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Last update: 08/23/2023

ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

ARC

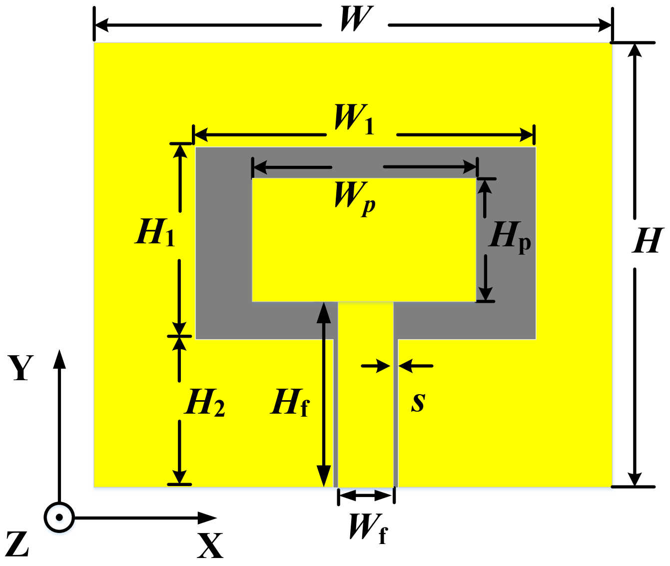
Antenna, RFID, and Computational EM Group

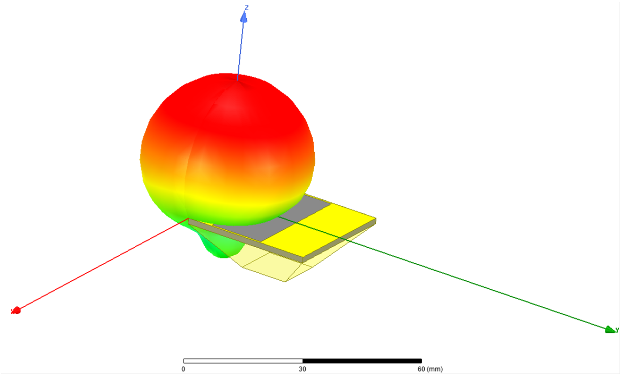
Outline

- Project 1: Cavity Backed Patch Antenna Design
  - Arrow Patch-Slot Antenna for 5G Lower Frequency Band Communications
  - Cavity Backed Patch-Slot Antenna for Lower Band 5G Communications
- Project 2: 3D Antenna: Maximizing Isotropicity and CP Coverage
  - 3D antenna in package design: Maximizing radiation pattern isotropicity and CP coverage
  - Antenna-on-package design: Achieving near-isotropic radiation pattern and wide CP coverage simultaneously
- Project 3: RFID Tag Antenna Design
  - Circularly polarized RFID tag antenna design for underground localization system
  - Underground localization system using a combination of RFID and IMU technologies
- Project 4: Human Tissues Properties in Antenna Design
  - Human tissues parameters and resolution for accurate simulations of wearable antennas
  - A Dual-Band Microstrip Patch Antenna for 5G Mobile Communications
  - A Dual-Band and Low-Cost Microstrip Patch Antenna for 5G Mobile Communications
- Project 5: Antenna Design based on Data-Informed Machine Learning (in process)
  - Machine Learning for Microstrip Patch Antenna Design: Observations and Recommendations
  - Machine Learning Design of Printed Patch Antenna
  - TBD…
- Project 6: Array Radiation Pattern Optimization in Near and Far Field (in process)
  - An Efficient Transmitarray Element using Diagonal Double-Headed Arrows with Vias
  - TBD…

Project 1:

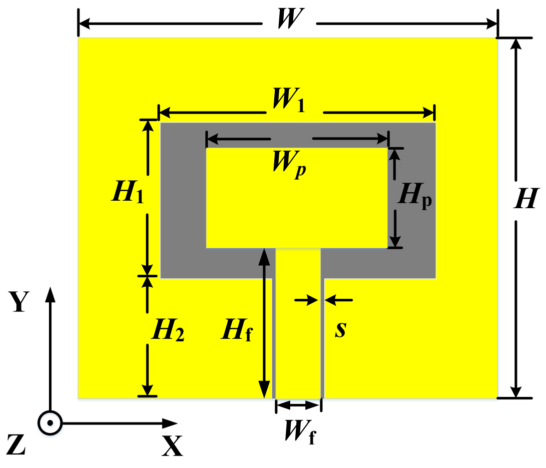
Cavity Backed Patch Antenna Design



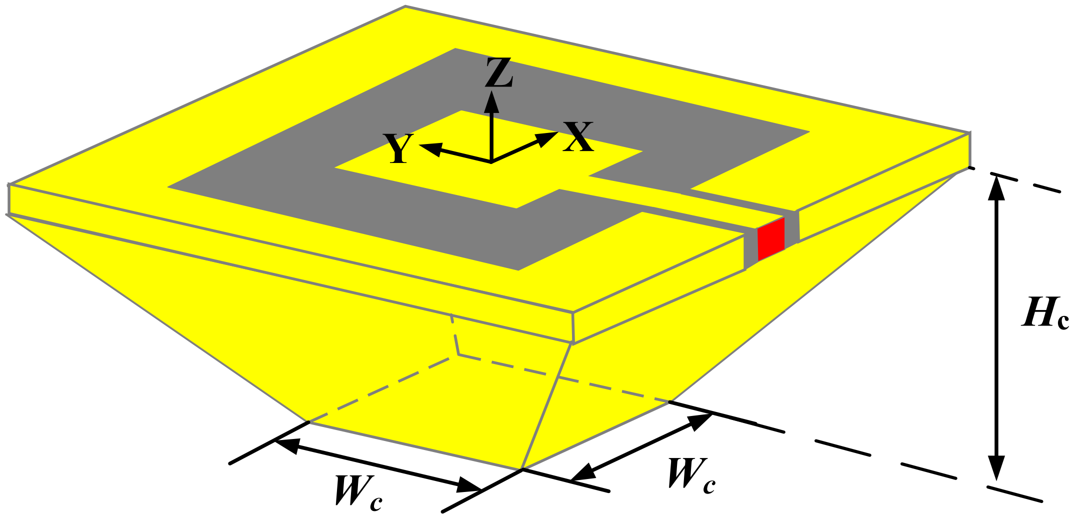


1. Feng, Yuhao, Yiming Chen, Atef Z. Elsherbeni, and Khalid Alharbi. "Arrow Patch-Slot Antenna for 5G Lower Frequency Band Communications." In 2020 International Applied Computational Electromagnetics Society Symposium (ACES), pp. 1-2. IEEE, 2020.
2. Chen, Yiming, Atef Z. Elsherbeni, Khalid Alharbi, and Rabah Aldhaheri. "Cavity backed patch-slot antenna for lower band 5G communications." In *2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science*, pp. 1-3. IEEE, 2020.

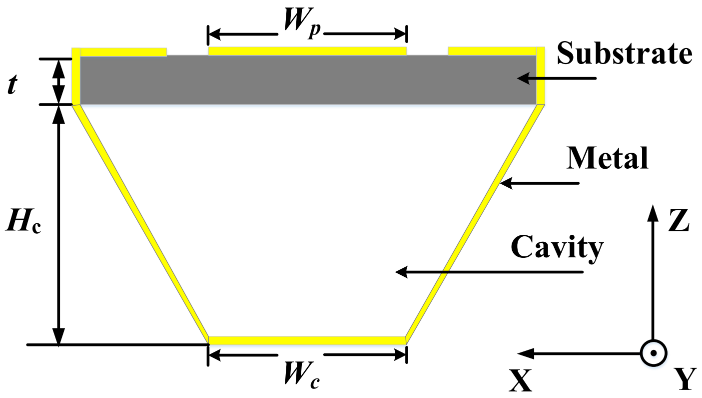
Single Antenna Element Structure



- (a) Top view



- (b) Side view

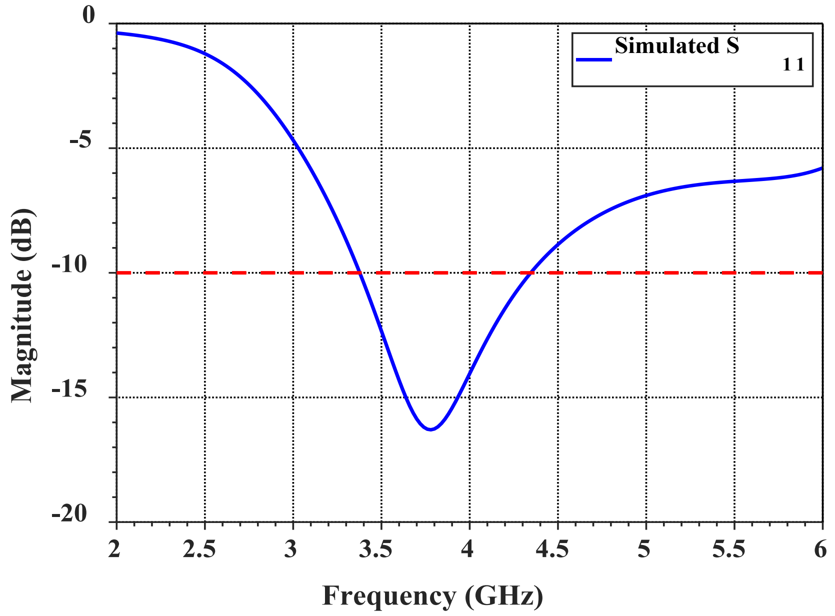


- (c) Cross section in xz plane

- The frequency range of the proposed antenna covers two 5G band: 3.55-3.7 GHz (unlicensed band) and 3.7-4.2 GHz (licensed band).
- These bands are announced by Federal Communications Commission (FCC) in 2018 as the 5G commercial bands for US.

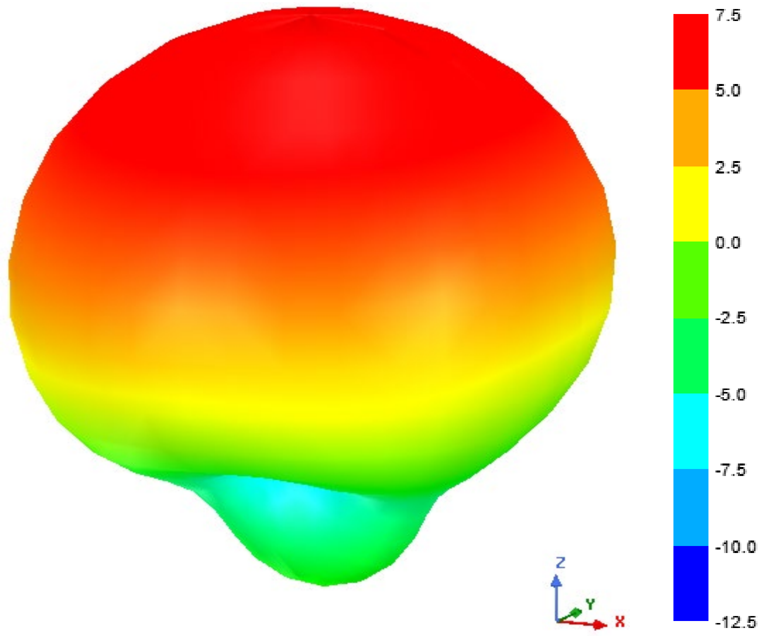
Simulated Results

Reflection coefficient



- -10 dB bandwidth: 3.38 GHz to 4.35 GHz

3D far-field gain pattern at 3.95 GHz



- Main beam: 5.68 dB
- Back beam: -4.27 dB

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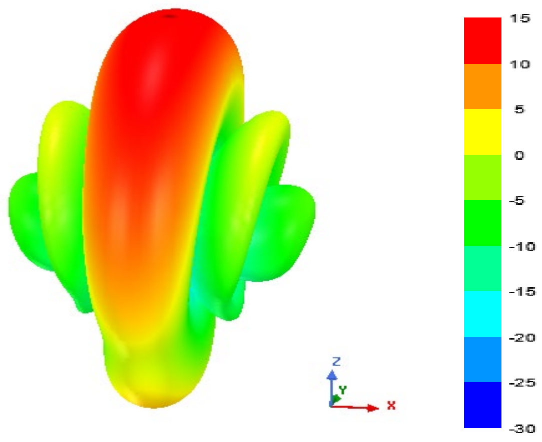
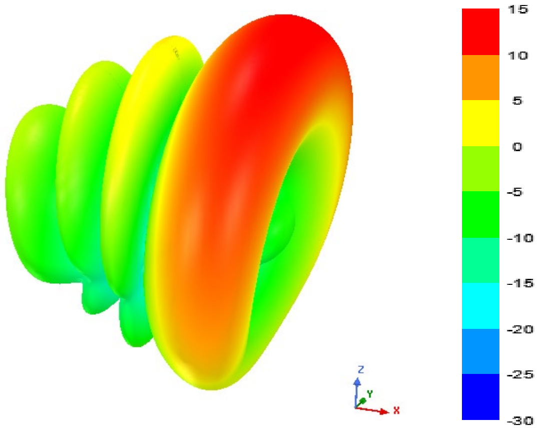
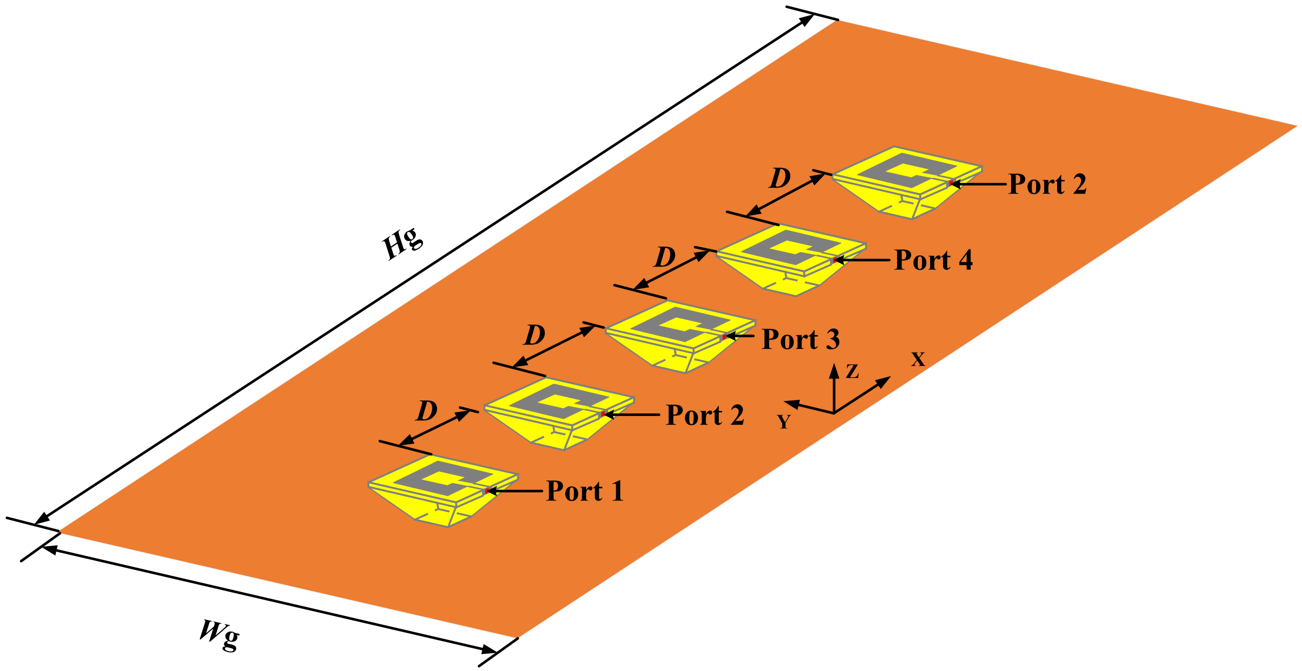
1×5 Linear array



