

Wide Band and Wide Steering Angle Terahertz Phased Array Transmitters in Silicon

January 27, 2020

Omeed Momeni

Radio & Wireless Week, San Antonio, TX



HISIES
High-Speed Integrated
Electronic Systems Lab

Outline

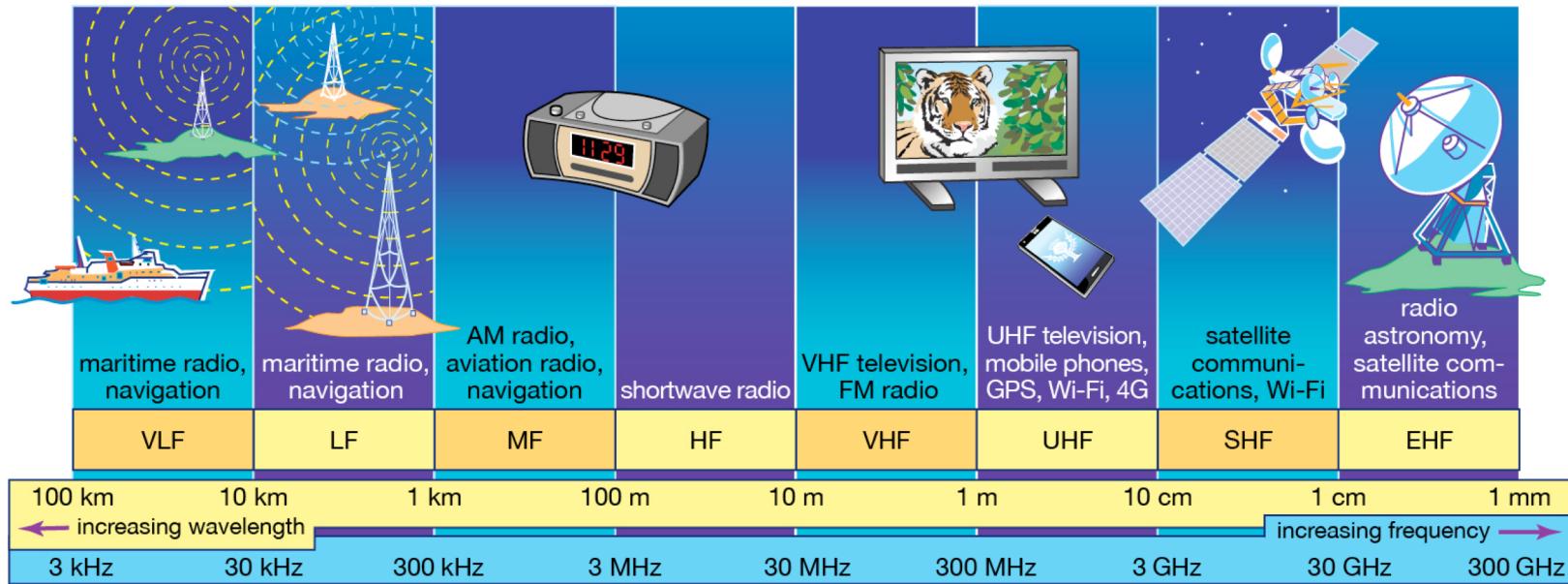
- Introduction
- Scalable Standing Wave Radiator Array
- Wideband Standing Wave Phased Array
- Conclusion

Why Higher Frequency?

- Higher Bandwidth → Less complicated systems/Higher data rate/Higher radar resolution

Shannon-Hartley Theorem:

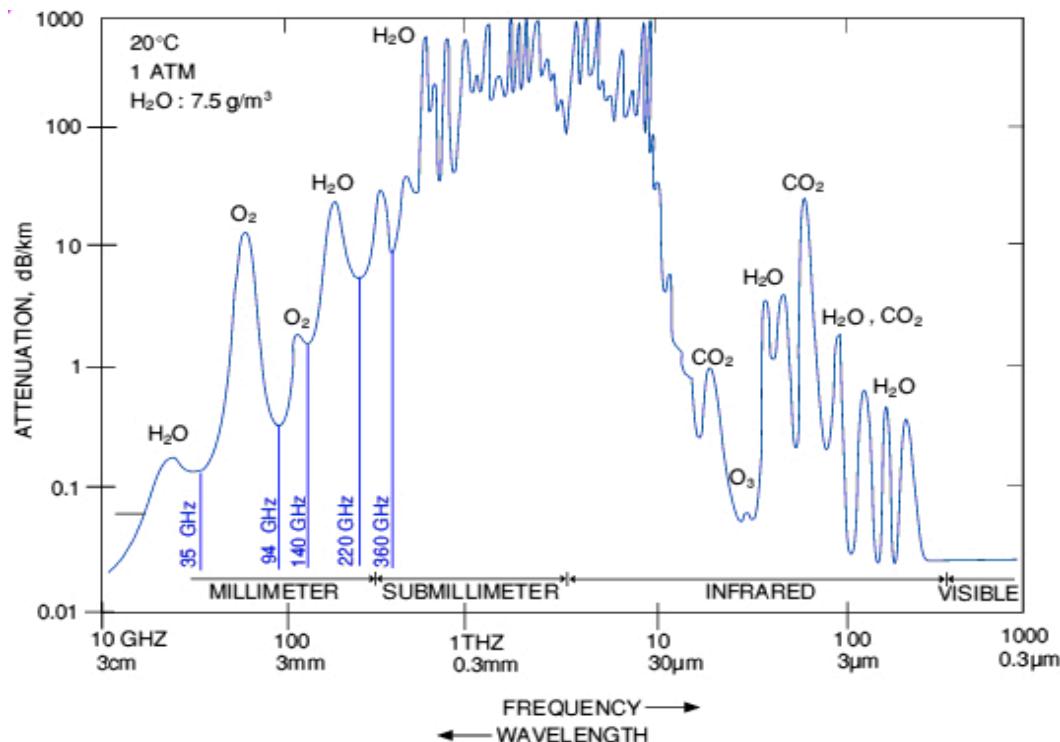
$$C = BW \cdot \log_2(1 + SNR)$$



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Why Higher Frequency?

