



WE1A-1

A Ka-Band 64-element Deployable Active Phased Array Transmitter on a Flexible Hetero Segmented Liquid Crystal Polymer for Small-Satellites

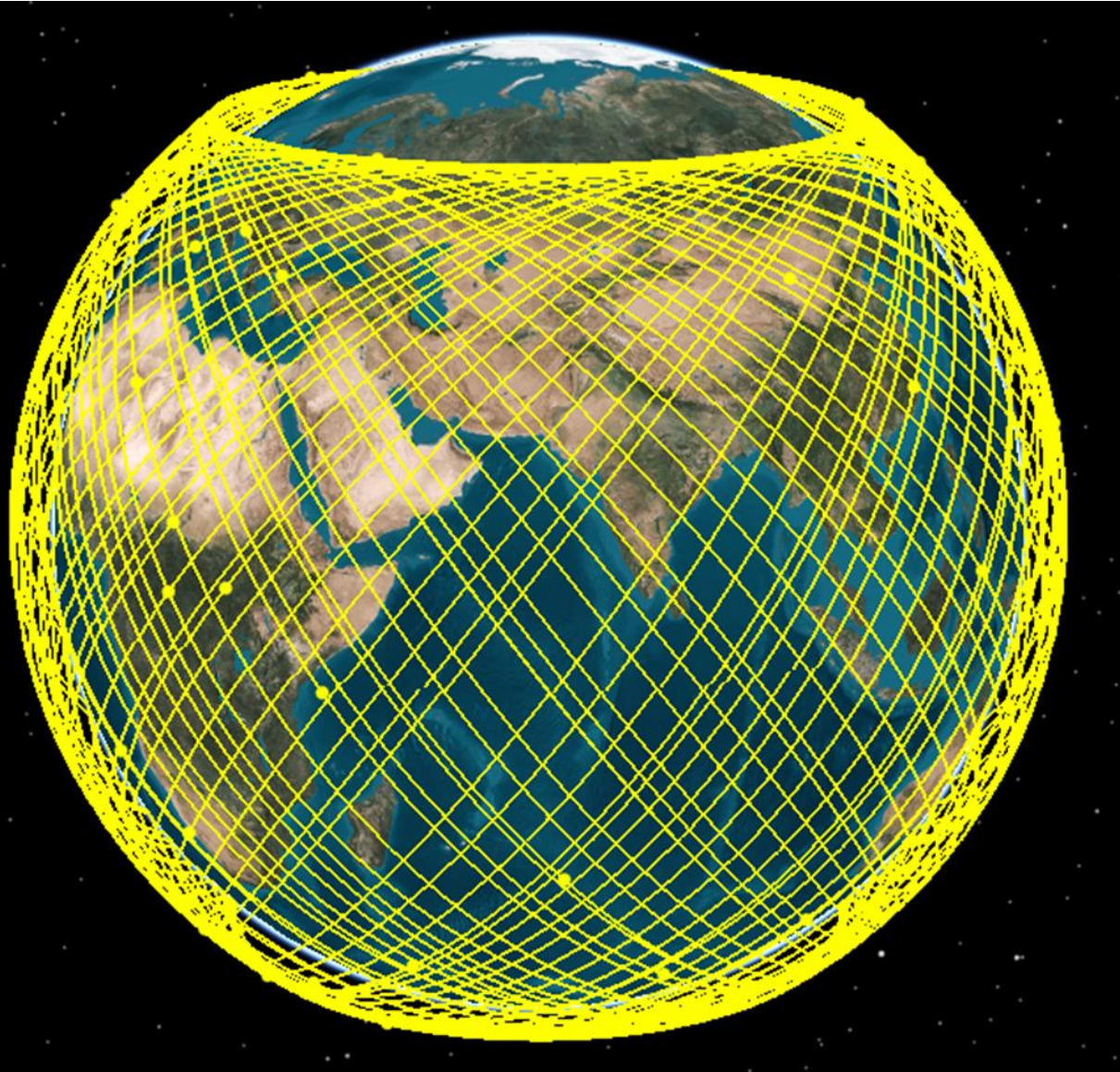
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- Motivation
- Deployable Active Phased Array TX
 - Proposed TX System
 - Antenna Design for Flexible Hetero-Segmented LCP Substrate
 - RF Distributions
 - Mechanical Deformation Calibration
- Measurement Results
- Conclusion

- **Motivation**
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- Ka-Band LEO SAT Constellation
 - 😊 High data rate
 - 😊 Low latency
 - 😊 any-where, any-when connectivity
 - High Throughput Satellite (HTS)



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- **Ka-Band LEO SAT Constellation**
 - 😊 High data rate
 - 😊 High resolution imagery data
 - 😊 Real-time and wide-extent data collection
 - Earth Exploration Satellite Service (EESS)
 - Against environmental solution, terrestrial disaster.

- Ka-Band LEO SAT Constellation

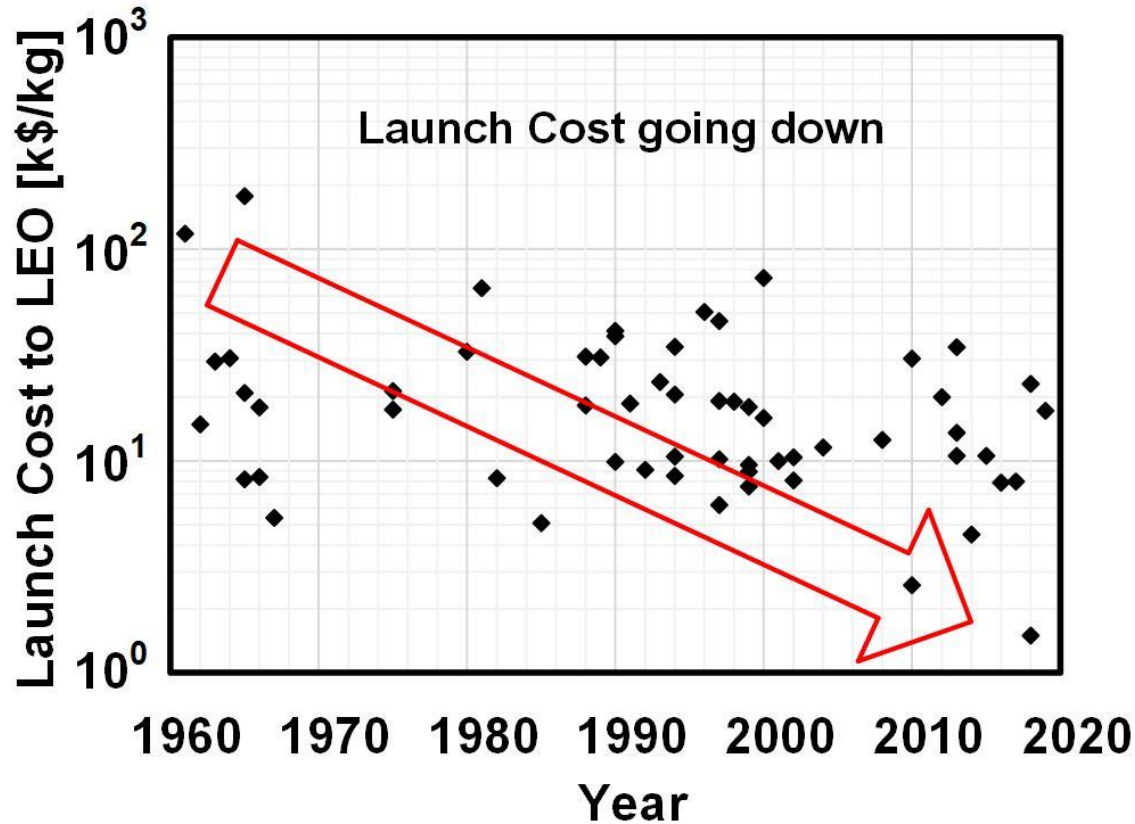
😊 Launch cost keep decreasing, But...

☹ Requires tremendous SATs

- Constellation: 1k ~ 10k SATs

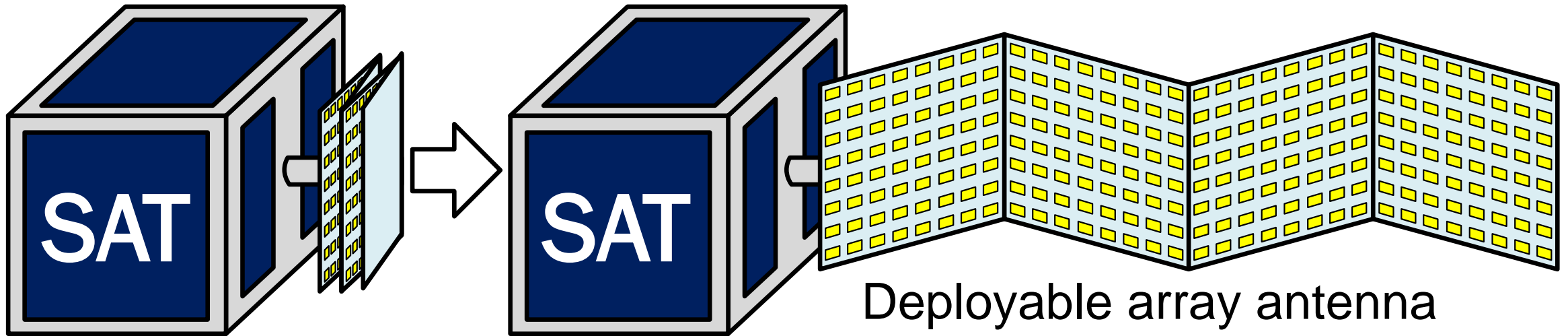
- Frequent SAT re-launch
(short lifetime, air drag in LEO)

➡ Still High Launch Cost



[9] T. G. Roberts. Space launch to low earth orbit: How much does it cost?

*HTS: High Throughput Satellite, EESS: Earth Exploration Satellite Service



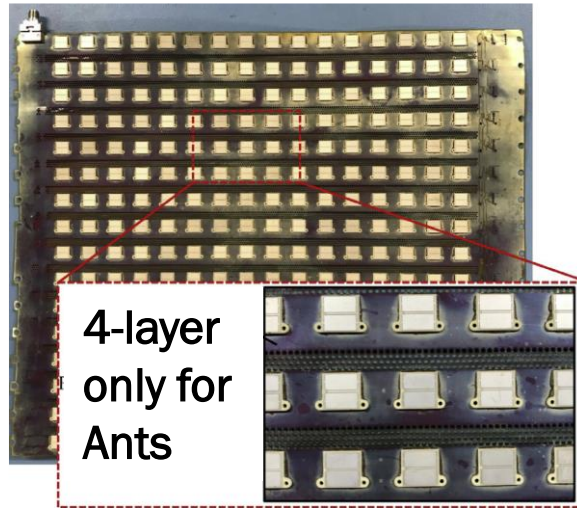
**Antenna Aperture Size
(EIRP)**

Trade-off

**Satellite Body Size
(Launch Cost)**

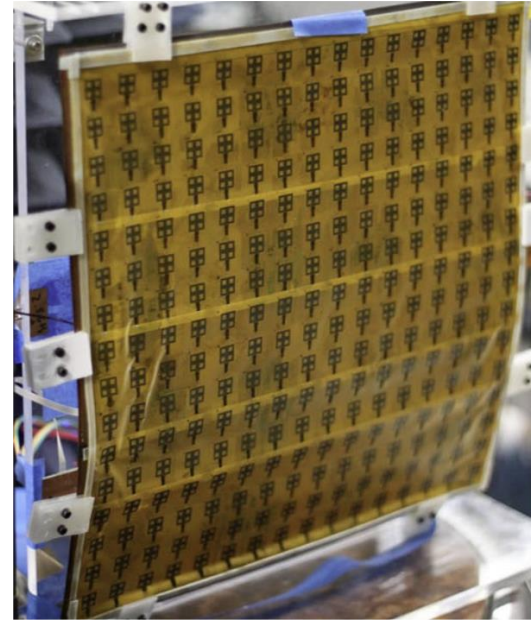
- Deployable array antenna → break through the trade-off

