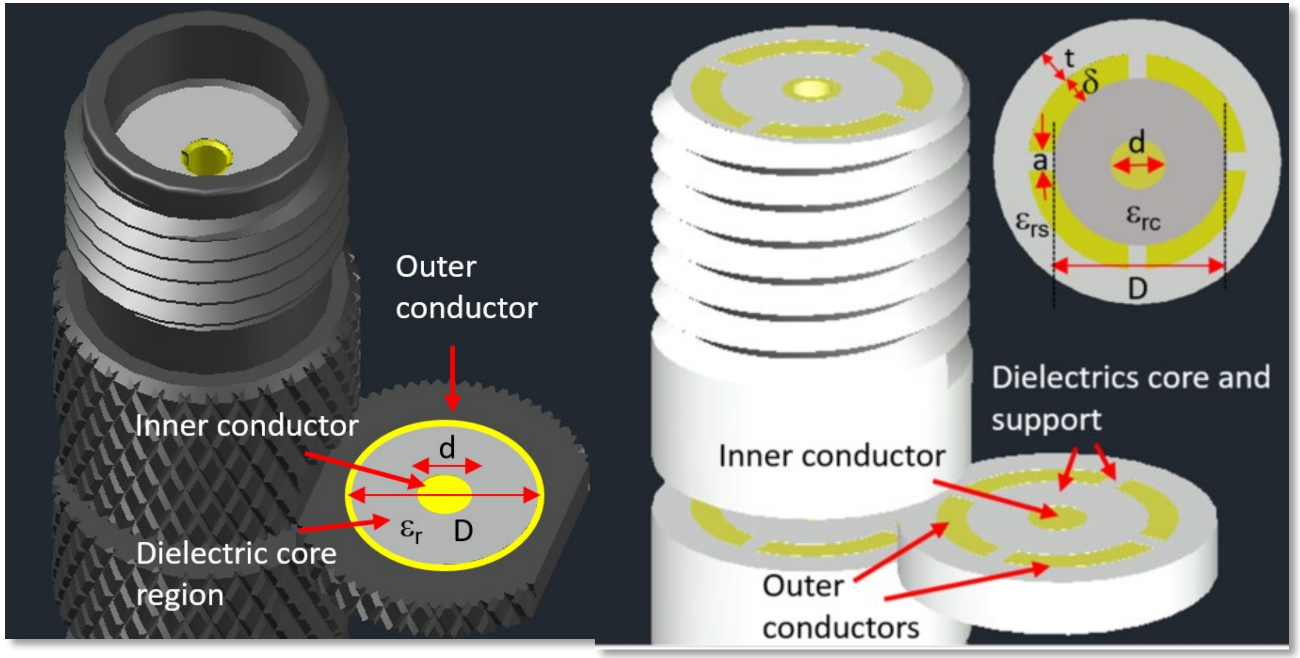
K. McParland, Z. Larimore, P. Parsons, A. Good, J. Suarez, and M. Mirotznik, "Additive Manufacture of Custom Radiofrequency Connectors," *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Vol 12, No 1.,* (2022)

Design and Additive Manufacture of RF Connectors

Equation for a 50 Ω characteristic impedance:

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} log_{10}\left(\frac{D}{d}\right)$$

Fig.	D (mm)	d (mm)	ε_r	t (mm)	δ (mm)	a (mm)	ε_{rc}	ε_{rs}
left	4.7	1.4	2.1	NA	NA	NA	NA	NA
right	3.62	1.2	NA	0.77	0.6	0.4	1.75	2.68



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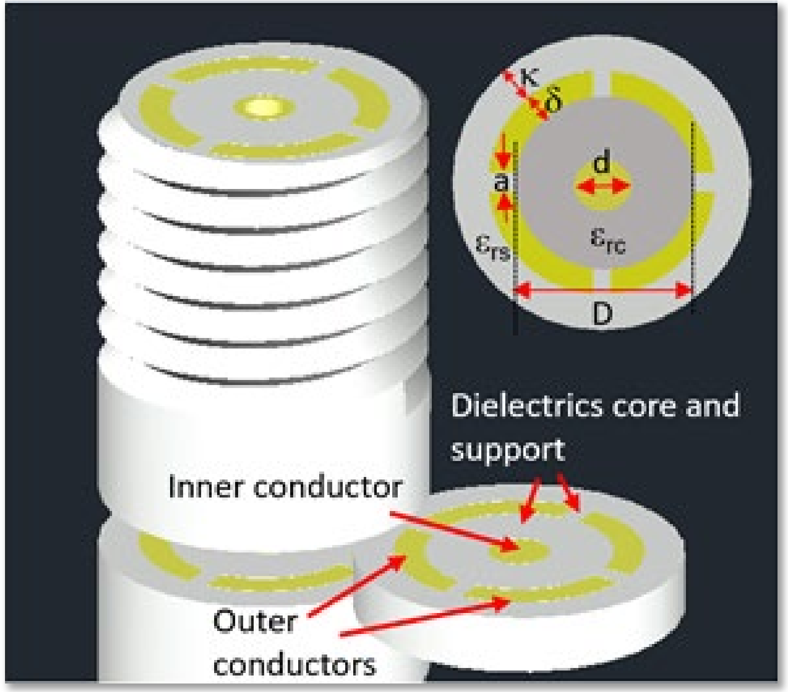
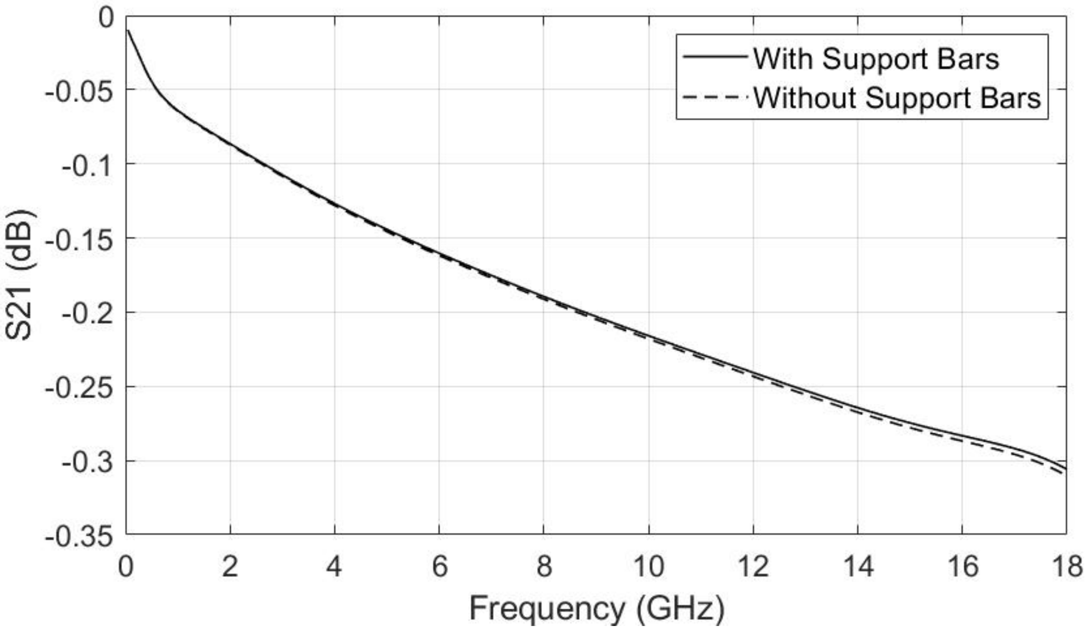
Design and Additive Manufacture of RF Connectors

- Simulations were performed using HFSS to determine the impact of the support bars
  - 15 mm device length





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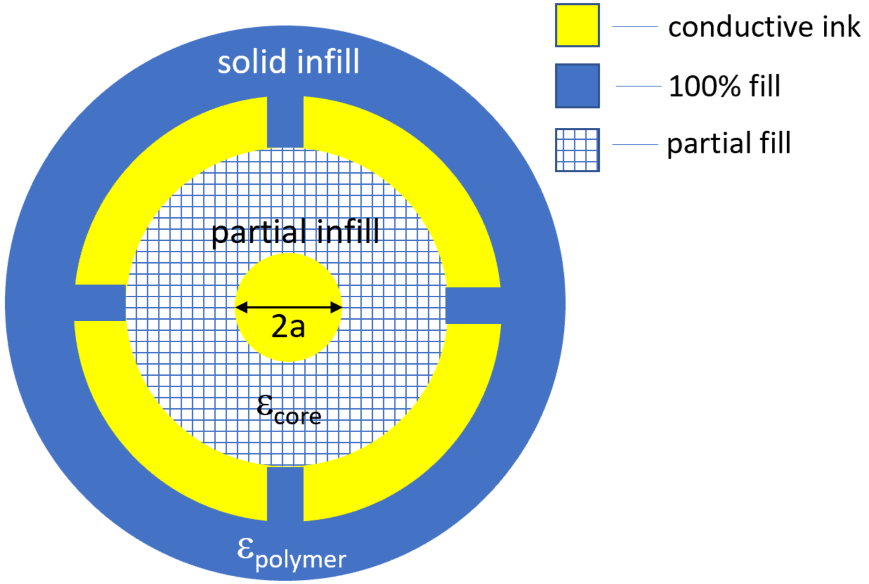
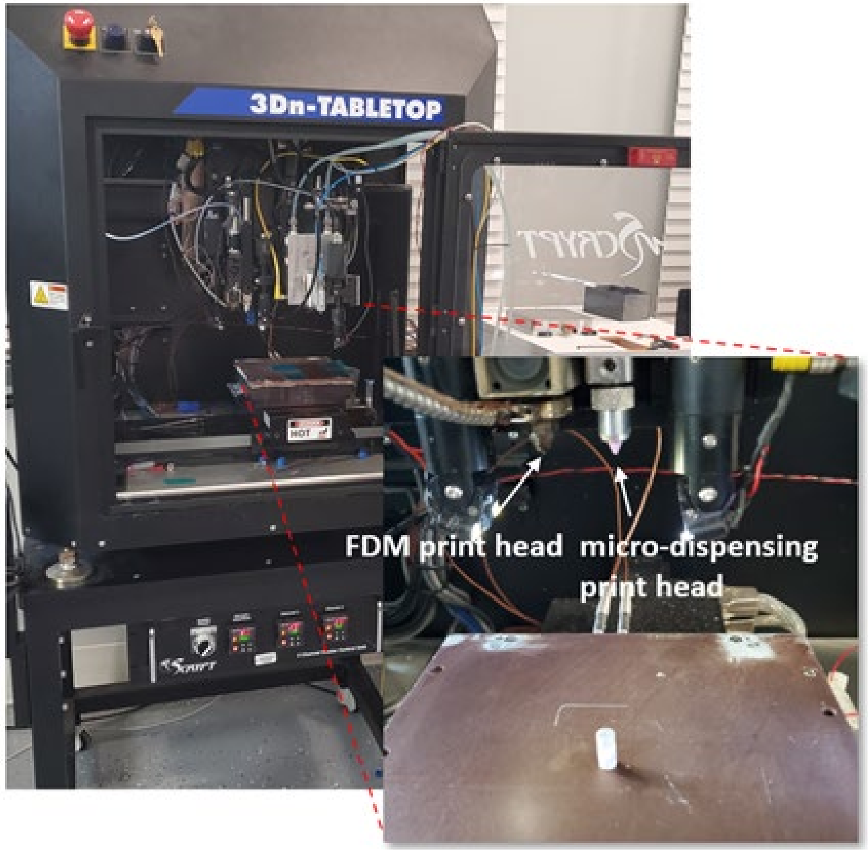
Design and Additive Manufacture of RF Connectors

- Fabrication
  - Printed on nScrypt Tabletop platform
  - Polycarbonate filament used for desirable RF properties and mechanical strength [5]





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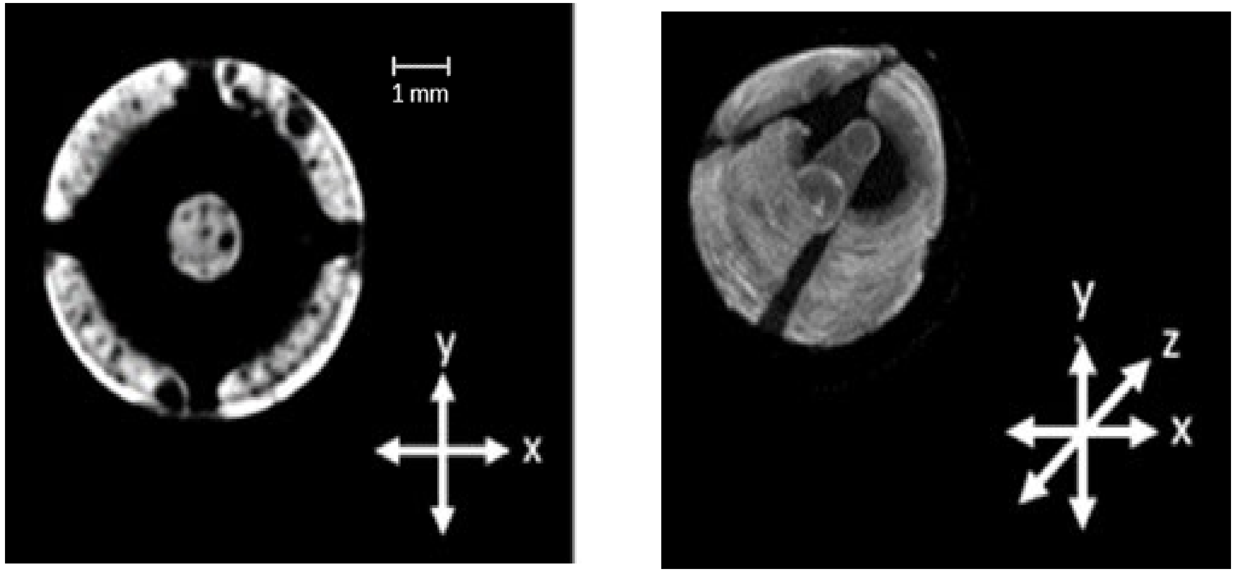
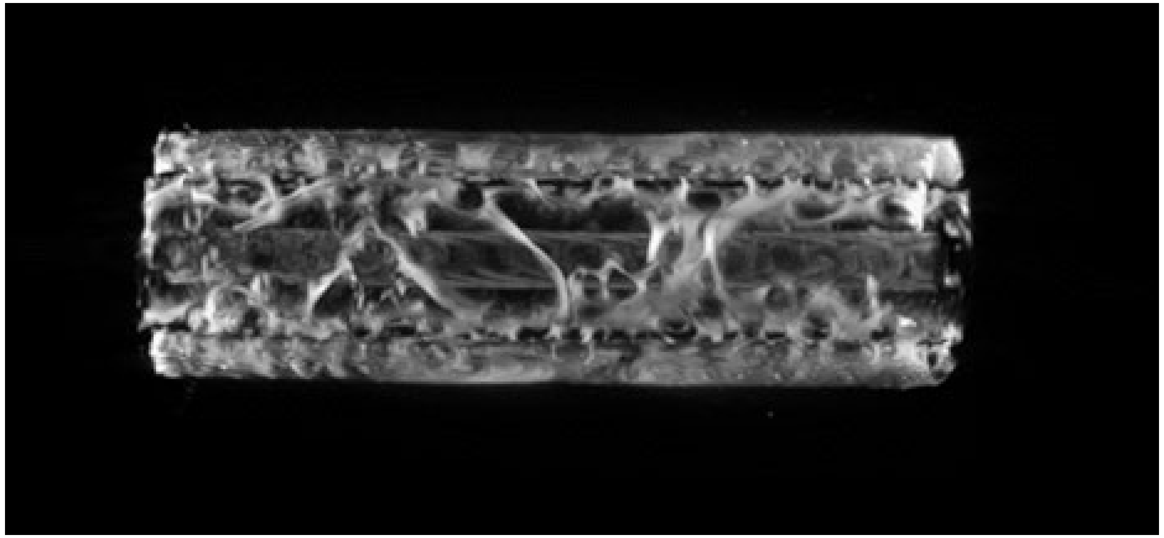
Design and Additive Manufacture of RF Connectors

Lessons Learned: Choosing the right ink is very important!