(a)



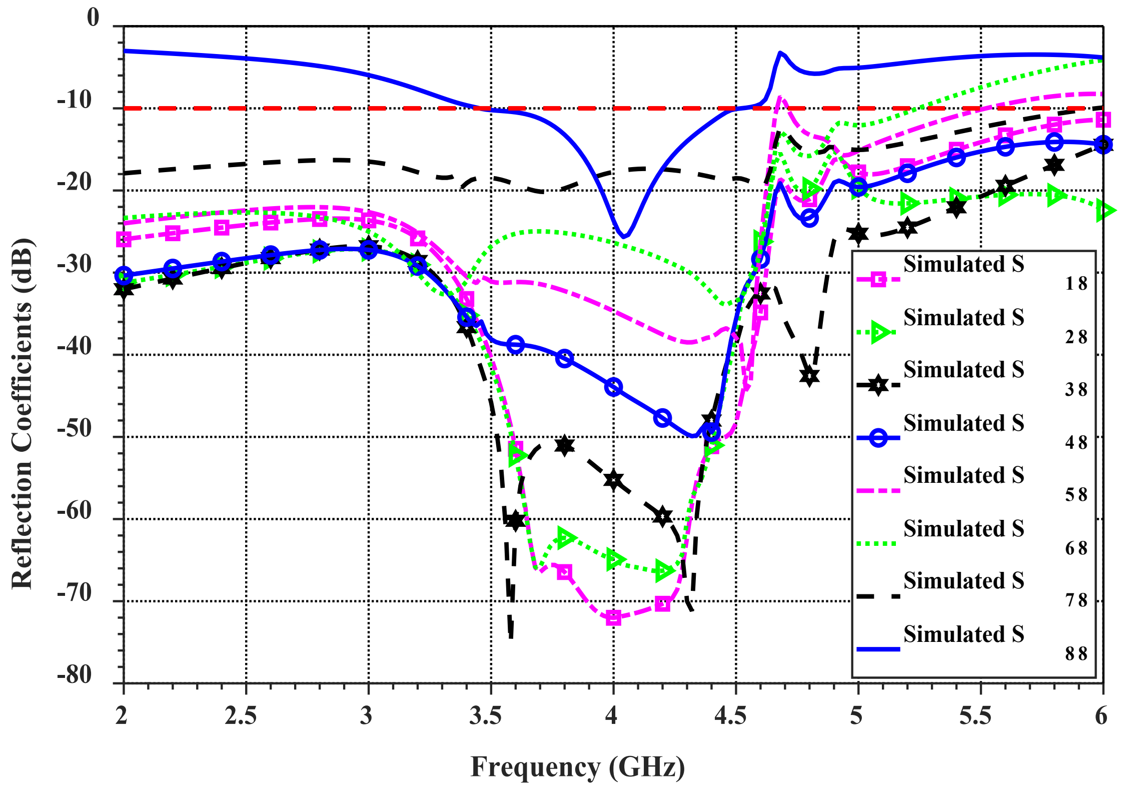
(b)



(c) A linear array of 1× 5 elements with a metal ground.

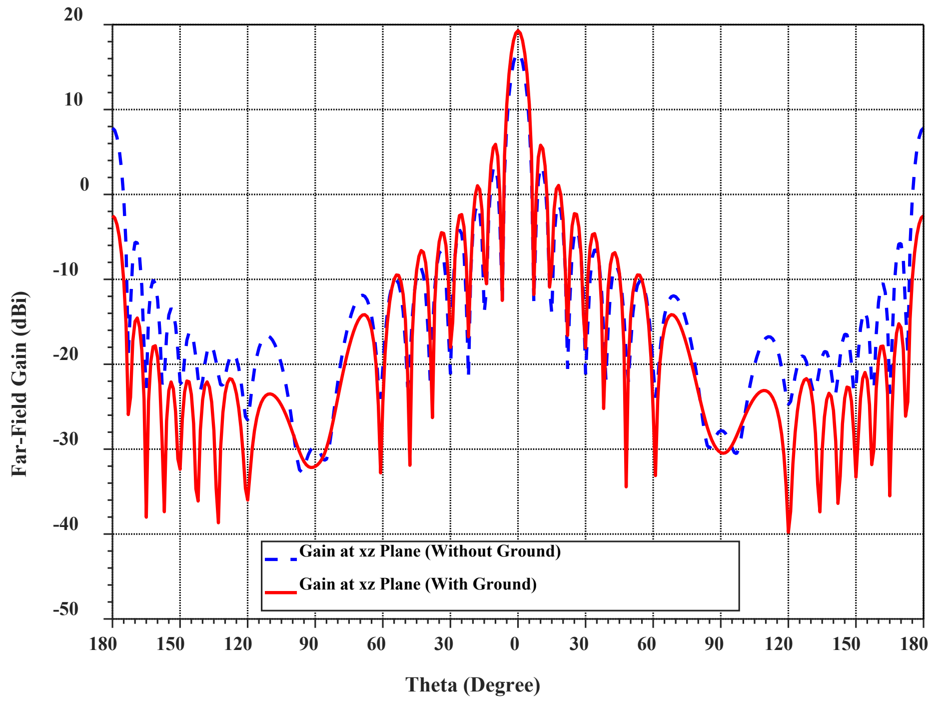
1×15 Linear Array Simulated Results

Reflection coefficient



The -10 dB bandwidth: 3.46 GHz to 4.51 GHz

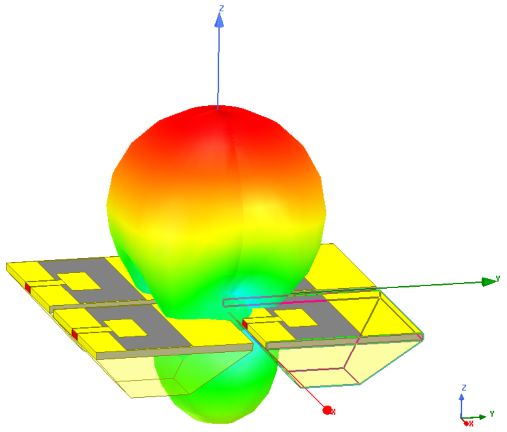
3D far-field gain pattern at 3.95 GHz

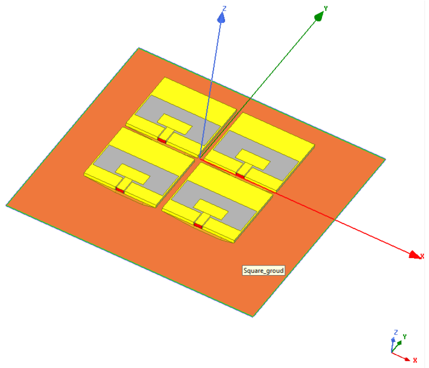


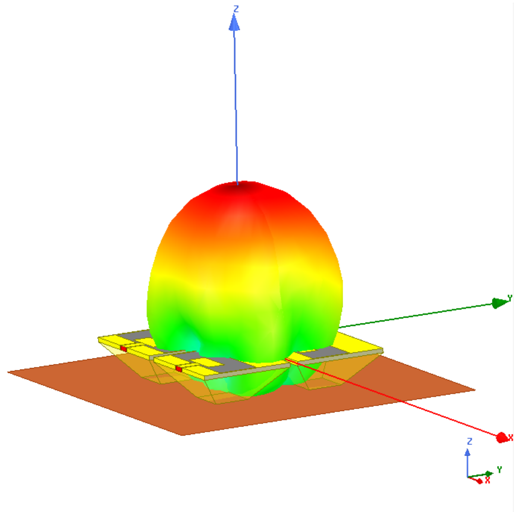
- **With ground:**
  - Main beam (19.28 dB); Back beam (-2.51 dB)
- **Without ground:**
  - Main beam (16.69 dB); Back beam (8.87 dB)

Planar Array Simulated Results

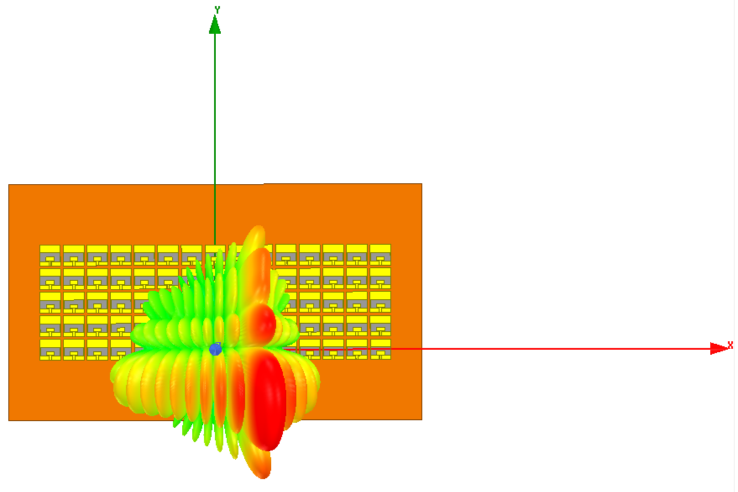
2×2 Array with/wo Ground Plane

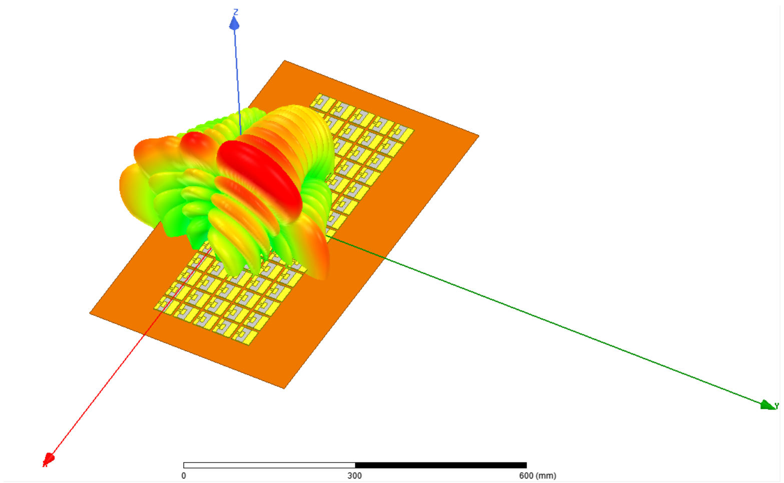






5×15 Array with Ground Plane



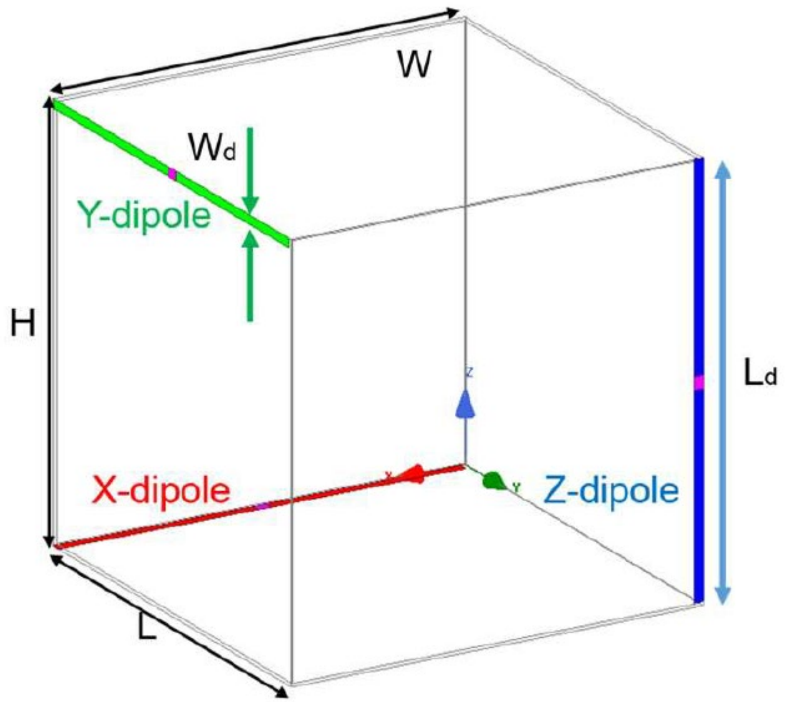


Further Work

- Better radiation performance for 1x15 linear array with additional ground.
- Fabrication and chamber measurement will be our next task.
- Two-dimensional planar array will be used to generate pencil shaped beam.
- Phase optimized excitation will be investigated for beam scanning.

Project 2:

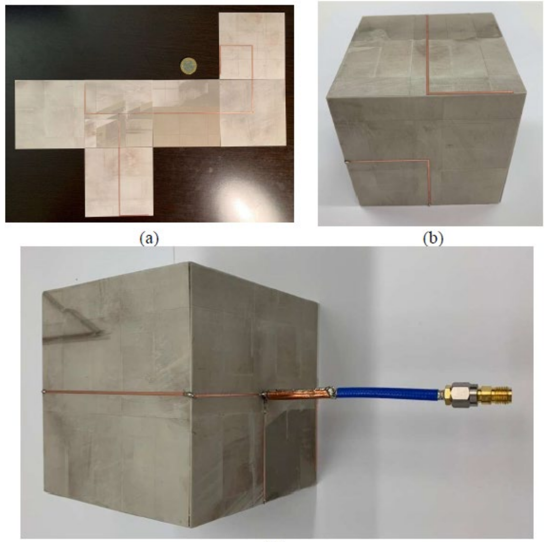
3D Antenna: Maximizing Isotropicity and CP Coverage



1. Su, Zhen, Kirill Klionovski, Hanguang Liao, Atif Shamim, Y. Chen, and A. Elsherbeni. "3D antenna in package design: Maximizing radiation pattern isotropicity and CP coverage." In 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, pp. 263-264. IEEE, 2020.
2. Su, Zhen, Kirill Klionovski, Hanguang Liao, Yiming Chen, Atef Z. Elsherbeni, and Atif Shamim. "Antenna-on-package design: Achieving near-isotropic radiation pattern and wide CP coverage simultaneously." IEEE Transactions on Antennas and Propagation 69, no. 7 (2020): 3740-3749.