Prior Arts



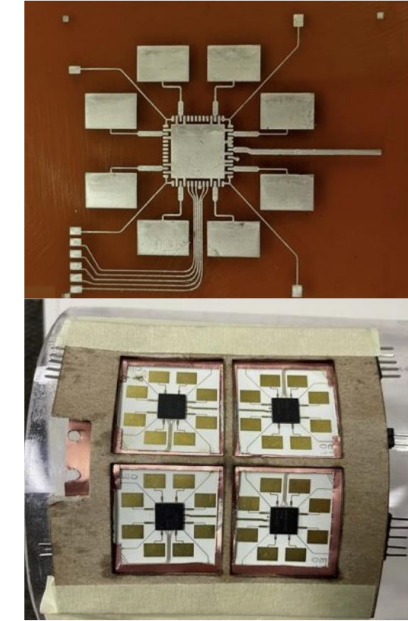
EuCAP2020 [11]

- Rigid-Flex, 2-layer/2-layer
- 10GHz
- Antenna array
- ☺ Thin & lightweight
- ☹ Not enough layers for higher integration



NPJ Flexible Electron [2]

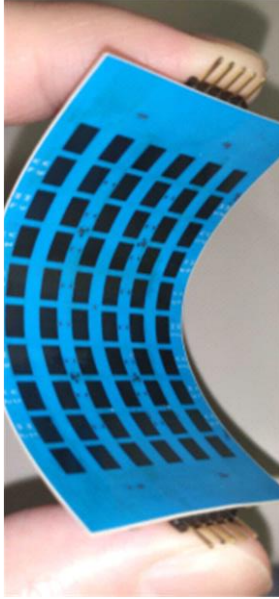
- Flex, 4-layer
- 10GHz WPT
- Active phased array
- ☺ Thin & lightweight
- ☹ Not enough layers for higher integration (in shorter wavelength)



IMS2022[10]

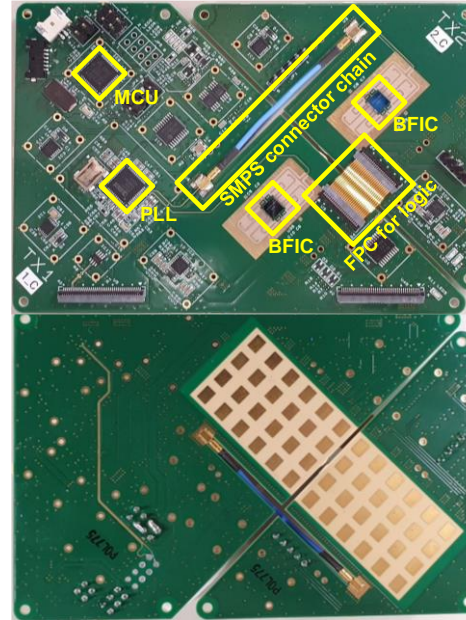
- Flex, 2-layer, Inkjet-printed
- 19GHz 5G, SATCOM
- Active phased array
- ☺ Thin & lightweight
- ☹ Not enough layers for higher integration

Prior Arts



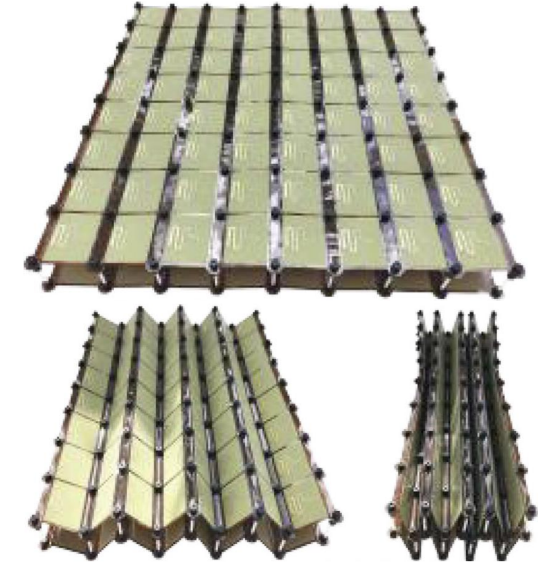
IMS2022 [6]

- Flex, 4-layer
- 28GHz 5G, SATCOM
- Active phased array
- 😊 High Integration
- 😊 Thin & lightweight
- 😞 Not enough layers for higher integration



IMS2021 [1]

- Rigid, 5-layer
- 28GHz 5G, SATCOM
- Active phased array
- 😊 High Integration
- 😞 Thick & Heavy

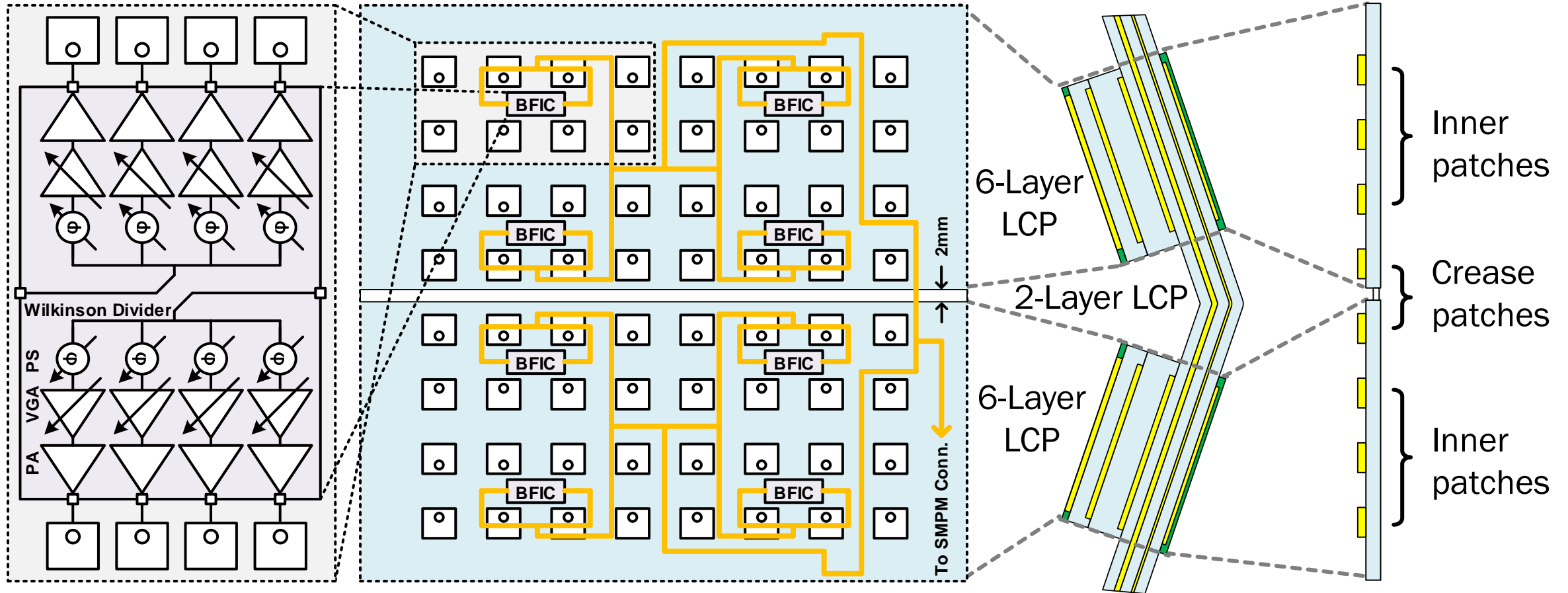


OJAP2021 [12]

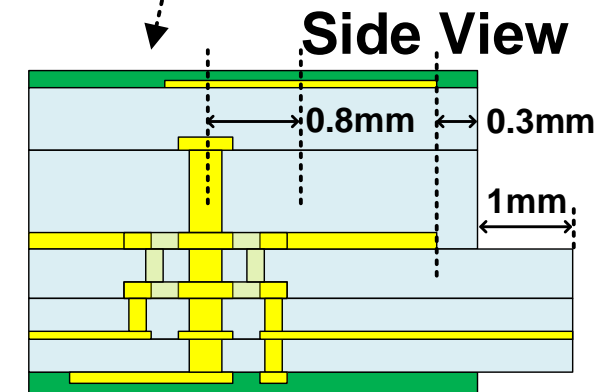
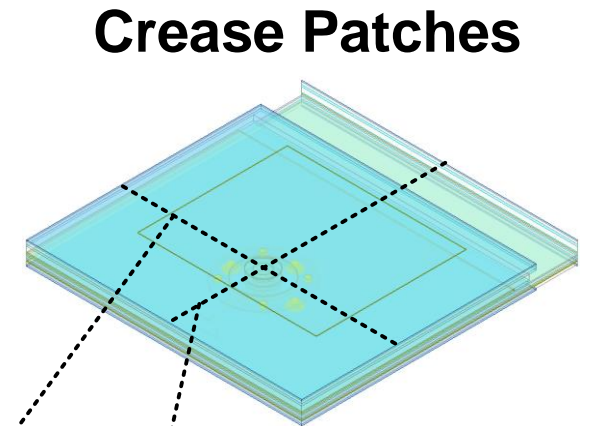
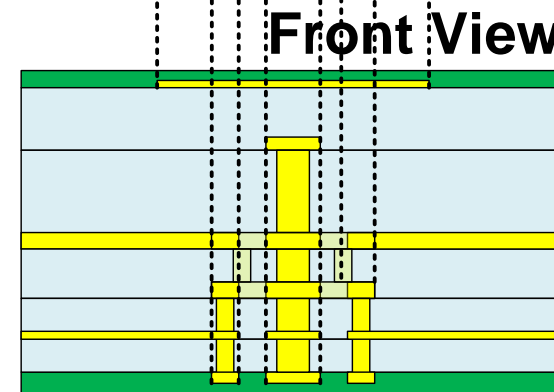
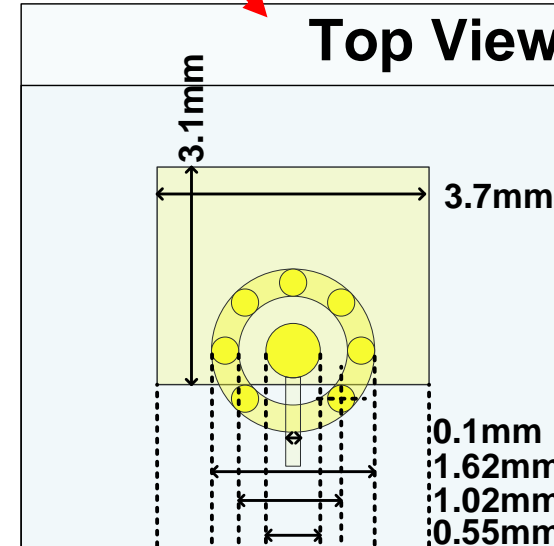
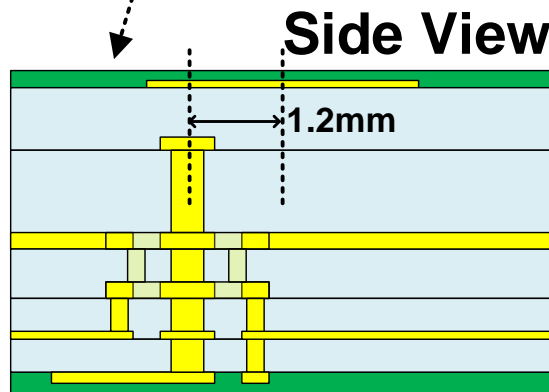
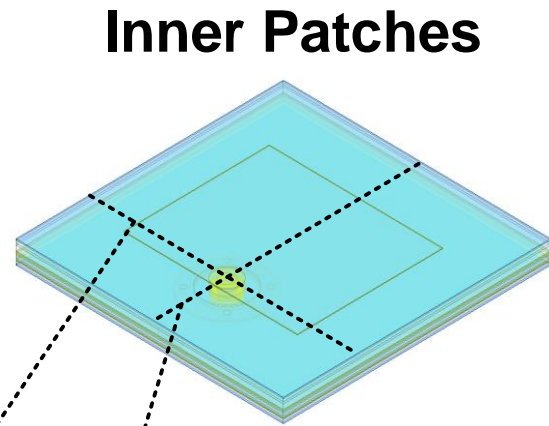
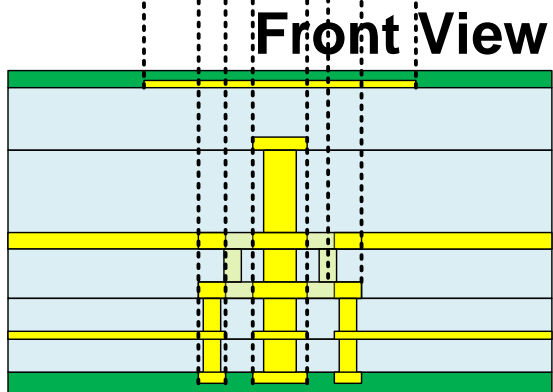
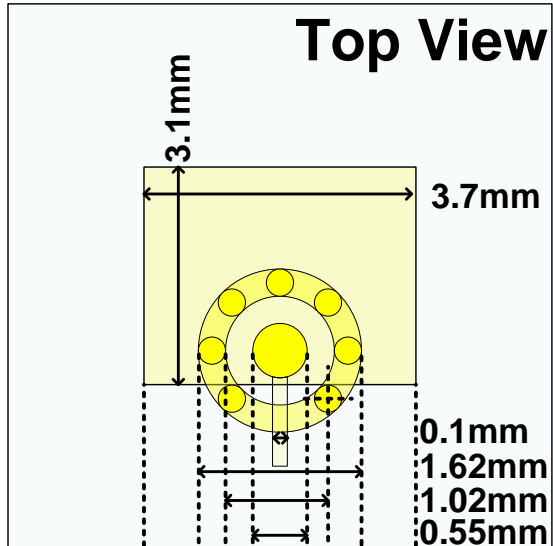
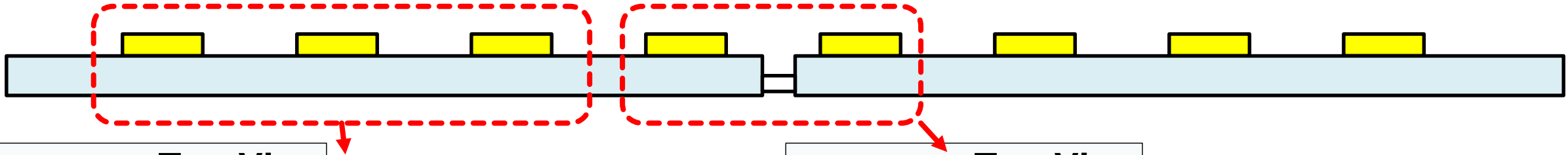
- Rigid-Flex, 1-layer/2-layer
- 1.5GHz
- Antenna array
- 😊 High stow rate
- 😞 Challenging fabrication in Ka-band