- Less Interference → Higher allowed power → Higher SNR
- Isolation → More Frequency reuse
- Unique Signatures (e.g., passes through fog, smoke, dust)

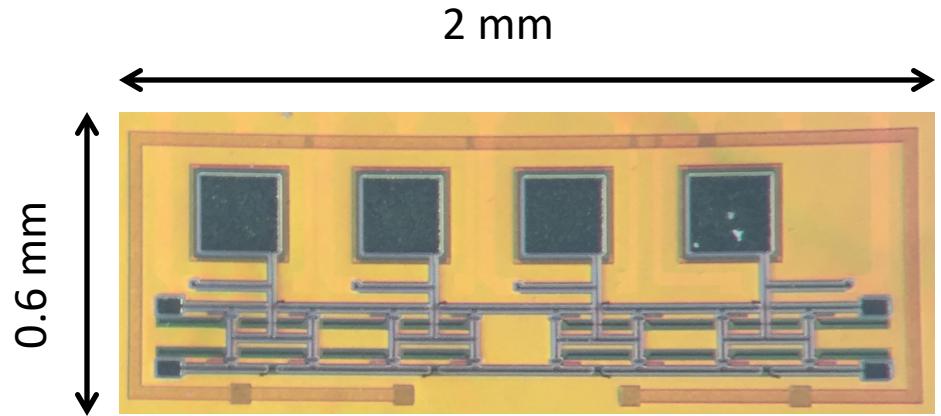


Why Higher Frequency?

- Smaller Structures → System on chip



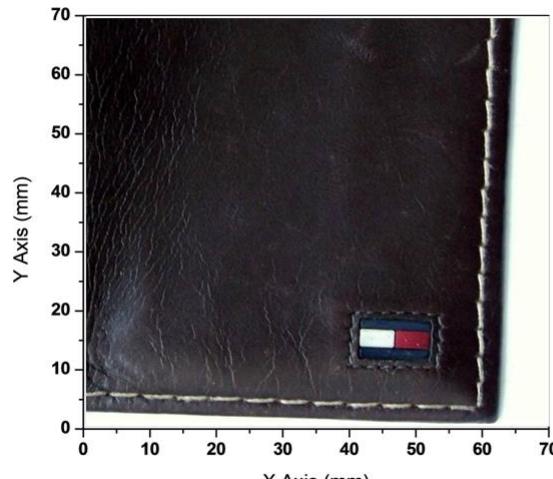
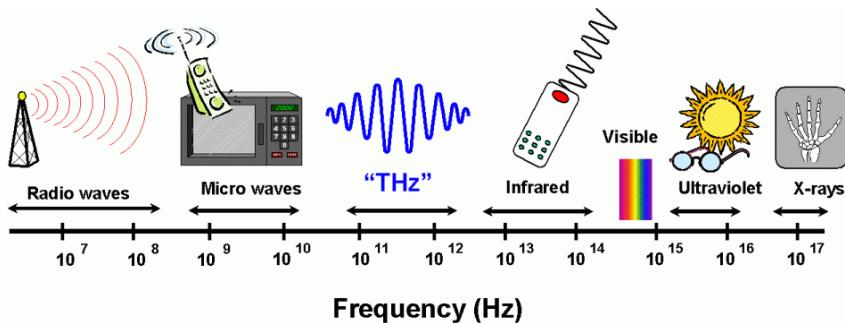
Antenna size at ~2 GHz



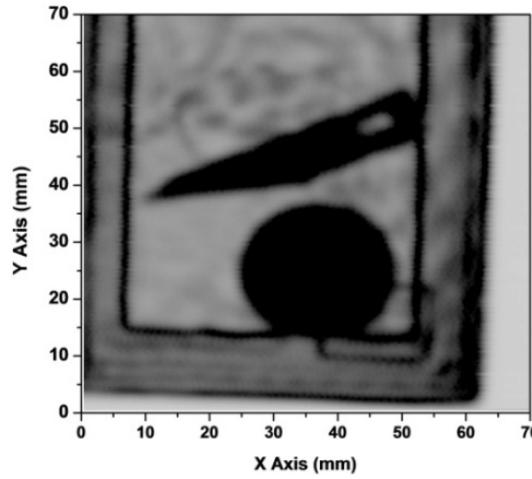
Antenna size at ~370 GHz

Application of Terahertz Systems

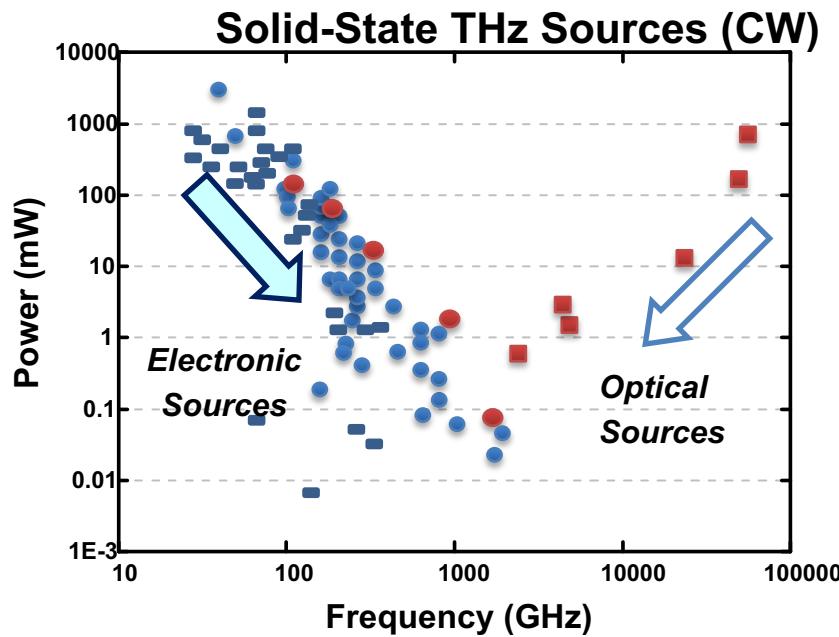
- Imaging (e.g., detection of concealed weapons, cancer diagnosis, and semiconductor wafer inspection)
- Compact range radars/sensing
- High data rate communication (e.g., 100 Gbps)



Courtesy of Ruinan Han



Challenges



Fundamental Challenges:

- Transistors offer no power gain above f_{max}
- Limited power efficiency of devices
- Limited break down voltage
- Quality factor of passives is low

High power signal generation is the main challenge in realizing on-chip THz systems.