Micro-CT Imaging: Custom Ink



Micro-CT Imaging: Commercial Ink



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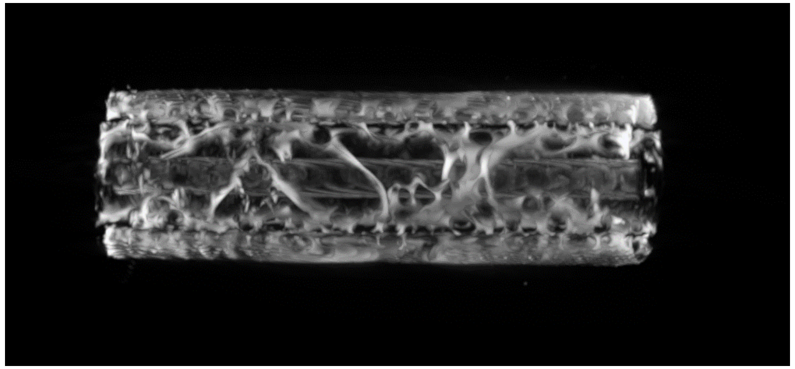

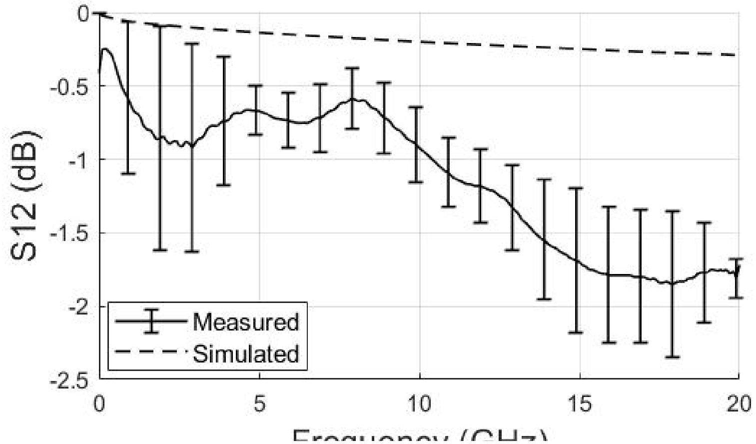

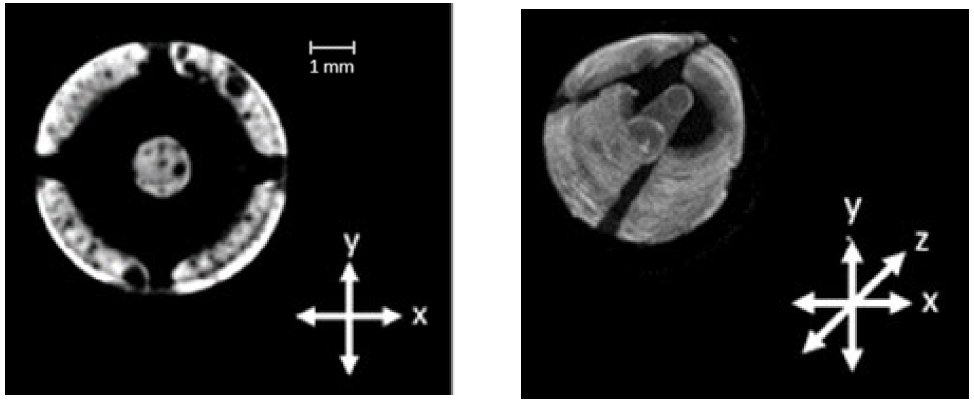

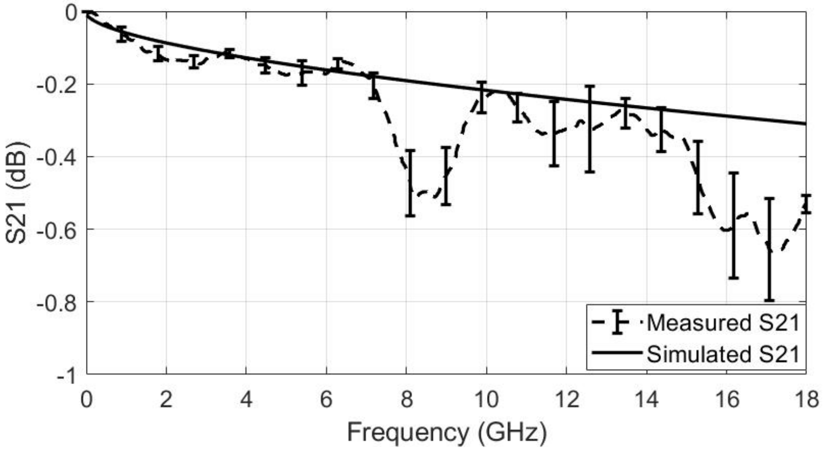

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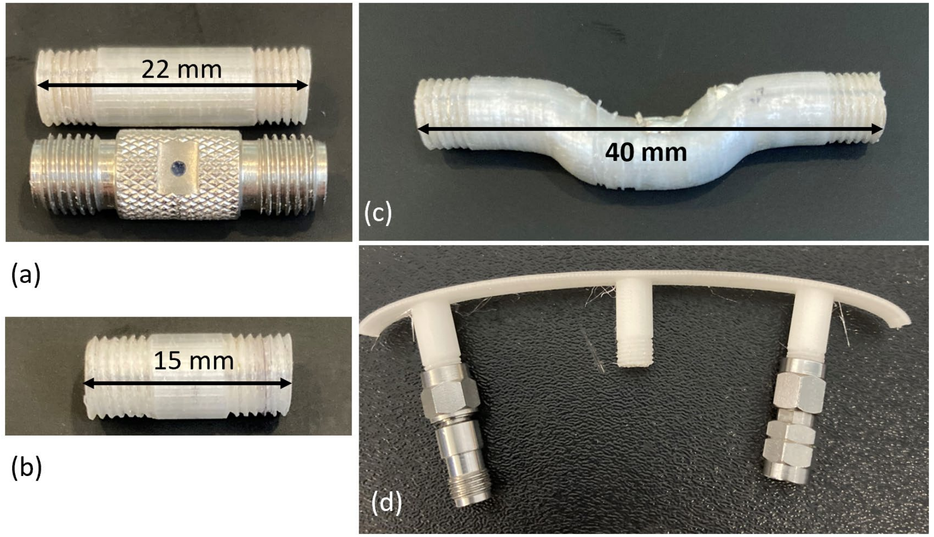
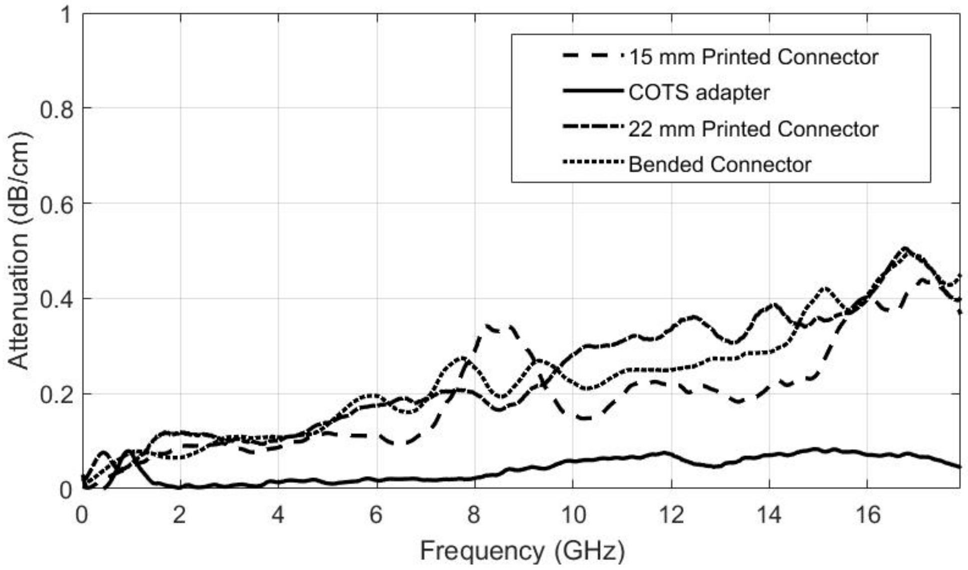
Design and Additive Manufacture of RF Connectors

- Several variations of connectors were printed and electrically characterized
  - While printed connectors do not perform as well as COTS connectors, an attenuation of <0.5 dB/cm up to 18 GHz is still reasonable for many applications





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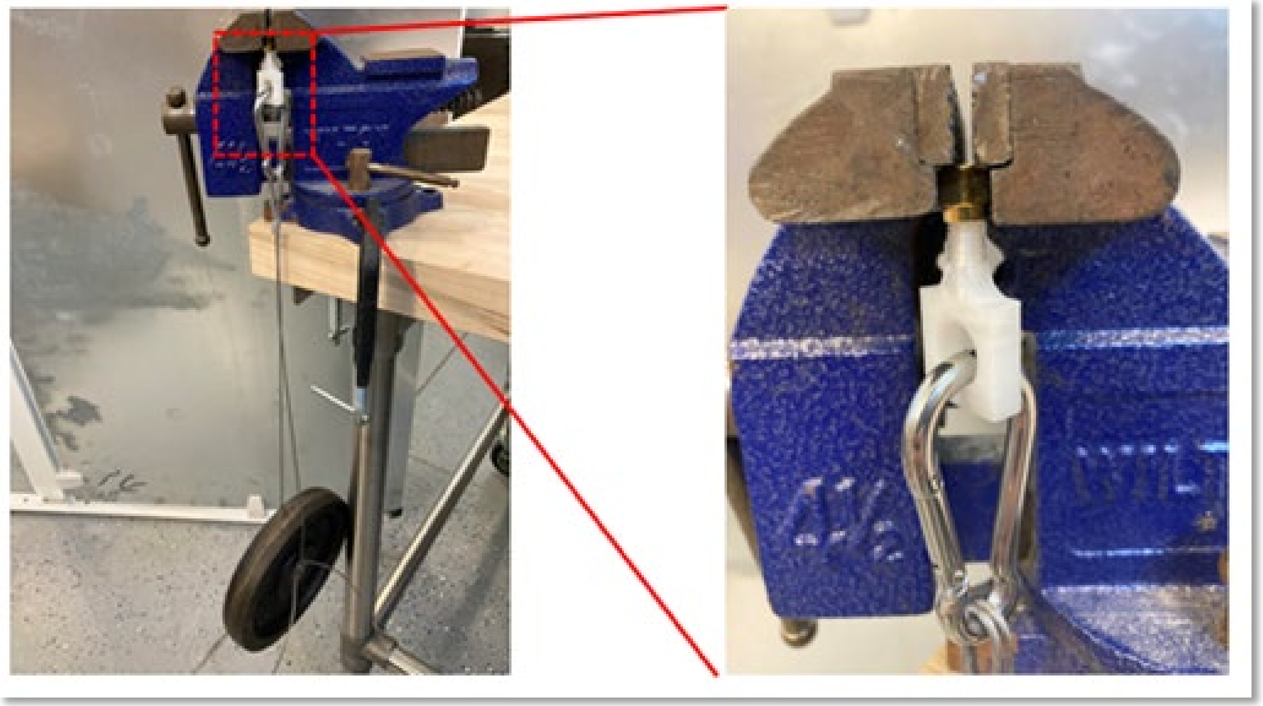
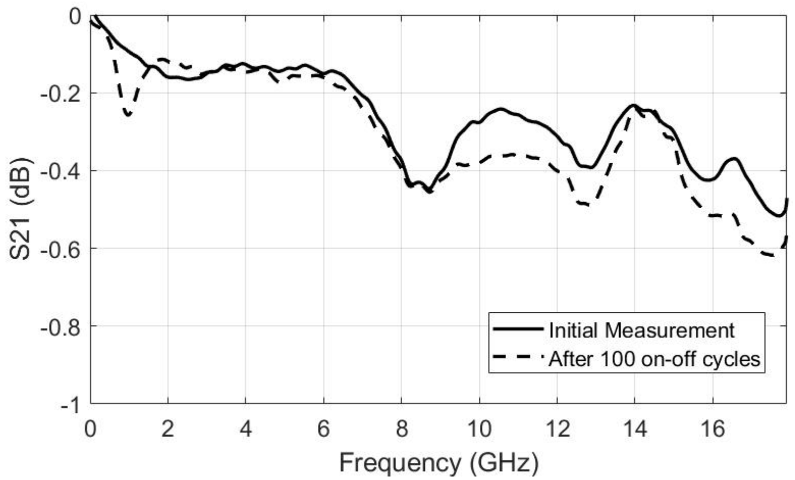
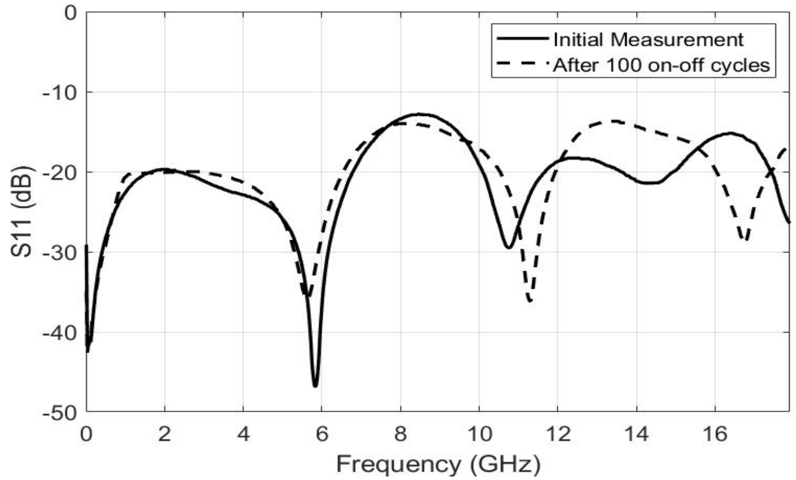
Design and Additive Manufacture of RF Connectors

- Mechanical Characterization
  - Weight Test
  - Durability Test







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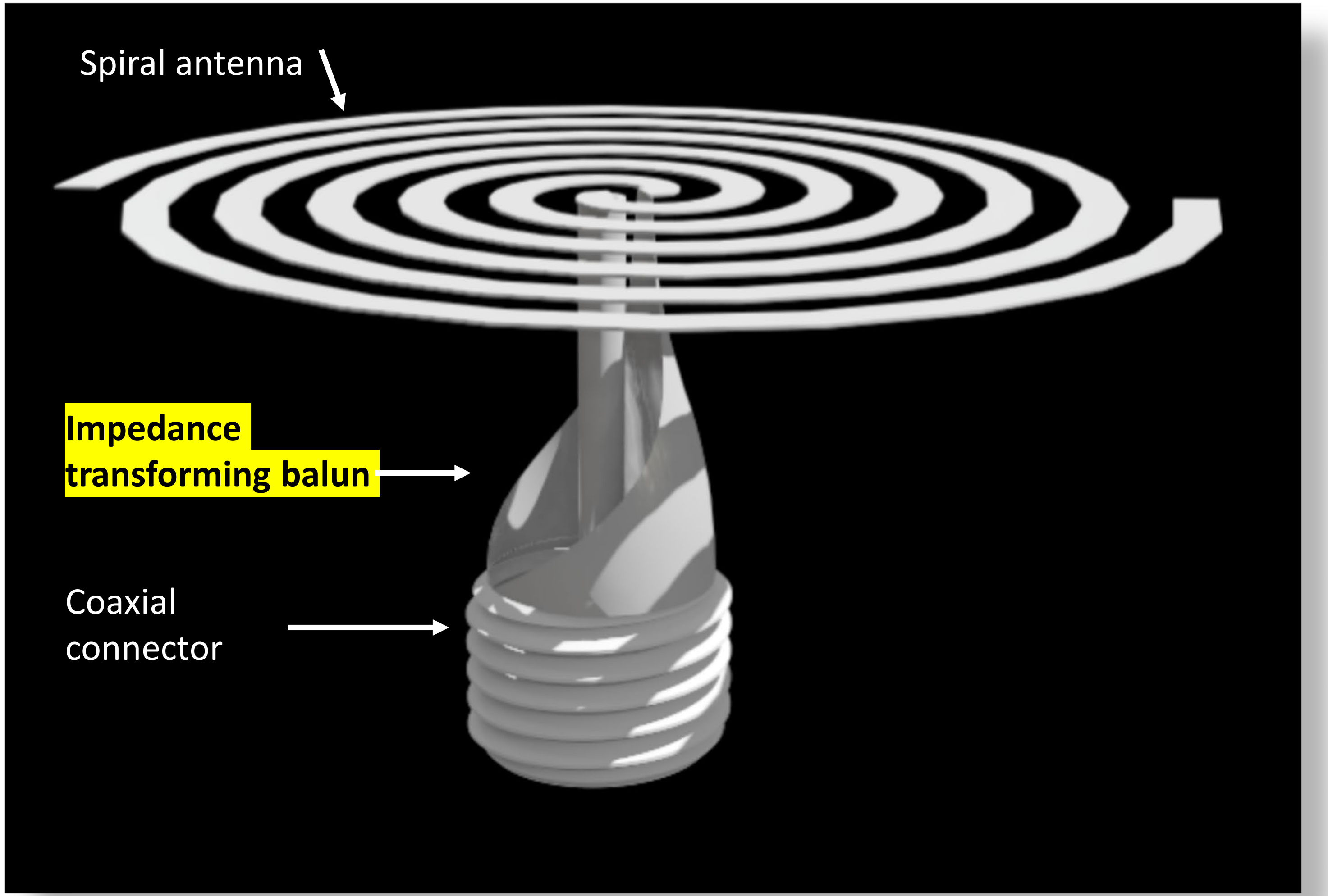
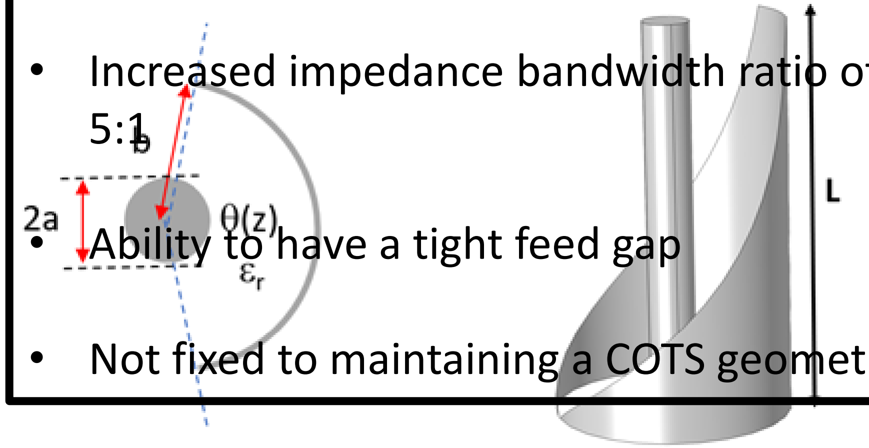


Design and Additive Manufacture of Coaxial Tapered Baluns

- Baluns are necessary to impedance transform from input connector impedance (e.g., 50 Ω) to an input antenna impedance (e.g., ~160 Ω) **AND** balance the current densities on balanced two arm antennas
- Leveraged additive manufacturing to integrate a coaxial tapered balun to feed a broadband antenna
  - Seamless integration into printed connector

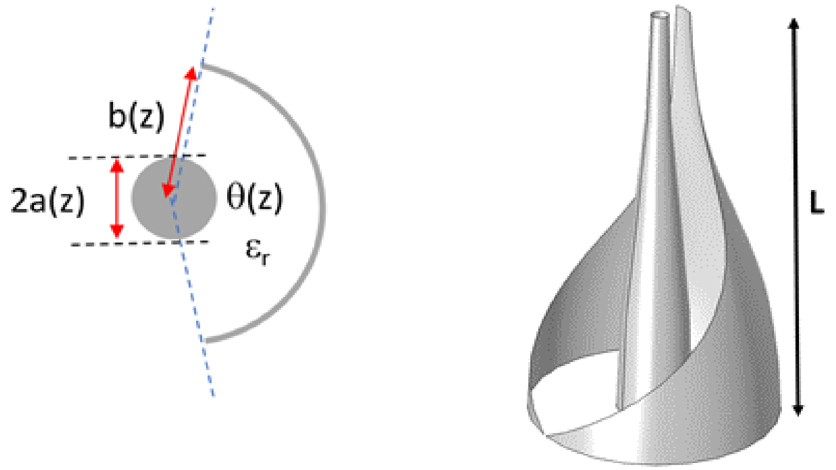
Originally proposed



Advantages to new design

- Increased impedance bandwidth ratio of 5:1
- Ability to have a tight feed gap
- Not fixed to maintaining a COTS geometry