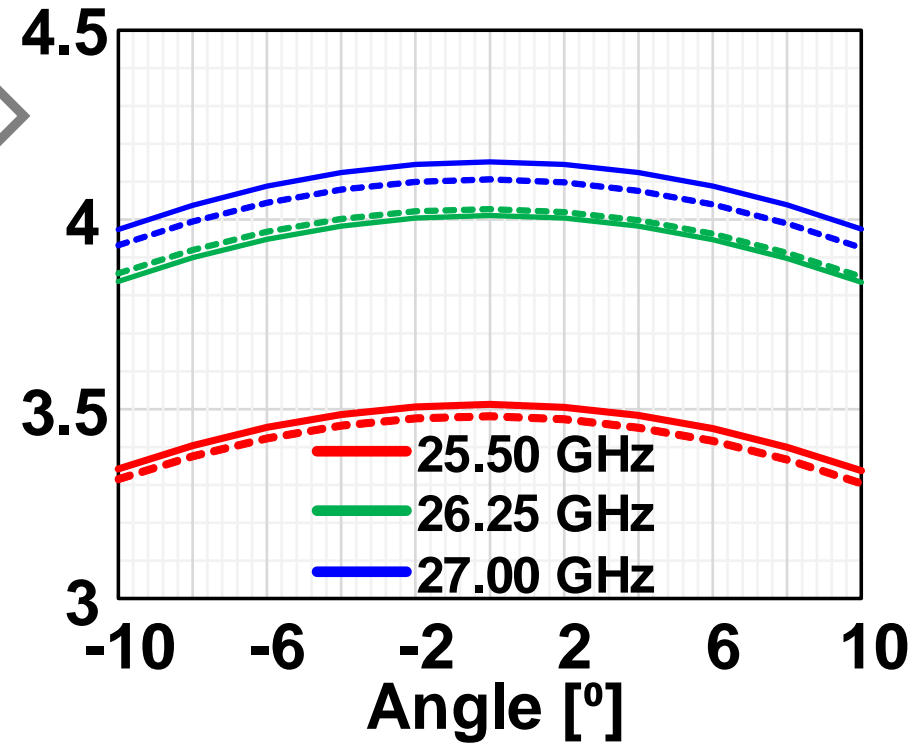
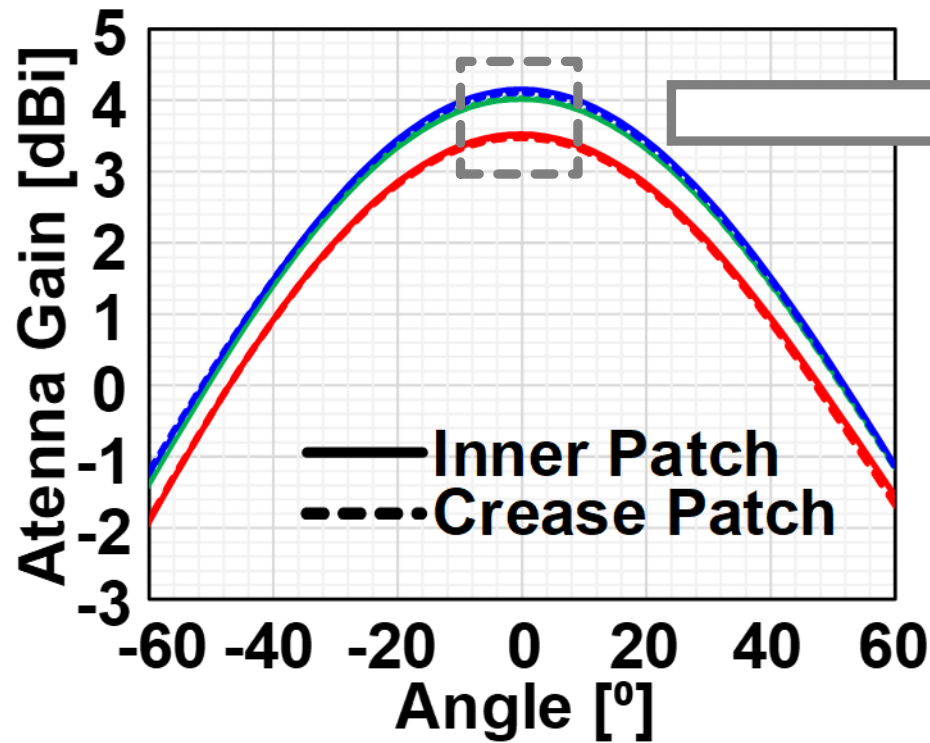
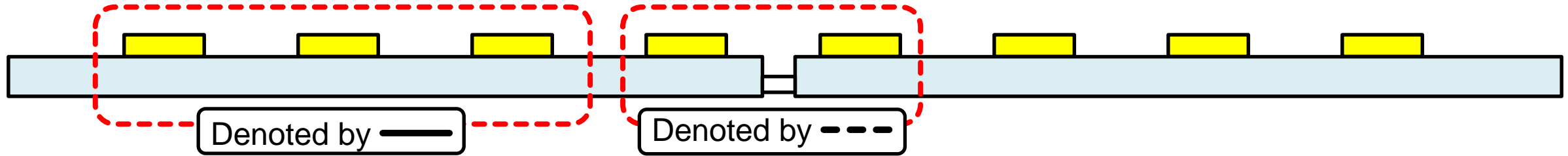
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Proposed TX Architecture