Challenges

- ❑ f_{\max} of transistors

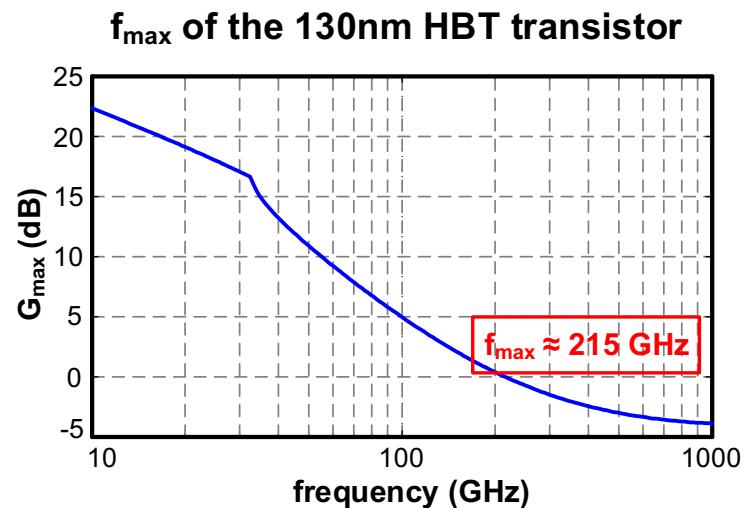
- ❑ Limited power generation
- ❑ Harmonic osc. to go beyond f_{\max}
- ❑ Must employ arrays of radiators

- ❑ Losses & parasitics of coupling networks

- ❑ Degrades power generation and operating freq.

- ❑ Q of varactors

- ❑ Limits freq. tuning range & output power



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- Wideband Standing Wave Phased Array
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Proposed Approach

- Employ standing wave distributed oscillator as array's building block
- Scalable uni-structure distributed array
 - Array extension by replication of unit cell
 - Inherently in phase
 - Structural coherency
- Tuning range extended
 - Avoiding varactors

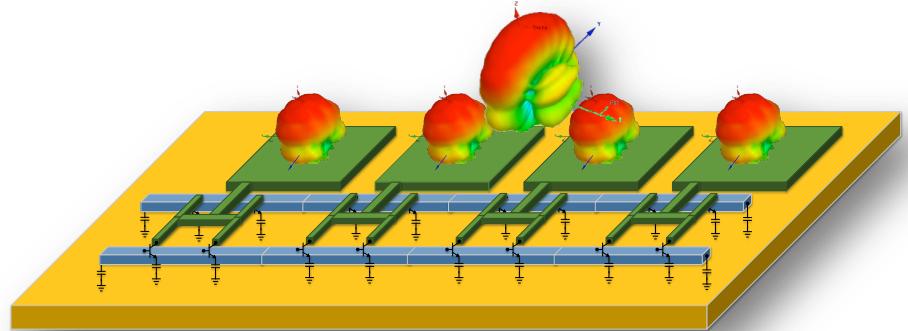
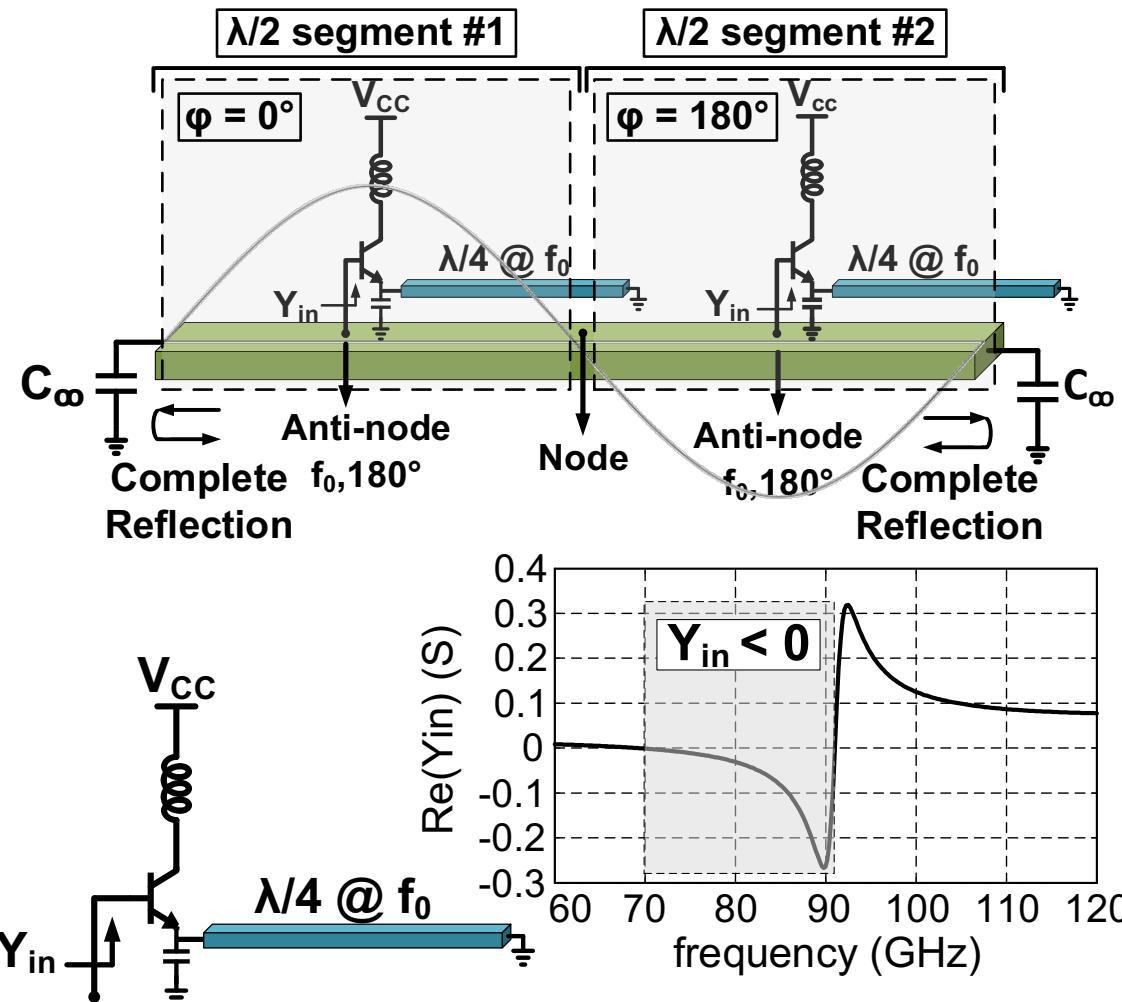