Performance

Fabrication



(a) (b) (c)

Fig. 13. (a). Fabricated six roger board with metallic patterns for antenna and phase shifter. (b). The glued antenna on package (c).The antenna on package with bazooka balun

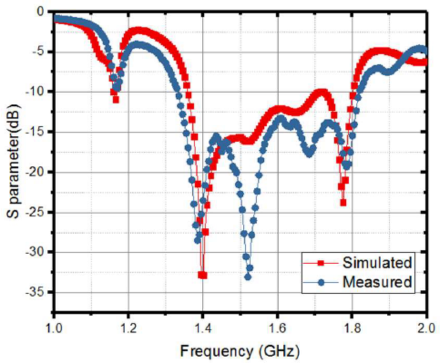
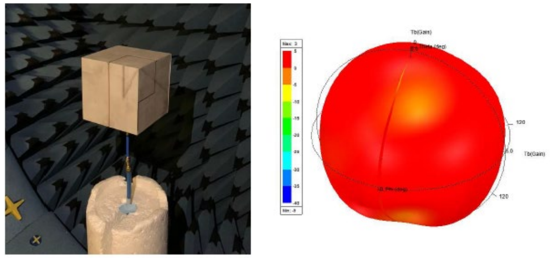


Fig. 14. Measured and simulated S parameters of the total antenna system.

The -10 dB bandwidth: 1.34 GHz to 1.81 GHz

Isotropicity and CP Coverage



(a) (b)

Fig. 15. (a). The radiation pattern measurement setup in Satimo Chamber (b). the 3D radiation pattern.

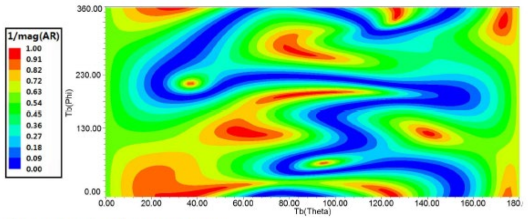
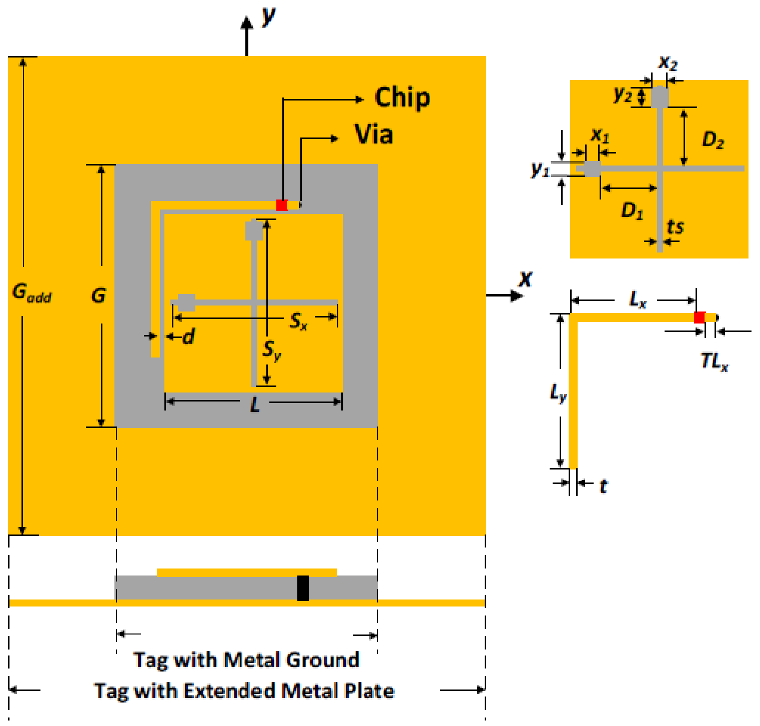


Fig. 16. Measured CP coverage.

Table I. Comparison between simulated and measured results

	7dB isotropy	CP coverage
Simulation	94.01%	17.3%
Measurement	92.86%	17.2%

Project 3:
RFID Tag Antenna Design



1. Chen, Yiming, and Atef Z. Elsherbeni. "Circularly polarized RFID tag antenna design for underground localization system." In 2021 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), pp. 205-206. IEEE, 2021.

Performance

Impedance Matching

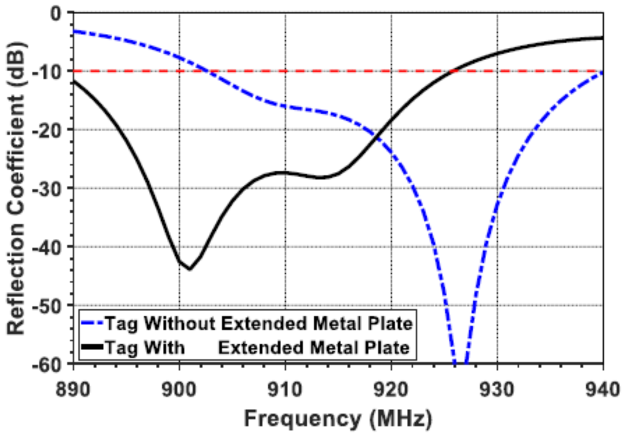


Fig. 2. Simulated S_{11} for the CP tag antenna with and without extended metal plate.

Radiation Performance

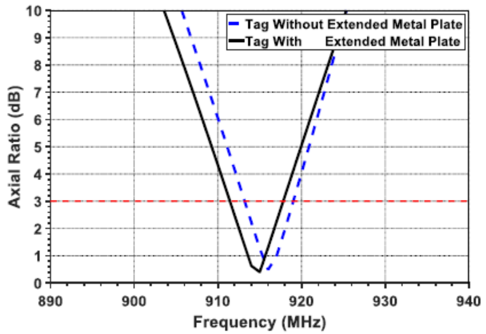


Fig. 3. Simulated axial ratio for the CP tag antenna with and without extended metal plate.

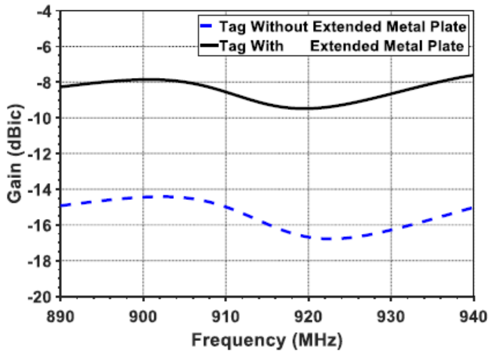


Fig. 4. Simulated gain for the CP tag antenna with and without extended metal plate.

Properties for the Read Range Calculation

$$r_{max} = \frac{\lambda_0}{4\pi}\sqrt{\frac{P_t G_t G_r \rho (1-|\Gamma|^2)}{P_{th}}}$$

Wavelength at 915 MHz: 0.32 m

CP Tag Gain: -9.24 dBic at 915 MHz

Polarization loss factor

Reflection coefficient at 915 MHz: |Γ|=0.25

CP Reader antenna Gain: 1,2,3 dB at 915 MHz

Threshold power of Higgs 4: -16 dBm

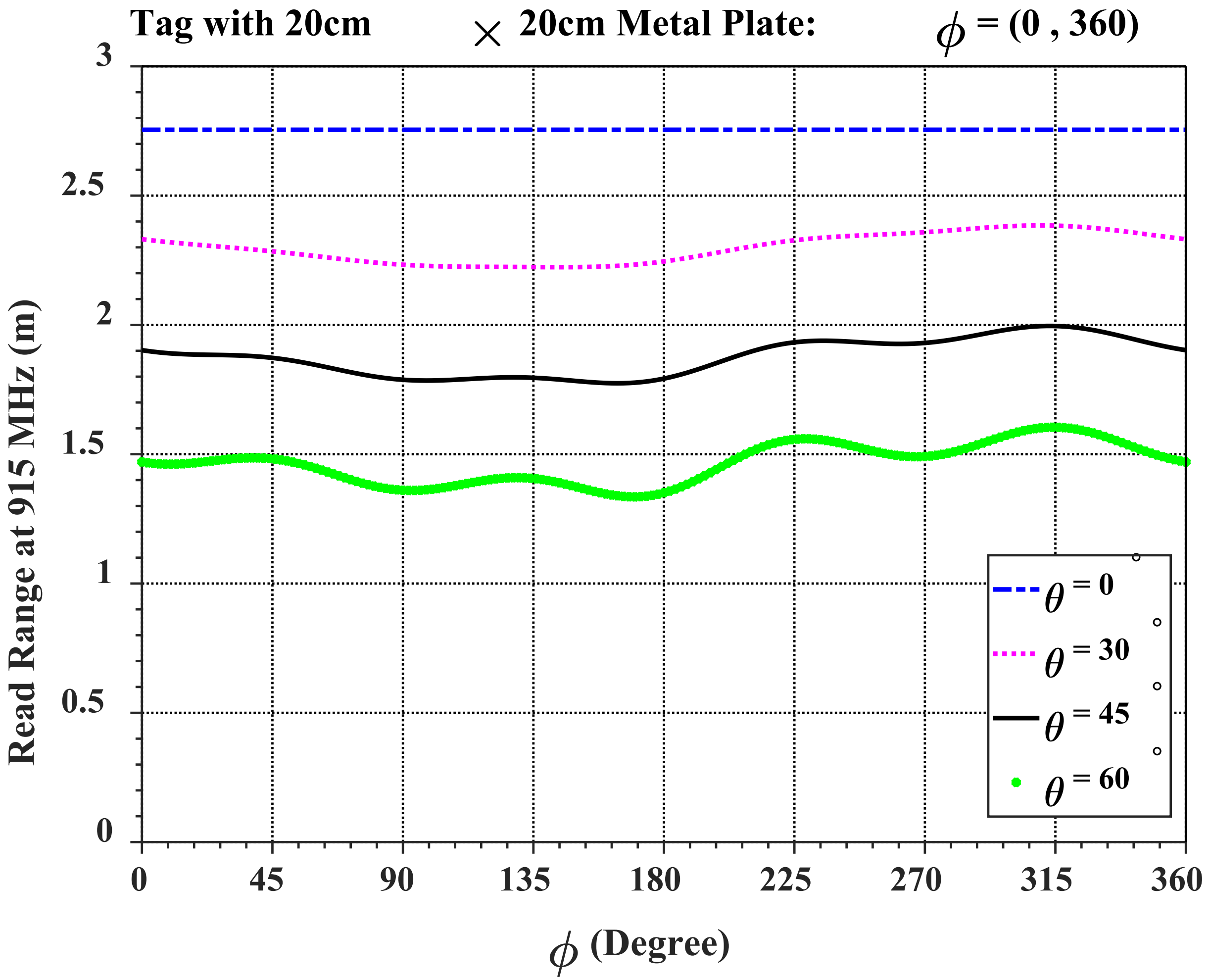
Read Sensitivity	Up to -19 dBm*
Write Sensitivity	Up to -16 dBm*

*on a 2.15 dBi gain dipole antenna

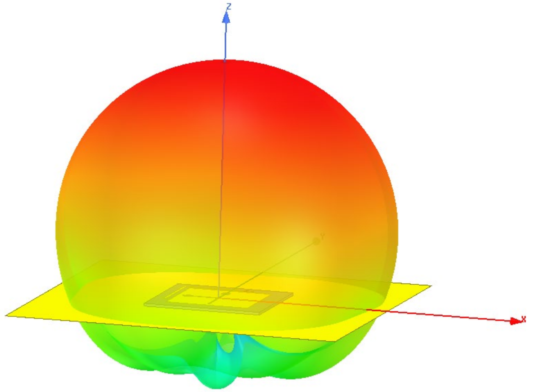
Reader output power: 30 dBm

RF Power Output	Separate read and write levels, command-adjustable from +5 dBm to +31.5 dBm (1.4W) with .5 dBM accuracy above +15 dBm[1]

Read Range for Tag with 20cm*20cm Metal Plate: Phi=(0,2pi)



- Read range comparison
- At 915 MHz
- Phi varies from 0 to 2π for all cases
- Different Theta:
  - 0°
  - 30°
  - 45°
  - 60°

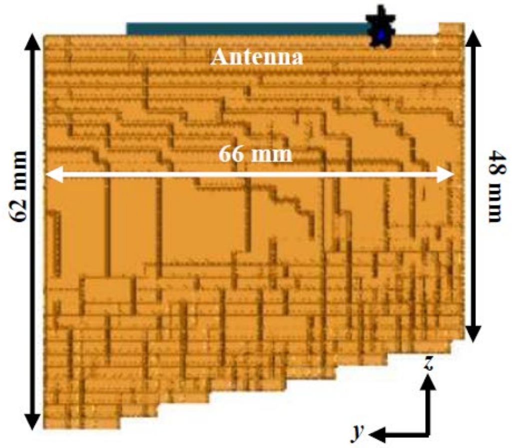


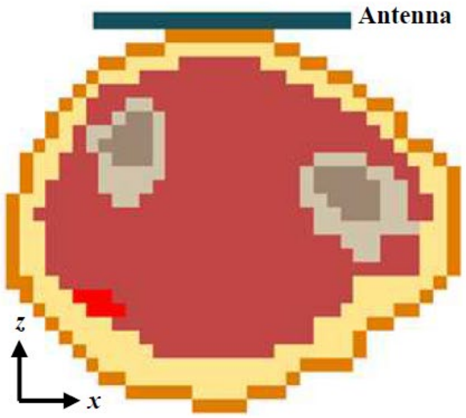
Dimension Tuning for Tag with Different Metal Plates

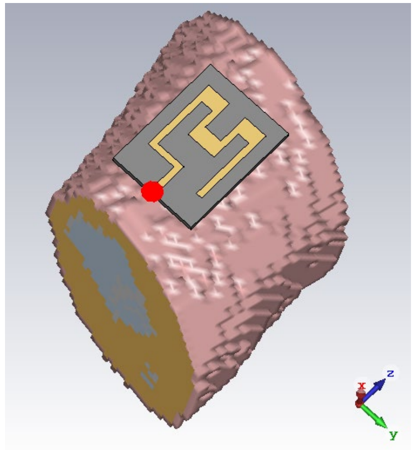
Properties	Tag with 7*7 cm^2 Metal Plate	Tag with 10*10 cm^2 Metal Plate (Before Optimization)	Tag with 20*20 cm^2 Metal Plate (Before Optimization)	Tag with 20*20 cm^2 Metal Plate (After Optimization)
S11 at 915 MHz	-17.7 dB	-16.7 dB	-17.7 dB	-27.5 dB
S11 -10 dB Bandwidth	902-939 MHz	903-939 MHz	904-940 MHz	890-926 MHz
AR at 915 MHz	1.26 dB	4.07 dB	3.38 dB	0.4 dB
AR 3 dB Bandwidth	913.2-919 MHz	916.3-923.1 MHz	915.5-922.1 MHz	911.4-917.8 MHz
Far-Field Gain at 915 MHz	-15.95 dB	-9.5 dB	-9.09 dB	-9.24 dB
Read Range	1.2 m	2.49 m	2.64 m	2.75 m

Project 4:

Human Tissues Properties in Antenna Design







1. Chen, Yiming, Fatih Kaburcuk, Rachel Lumnitzer, Atef Z. Elsherbeni, Veysel Demir, and Atif Shamim. "Human tissues parameters and resolution for accurate simulations of wearable antennas." In 2021 International Applied Computational Electromagnetics Society Symposium (ACES), pp. 1-4. IEEE, 2021.