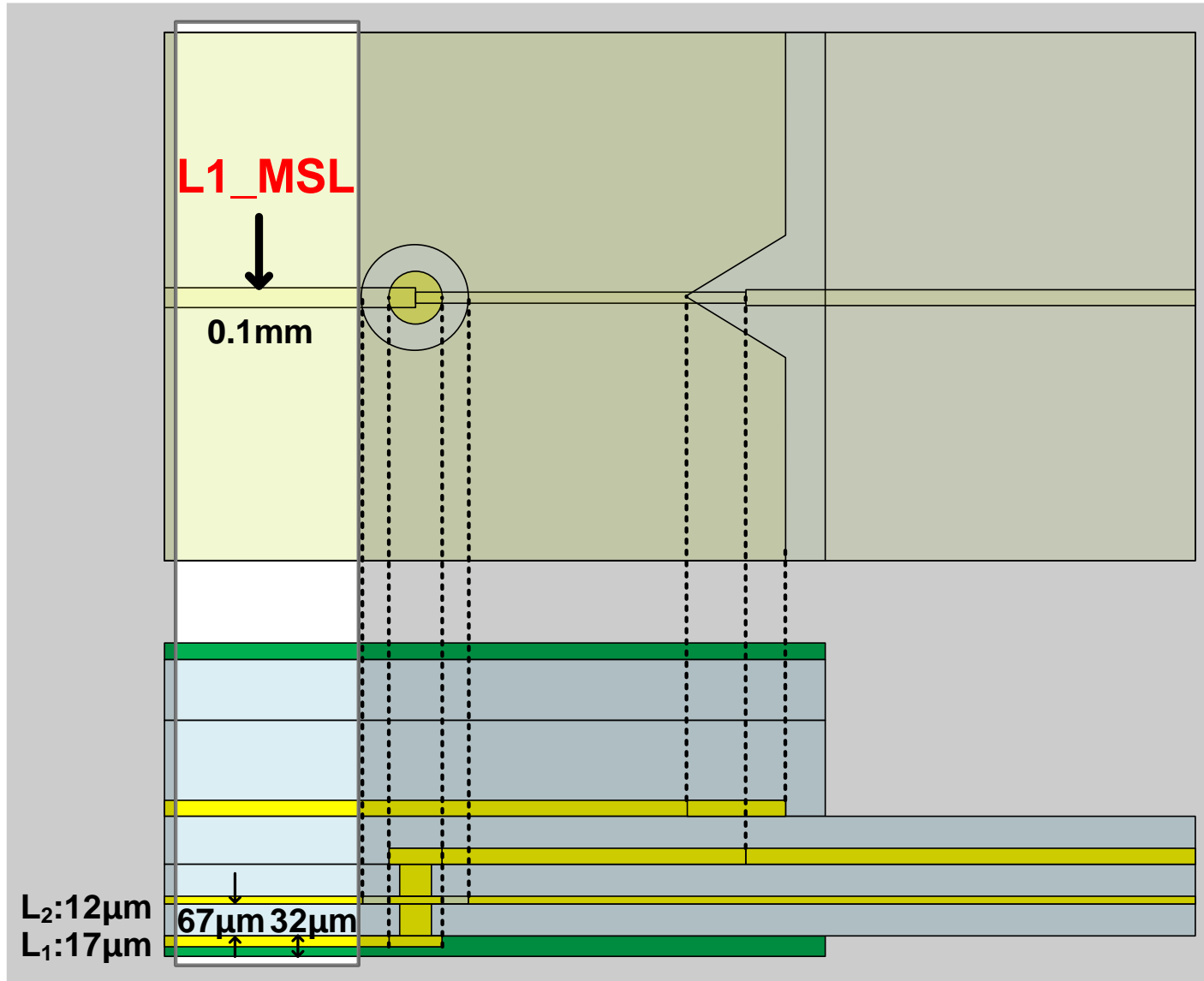


[7] D. You, RFIC2022

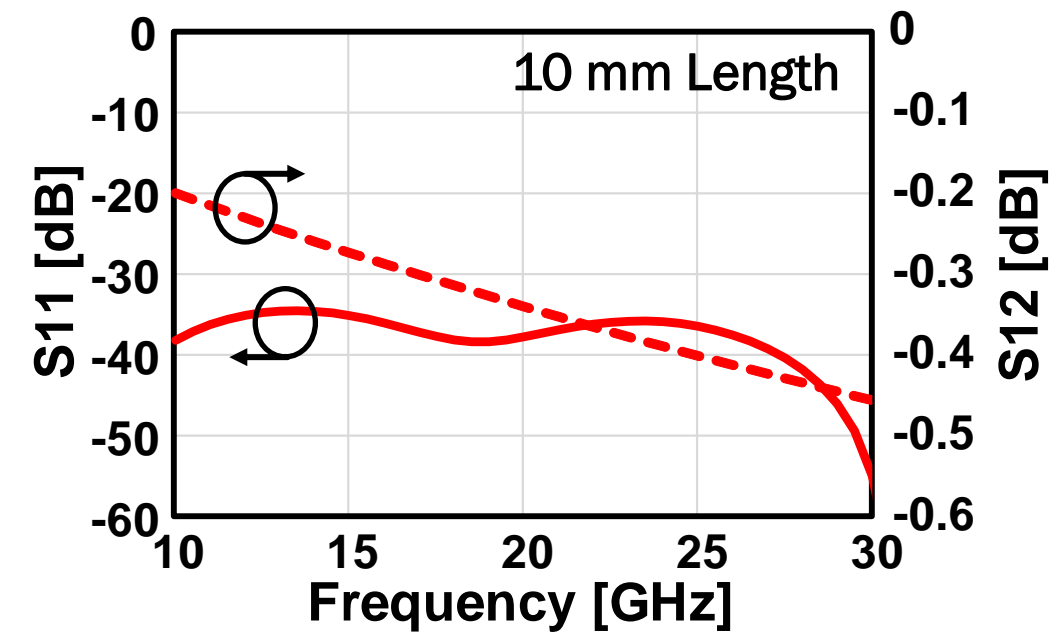


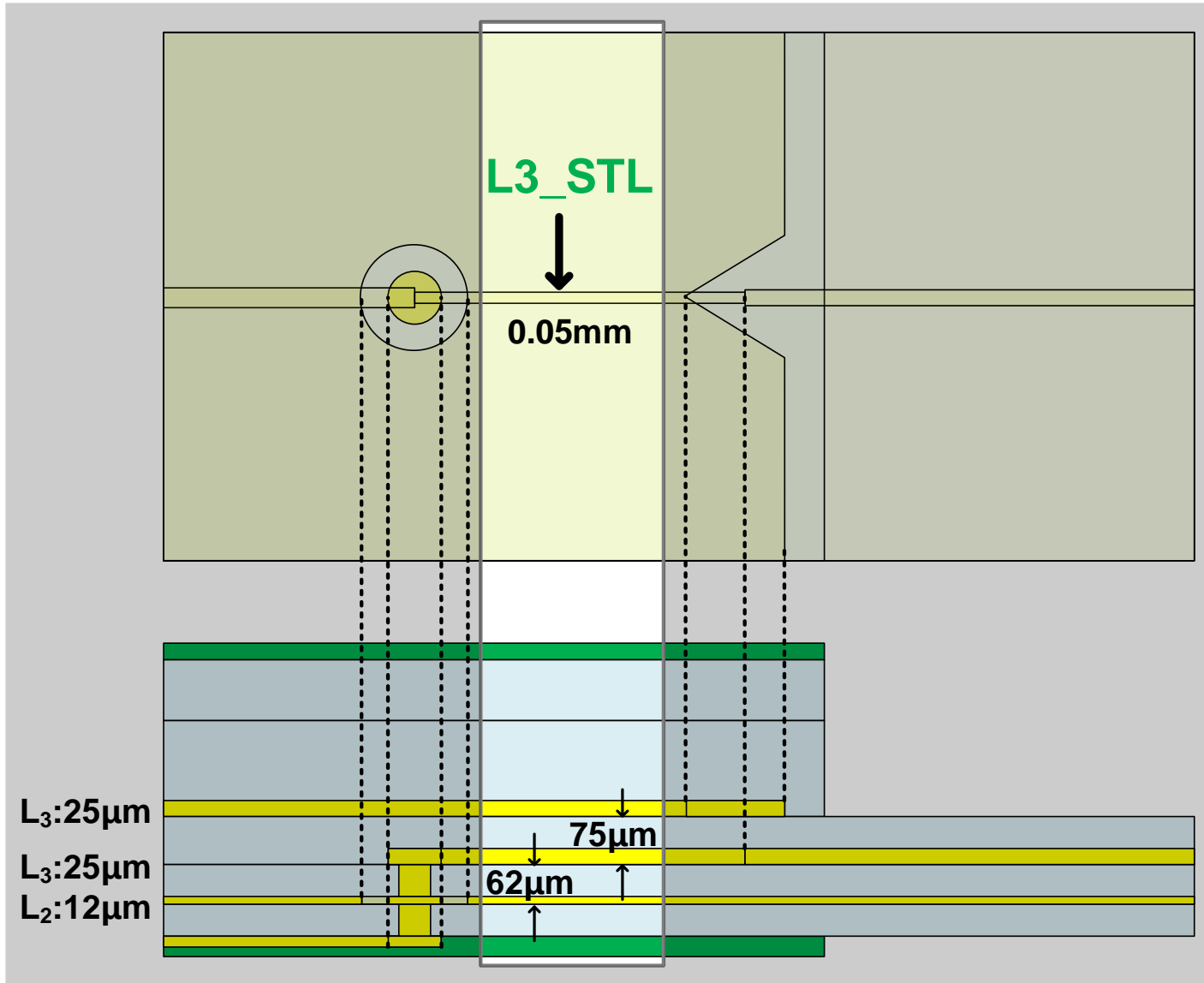


- Less than **0.05 dB offset** btw. Inner patches and crease patches.