New design and features



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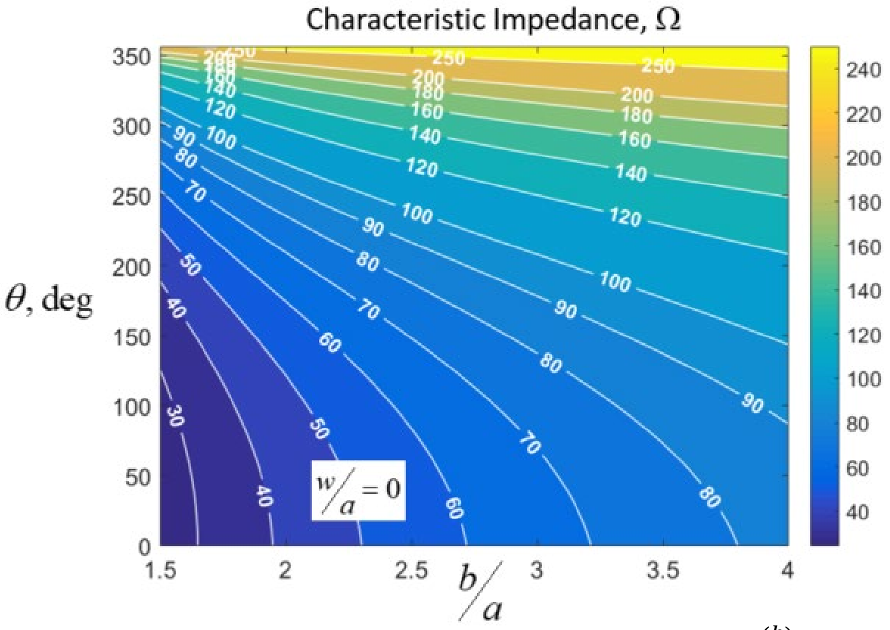
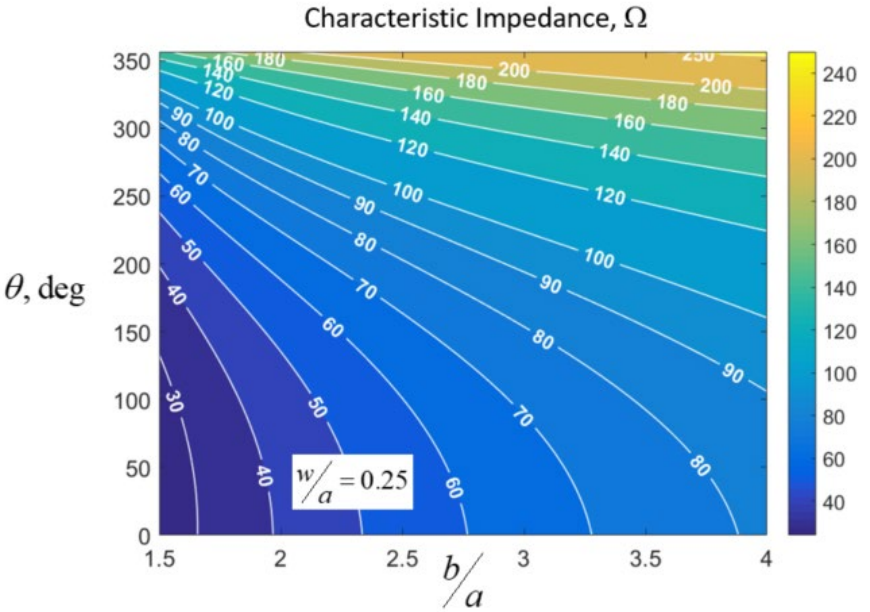
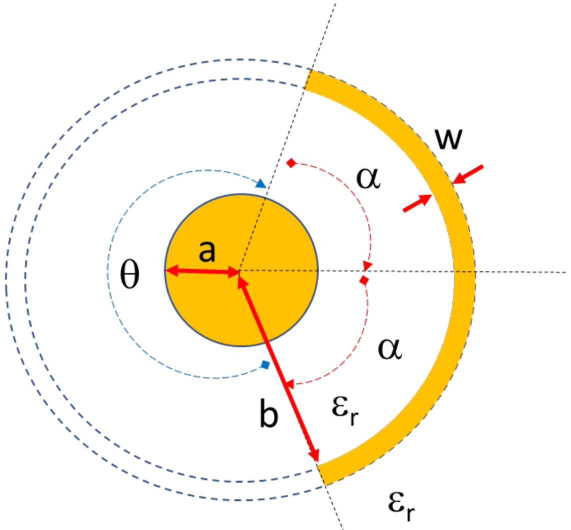
Design and Additive Manufacture of Coaxial Tapered Baluns

- Through AM, the impedance can be tailored based on the application
  - Comsol Multiphysics' 2D mode solver was used to generate the relationship between (*a*), (*b*), and (*θ*)







$$Z_o\left(\xi,\varepsilon_r,\frac{b}{a},\frac{w}{a}\right)\approx\frac{\eta_o}{2\pi\sqrt{\varepsilon_r}}ln\left(\frac{b}{a}\right)-\frac{260}{\sqrt{\varepsilon_r}}\cdot\frac{\left(\frac{b}{a}\right)-1}{4\left(\frac{b}{a}\right)-3}(1-\xi)\cdot ln\left(\xi\frac{9\left(\frac{b}{a}\right)-4}{12\left(\frac{b}{a}\right)-9}\right)+\frac{1}{\sqrt{\varepsilon_r}}\cdot\frac{\left(\frac{b}{a}\right)-1}{2\left(\frac{b}{a}\right)-1}\cdot\frac{\cos(10\xi)}{\xi}-\frac{1}{\sqrt{\varepsilon_r}}\frac{\left(\frac{w}{a}\right)\cdot\left(100-\left(\frac{b}{a}\right)\right)}{7\left(\frac{w}{a}\right)+1}\cdot\frac{e^{-\frac{15\left(\frac{b}{a}\right)-6}{10\left(\frac{b}{a}\right)-11}\xi}}{\sqrt{\xi}},$$

where $\xi=\frac{\alpha}{180^0}$.

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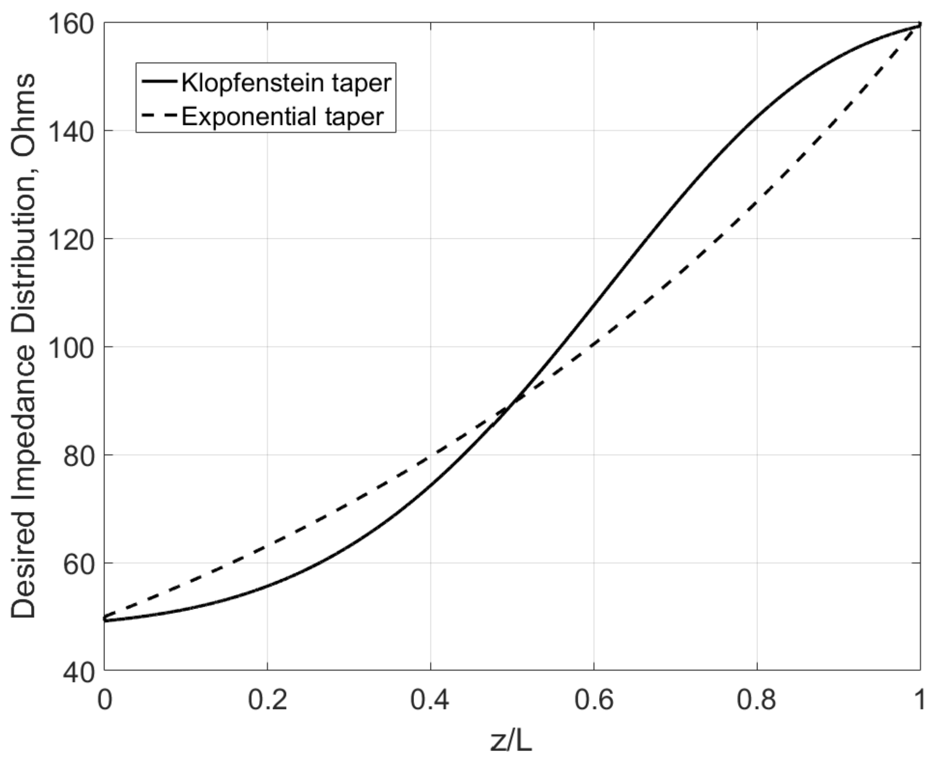
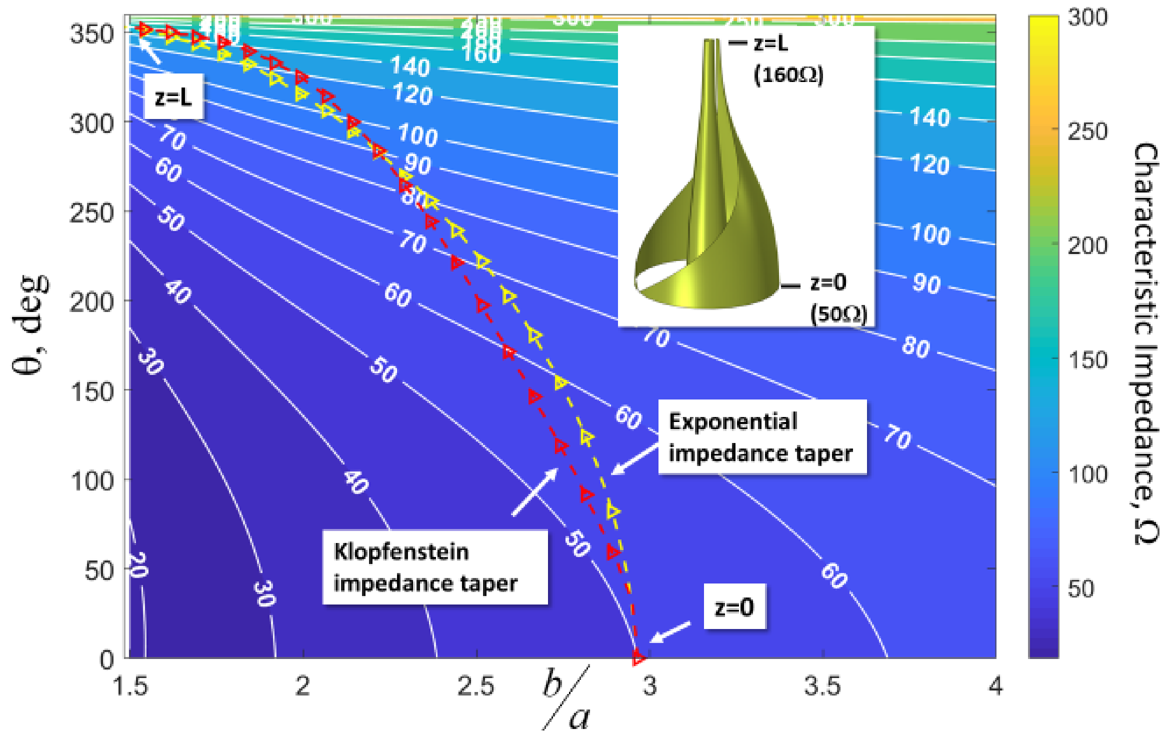
Design and Additive Manufacture of Coaxial Tapered Baluns





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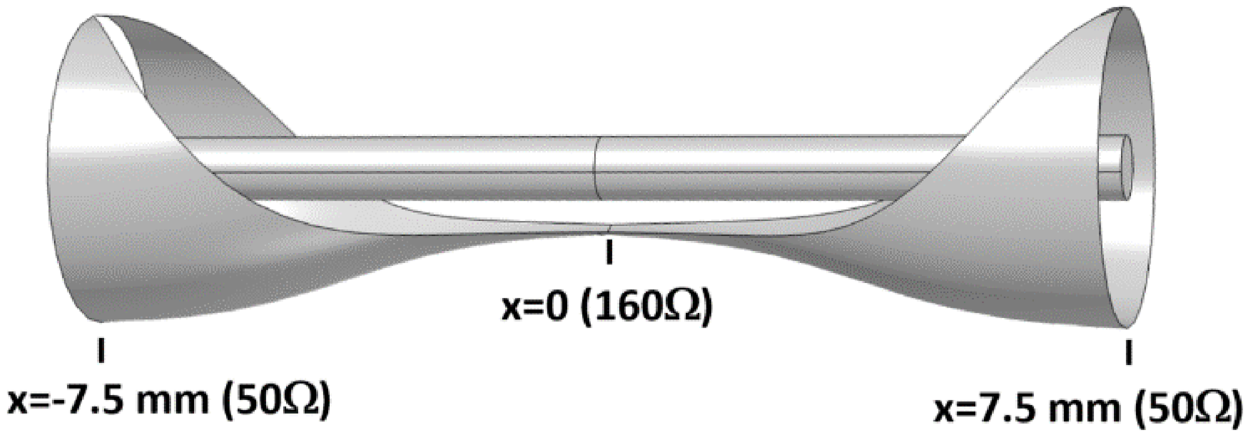
Design and Additive Manufacture of Coaxial Tapered Baluns

- Common technique to experimentally validate a balun taper is by implementing a Back-to-Back configuration

Parameter	Minimum Value	Maximum Value
Z, Ω	50	160
b/a	1.5	3.0
a, mm	0.6	0.6
L, mm	15	15
w, mm	0.6	0.6
f, GHz	8.0	18.0
ε_r	1.75	1.75



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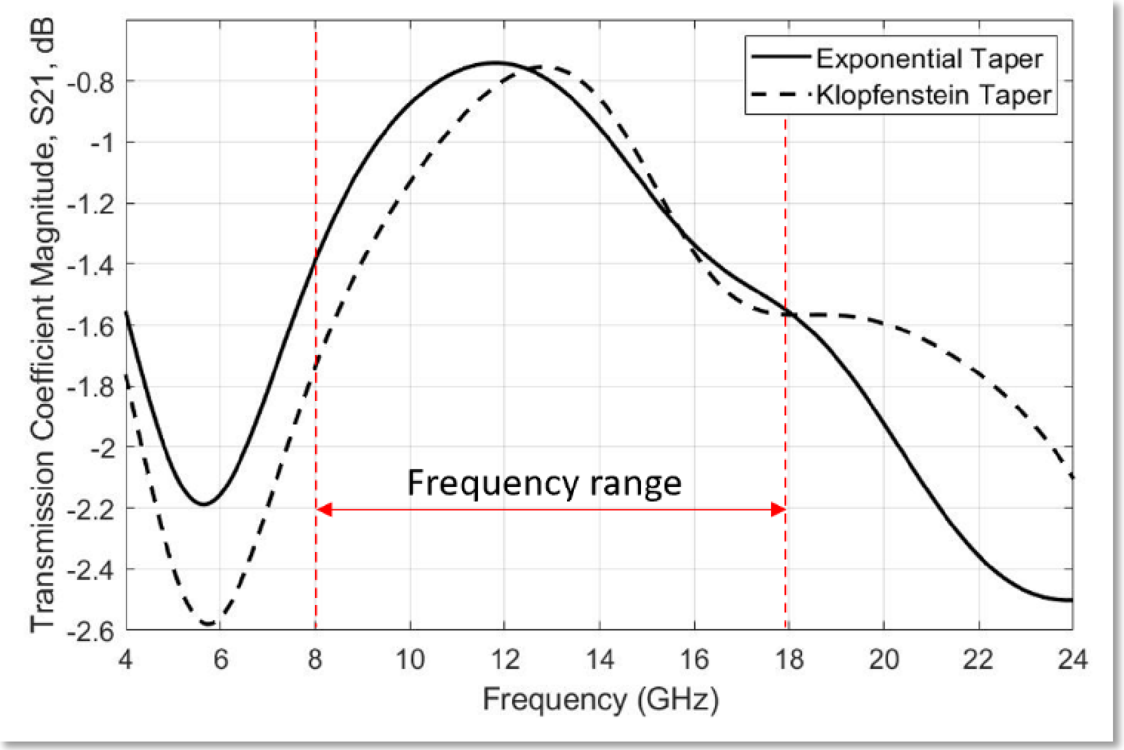
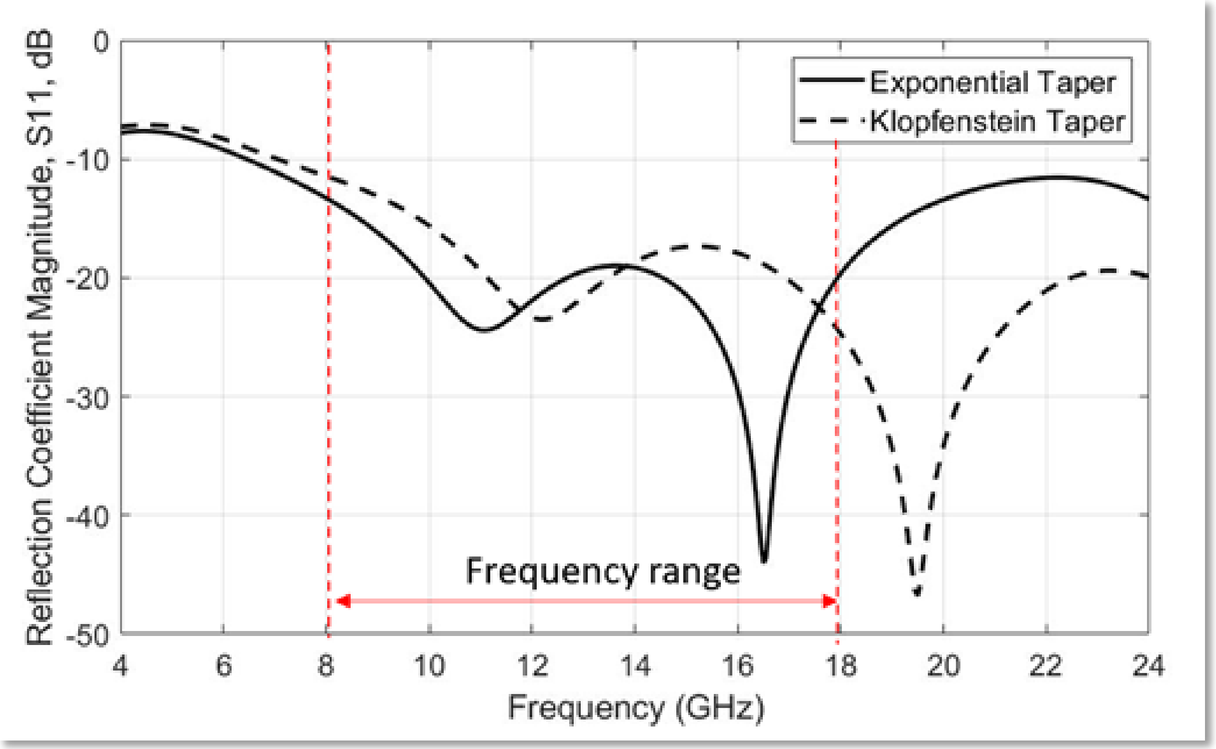
Design and Additive Manufacture of Coaxial Tapered Baluns