Performance Comparison: CEMS and CST

Impedance Matching

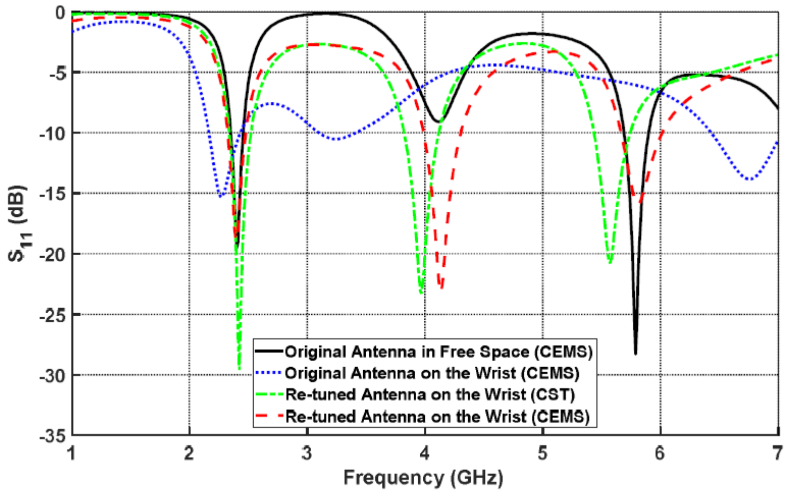
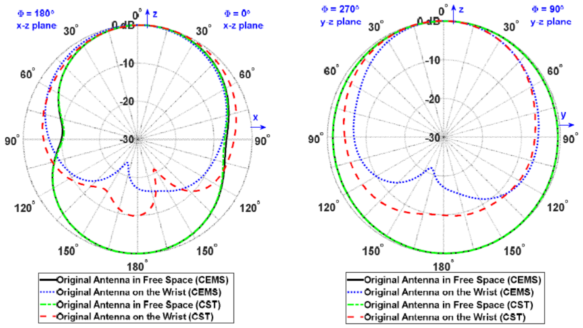


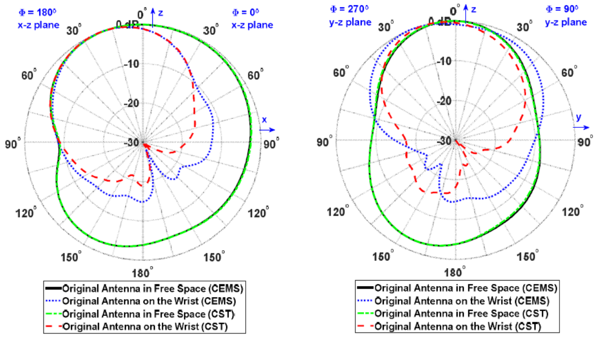
Fig. 3. S_{11} comparisons of the original and re-tuned antenna in free-space and on the wrist using CEMS and CST.

Radiation Performance



(a) (b)

Fig. 4. Relative gain comparisons at 2.4 GHz of the original antenna in free space and on the wrist using CEMS and CST in: (a) *x-z* plane; (b) *y-z* plane.



(a) (b)

Fig. 5. Relative gain comparisons at 5.8 GHz of the original antenna in free space and on the wrist using CEMS and CST in: (a) *x-z* plane; (b) *y-z* plane.

Comparison of Max Gain of the Antenna Obtained Using CEMS and CST

Gain (dB)			At 2.4 GHz		At 5.8 GHz		3D Max Gain (dB)	
			E plane	H Plane	E plane	H Plane	2.4 GHz	5.8 GHz
CEMS	original antenna	in free space	1.88	1.91	4.40	4.33	1.95	4.40
		on wrist	-4.02	-4.02	-3.61	-3.90	-4.01	-3.02
	re-tuned antenna	in free space	2.98	2.76	4.55	5.27	3.01	5.66
		on wrist	-3.01	-3.04	4.36	3.72	-3.01	4.40
CST	original antenna	in free space	1.87	1.91	4.42	4.39	1.94	4.42
		on wrist	-4.36	-4.43	4.16	3.44	-4.32	4.43
	re-tuned antenna	in free space	2.56	2.50	5.71	6.13	2.58	6.28
		on wrist	-2.17	-2.17	6.79	6.39	-2.17	6.83

Please note that the gain is for the max gain, not the gain at theta=0, phi=0.

Comparison of S11 of the Antenna Obtained Using CEMS and CST

S11 (dB)			At 2.4 GHz	At 5.8 GHz	3D Max Gain (dB) 2.4 GHz	3D Max Gain (dB) 5.8 GHz
CEMS	original antenna	in free space	-19.5478	-25.5239	1.95	4.40
		on wrist	-10.8379	-6.0991	-4.01	-3.02
	re-tuned antenna	in free space	-3.9675	-11.2481	3.01	5.66
		on wrist	-18.8529	-15.6908	-3.01	4.40
CST	original antenna	in free space	-19.334	-28.599	1.94	4.42
		on wrist	-6.3245	-7.0096	-4.32	4.43
	re-tuned antenna	in free space	-8.691	-8.6486	2.58	6.28
		on wrist	-21.517	-8.4886	-2.17	6.83

Material Conductivity

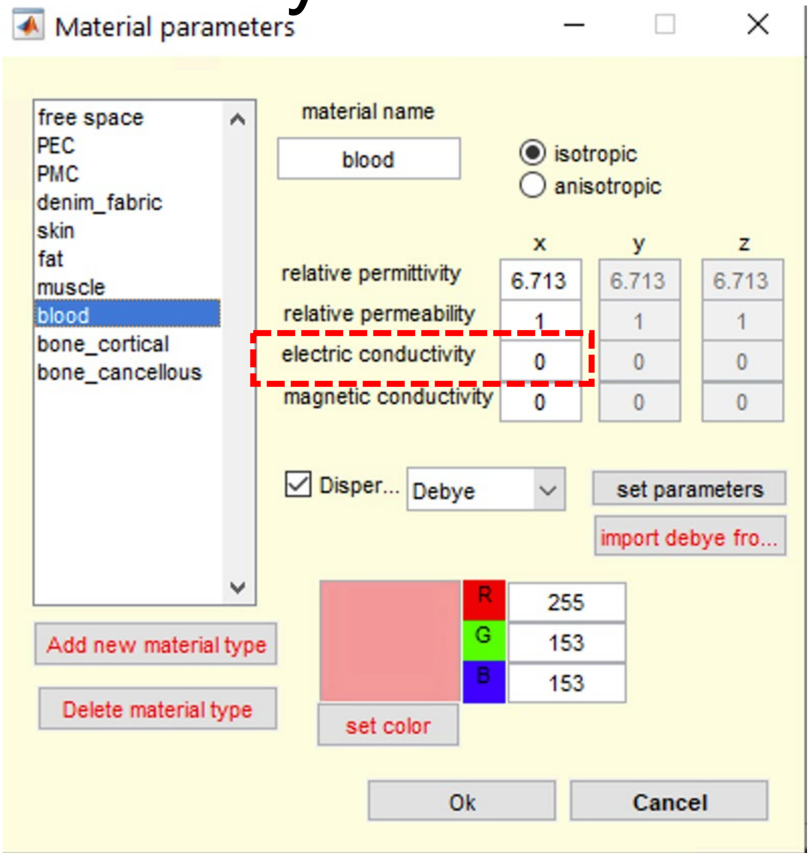
▪ CST

- Denim: Lossless;
- Human Tissue: Corresponding electrical conductivity calculated by Macro.

However, if CEMS uses lossless properties for the human tissue, the gain should be high. The current situation is that CST has higher gain.

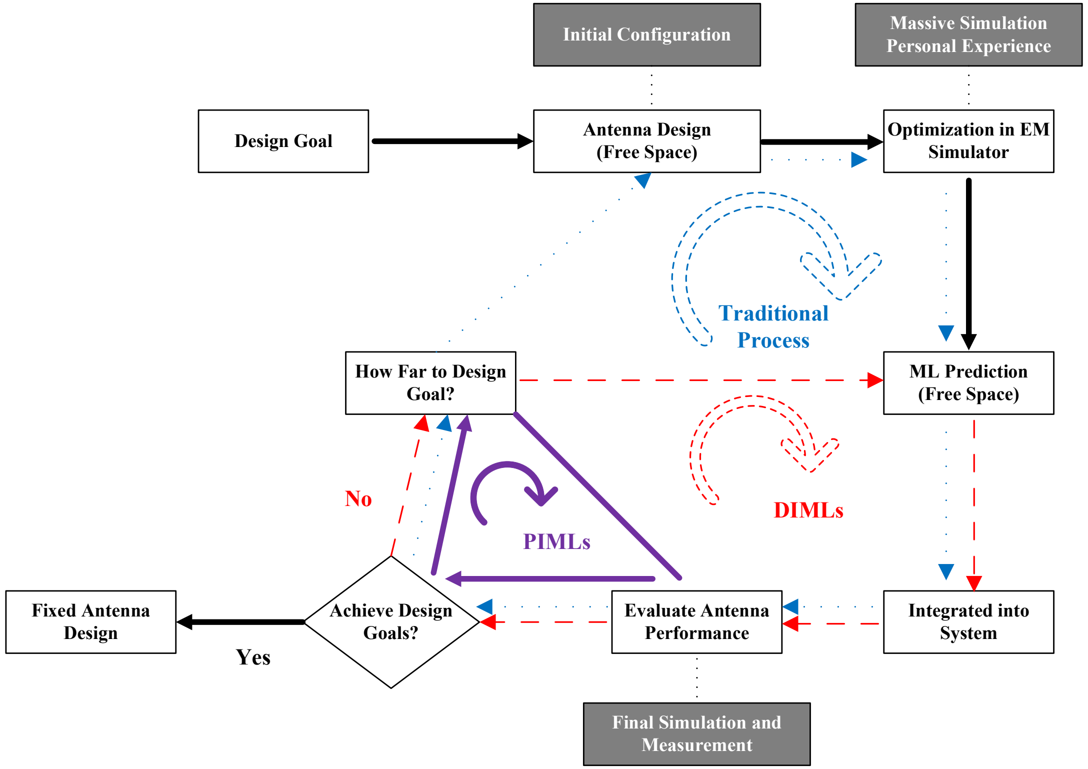
▪ CEMS

- Denim: Lossless;
- Human Tissue: Zero conductivity.



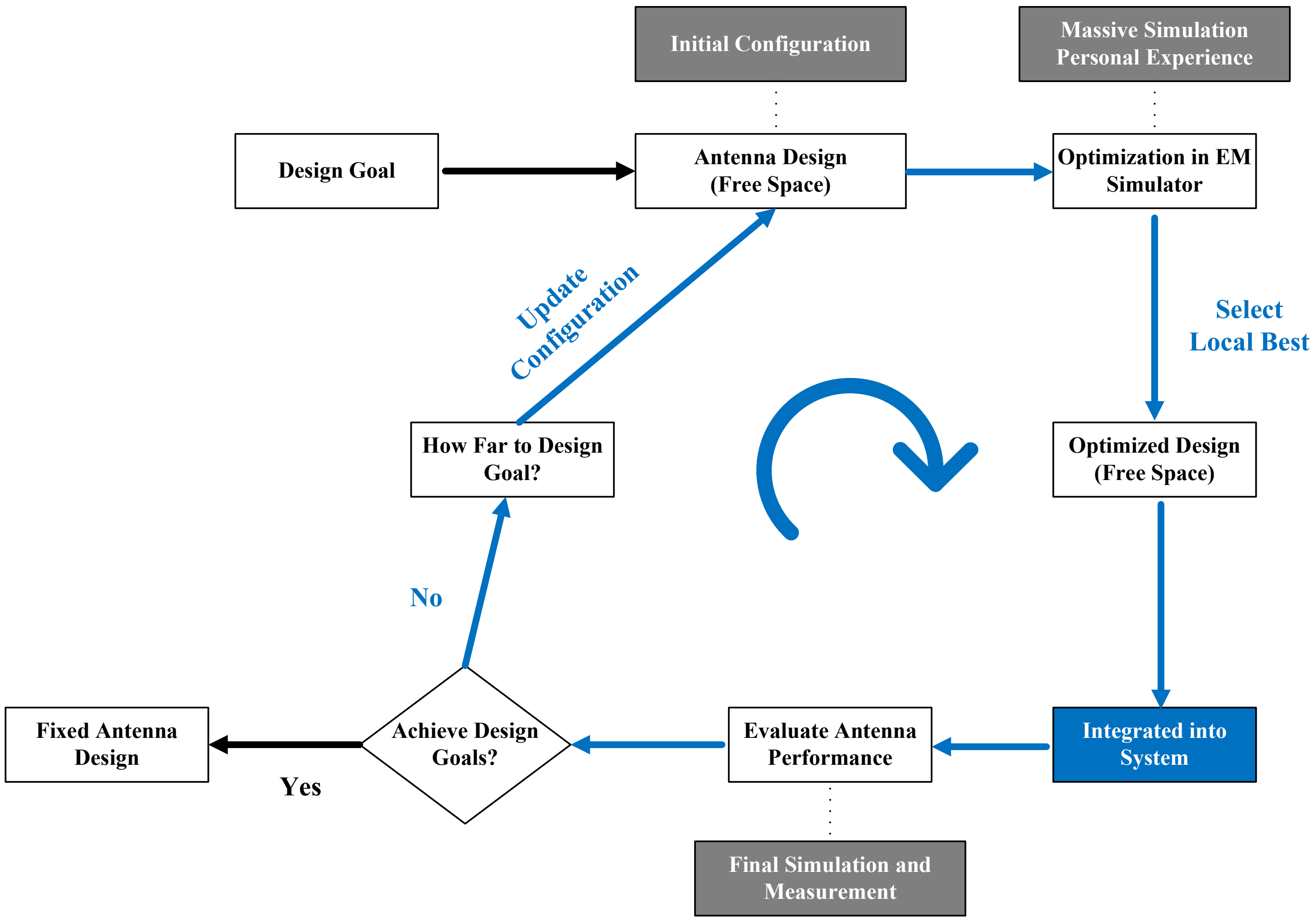
Project 5:

Antenna Design based on Data-Informed Machine Learning



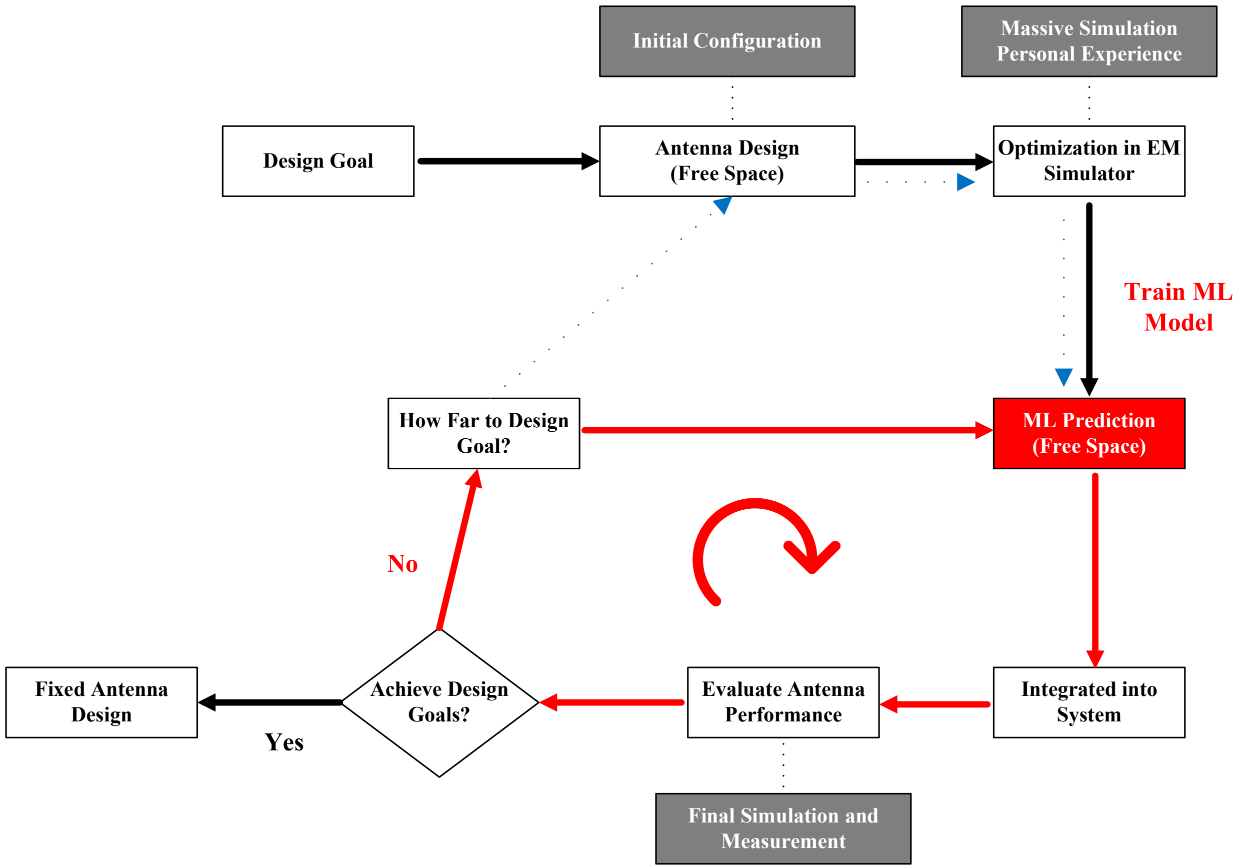
1. Chen, Yiming, Atef Z. Elsherbeni, and Veysel Demir. "Machine learning for microstrip patch antenna design: Observations and recommendations." In 2022 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), pp. 256-257. IEEE, 2022.
2. Chen, Yiming, Atef Z. Elsherbeni, and Veysel Demir. "Machine Learning Design of Printed Patch Antenna." In 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), pp. 201-202. IEEE, 2022.
3. TBD…

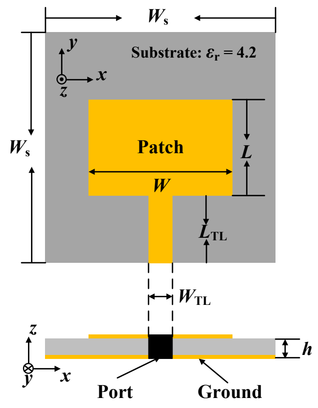
Traditional Antenna Integration Process



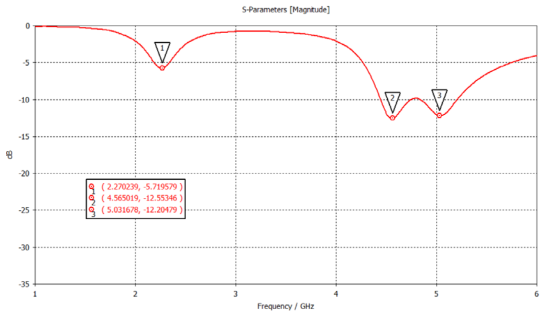
- Thermal Issue
- Desense Issue
  - Degradation in sensitivity due to noise source
- Resonance shift
- Polarization Discrimination
- Radiation Degradation
- EM Interference (EMI)
- EM Compatibility (EMC)

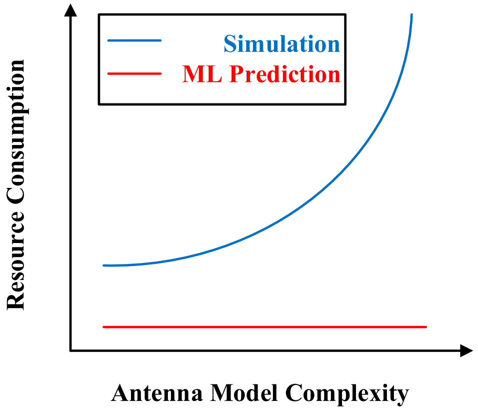
ML Improved Integration Process





Design Goals:
- Work at 2.4 and 5 GHz
- Low cost
- Space limitation: W, L, H
- Antenna gain: 5 dB

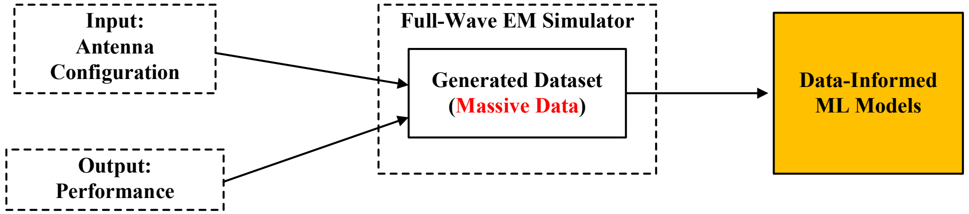


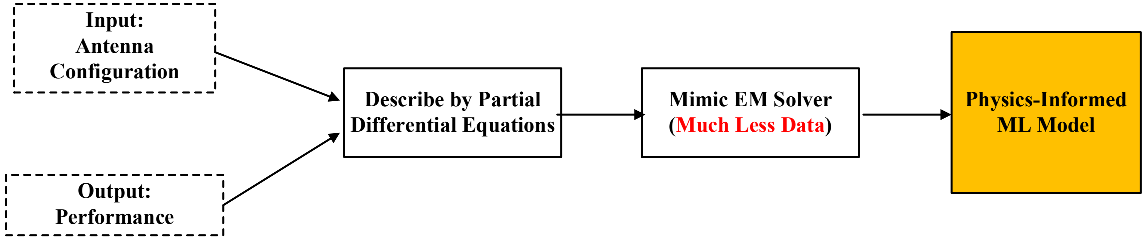


For Single Antenna Model:
- Simulation: Time and resource consuming increase with the model complexity.
- Prediction: almost real-time
- However, ML training process take lots of resources.

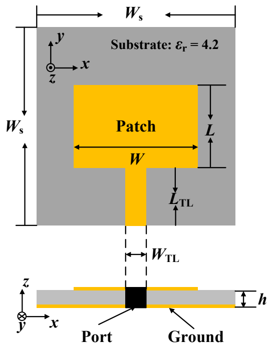
Motivation

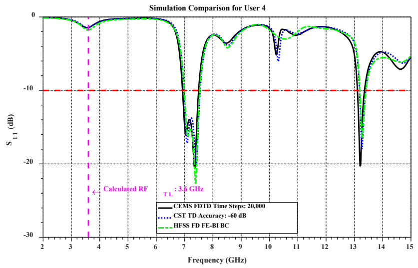
- Well-trained models are used to predict the **reflection coefficient** (S_{11}) of antenna:
  - Reflection coefficient is one of the most important metrics to evaluate the antenna performance
  - Other metrics will be involved in the future work, like gain, polarization, radiation efficiency …
- All proposed ML models are data-driven, so they are called Data-Informed Machine Learning methods (**DIMLs**)
- **Automatic** dataset generation methods proposed in this presentation can be used on other workflows.
- The well-trained models can be integrated in the **large-scale** model.
- DIML is a necessary step for Physics-Informed Machine Learning methods (**PIMLs**)

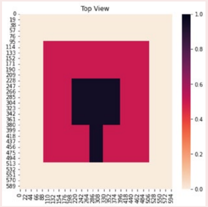
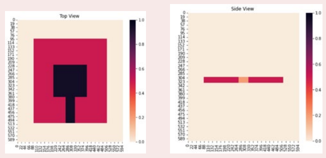




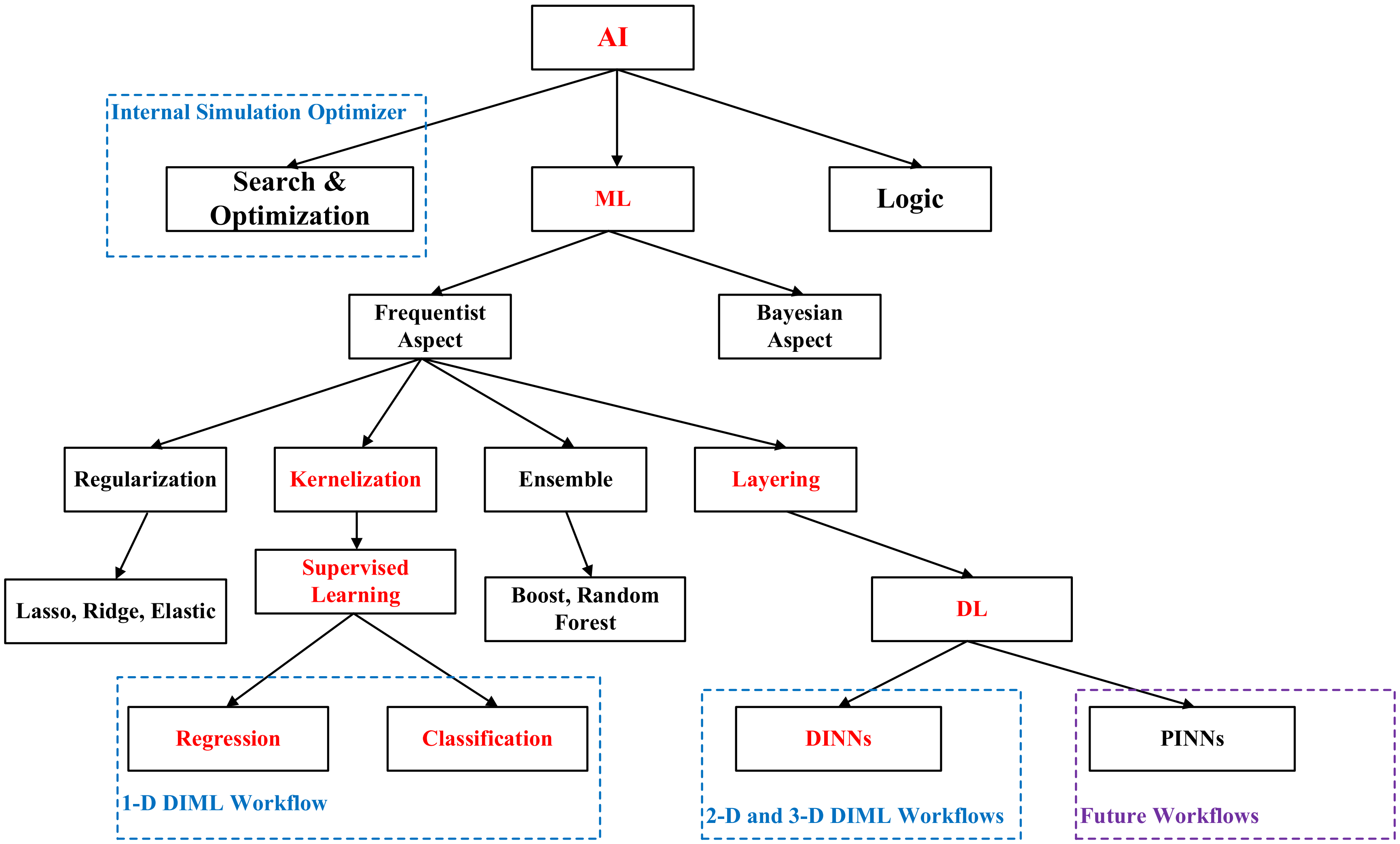
Datasets Comparison





		1-D Dataset	2-D Dataset	3-D Dataset
Input	Format	Feature List	One Image	Two Images
	Details	(L, W, W_{TL}, h, ε_r)		
Output	Format	(Class, RF)	A list	A list
	Details	(Binary classification, Regression for 1st resonance)	S11 in a frequency range	S11 in a frequency range

General Workflows



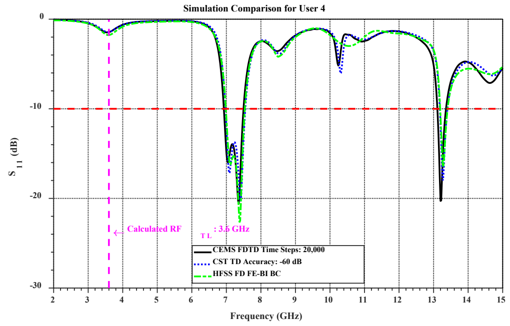
1-D Workflow

- The **Definition** of 'Resonant Frequency':
  - The 1st **minimum** value below **-10 dB** reflect coefficients (S_{11}) in the frequency band.