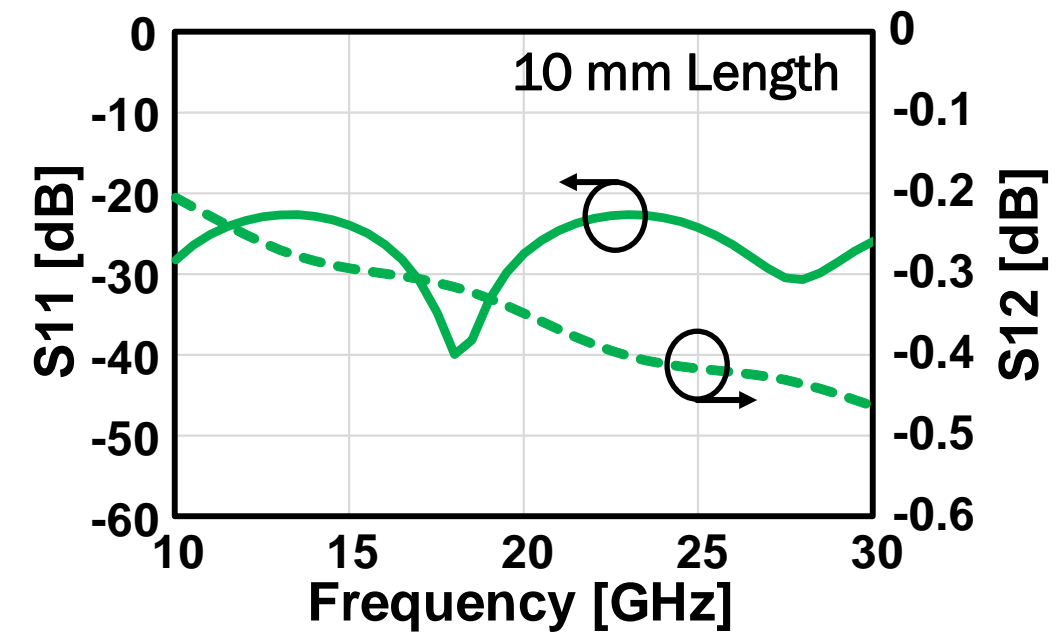


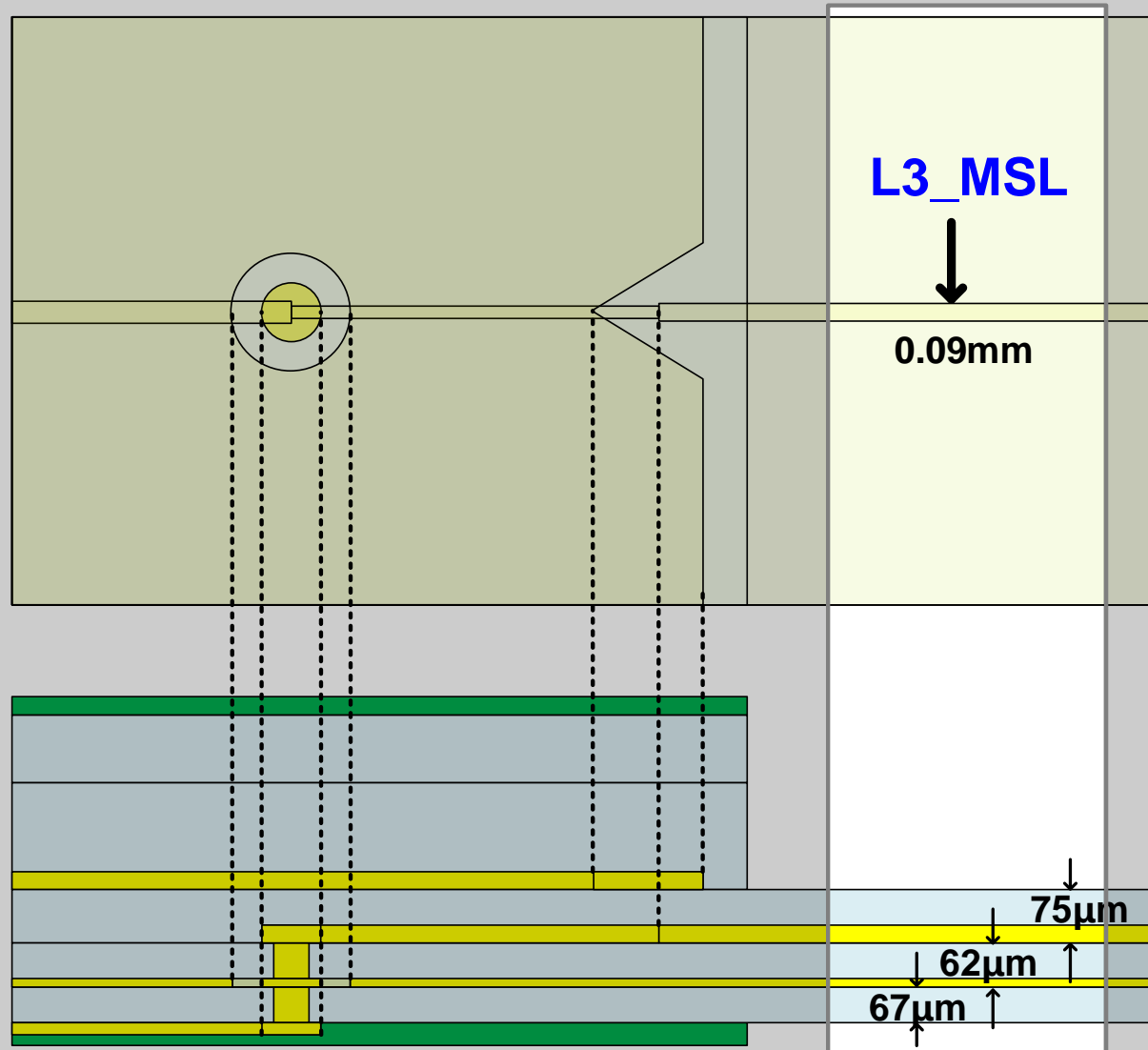
- Microstrip line on L_1 Layer



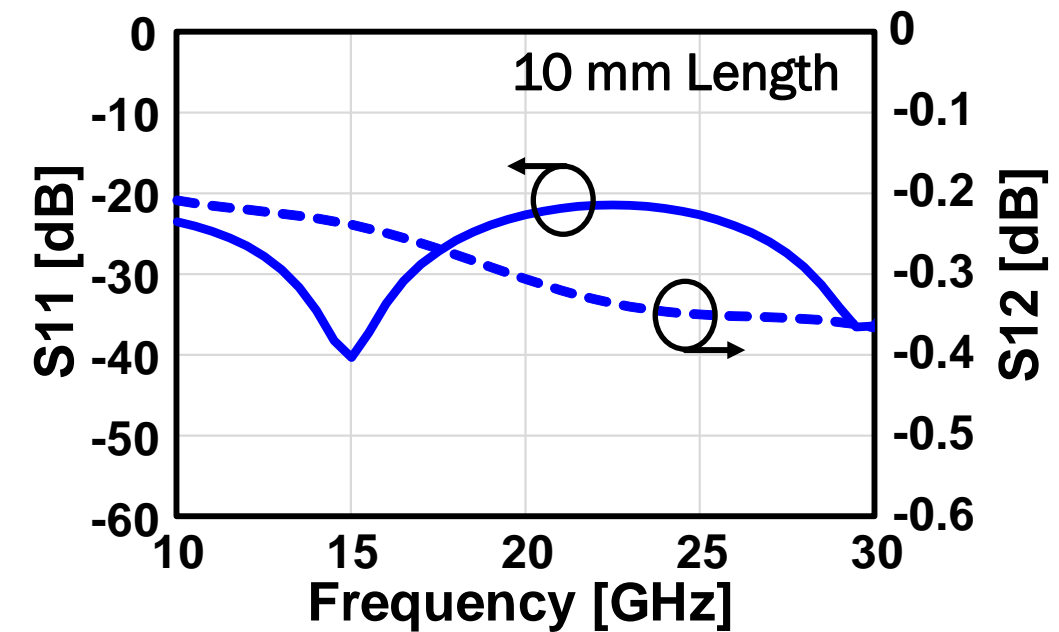


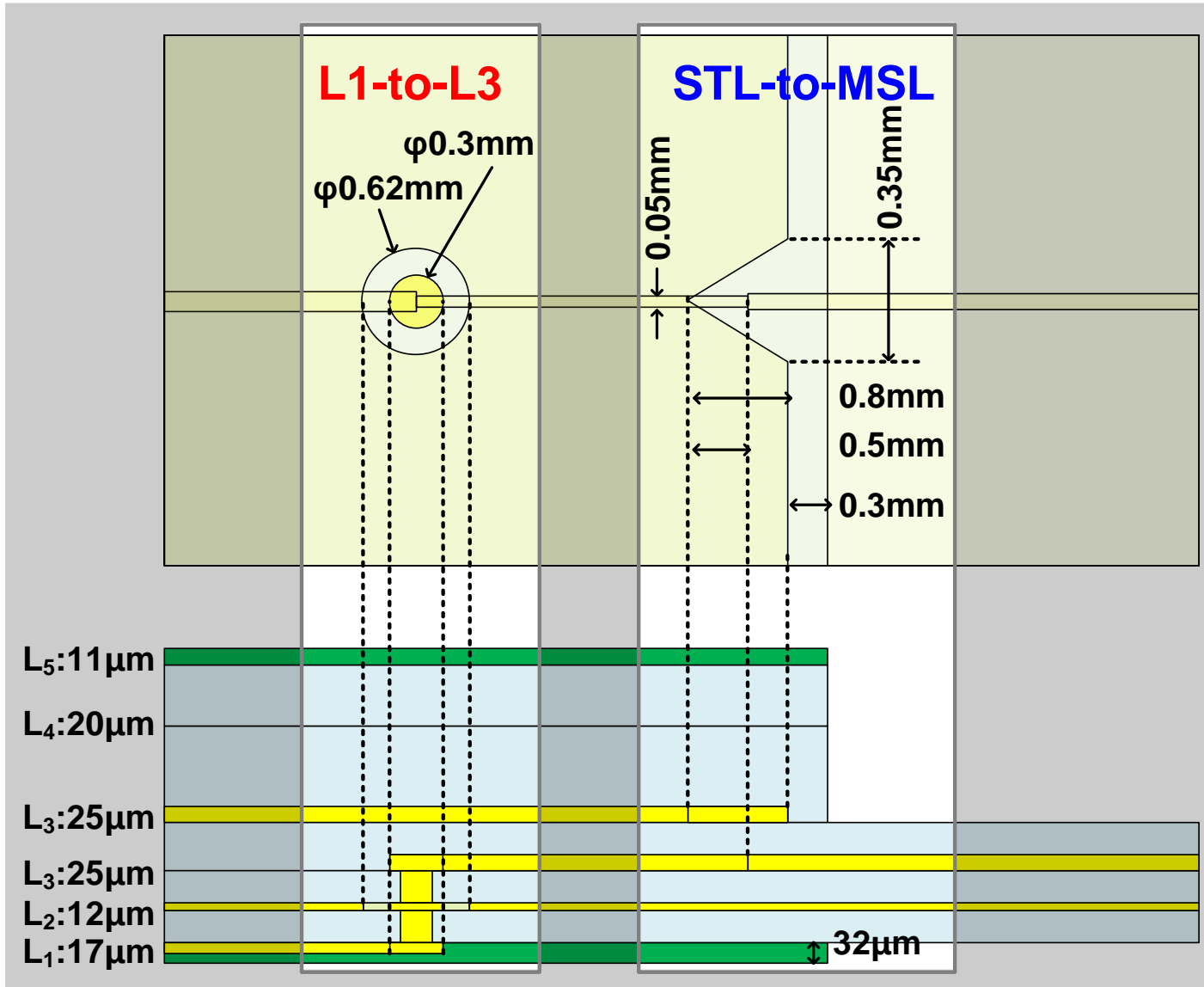
- Strip line on L_3 Layer



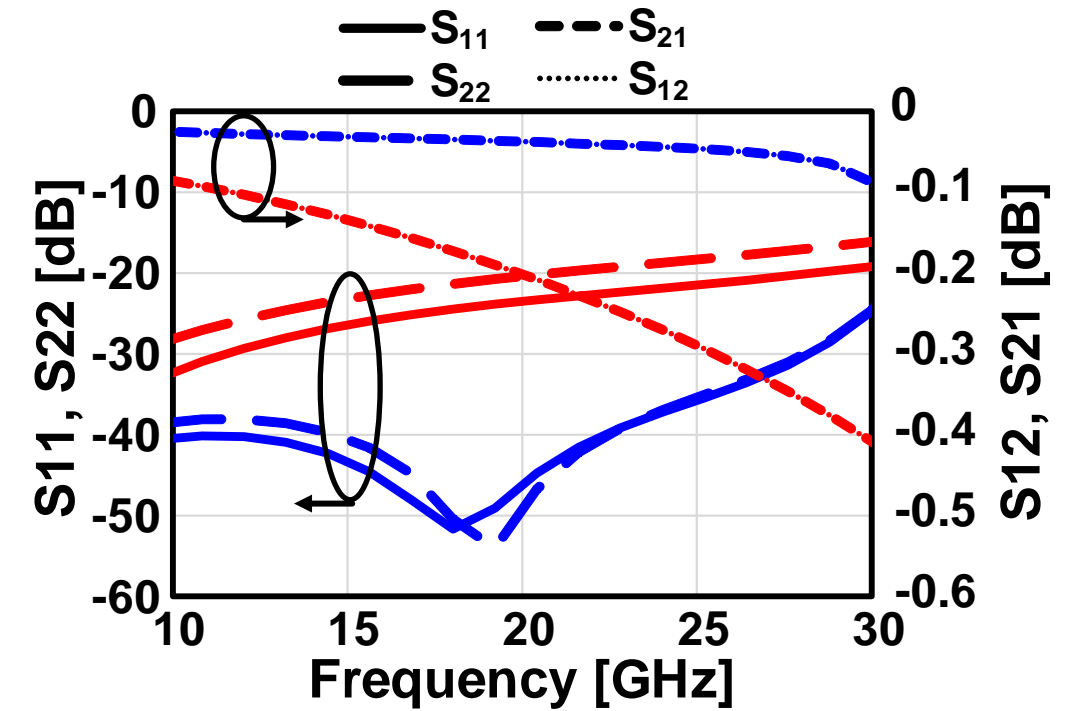


- Microstrip line on L₃ Layer



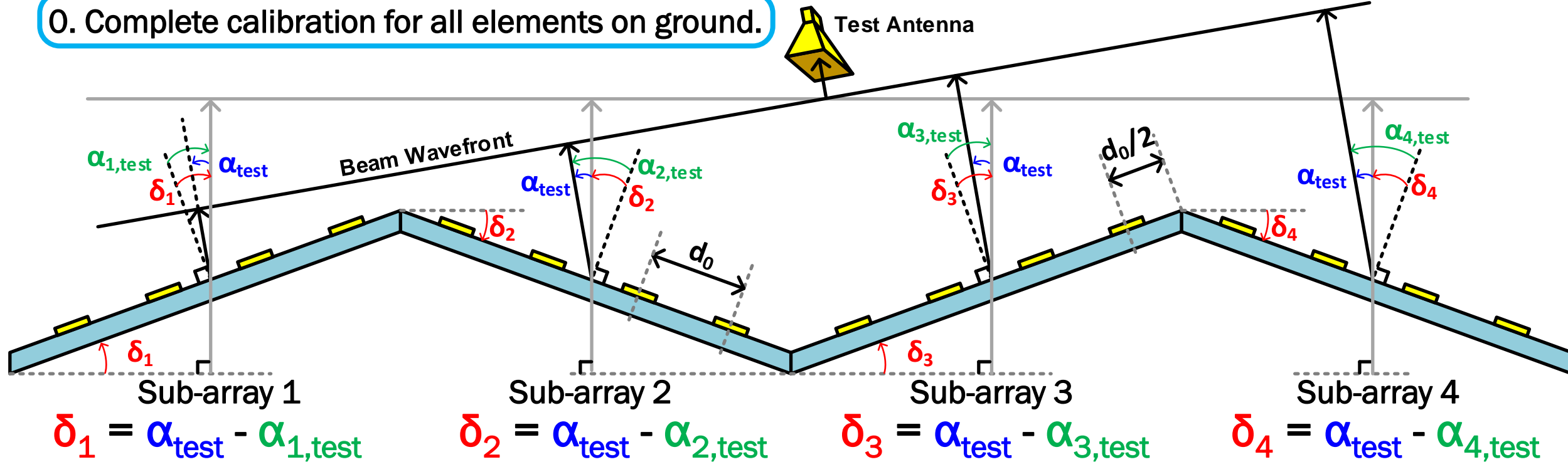


- Transition: L_1 to L_3
- Transition: STL to MSL



*STL: SStrip Line, MSL: MicroStrip Line

0. Complete calibration for all elements on ground.



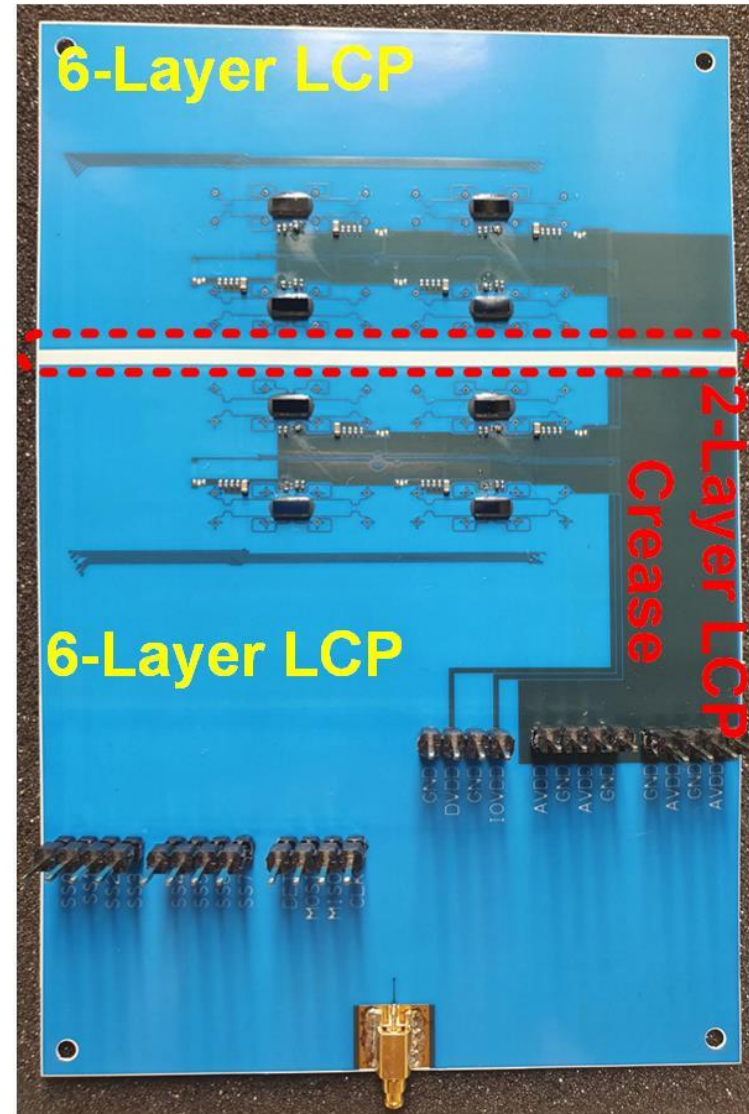
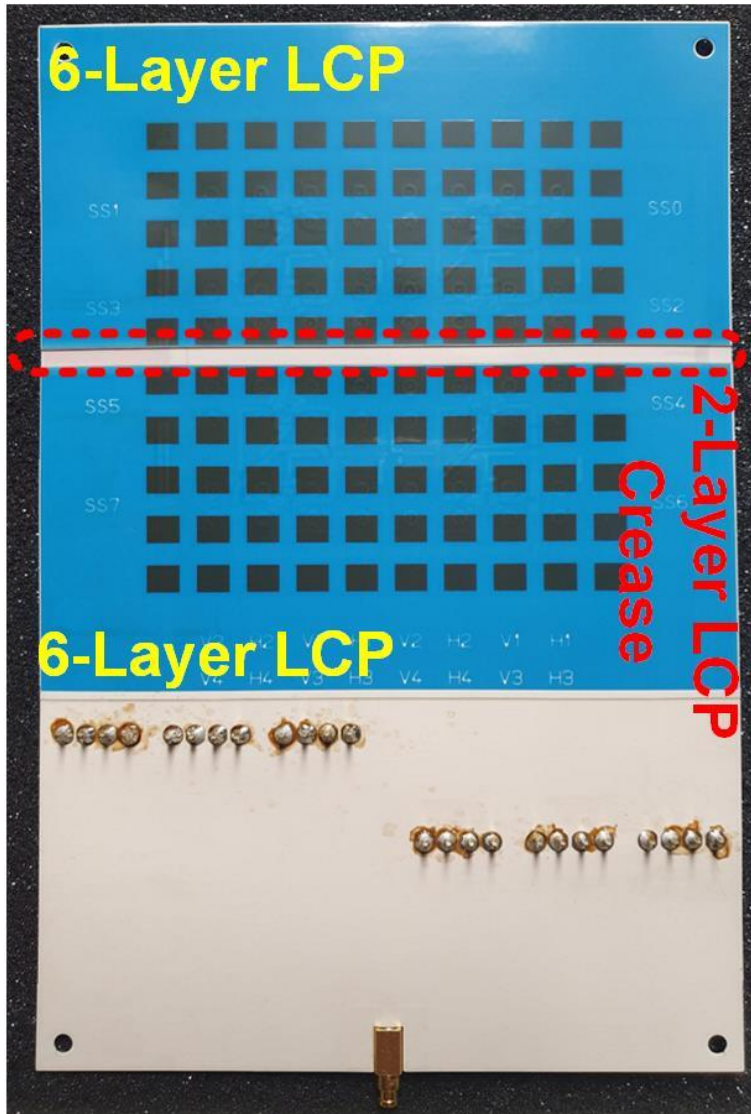
1. Conduct the beam sweeping for **every sub-array** to find direction ($\alpha_{n,\text{test}}$) in which the received test signal be the biggest.