- Simulated comparison of the exponential and Klopfenstein tapers





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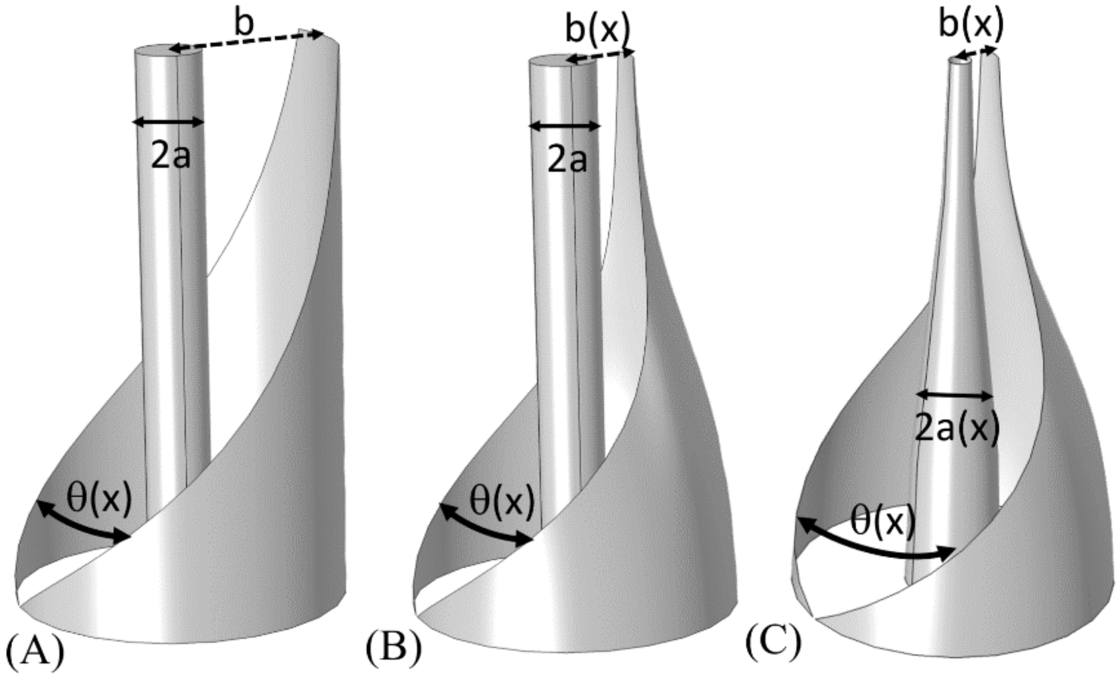
Design and Additive Manufacture of Coaxial Tapered Baluns

- Three tapers were considered for this study



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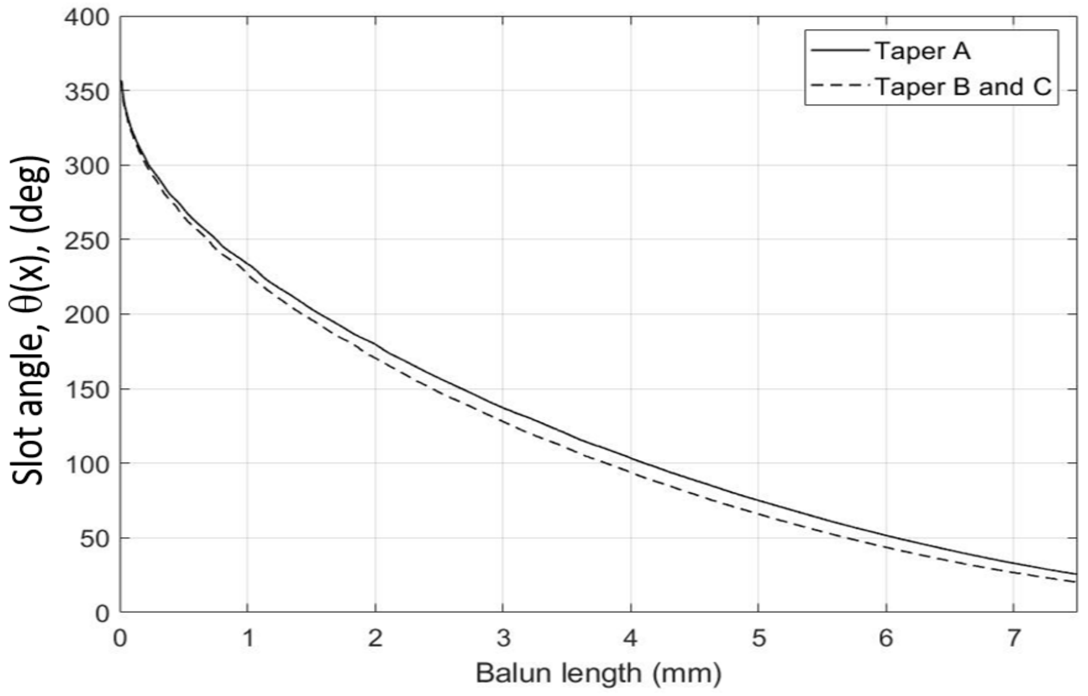
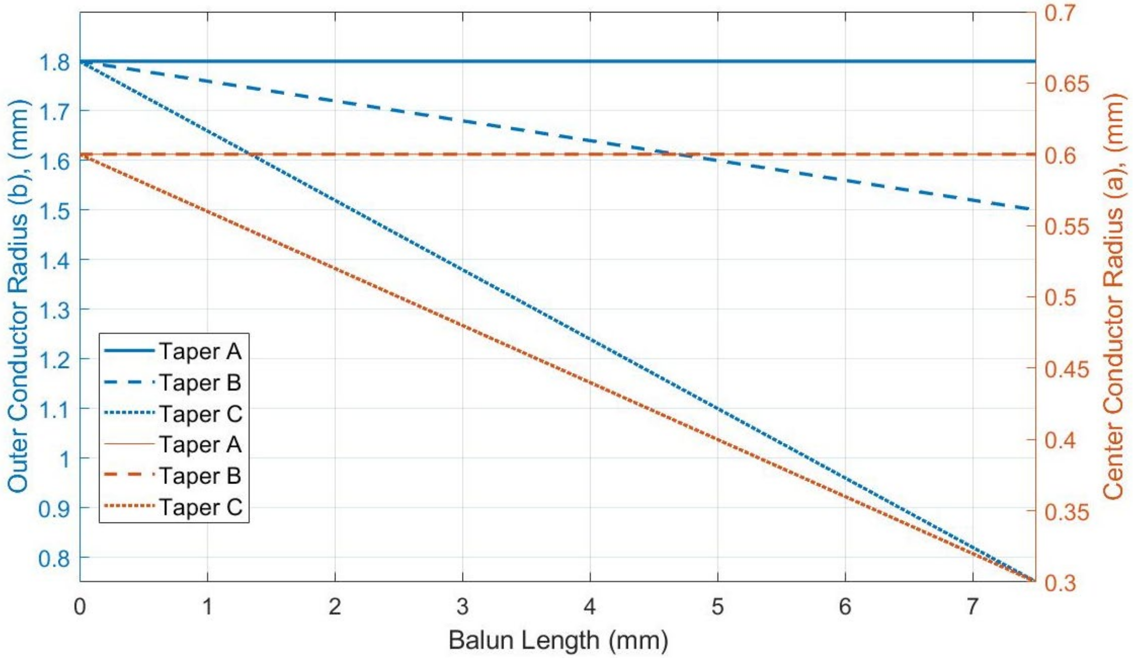
Design and Additive Manufacture of Coaxial Tapered Baluns

- Identical b/a ratio was utilized for Tapers B and C





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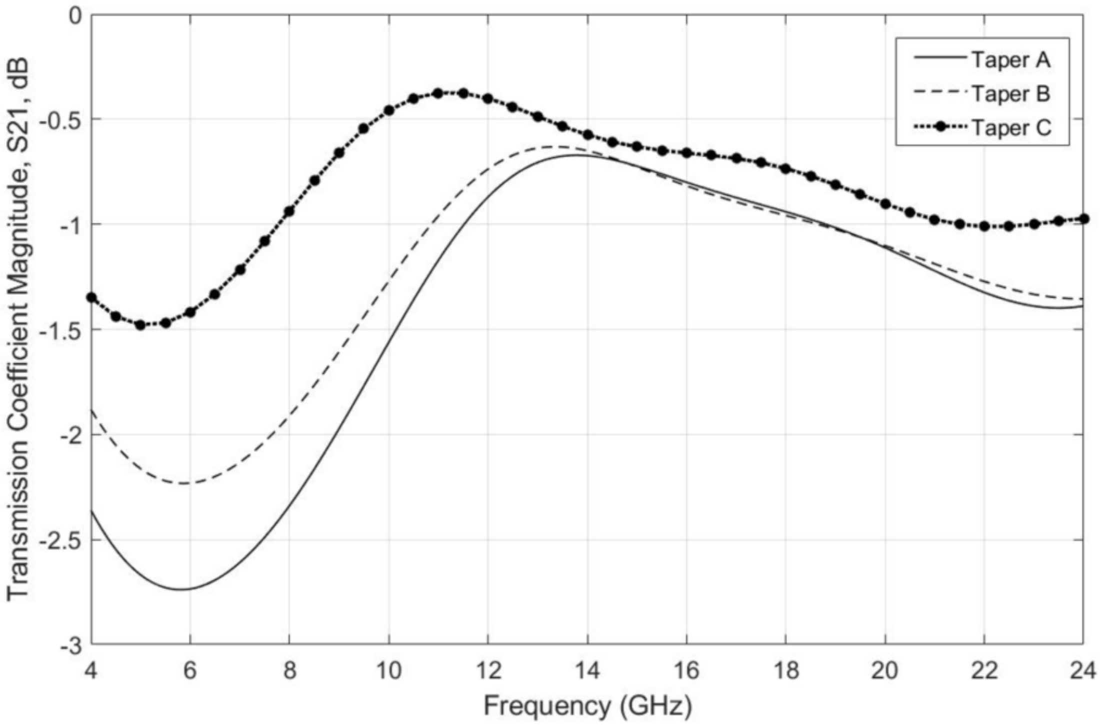
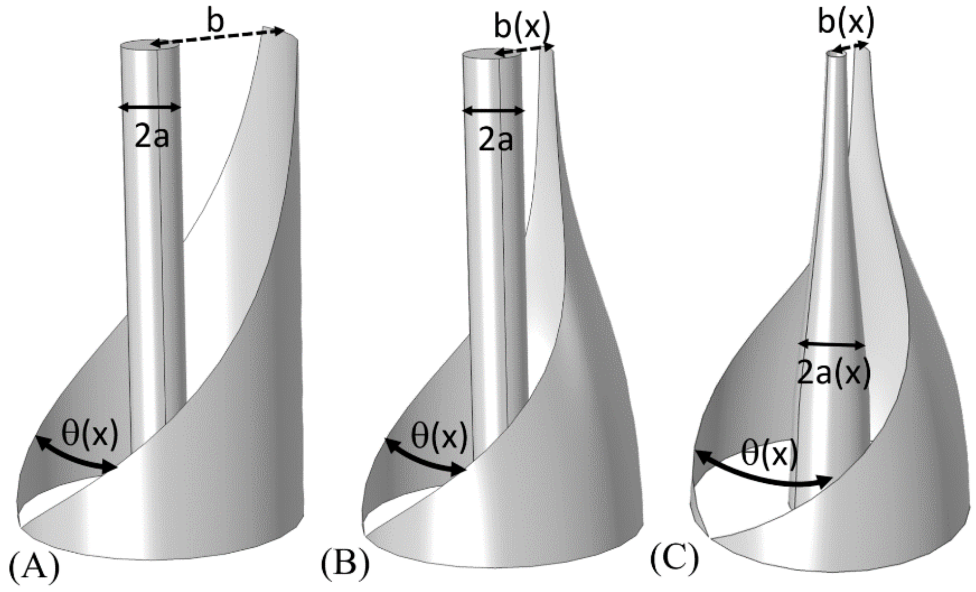
Design and Additive Manufacture of Coaxial Tapered Baluns

- Triple-taper design simulation results indicate better coupling of the desired quasi-TEM mode and less energy transitioning to lossy higher order modes





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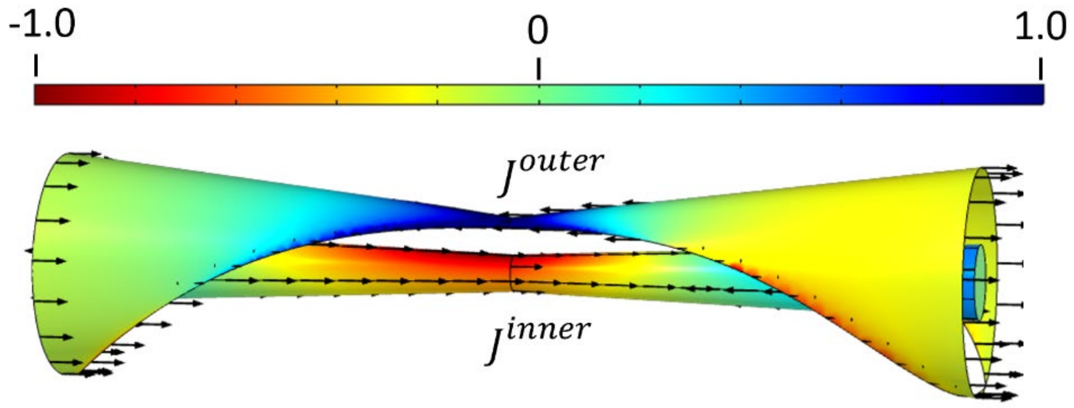
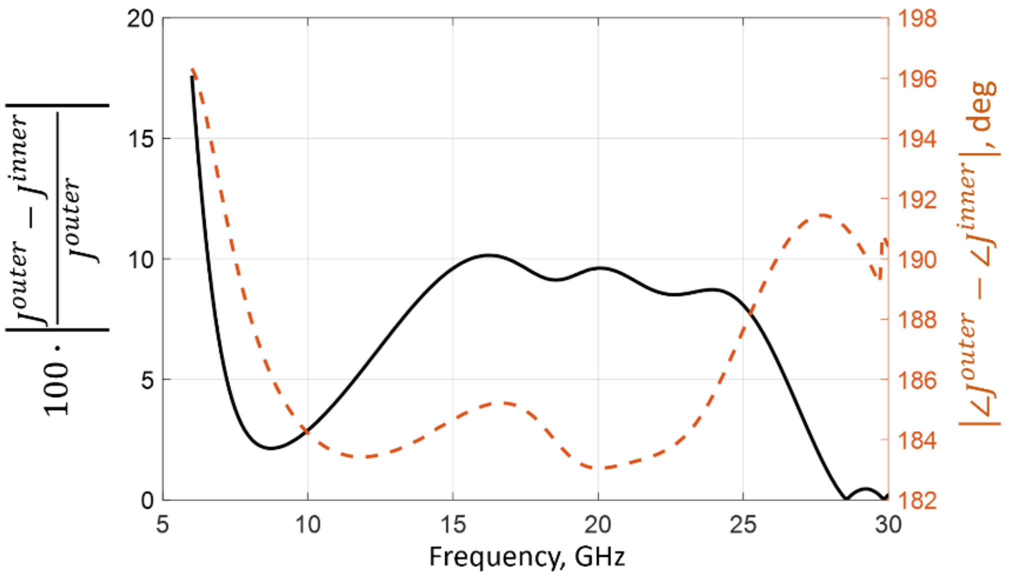
Design and Additive Manufacture of Coaxial Tapered Baluns

- COMSOL Multiphysics was used to simulate the current density amplitude and phase difference





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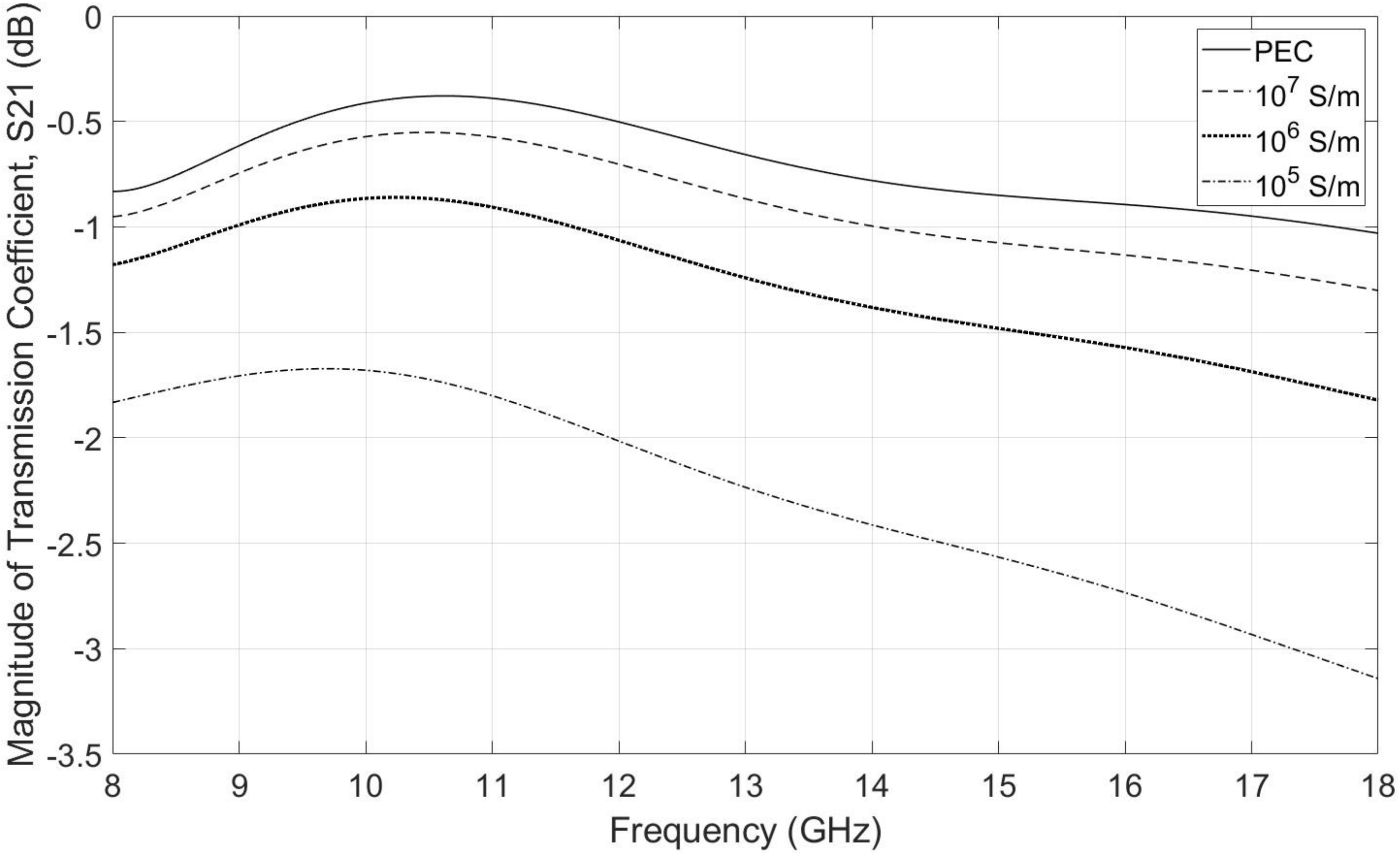
Design and Additive Manufacture of Coaxial Tapered Baluns