- CEMS-Python Interface for the **parameter sweep** as the automatic process of dataset generation.

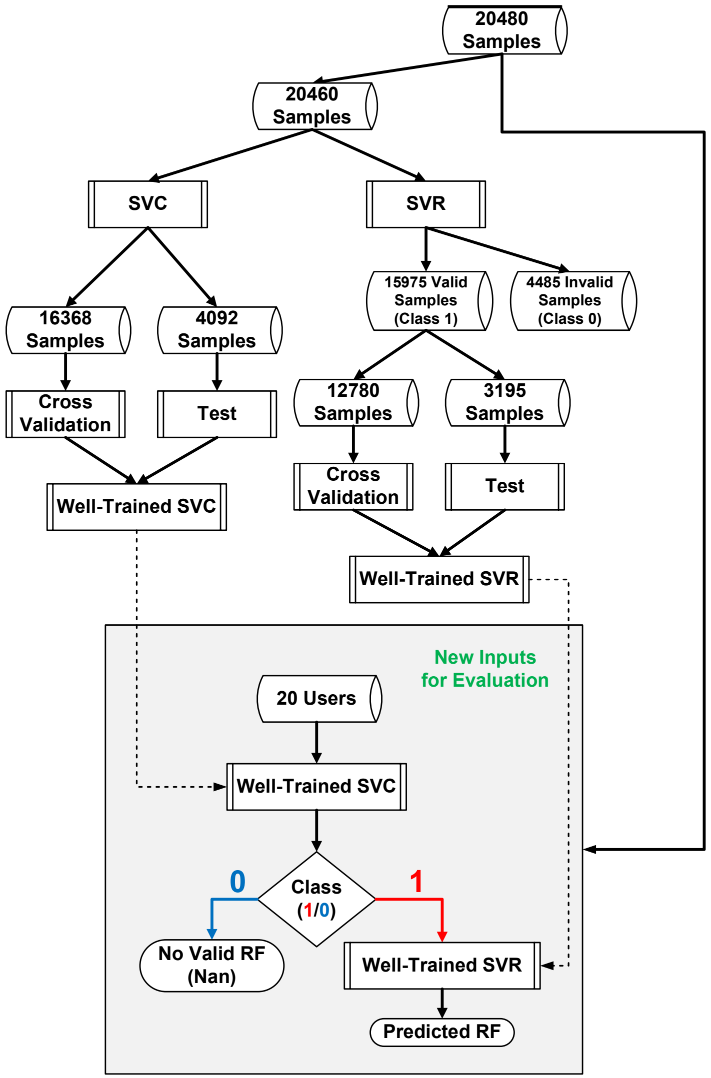
- **20 Users** are selected randomly for the final evaluation of well-trained models.

- **80/20 splitting** is applied on SVC and SVR models for train/test sets.



- Binary Classification:
  - Have valid resonance: class 1
  - No valid resonance: class 0

- Regression:
  - Predicted resonant frequency for the predicted class 1



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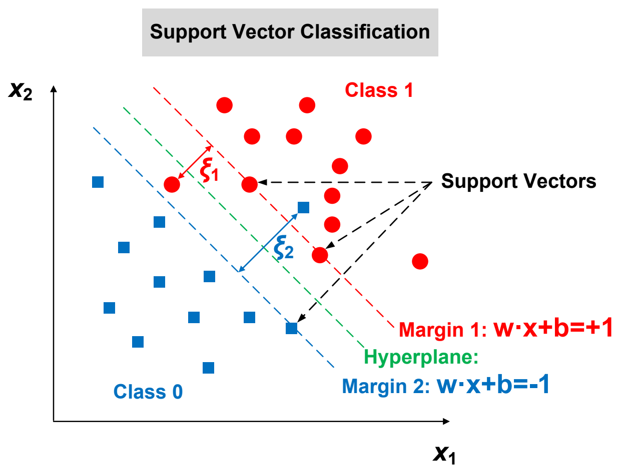
1-D Workflow: SVM Models



Objective Function:

$$\begin{cases} w\cdot x_i + b \le -1, \forall x_i \text{ of Class } 0 \\ w\cdot x_i + b \ge +1, \forall x_i \text{ of Class } 1 \end{cases}$$

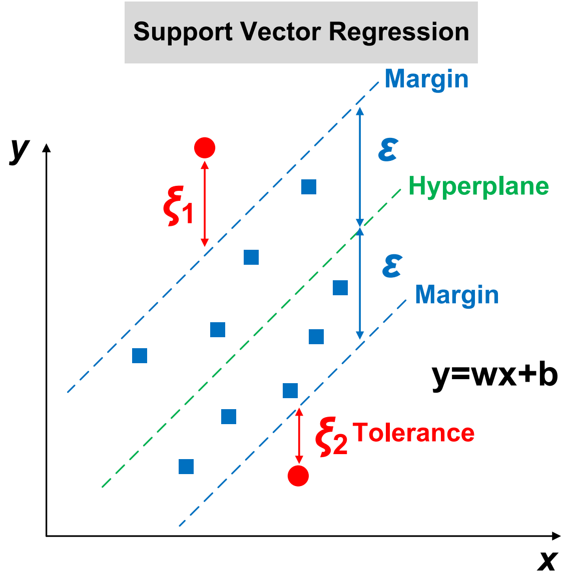
$$\begin{cases} \min\limits_{w,b} \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N}\xi_i \\ y_i(w\cdot x_i + b) \ge 1-\xi_i, \forall x_i \\ \xi_i \ge 0 \end{cases}$$

Evaluation Metrics:

	Predicted	
True	TP	FN
	FP	TN

$$Acc = \frac{TP+TN}{TP+TN+FP+FN}$$

$$F_1 = \left(\frac{\frac{TP+FP}{TP} + \frac{TP+FN}{TP}}{2}\right)^{-1}$$



Objective Function:

$$y = wx + b$$

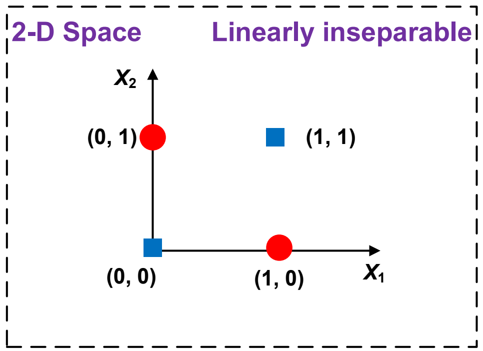
$$\begin{cases} \min\limits_{w,b} \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N}\xi_i \\ \|y_i - wx_i - b\| \le \varepsilon + \xi_i \\ \xi_i \ge 0 \end{cases}$$

Evaluation Metrics:

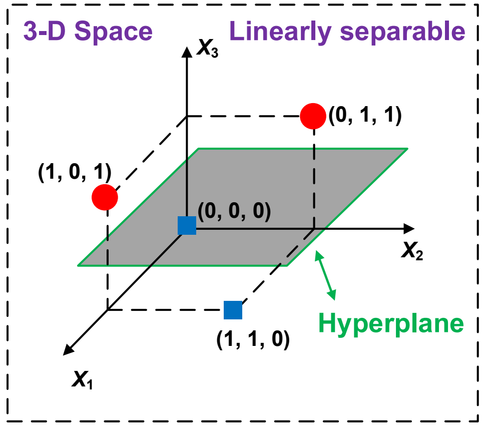
$$R^2(y,\hat{y}) = 1 - \frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \frac{1}{n}\sum_{i=1}^{n}y_i)^2}$$

$$RMSE(y,\hat{y}) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}$$

Kernel Method



$(x_1, x_2) \xrightarrow{\Phi(X)} (x_1, x_2, (x_1-x_2)^2)$



Cover Theorem: Higher-dimensional space is more linearly separable than lower-dimensional space.

1-D Workflow: Results

- The hyperparameters for SVC and SVR are optimized using **5-fold 3-repeated** cross validation.
- Testing for SVC model with **4092** samples:
  - *Acc* score: 0.967
  - F_1 score: 0.979
- Testing for SVR model with **3195** samples:
  - R^2 score: 0.926
  - RMSE loss: 0.610
- The evaluation of the well-trained models are presented based on **20 users**, which are shown on the right.

User ID	Simulation		SVC		SVR for RF (GHz)	
	RF (GHz)	BW (MHz)	True	Predict	Predict	r_E
1	4.14	40	1	1	4.23	2.15%
2	5.00	60	1	1	5.11	2.16%
3	6.04	20	1	1	6.85	13.41%
4	7.04	540	1	1	6.72	4.53%
5	8.02	540	1	1	8.05	0.43%
6	9.06	180	1	1	9.09	0.29%
7	10.02	880	1	1	9.89	1.35%
8	11.04	140	1	1	10.63	3.69%
9	11.98	140	1	1	11.73	2.07%
10	12.9	380	1	1	12.92	0.19%
11	14.02	360	1	1	13.80	1.59%
12	4.14	0	0	1	5.03	21.47%
13	8.14	0	0	1	6.81	16.77%
14	0	0	0	0	Nan	Nan
15	0	0	0	0	Nan	Nan
16	0	0	0	0	Nan	Nan
17	13.82	Inf	0	0	Nan	Nan
18	14.58	Inf	0	0	Nan	Nan
19	Inf	Inf	0	0	Nan	Nan
20	Inf	Inf	0	0	Nan	Nan

$$r_E = \left| \frac{RF_x - RF_{simulation}}{RF_{simulation}} \right| \times 100\%$$

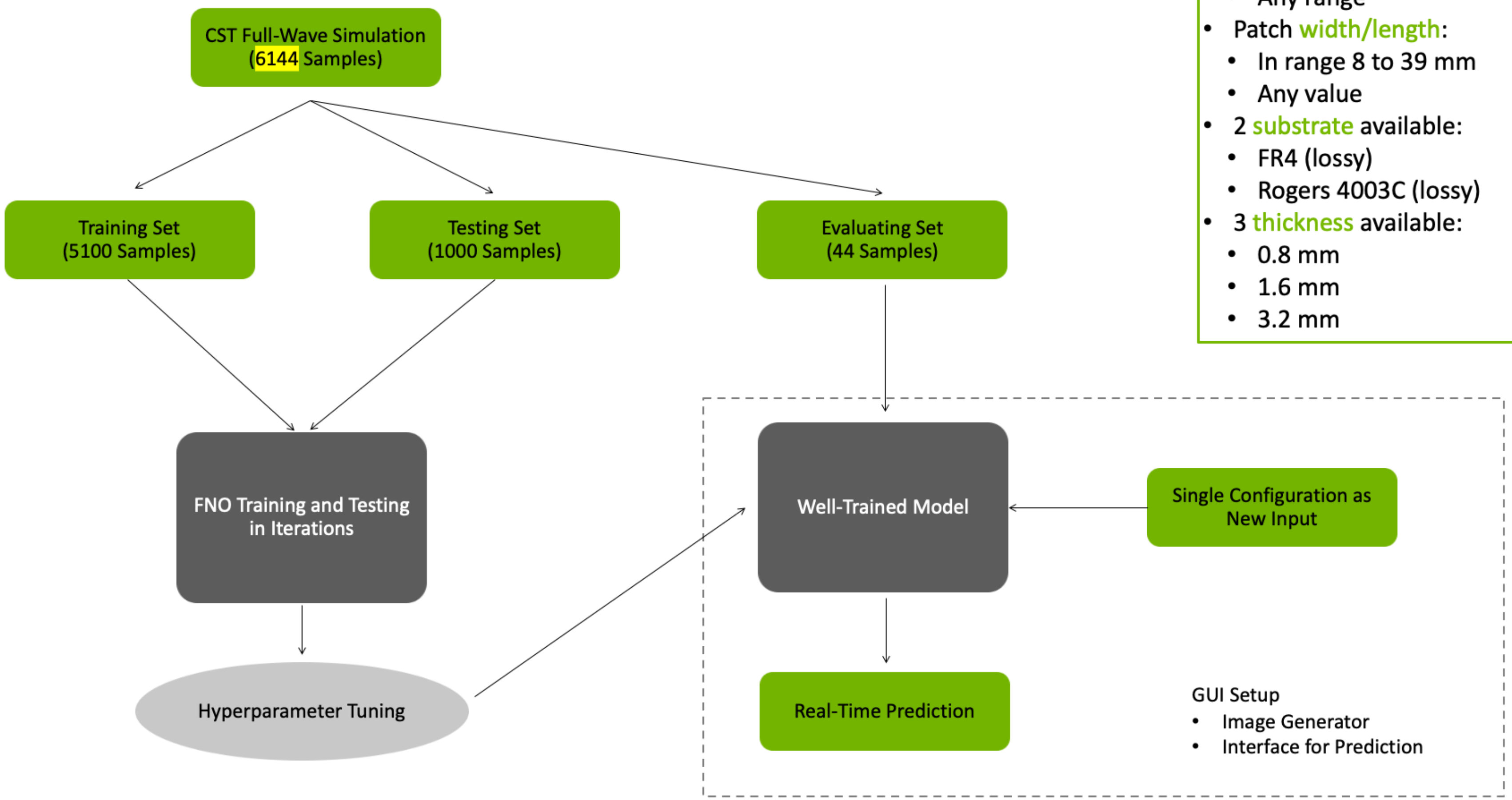
Following Improvement:

- **User 3:** **Local optimization for SVR around 6 GHz**
- **User 12-13:** **Multiple classification for different groups in Class 0**