2. Derive δ_n from the equation $\delta_n = \alpha_{\text{test}} - \alpha_{n,\text{test}}$ (knowns: α_{test} , $\alpha_{n,\text{test}}$).

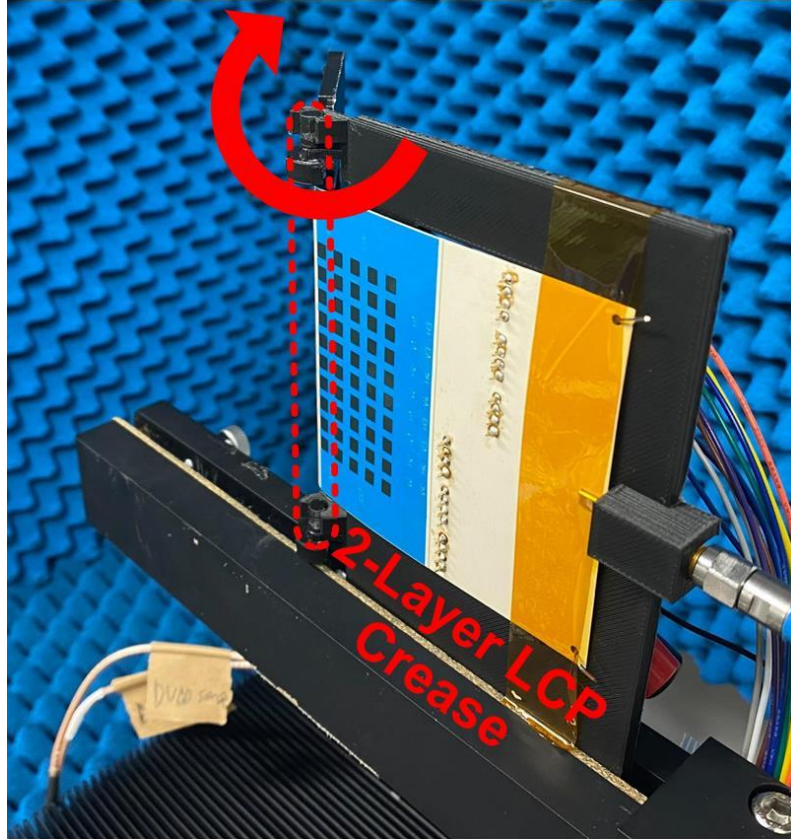
3. Offset the δ_n from the wanted beam direction, α to get the beam angles, α_n for every sub-array.

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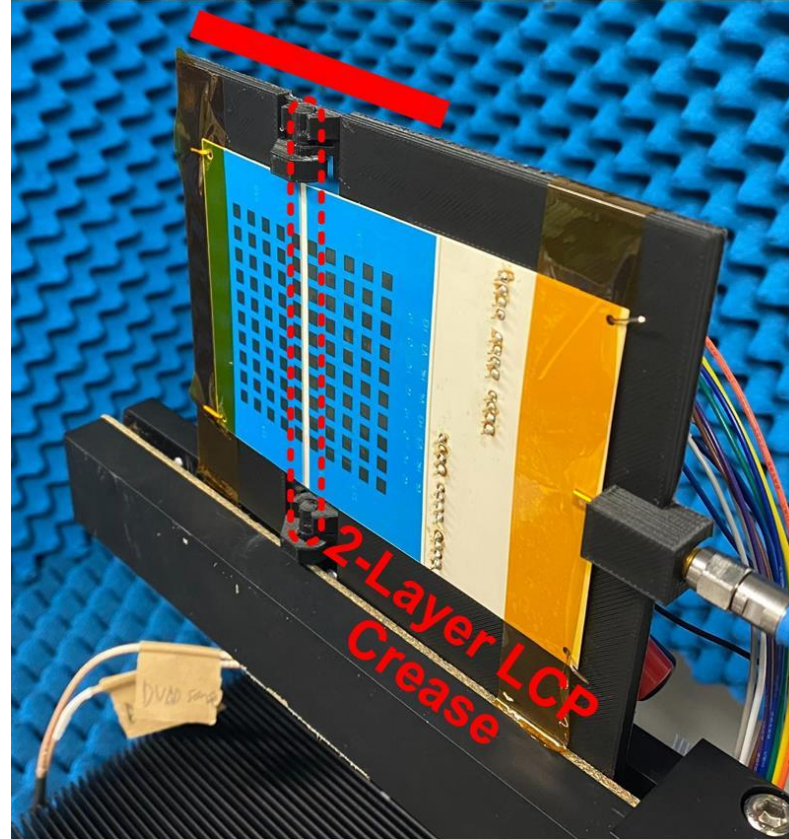
Fabricated Deployable Phased Array



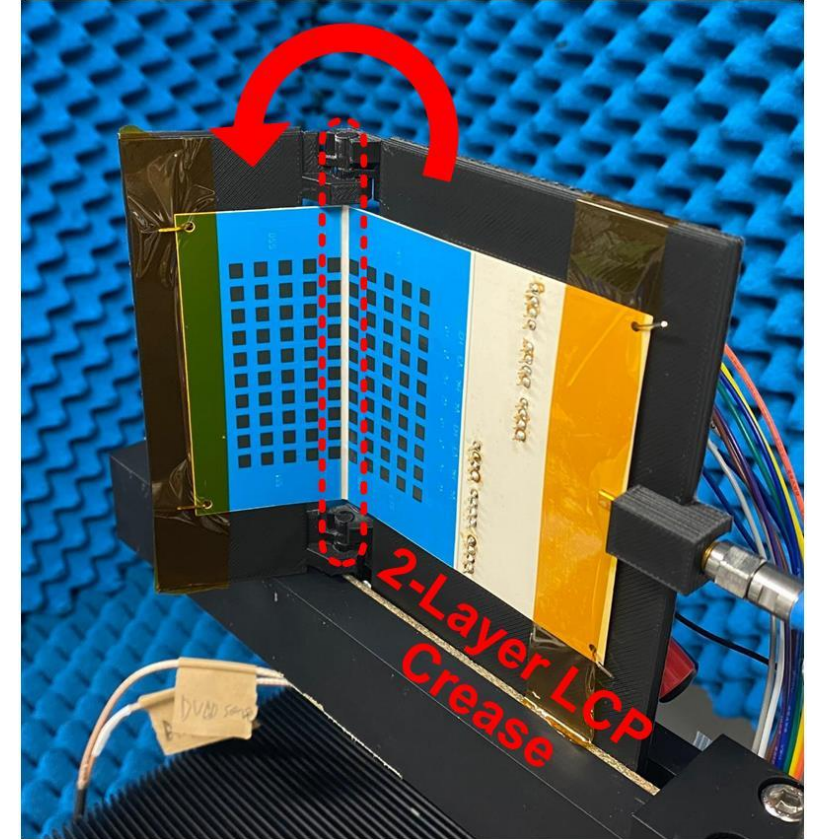
- Prototype deployable TX with a single crease.
- 8×8 antenna array driven by 8 BFICs [7].
- 1 kg/m² areal mass (9.65 g in total).
- 3.0 mm Max. thickness @SMPM connector (Header pin excluded)
- 1.4 mm thickness @ BFIC