Illustration of the proposed architecture

Standing Wave Oscillator (SWO)

- Superposition of reflected waves forms a standing wave
- Narrow band $-g_m$ to prevent undesired modes

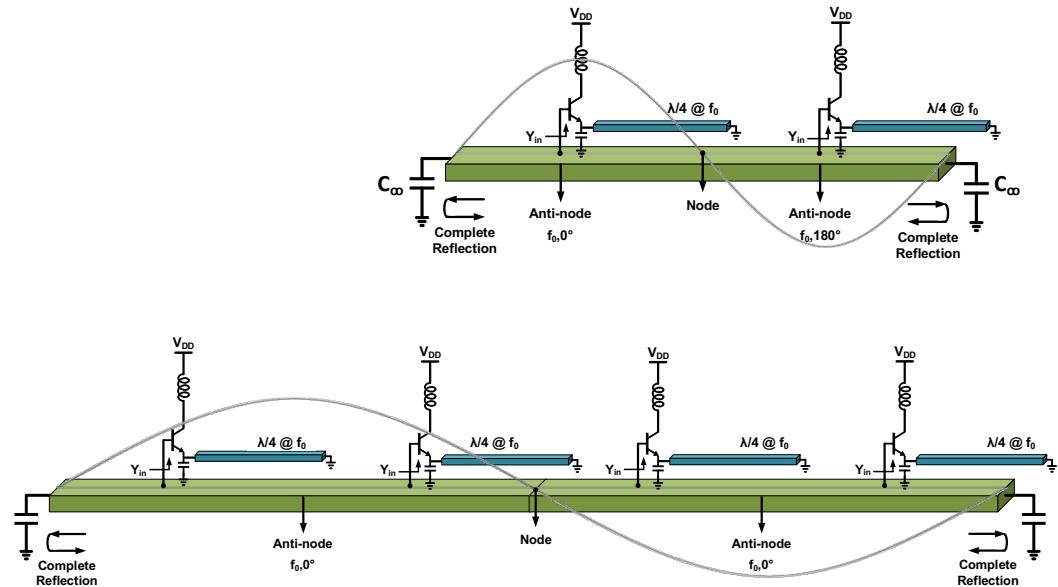


Scaling and Modes

Unit Standing Wave Oscillator

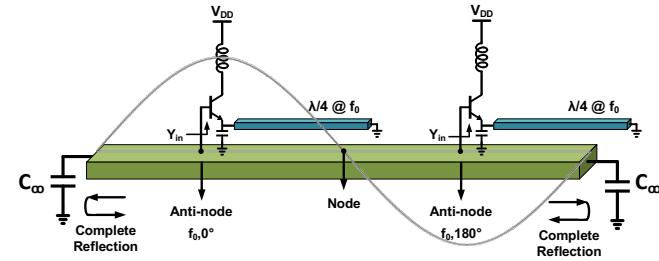
Wide-band $-g_m$

- ✗ Electrical length unchanged (λ)
- ✗ Frequency of operation halved
($f_0/2$)



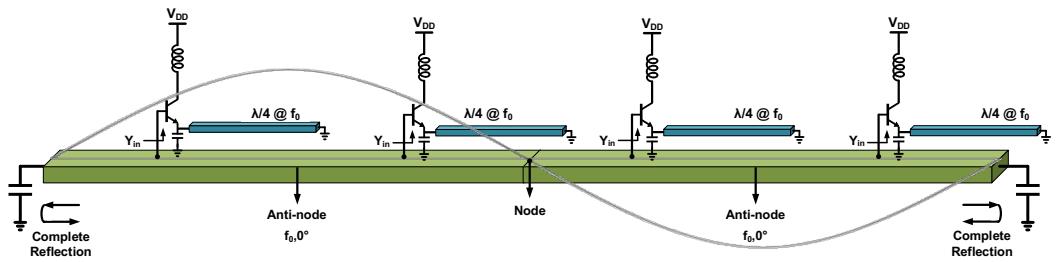
Scaling and Modes

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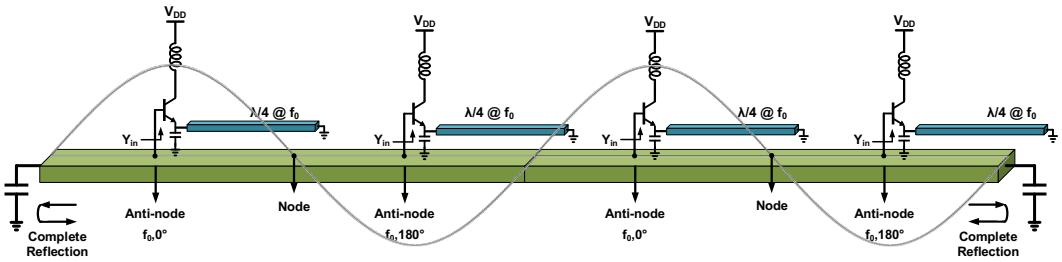
Wide-band $-g_m$