- Simulations of exponential taper were performed to demonstrate impact of various conductivities



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Design and Additive Manufacture of Coaxial Tapered Baluns

- Similar print parameters were used to fabricate Back-to-Back balun as printed connectors
- Video illustrating how the balun is printed to show the 3 tapers in a single device

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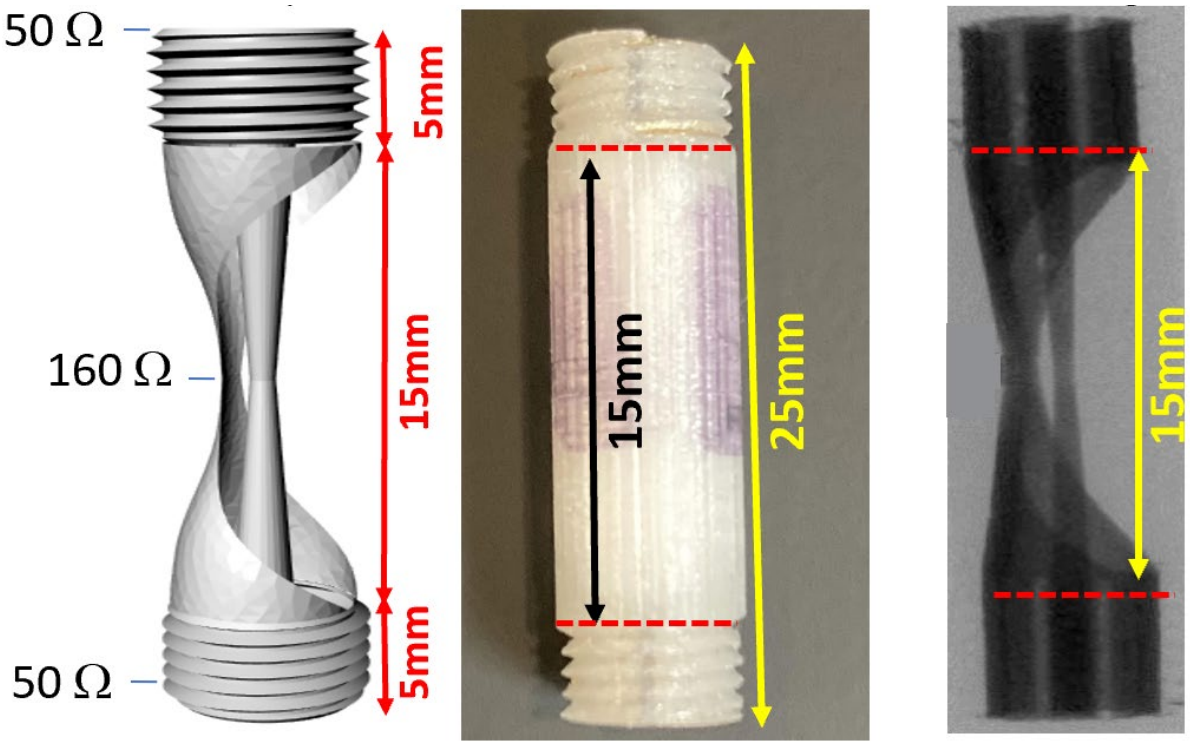
Design and Additive Manufacture of Coaxial Tapered Baluns

Fabricated back-to-back balun with integrated SMA connectors



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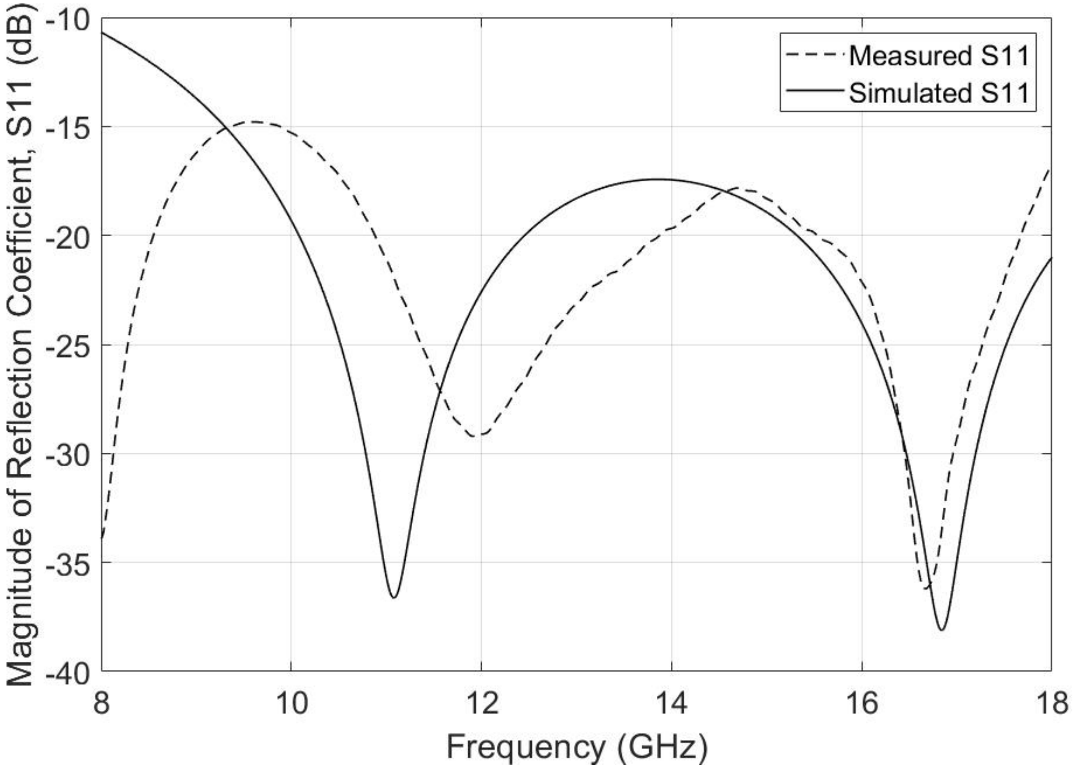
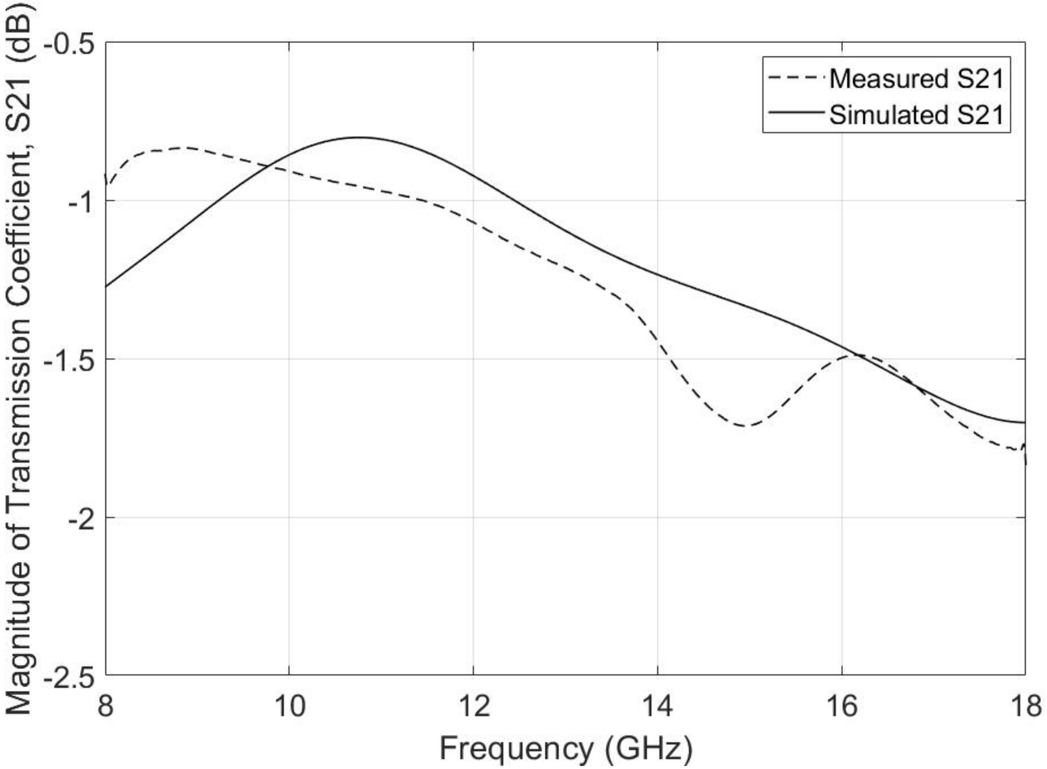
Design and Additive Manufacture of Coaxial Tapered Baluns

- Back-to-Back balun experimental results of exponential taper
  - Conductivity of 10^6 S/m shows good agreement with measured data





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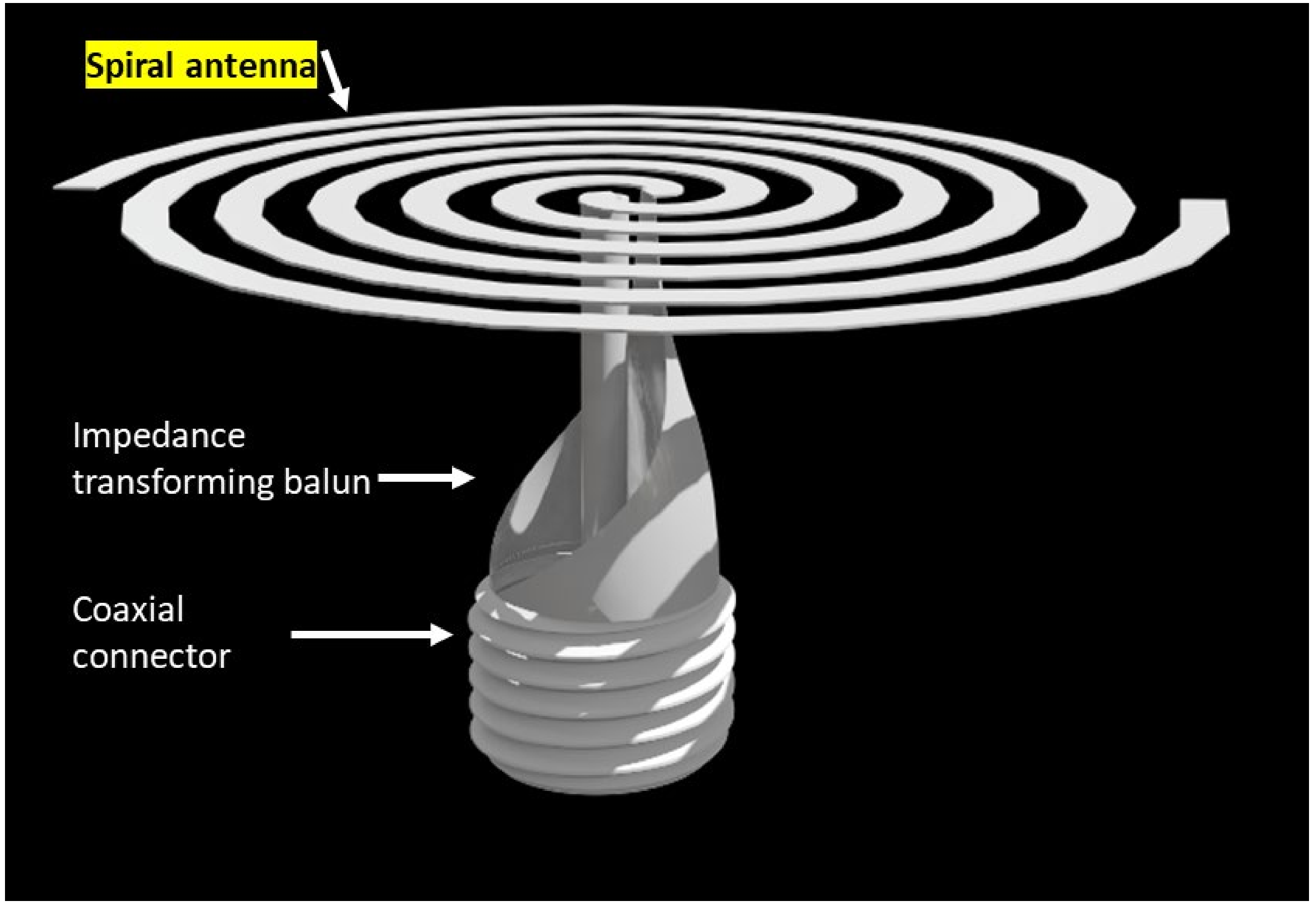

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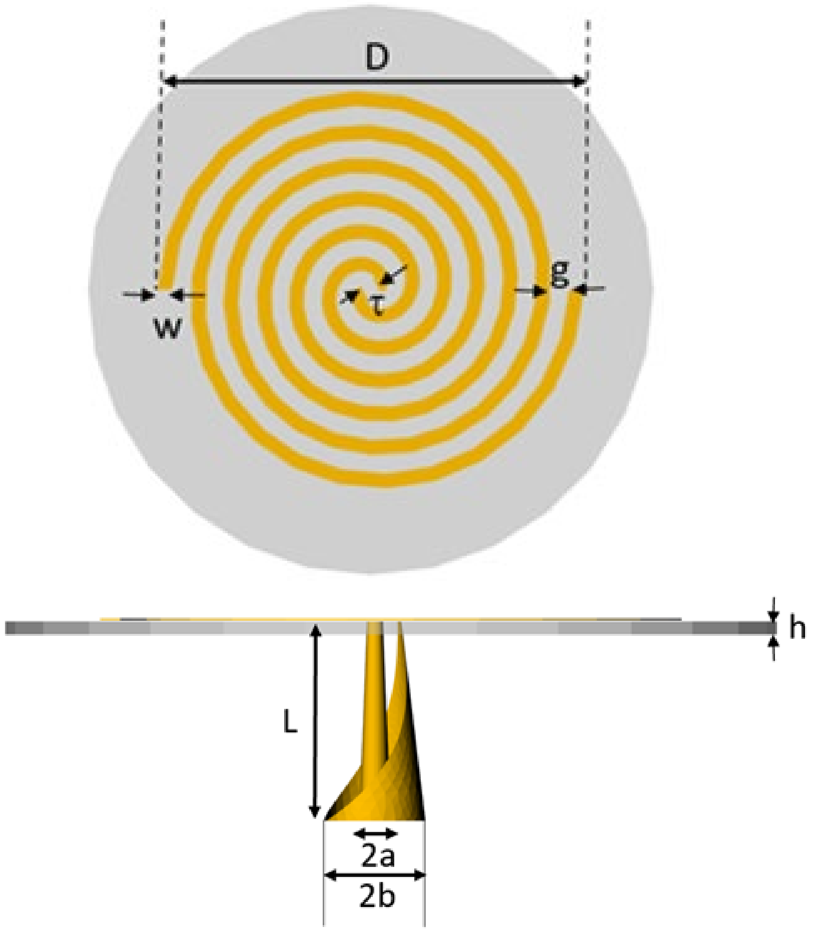
Triple-Tapered Balun Integrated with Spiral Antenna



Parameter	Dimension/Value
Arm width (w)	1.25 mm
Gap width (g)	0.9 mm
Spiral Diameter (D)	29 mm
Feed Gap (t)	0.95 mm
Balun Length (L).	7.5 mm
Substrate Thickness (h)	1.6 mm
Substrate Permittivity (ε_r)	1.75

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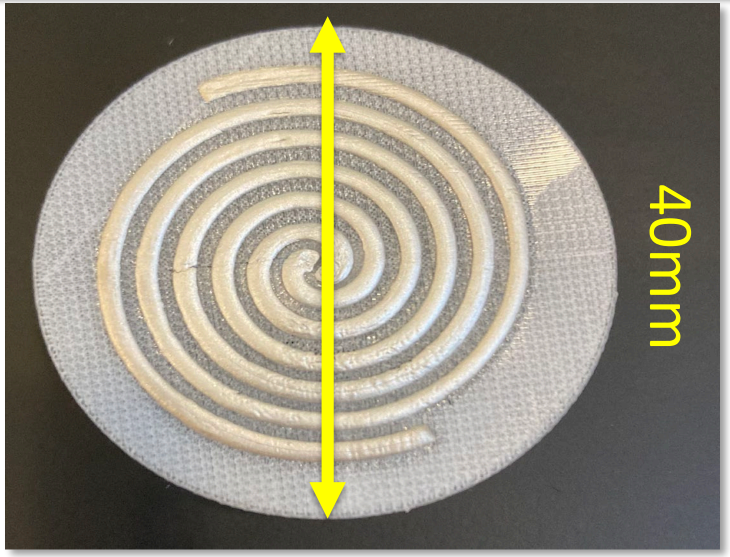
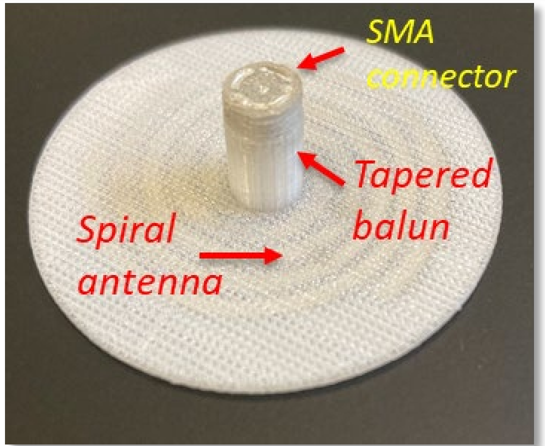
Triple-Tapered Balun Integrated with Spiral Antenna