Outward-fold

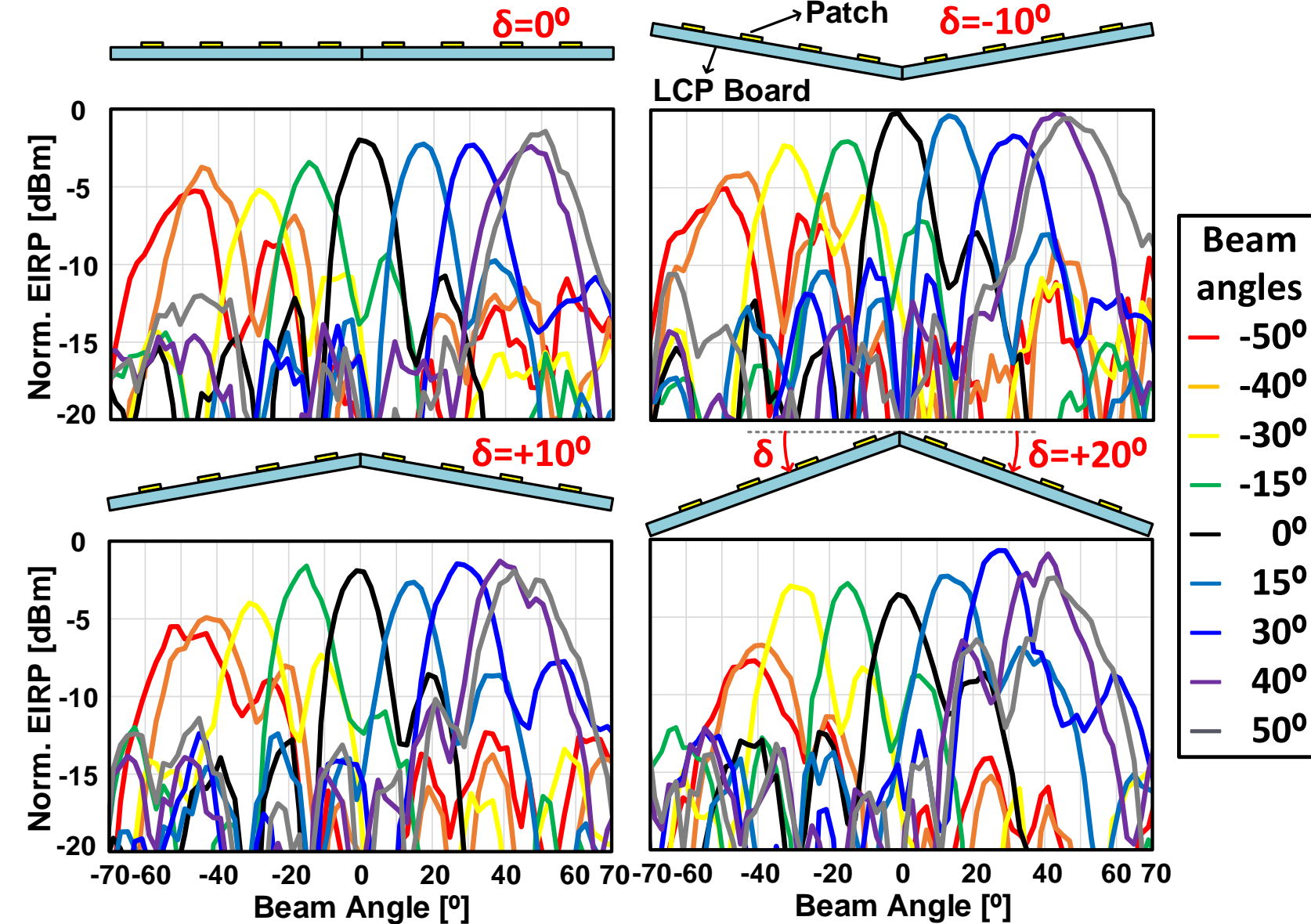


Flat State



Inward-fold

Measured Beam Patterns

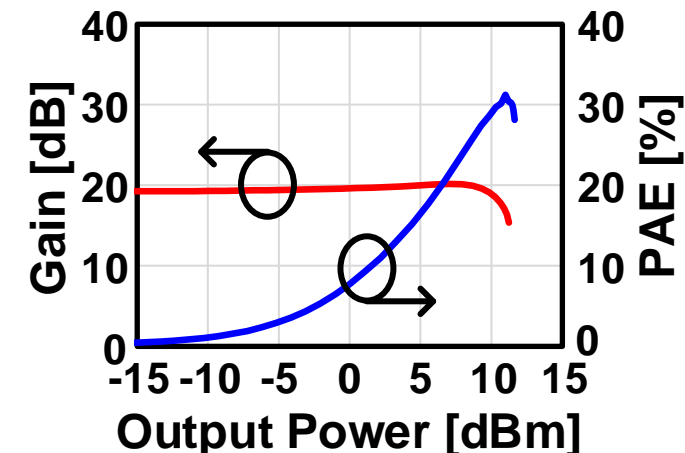
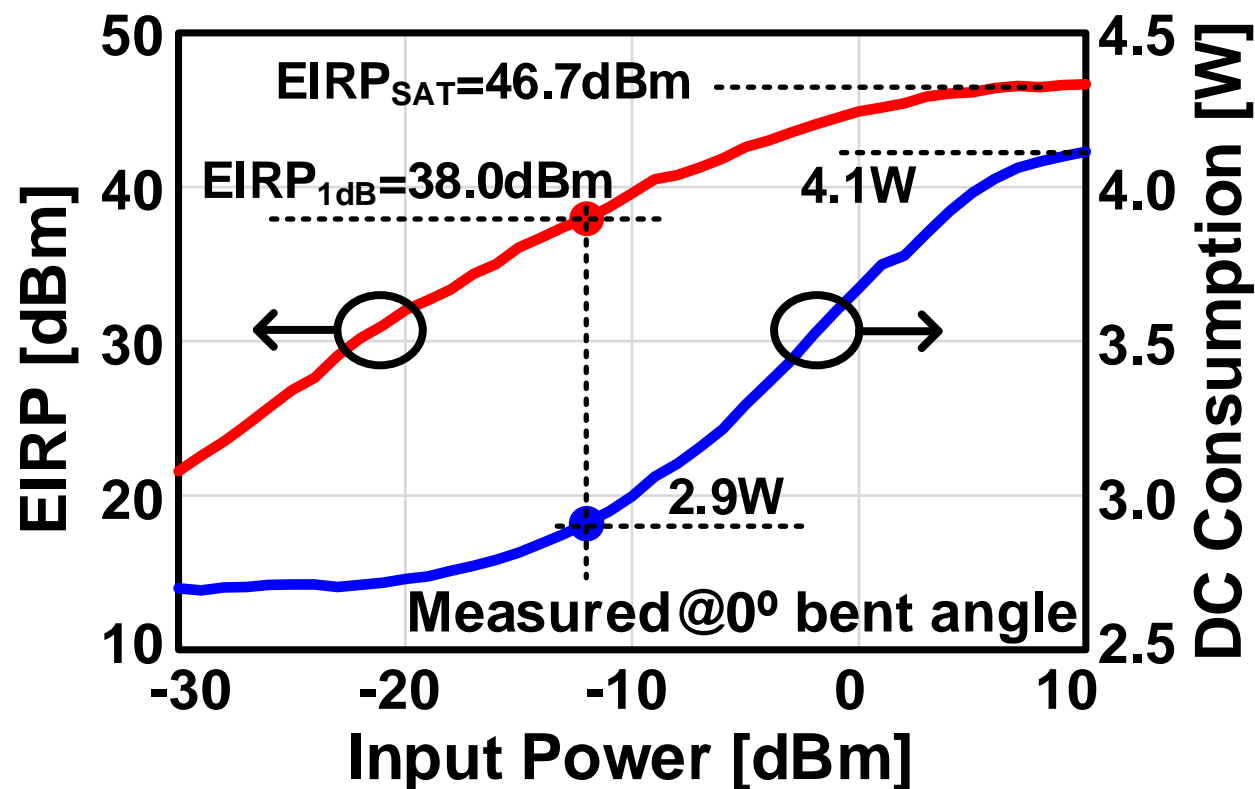


- Calibrated for bent angle, $\delta = -10^\circ \sim +20^\circ$.

Measured EIRP

Single PA (two stage) Gain and Efficiency

*Measured with 64-element array

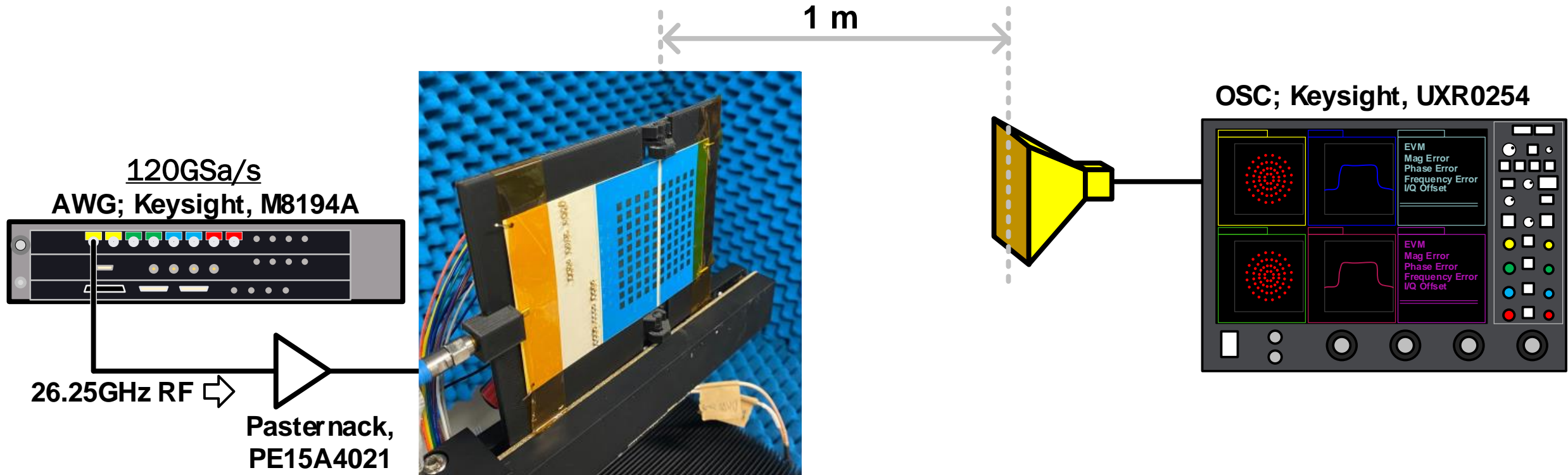


EIRP

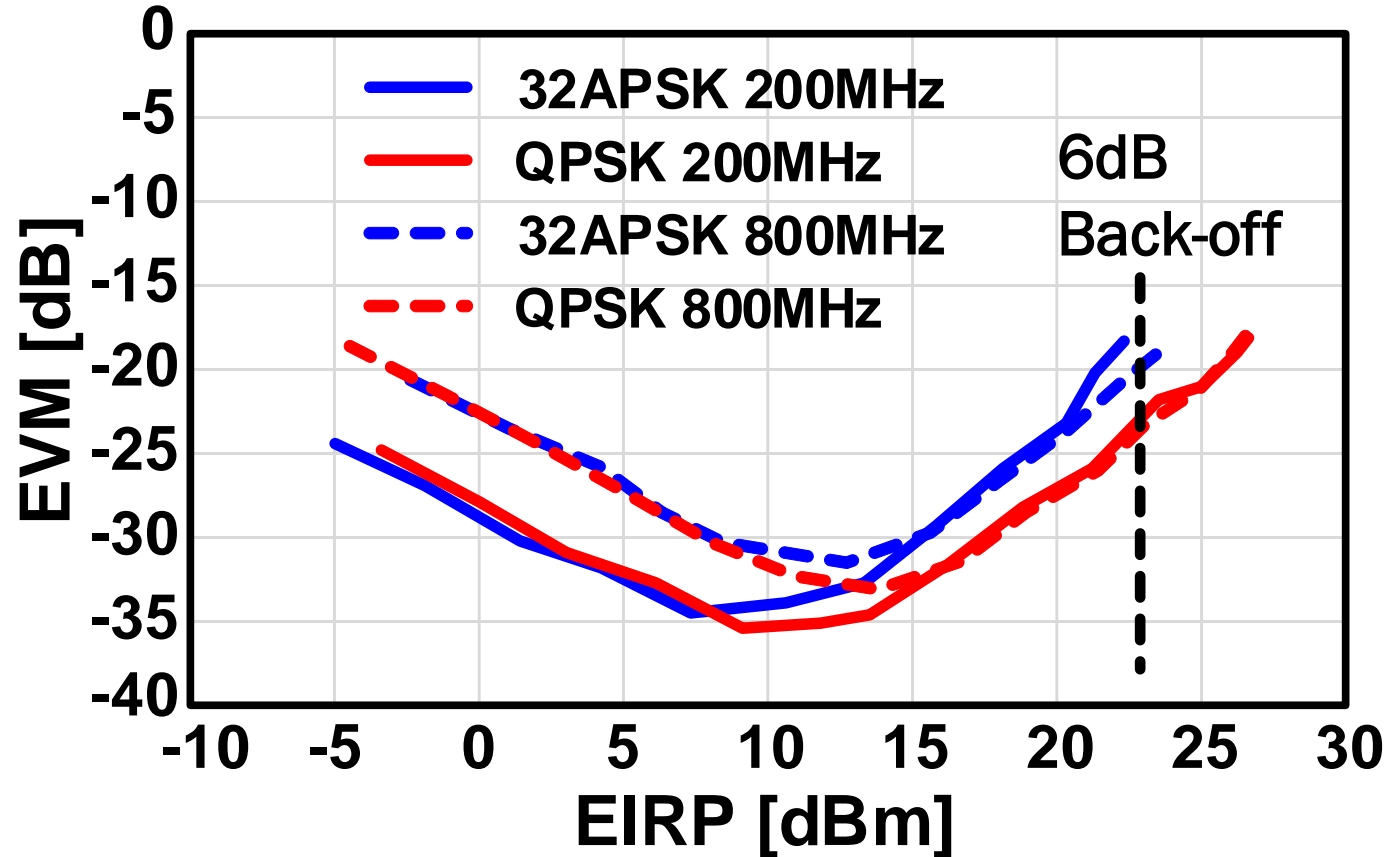
$$\begin{aligned}
 &= \text{Total PA Output Power} \times \text{Array Gain} \\
 &= \underbrace{11 \text{ dBm}}_{\text{Single PA } P_{OUT}} + \underbrace{10 \times \log_{10}(64)}_{\text{\# of PAs}} + \underbrace{19.4 \text{ dBi}}_{\text{Array Gain (Simulated)}} \\
 &= 48.5 \text{ dBm}
 \end{aligned}$$