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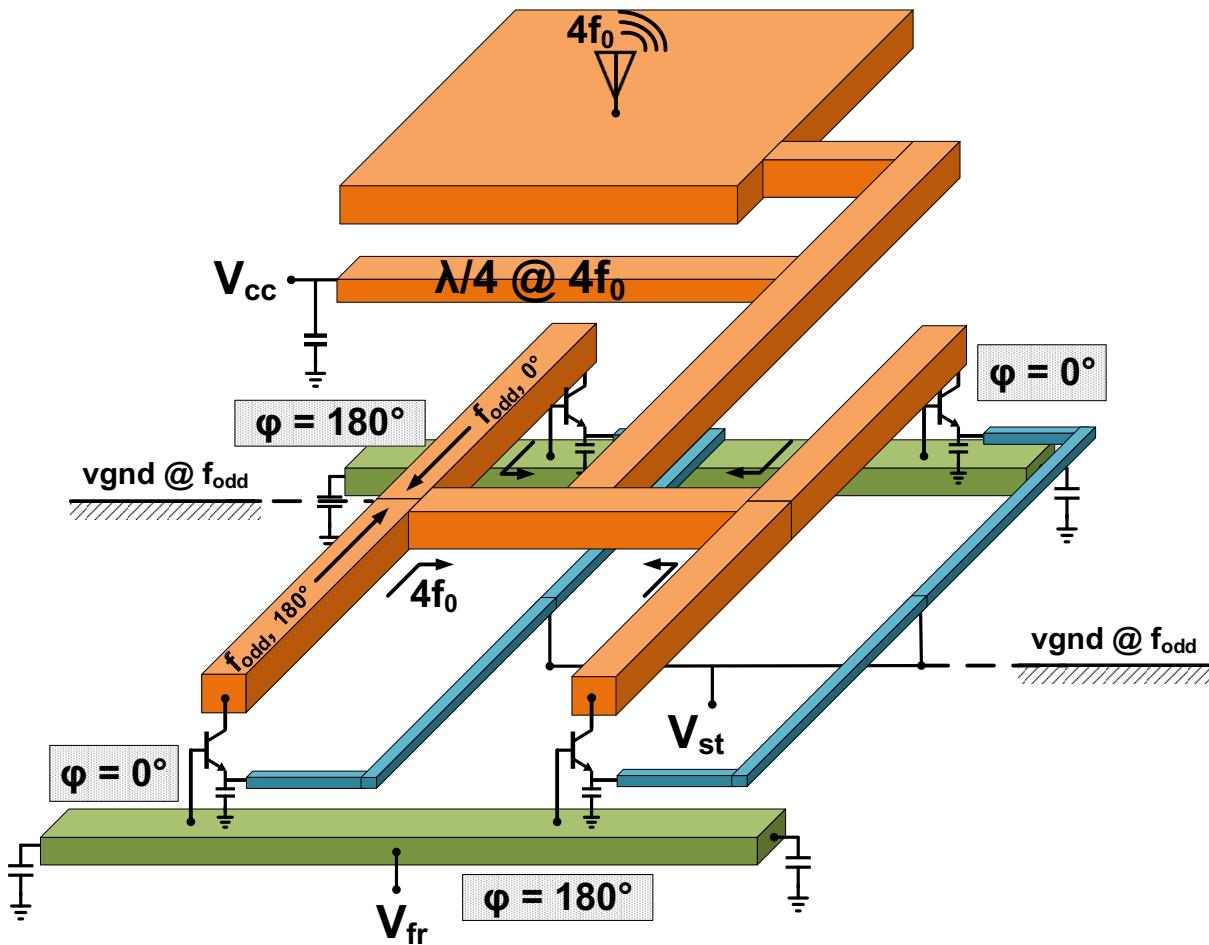
Narrow-band $-g_m$

- ✓ Electrical length doubled (2λ)
- ✓ Frequency of operation unchanged (f_0)



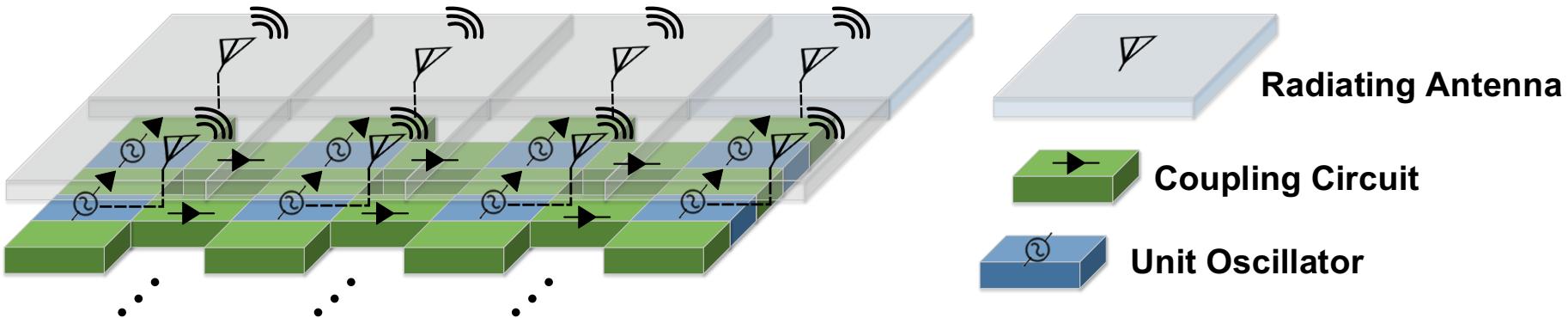
Unit Cell: SWO

- Odd/even harmonics cancel/combine
- V_{fr}/V_{st} for freq. tuning/beam steering
- 4th harm. extraction & radiation by on chip antennas