3-D Workflow

Training, Testing and Evaluating

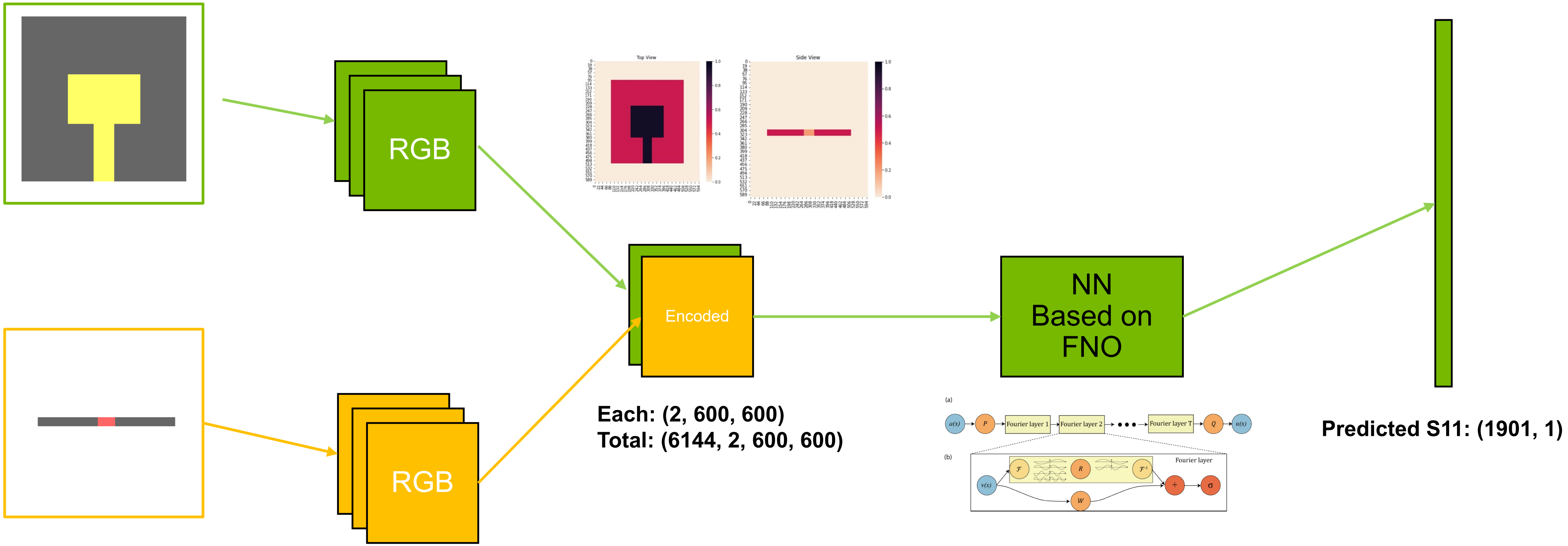
3-D ML Antenna Design



New Inputs Variables:

- Frequency range:
  - 1 to 20 GHz
  - Any range
- Patch width/length:
  - In range 8 to 39 mm
  - Any value
- 2 substrate available:
  - FR4 (lossy)
  - Rogers 4003C (lossy)
- 3 thickness available:
  - 0.8 mm
  - 1.6 mm
  - 3.2 mm

3-D Workflow



	column 1	column 2	column 3	column 4	column 5	column 6
1		[R, G, B]	Color_Name	Material	Encoded_Values_[0,1]	Groups
2	0	[255, 255, 255]	White	Background	0.0	Fixed [0.0, 0.2]
3	1	[255, 102, 102]	Red	Port	0.2	Fixed [0.0, 0.2]
4	2	[229, 165, 102]	Brown	Rogers 4003C (lossy)	0.4	Dielectric [0.3, 0.7]
5	3	[102, 102, 102]	Gray	Fr4 (lossy)	0.5	Dielectric [0.3, 0.7]
6	4	[255, 255, 102]	Yellow	Copper (lossy)	0.95	Metal [0.8, 1.0]

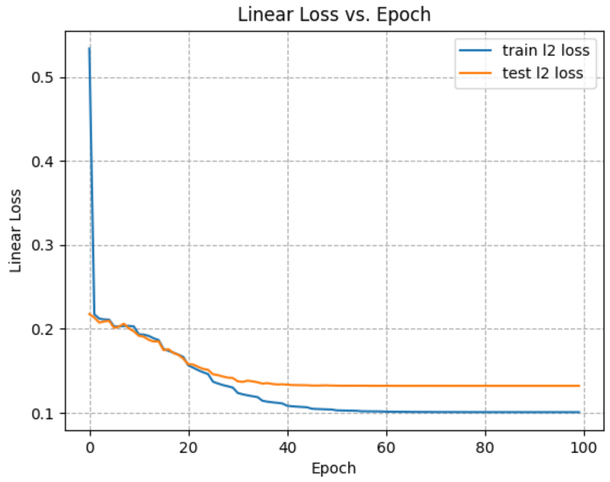
3-D Workflow: Test Results

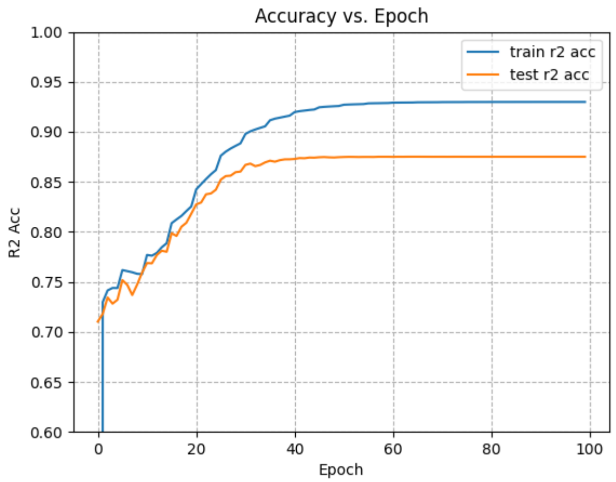
Name	Input Shape	Output Shape
Train Set	(5100, 2, 600, 600)	(5100, 701)
Test Set	(1000, 2, 600, 600)	(1000, 701)
Evaluation Set	(44, 2, 600, 600)	(44, 701)

- HPC Configuration
  - CPU: Intel Xeon Platinum 8174 @ 3.1 GHz
  - GPU: Nvidia Tesla V100 32GB
- Time Consuming

	Single GPU
Each Epoch	5.82 mins
100 Epochs	10.25 hours

Performance Metrics





Final Performance on Train and Test:

- Train L2 loss: 0.1008
- Test L2 loss: 0.1322
- Train R2 Score: 0.9299
- Test R2 Score: 0.8751

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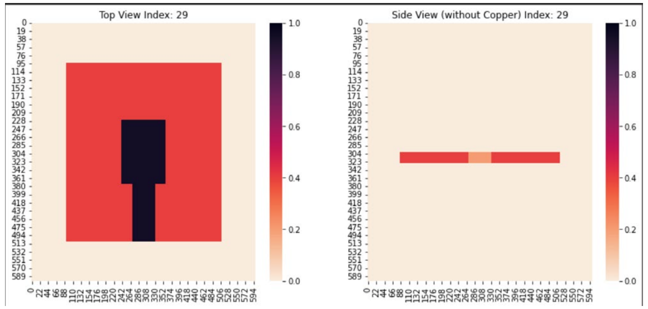
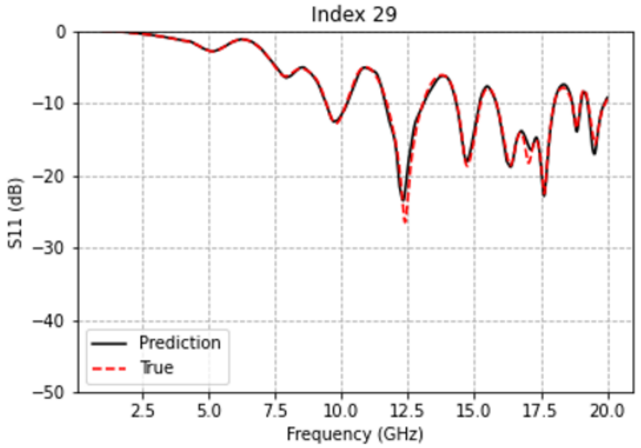
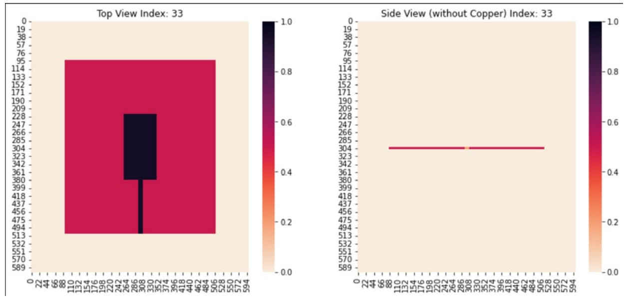
3-D Workflow: Evaluation Results

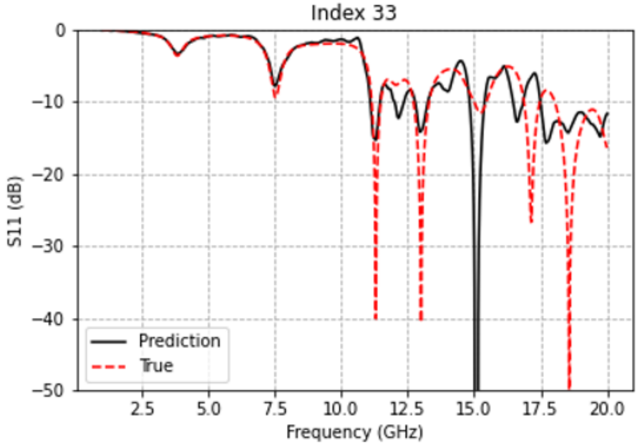
Acceptable Prediction



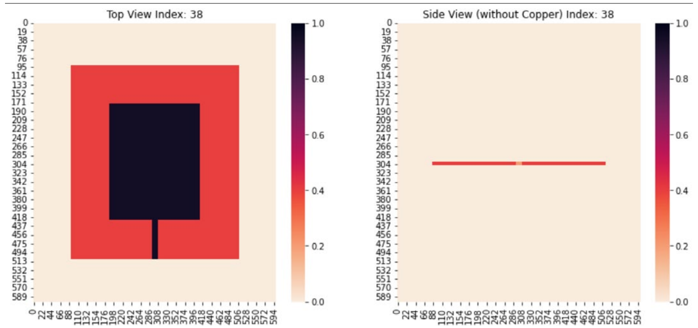


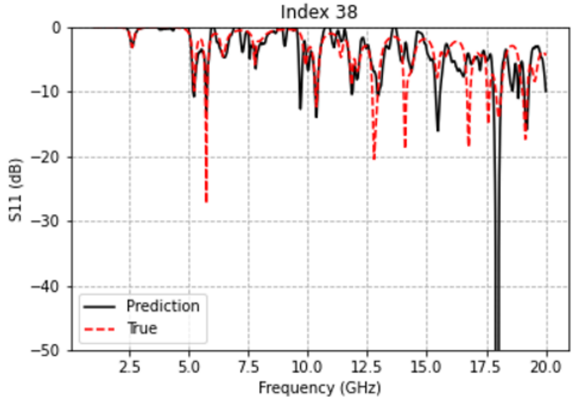
Prediction out of Range





Not Acceptable Prediction



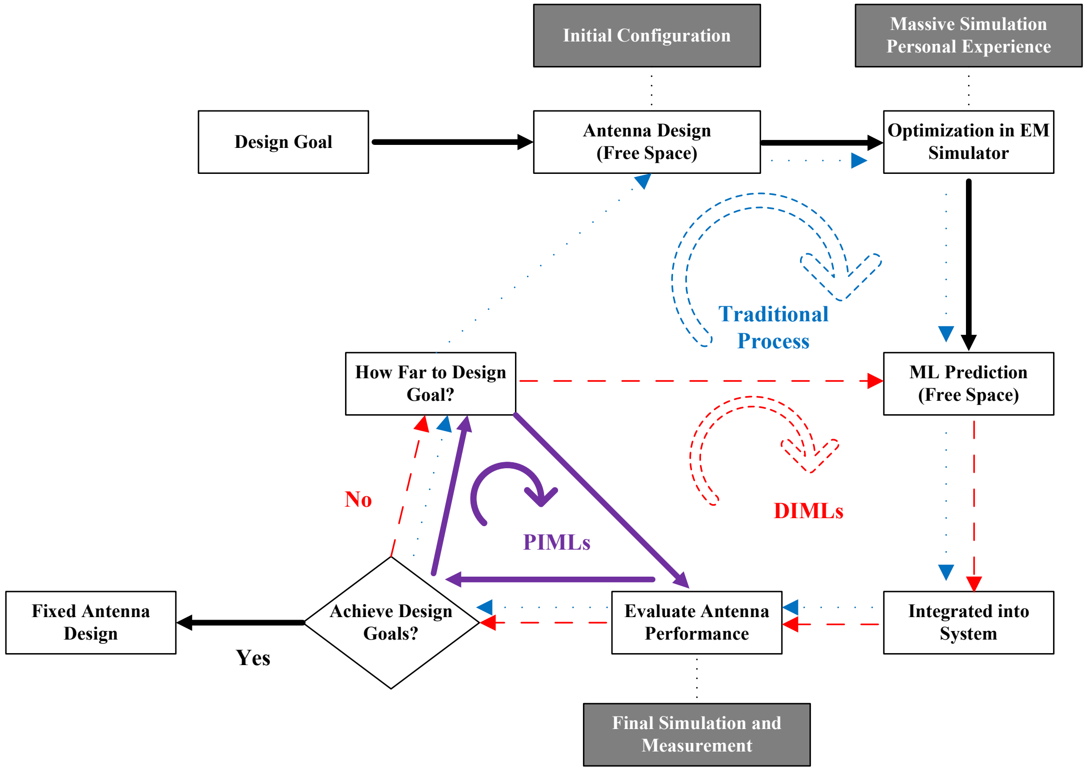


Suffer from: Fringing Effect

Conclusion and Future Work

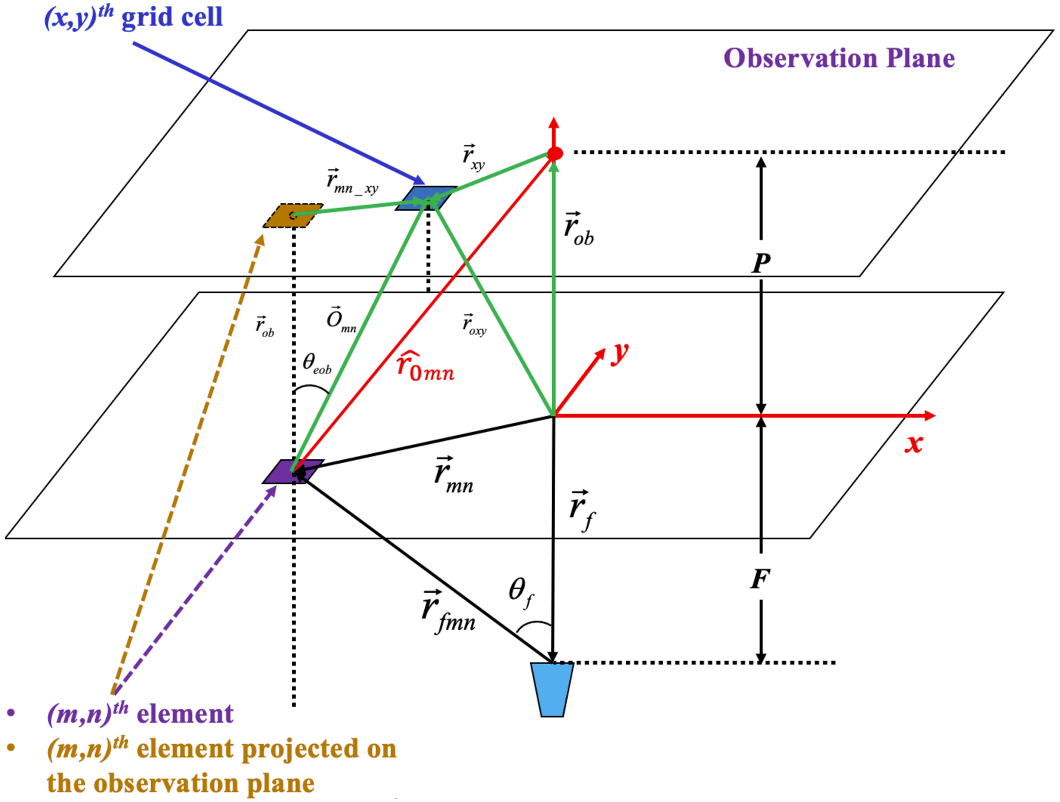
- Achieved:
  - **Real-time** prediction for antenna's reflection coefficients
  - **Automated** dataset generation methods
  - **Completed templates** for the whole workflow related to the ML based antenna design