*1.8 dB additional loss at output
→ line loss, thermal gain drop

Over-The-Air Measurement Setup

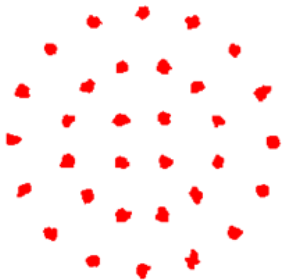
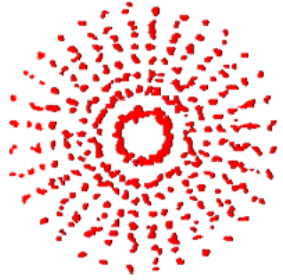




*Measured with 8-element array



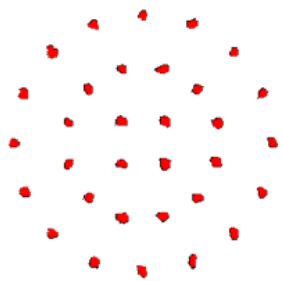
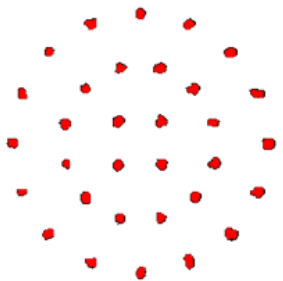
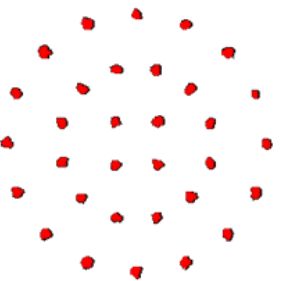
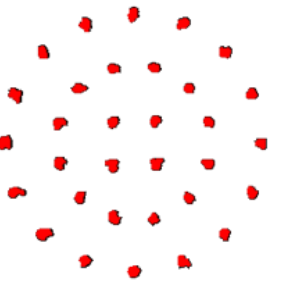
- 32-APSK @ 6dB Back-off point

*** @ Boresight beam angle & flat-board state**

8-element OTA Meas. with 1500MBaud BW				
Modulation	32APSK	256APSK	QPSK	32APSK
Constellation				
EVM [dB]	-28.9	-28.3	-19.1	-21.6
EIRP [dBm]	13.3	12.3	23.2	22.8

- QPSK & 32-APSK @ 6 dB Back-off point.
- 256-APSK @ Max. SNR power level.

***Calibration Applied**

8-element OTA Meas. With 200MBaud under Bent-Board Condition				
Bent Angle, δ	0°		10°	
Beam Angle, α	0°	30°	0°	30°
Constellation				
EVM [dB]	-34.6	-33.7	-34.5	-31.3
EIRP [dBm]	10.2	10.1	7.3	9.3

- Less than -30 dB EVM w/ 200MBaud under various bent angles and beam angles.

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- A novel **hetero-segmented flexible LCP substrate** is proposed, fabricated, and evaluated toward the future deployable active phased array system for SATCOM.
- The proposed mechanical deformation error calibration methodology compensates **bent board angle form -10° to $+20^{\circ}$** .
- The fabricated prototype deployable active phased array TX:
 - achieved 46.7 dBm saturated EIRP.
 - supports 32-APSK modulation at 6dB back-off power.
 - achieved **12 Gbps data rate** with a 1.5GBaud 256-APSK modulation.
- The deployable active phased array TX on the novel hetero-segmented flexible LCP substrate achieved
 - **1 kg/m²** lightweight areal mass (9.65g in total),
 - **3 mm** thickness

Acknowledgment

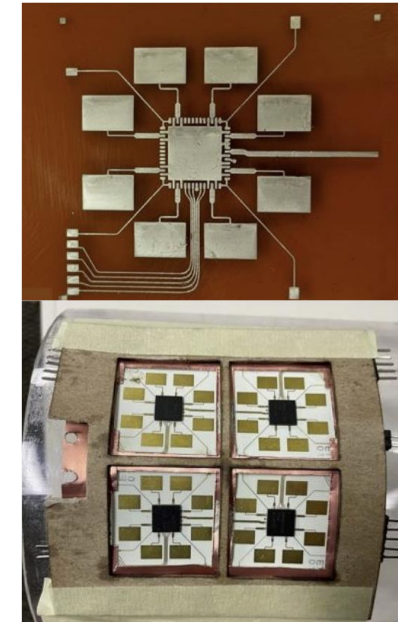
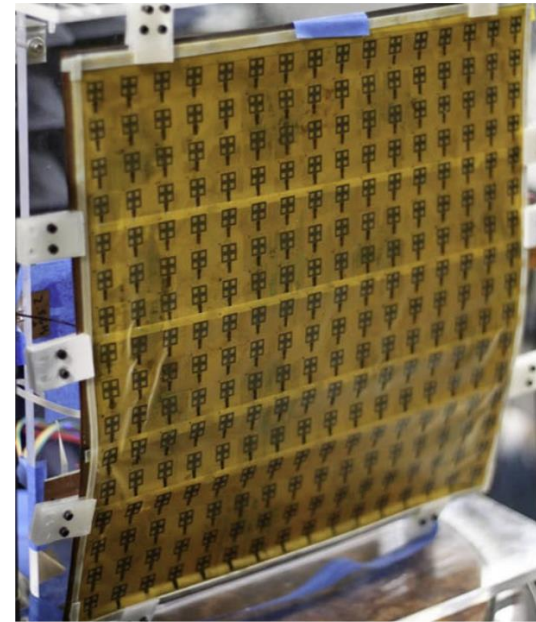
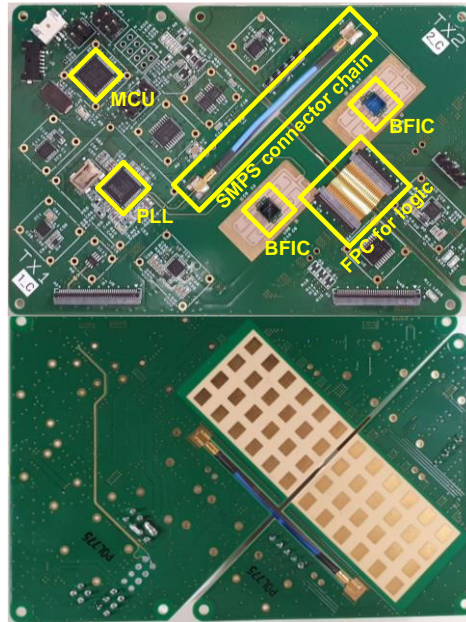
This work was supported in part by the MIC / SCOPE under Grant 192203002 and Grant 192103003; in part by the JSPS under Grant JP20H00236; in part by the MIC under Grant JPJ000254; in part by the JST / A-STEP under Grant JPMJTR211D; in part by the NICT under Grant 00601; in part by the STAR; and in part by the VDEC in collaboration with Cadence Design Systems, Inc., Mentor Graphics, Inc., and Keysight Technologies Japan, Ltd.

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- [7] D. You et al., “A flexible element antenna for Ka-band active phased array SATCOM transceiver,” in Proc. IEEE Asia-Pacific Microw. Conf. (APMC), Dec. 2020, pp. 991–993.
- [8] D. You et al., “A Ka-band dual circularly polarized CMOS transmitter with adaptive scan impedance tuner and active XPD calibration technique for satellite terminal,” in Proc. IEEE Radio Freq. Integr. Circuits Symp. (RFIC), Jun. 2022, pp. 15–18.

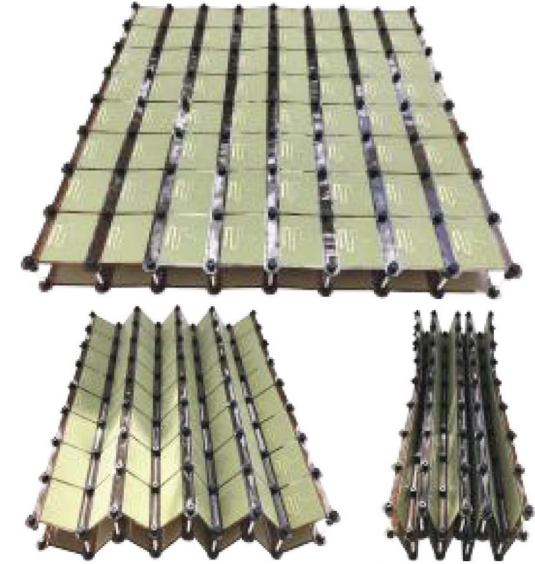
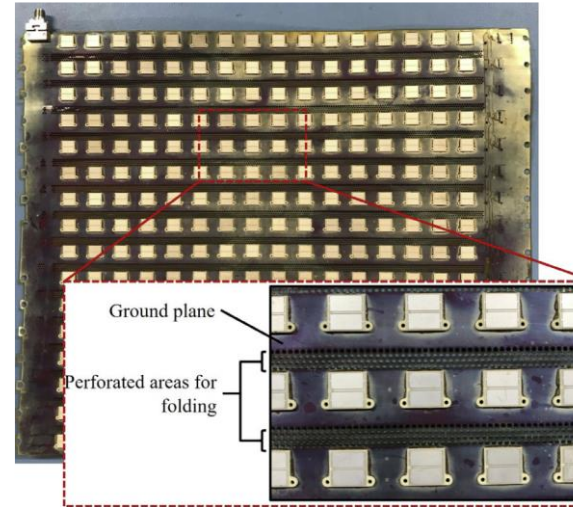
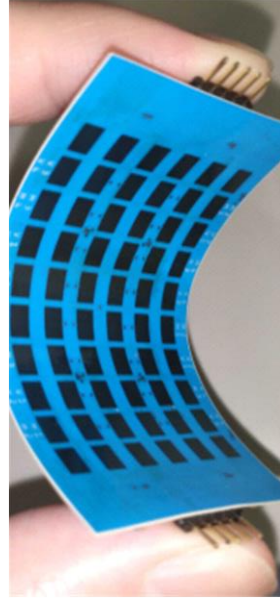
- [9] T. G. Roberts. Space launch to low earth orbit: How much does it cost? <https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/>
- [10] K. Hu, G. Soto-Valle, Y. Cui and M. M. Tentzeris, "Flexible and Scalable Additively Manufactured Tile-Based Phased Arrays for Satellite Communication and 50 mm Wave Applications," 2022 IEEE/MTT-S International Microwave Symposium - IMS 2022, Denver, CO, USA, 2022, pp. 691-694.
- [11] W. F. Moulder, R. N. Das, A. C. Maccabe, L. A. Bowen, E. M. Thompson and P. J. Bell, "Rigid-Flexible Antenna Array (RFAA) for Lightweight Deployable Apertures," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.
- [12] M. Carvalho and J. L. Volakis, "Deployable Rigid-Flexible Tightly Coupled Dipole Array (RF-TCDA)," in IEEE Open Journal of Antennas and Propagation, vol. 2, pp. 1184-1193, 2021.

Backup Slides

State-of-the-Arts



	IMS2021 [1]	Nature Electronics [2]	IMS2022 [10]
Structure	Rigid, 5-layer Megtron6	Flex, 4-layer DuPont	Flex, 2-layer RO4350
Frequency [GHz]	24	10	19
Integration	4x2 Ant, Amp, PS, Dig.	16x16 Ant, Amp, PS, Dig	32 Ant
Areal Mass [kg/mm ²]	3.5	1.06	Unknown
Thickness [mm]	2	10 (stowed)/ 40 (deployed)	0.5



	IMS2022 [6]	EuCAP2020 [11]	OJAP2021 [12]
Structure	Flex, 4-layer LCP	Rigid-Flex, 2-layer Acryl /2-layer RO4350	Rigid-Flex, 1-layer FR4 /2-layer Kapton
Frequency [GHz]	28	10	1.5
Integration	8×4 Ant, Amp, PS, Dig.	16×16 Ant	8×8 Ant
Areal Mass [kg/m ²]	0.26	1.1	4.2
Thickness [mm]	0.9	Unknown	50