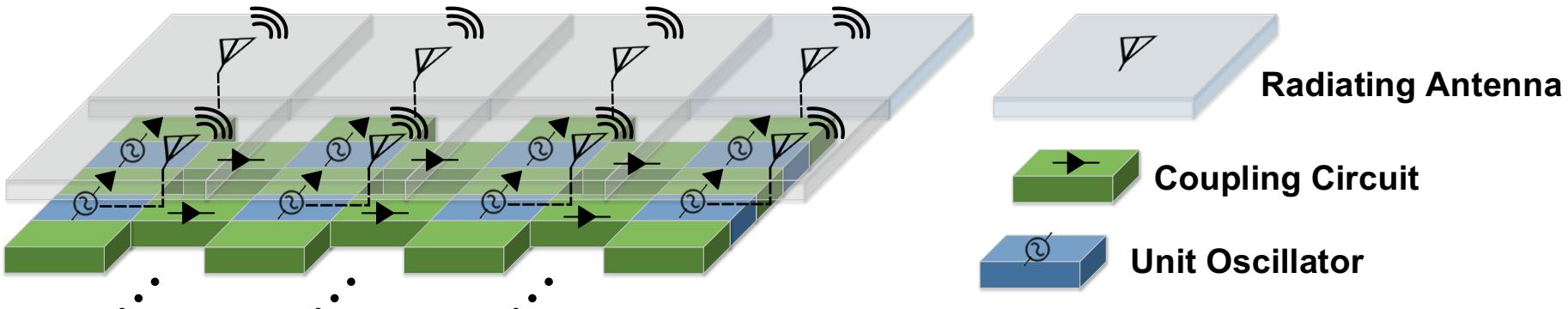
Array Structures

□ Conventional approach

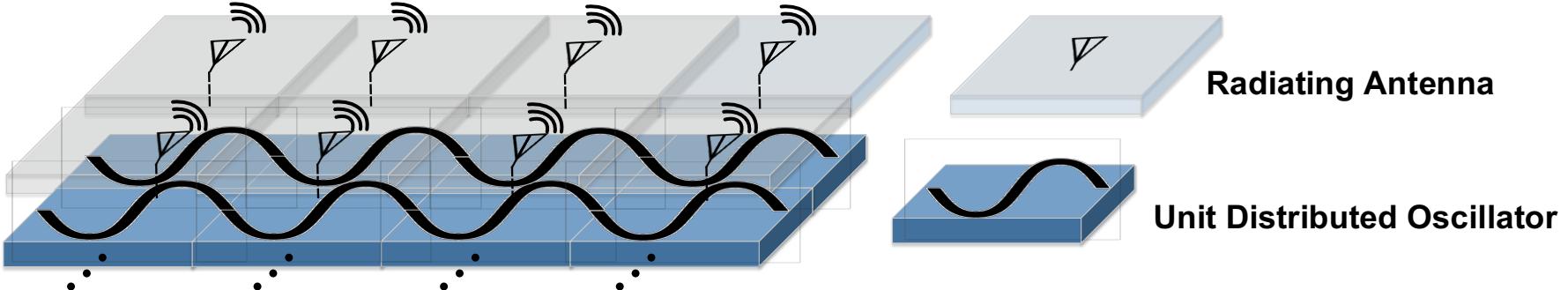


Array Structures

□ Conventional approach