- What we want to achieve in the future:
  - **Parameterize** the negative impact from integration
  - **Involve** more antenna types
  - **Involve** more performance as outputs
  - Multi-GPU support for train/test workflow



Project 6:

Array Radiation Pattern Optimization in Near and Far Field



1. Kiris, Orcun, Atef Z. Elsherbeni, and Yiming Chen. "An Efficient Transmitarray Element using Diagonal Double-Headed Arrows with Vias." In 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), pp. 195-196. IEEE, 2022.
2. TBD…

Transmitarray Unit Cell Design

Configuration

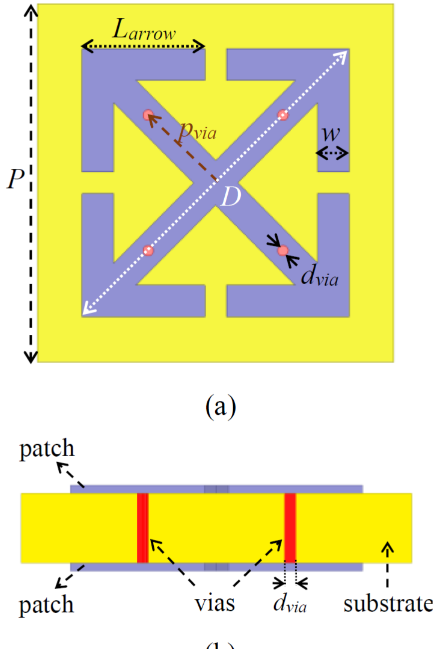


Fig. 1. The proposed element: (a) top and bottom view, (b) side view.

Transmitted Response: Periodic Boundary

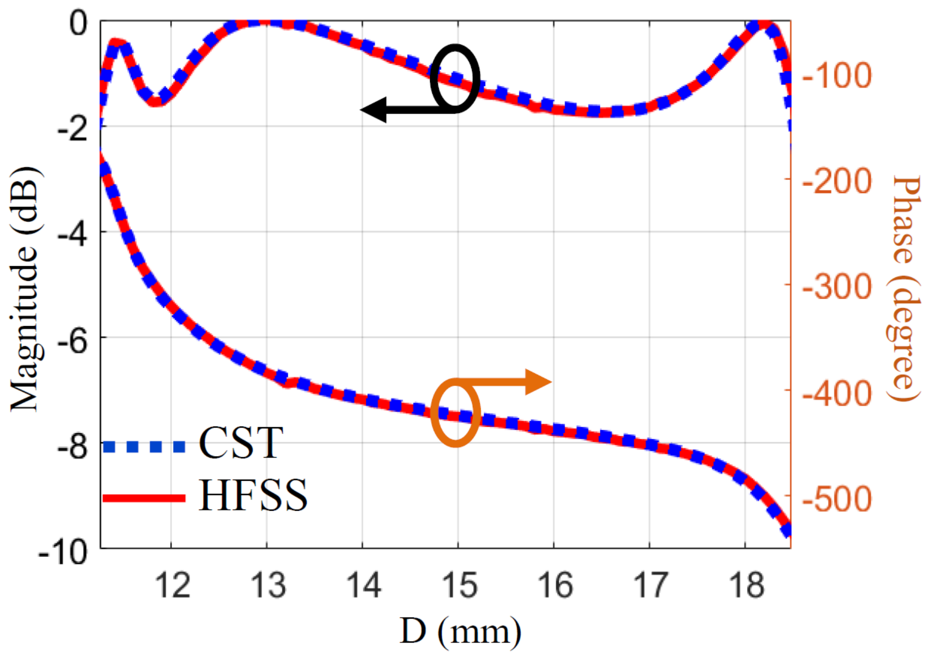
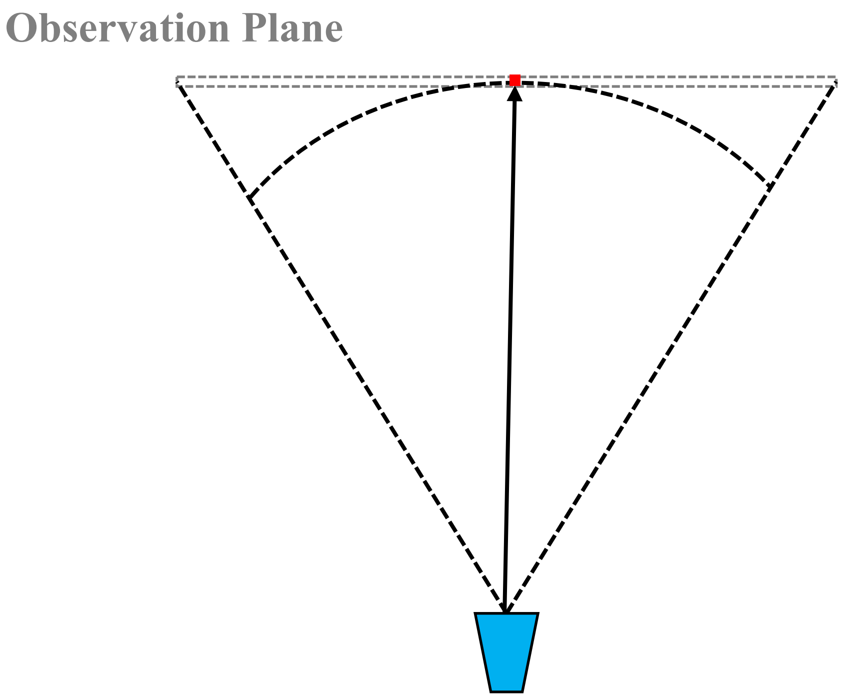


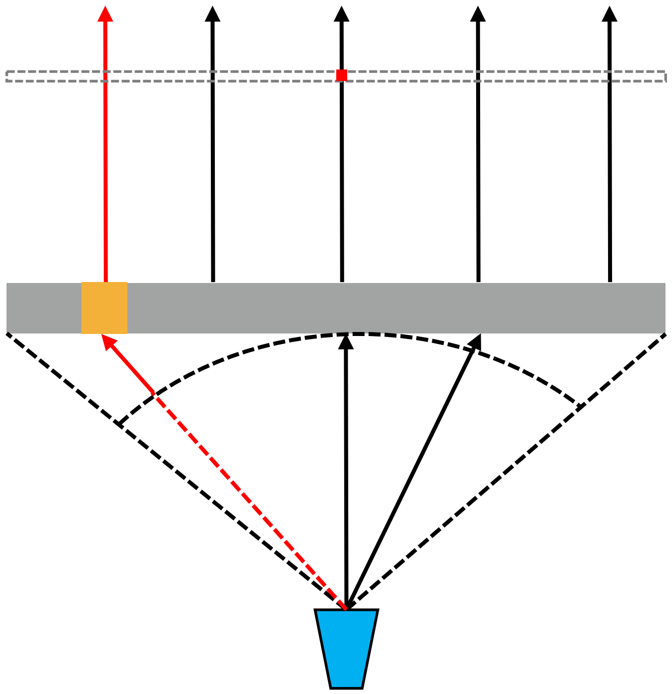
Fig. 2. Transmission and phase performance of the proposed element.

Metasurface Array for Different Scenarios

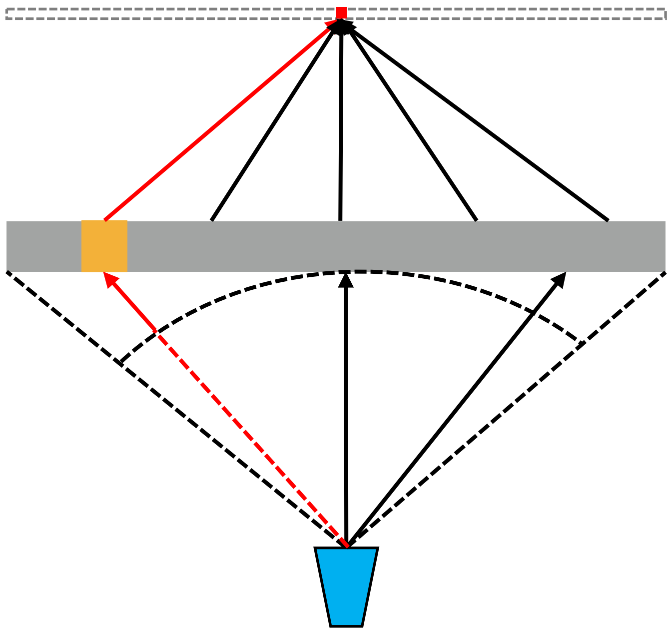
Only Feeding Horn



Feed Horn with FF Array



Feed Horn with NF Array



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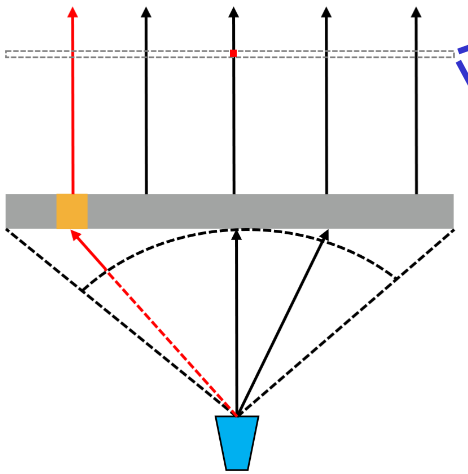
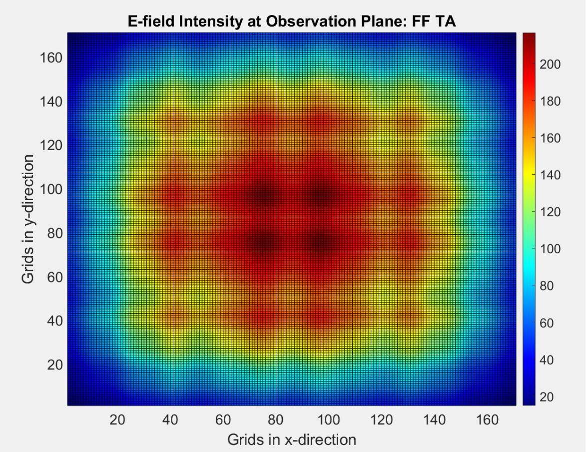
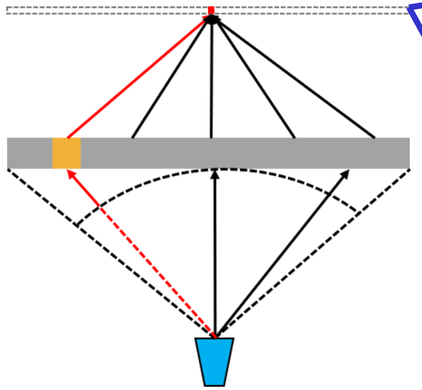
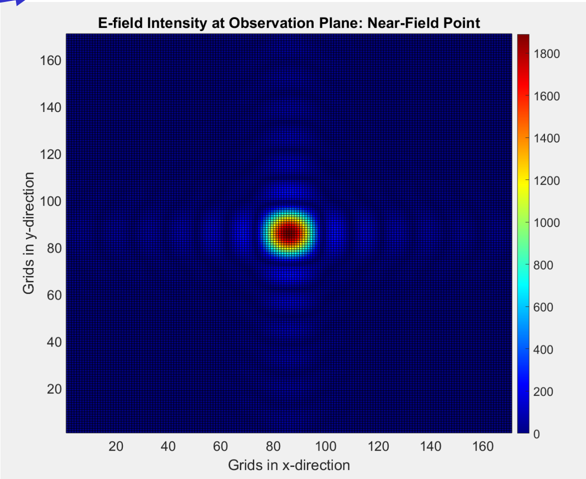
Focusing Gain between FF TA and NF TA

Displacement | **E-field Distribution** | **Focusing Gain**

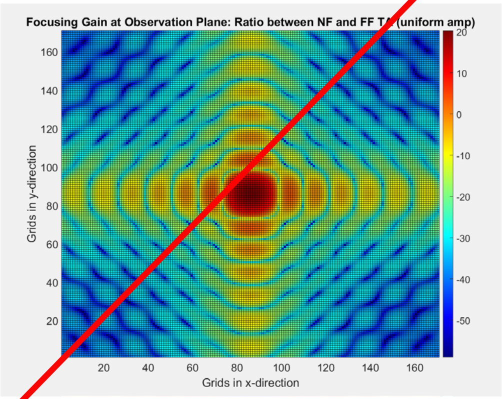


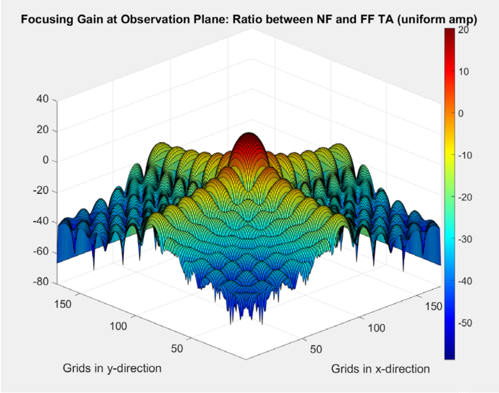






$$FG_{dB} = 20 \times \log_{10}\left(\frac{E_{NF}}{E_{FF}}\right)$$





$$FG_{dB,\max} = 20.24\,dB$$

$$FG_{dB,\min} = -66.33\,dB$$

Questions?

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