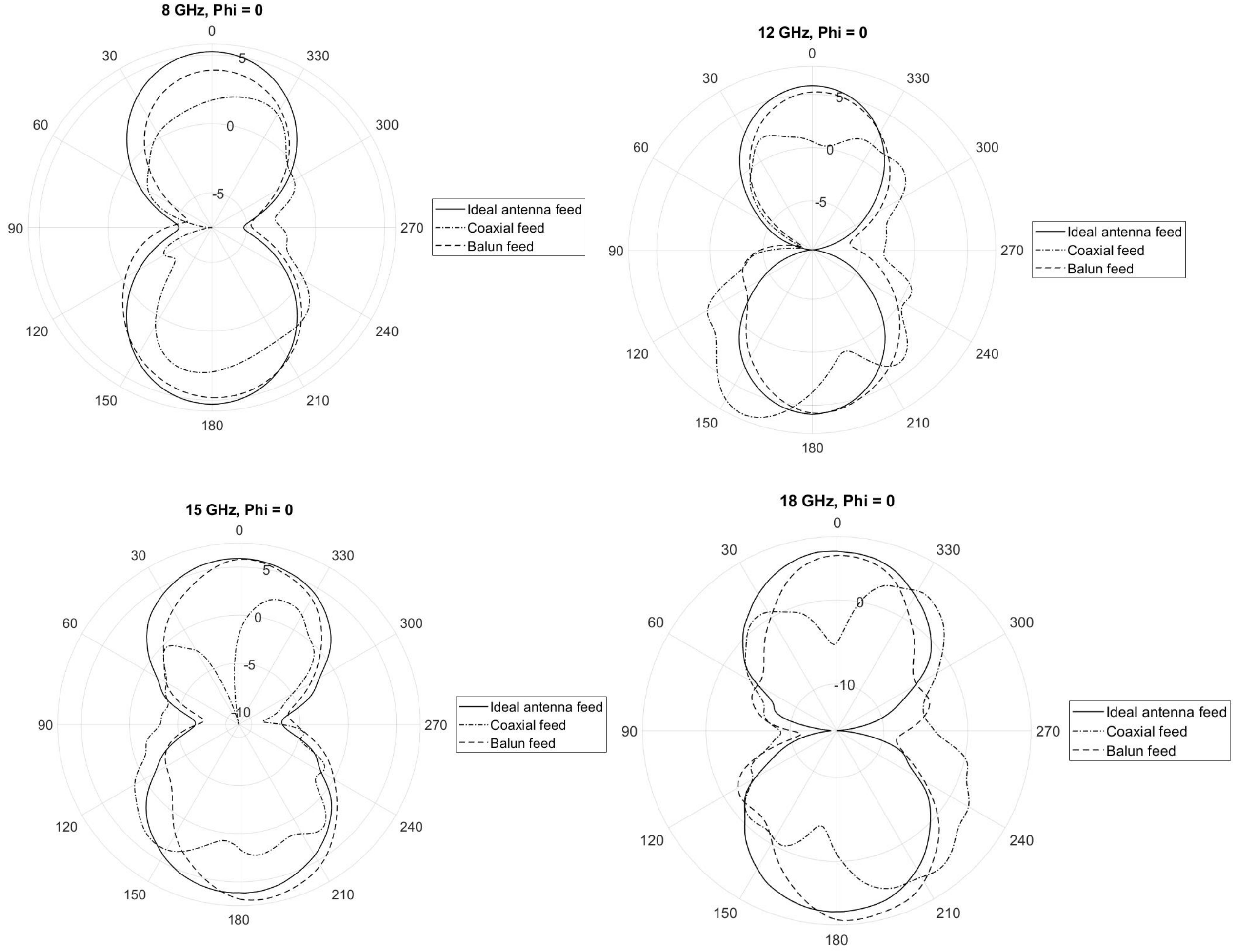
- Spiral antenna designed using HFSS
  - Initial design utilized lumped port to have an ideal source where the currents are known to be balanced
  - Lumped port was replaced with balun feed to simulate what will be printed
  - Axial ratio over the X- and Ku-bands < 2 dB
  - Radiation patterns between ideal source and balun feed show good agreement in simulation

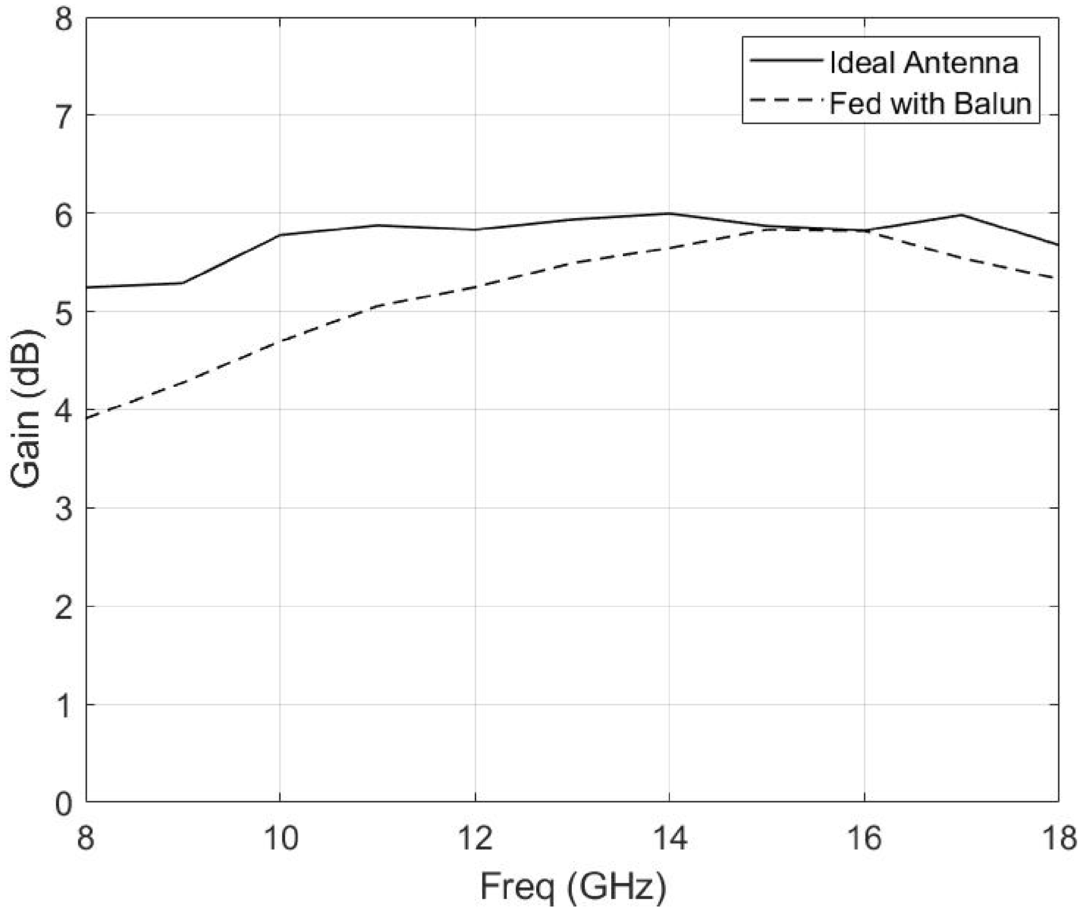




K. McParland and M. Mirotznik, "Design and Additive Manufacture of Multi-Tapered Coaxial Baluns ", *IEEE Transactions on Components, Packaging, and Manufacturing Technology* (2022) (**Submitted**)

Triple-Tapered Balun Integrated with Spiral Antenna





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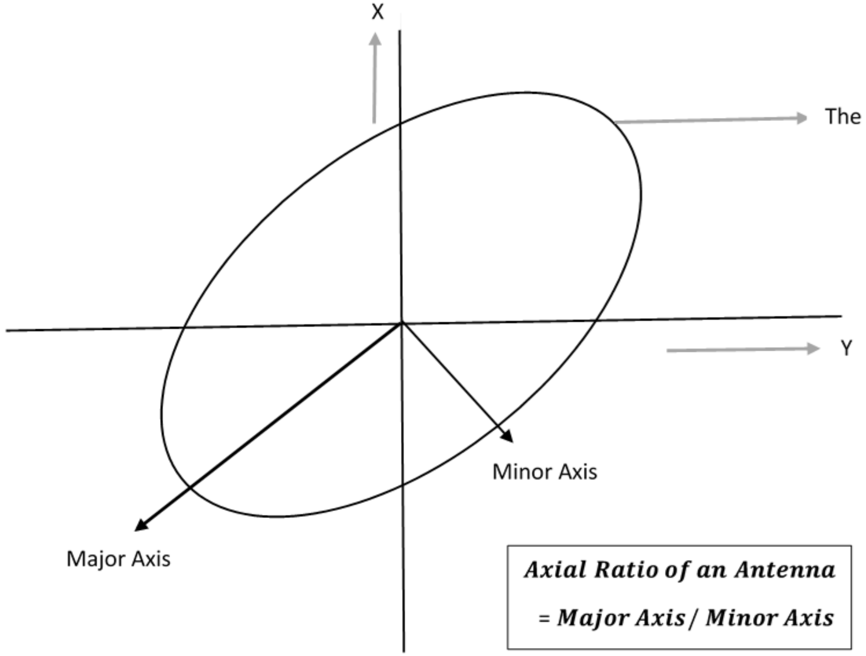
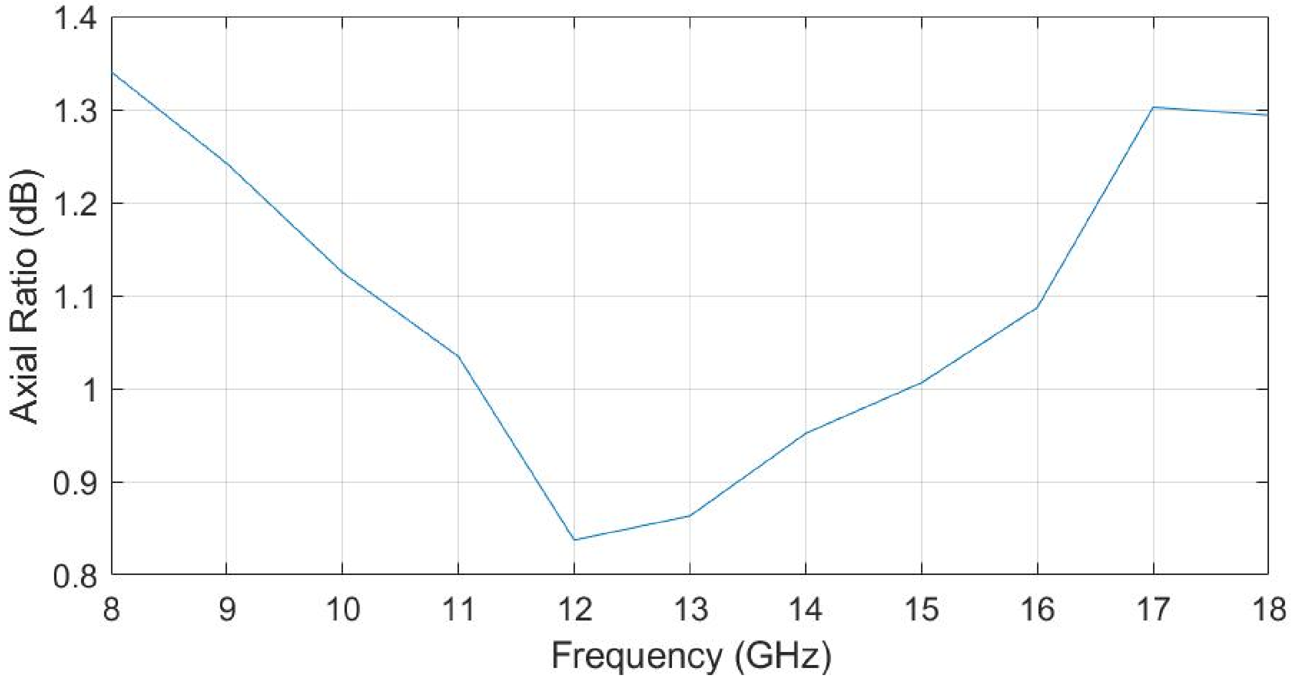
Triple-Tapered Balun Integrated with Spiral Antenna

- Simulated axial ratio
  - Axial ratio is defined as the ratio of the major and minor axis of a circularly polarized antenna



[6]



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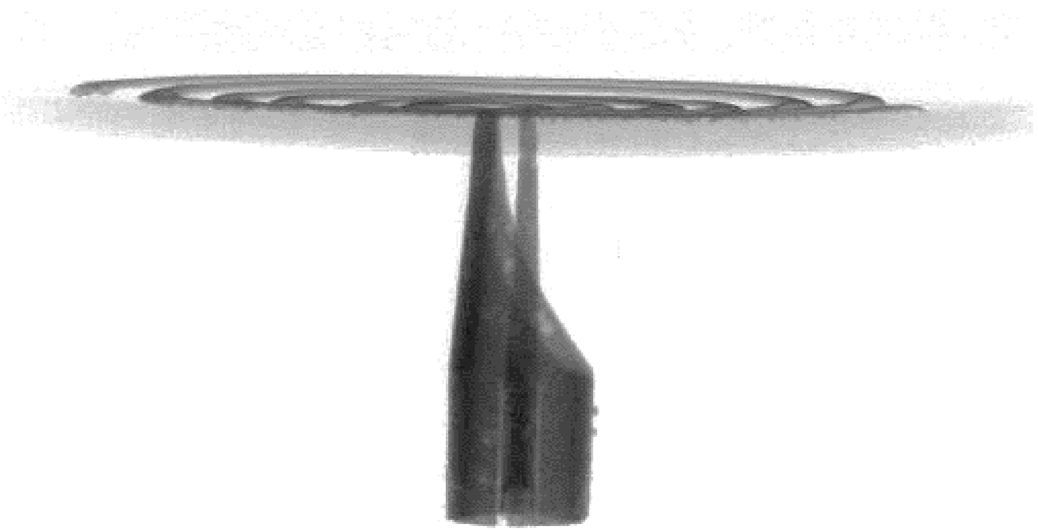
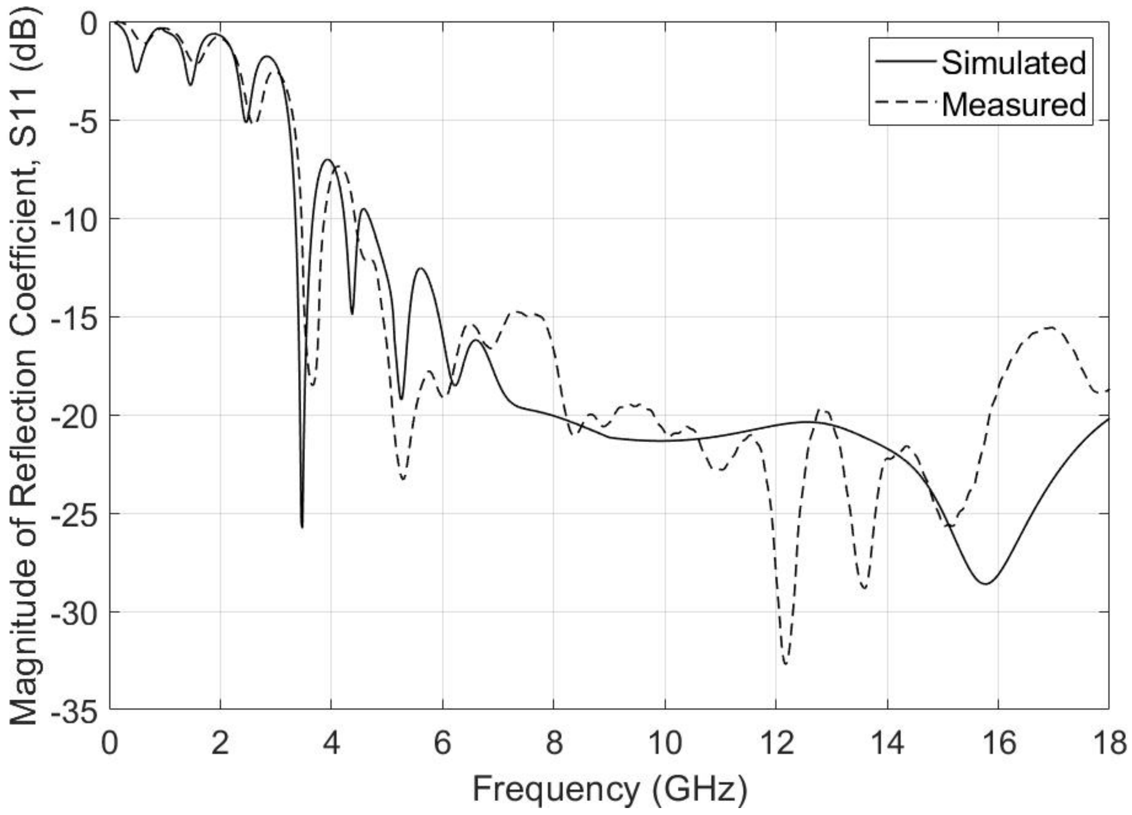
Triple-Tapered Balun Integrated with Spiral Antenna