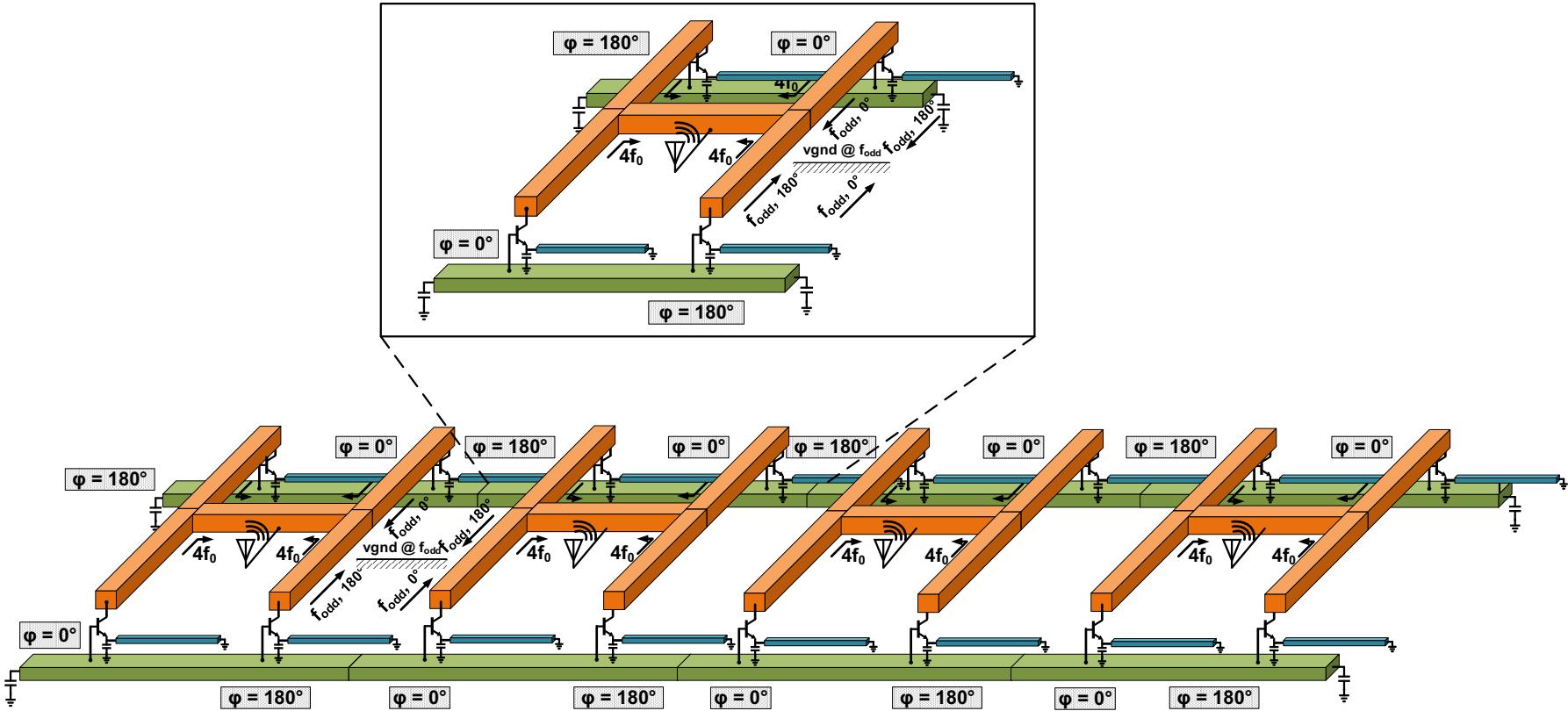


□ Uni-structure distributed architecture

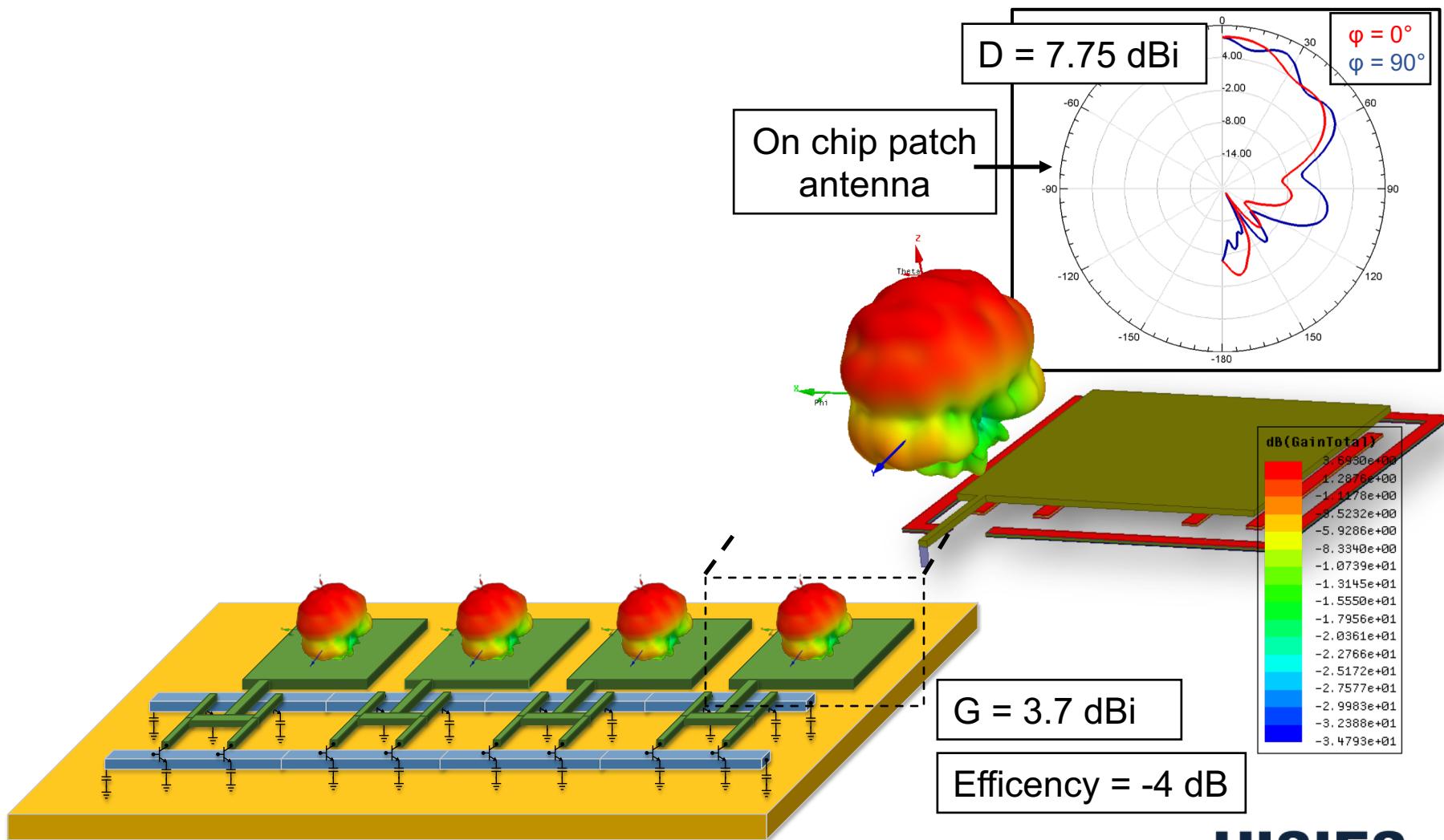


1X4 SW Radiator Array

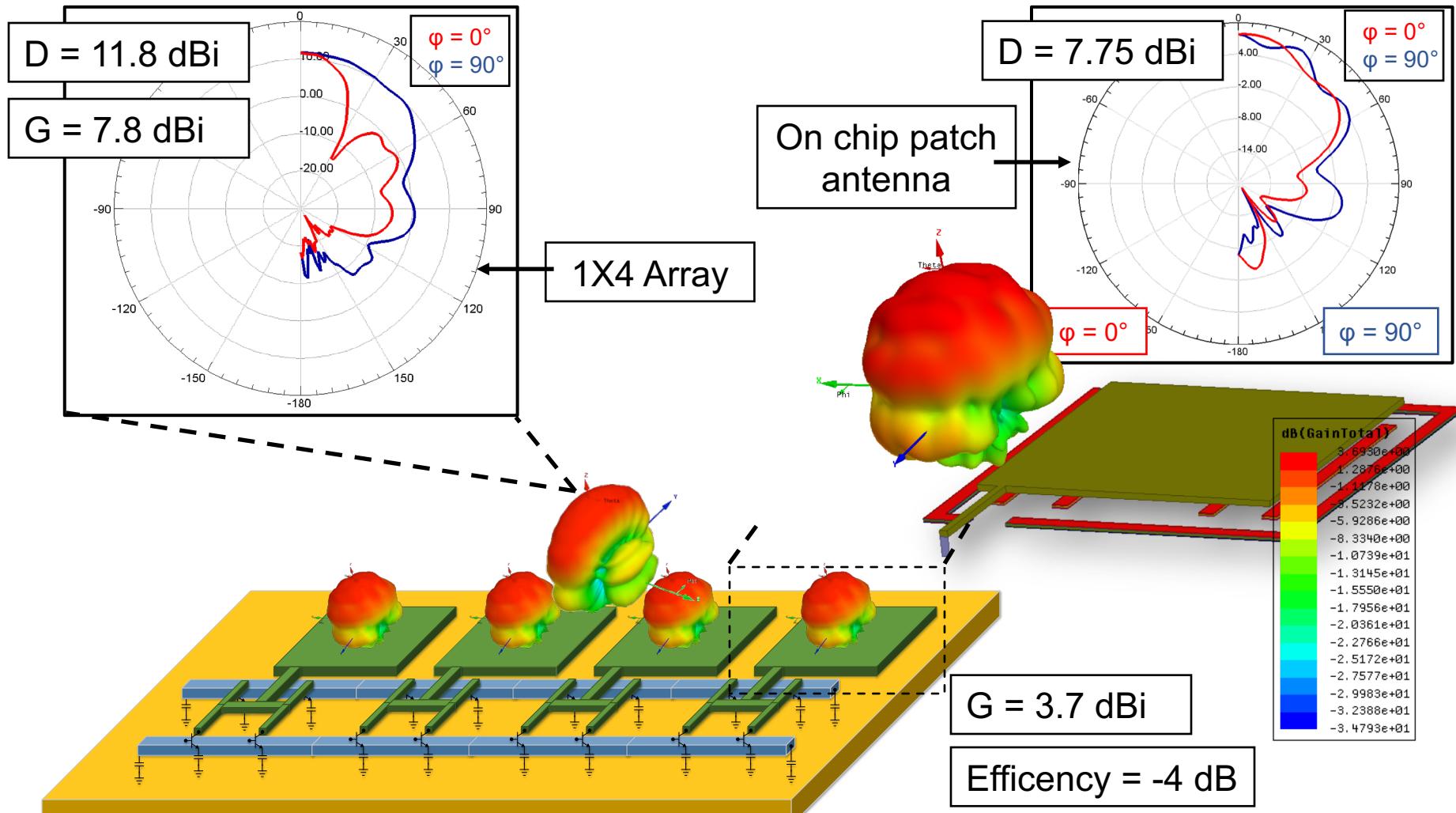