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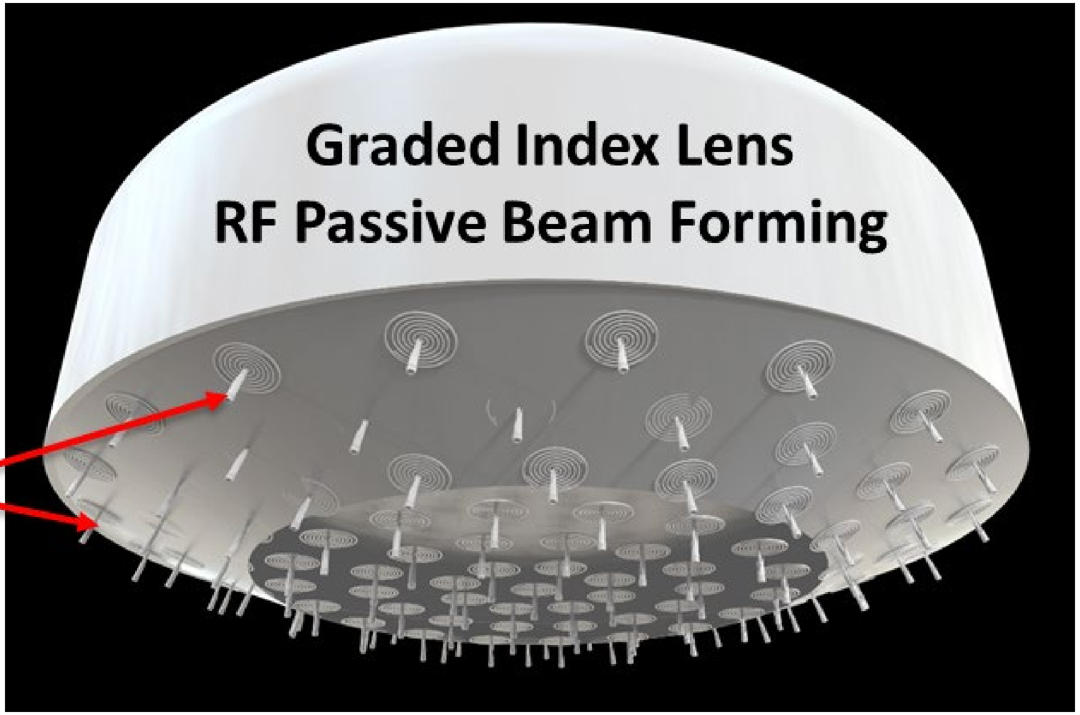
Presentation Outline

- Introduction
  - Motivation
  - Problem Statement
  - List of Contributions
  - Background
- Integrated Feed Design
  - Printed Connectors
  - Printed Broadband Baluns and Spiral Antennas
- Conformal Antenna Array for Beamforming
- Conclusion and Future Work

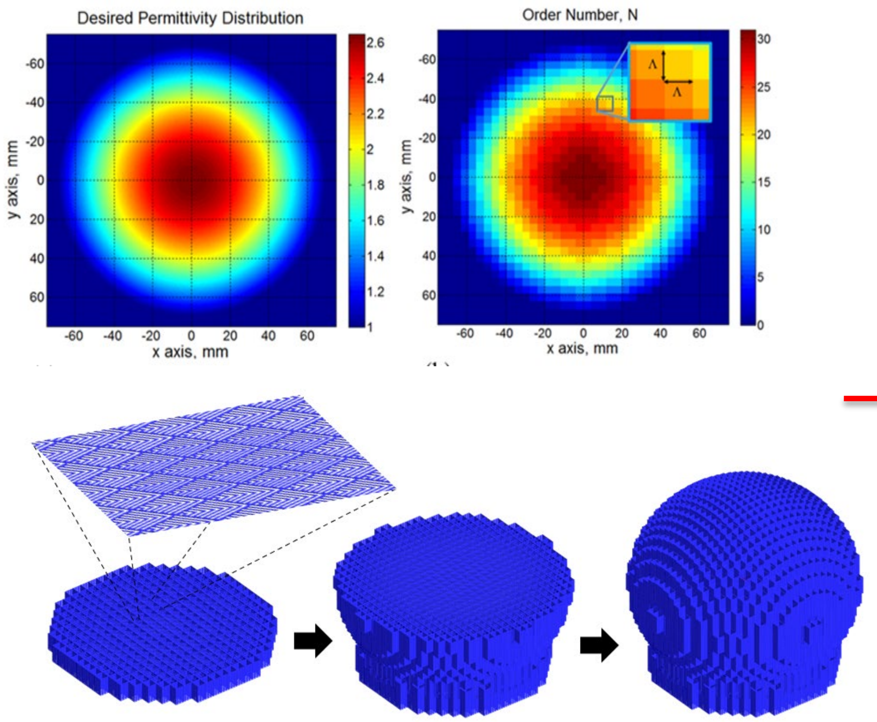
Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

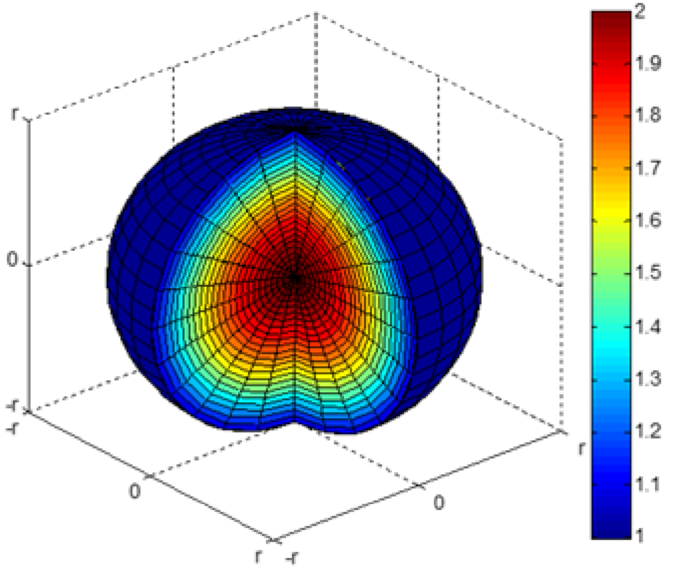
Conformal antenna feed network



Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

- Luneburg lens
    - Polycarbonate filament
    - Fabricated via FFF using space filling curves [7]

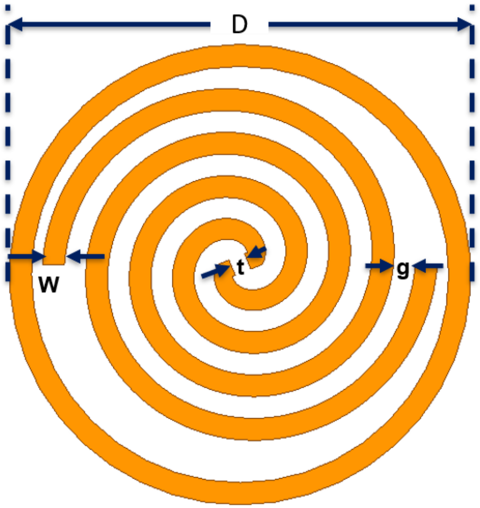


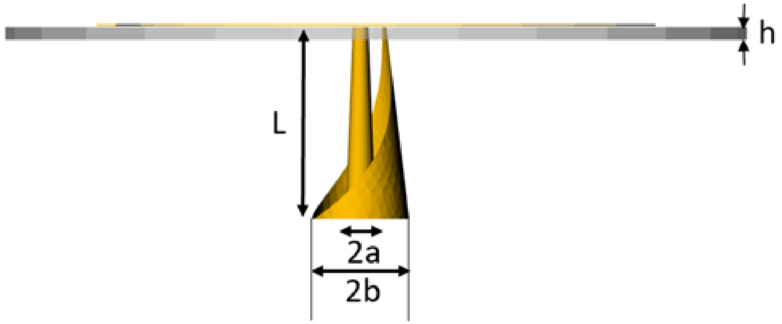


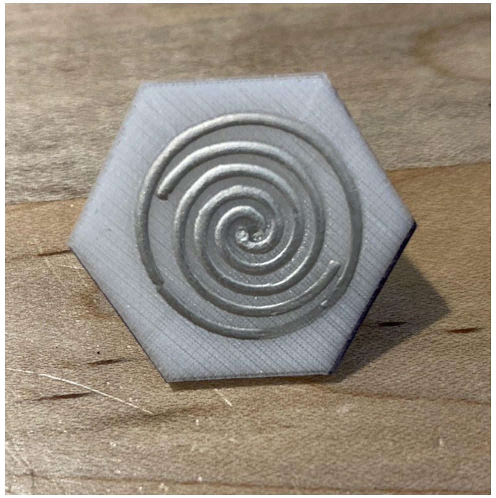
Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

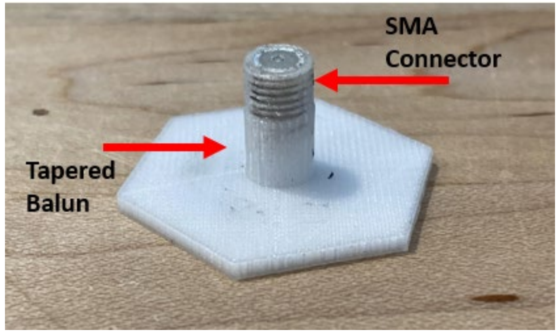
- Spiral antenna design
  - Compact spiral antenna was used to fit more elements behind Luneburg lens
  - Antenna uses a capacitive ring to reduce the total footprint by ~30% while maintaining operational bandwidth and gain [8]

Parameter	Dimension/Value
Arm width (w)	0.95 mm
Gap width (g)	0.6 mm
Spiral Diameter (D)	20 mm
Feed Gap (t)	0.7 mm
Balun Length (L).	7.5 mm
Substrate Thickness (h)	1.6 mm



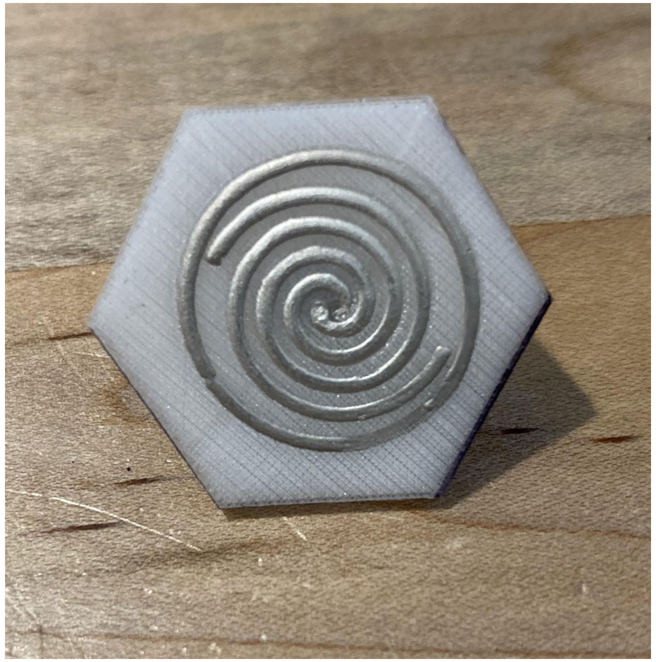


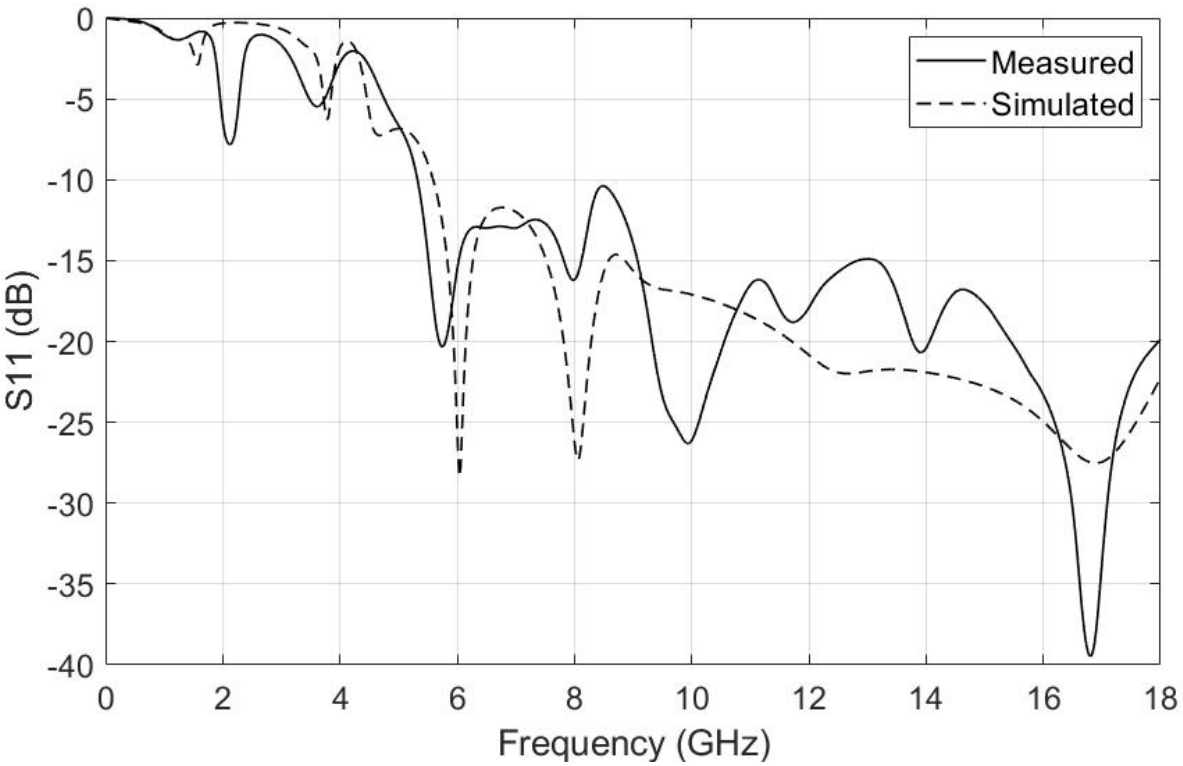




Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

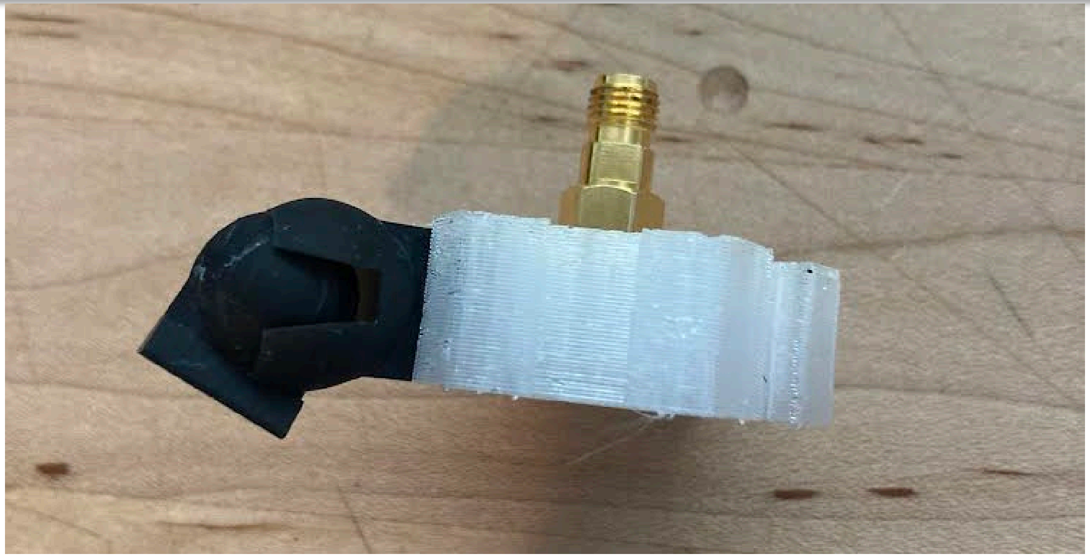
- Compact spiral antenna showed good impedance matching over wide frequency band (6 – 18 GHz)

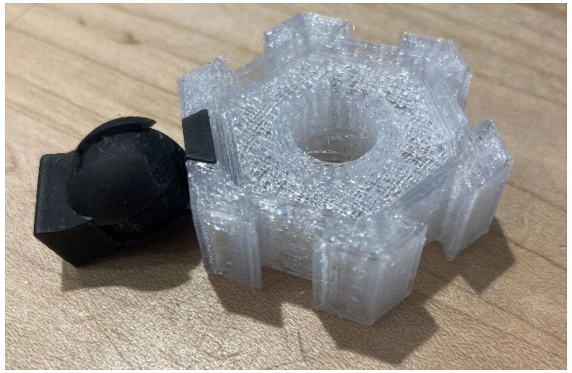




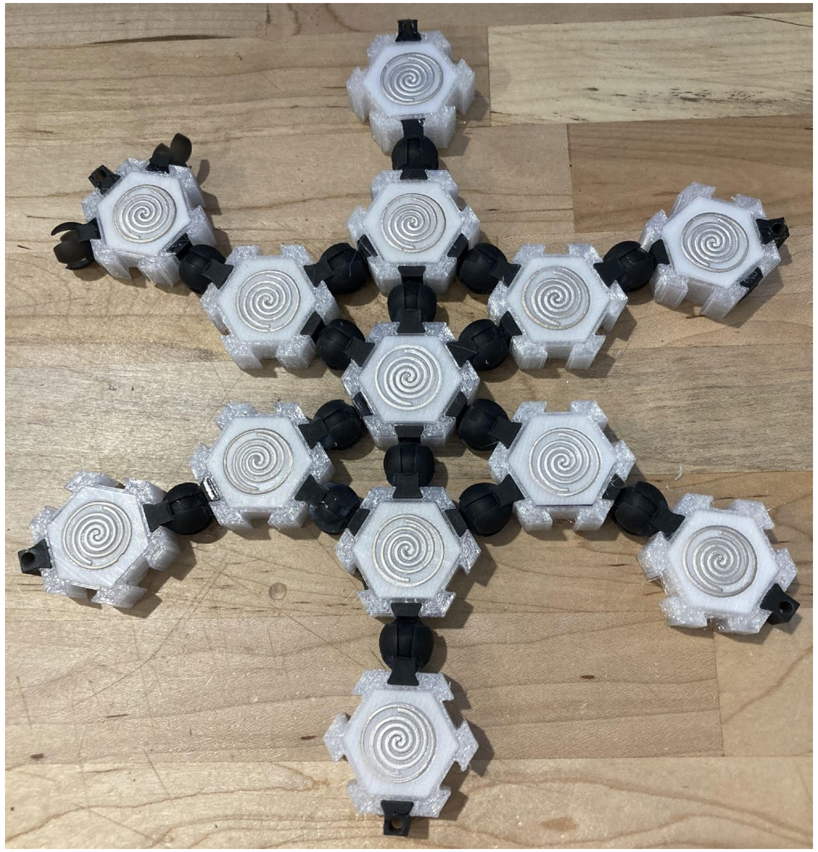
Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

- Implemented a ball-and-socket joint that enables modular array and reconfigurability
    - Polycarbonate bases were printed at low infill
    - Ball-and-socket joint was printed on the Fortify DLP system



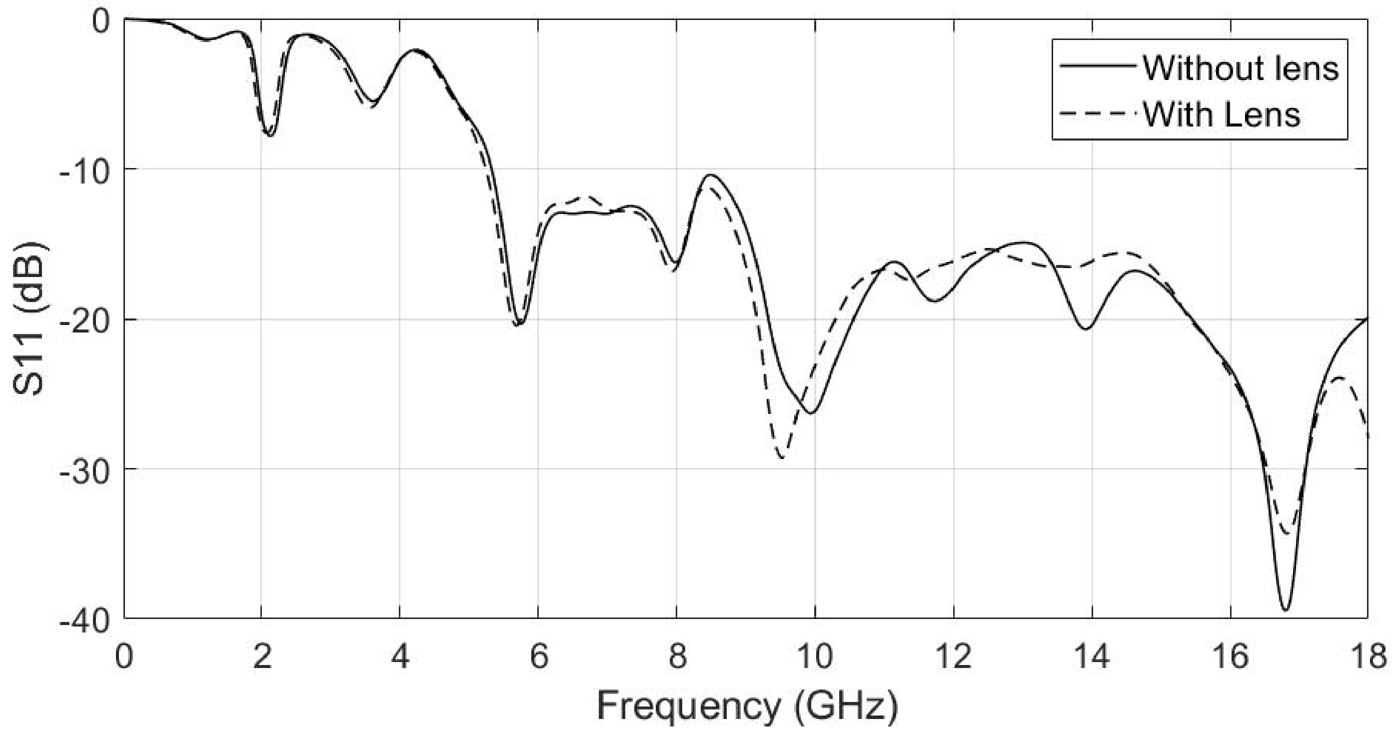


Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming



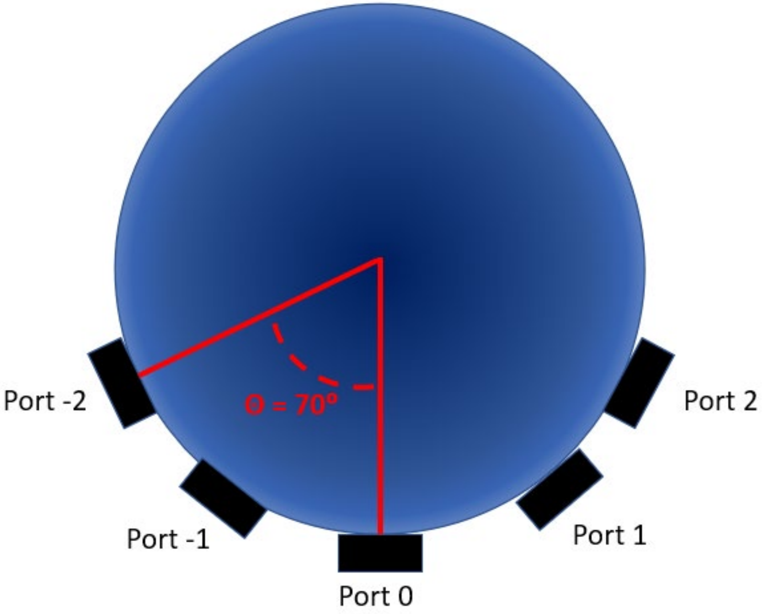
Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

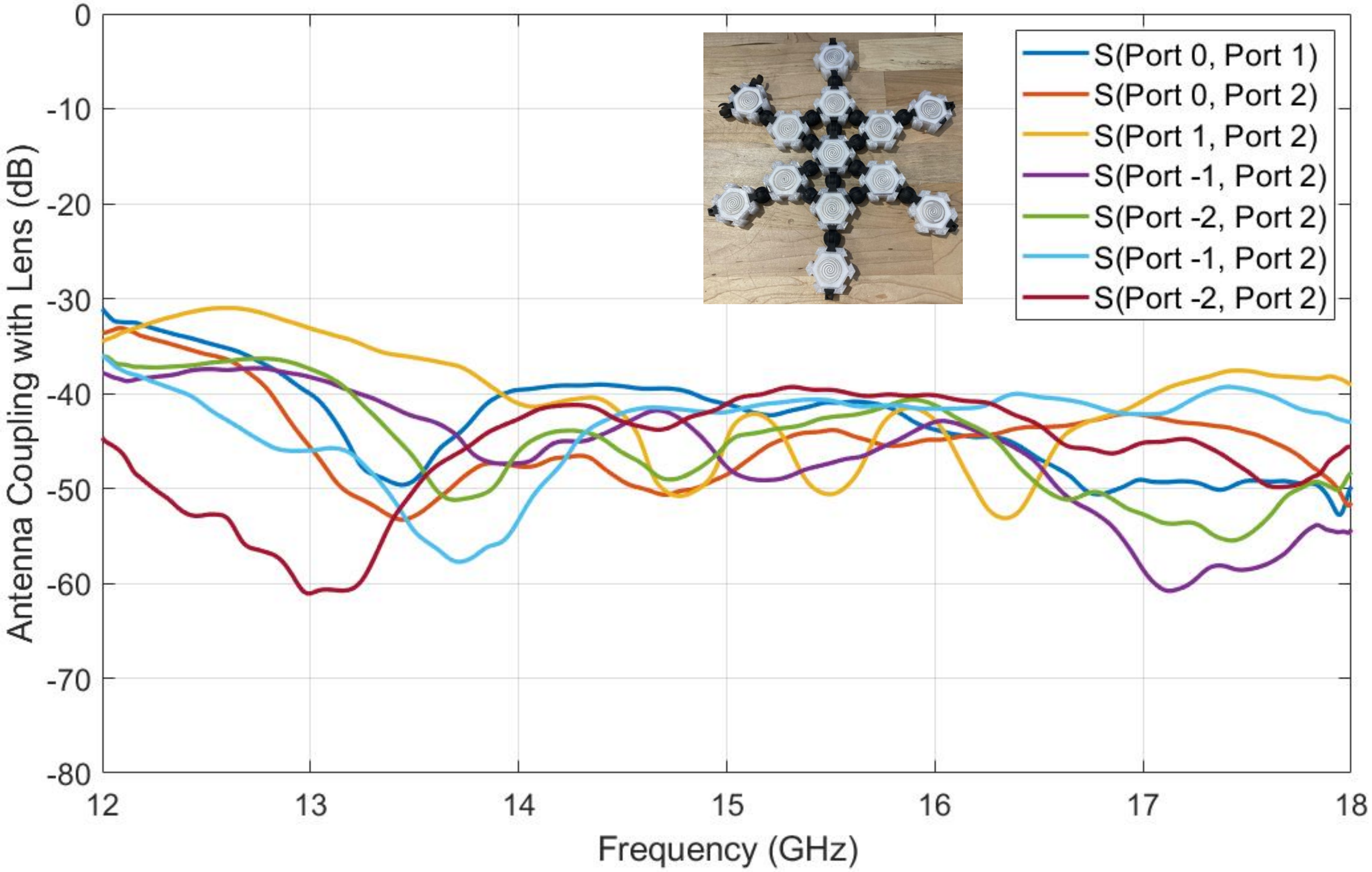
- Compact spiral antenna maintained good performance in the presence of the lens
- To evaluate the effect of the lens on the spiral antenna, a return loss measurement was performed



Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

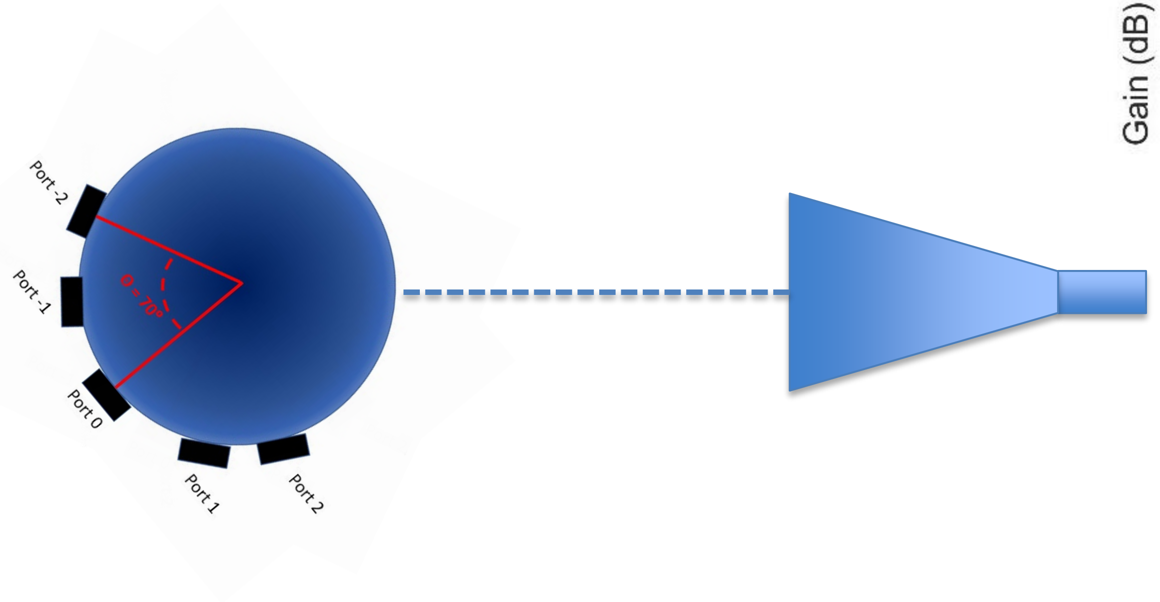
- Crosstalk interference measurements were taken into consideration
- Negligible interference between antenna elements

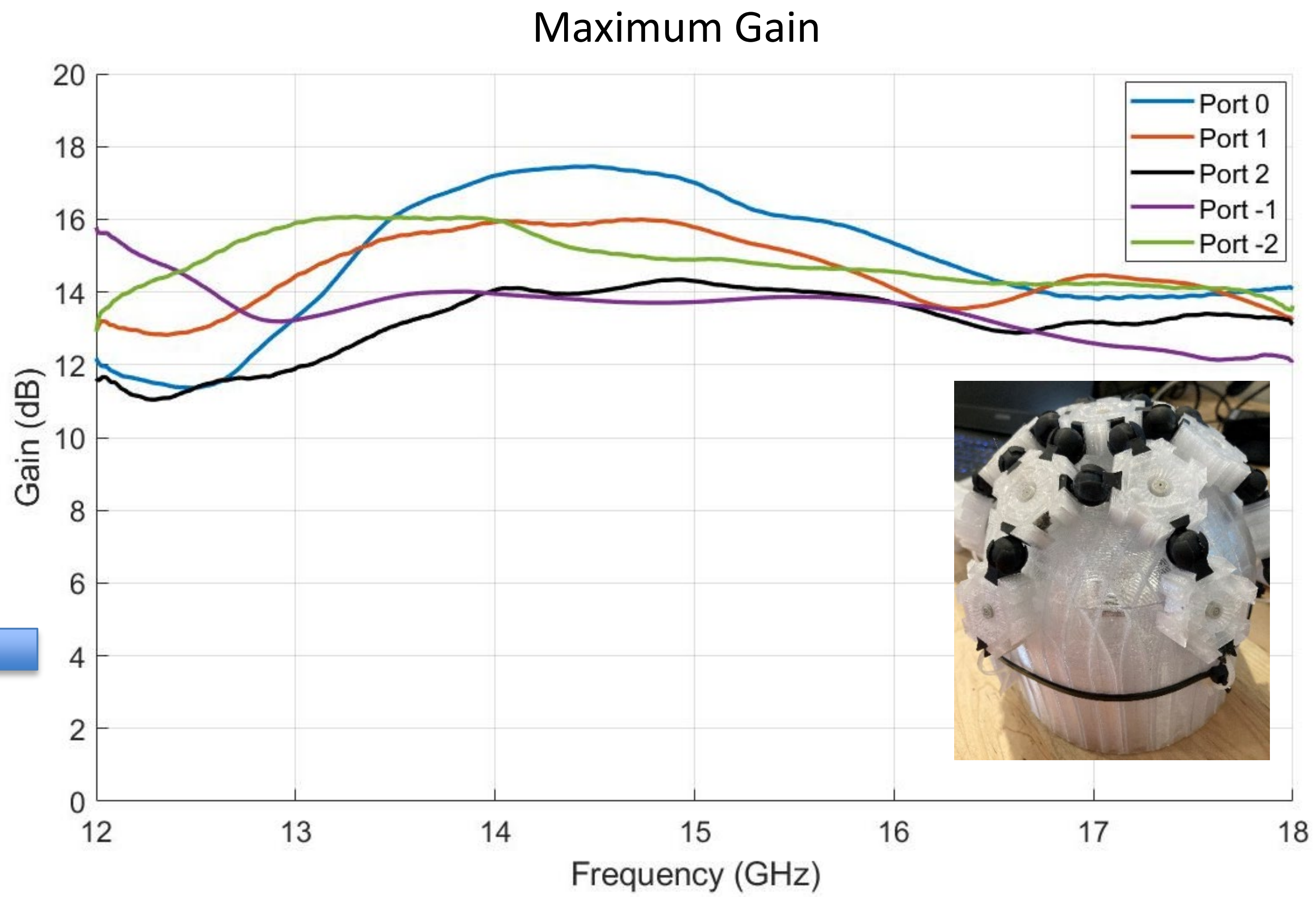




Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

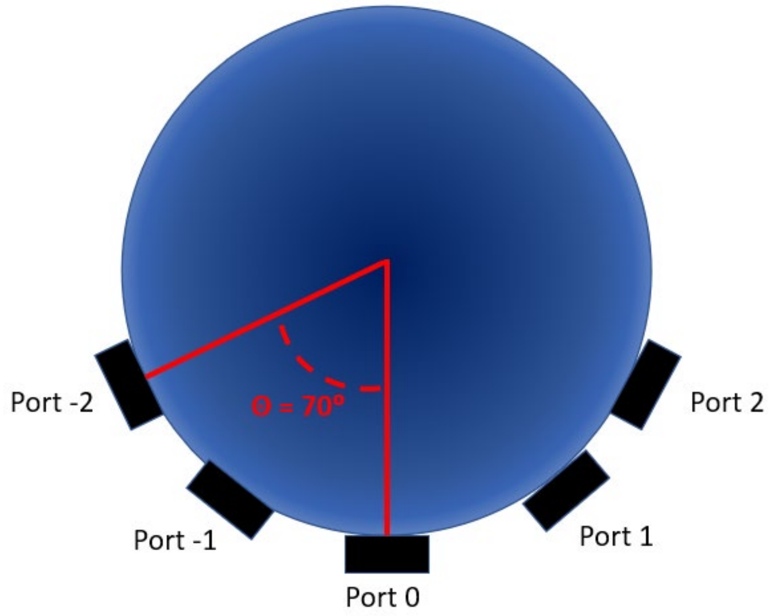
- Things to consider:
  - Uncertainties arise is the fabrication process (i.e., voids in conductor)
  - Further transmission losses in the printed connectors, integrated baluns, and spiral antennas





Conformal Integration of Antenna Feeds for Ultra-wide Scan Angle Passive Beamforming

- Maximum Gain was measured from 12 to 18 GHz
  - Reasonably consistent results were obtained although we did see measurable antenna to antenna variations due to uncertainties in the fabrication process
  - More comprehensive antenna measurements are underway including detailed beam patterns and axial ratios.



		Frequency			
Antenna Feed	Scan Angle	12 GHz	15 GHz	18 GHz	Average Gain
Port -2	-70º	18.5 dBi	19 dBi	19 dBi	18.85 dBi
Port -1	-35º	18.1 dBi	19.1 dBi	19.4 dBi	19.1 dBi
Port 0	0º	19.4 dBi	19.8 dBi	19.9 dBi	19.6 dBi
Port 1	35º	17.8 dBi	18.2 dBi	18.5 dBi	18.2 dBi
Port 2	70º	18.9 dBi	19.1 dBi	19.4 dBi	19.2 dBi