□ The proposed 1X4 scalable standing wave array



Radiation Structure Simulation

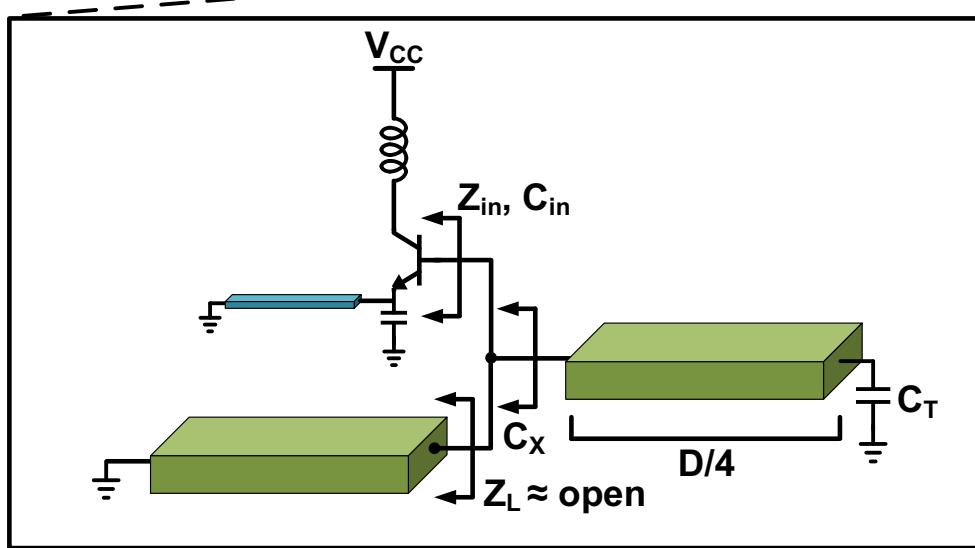
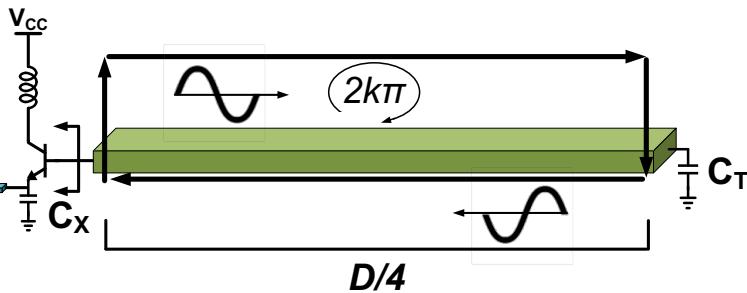
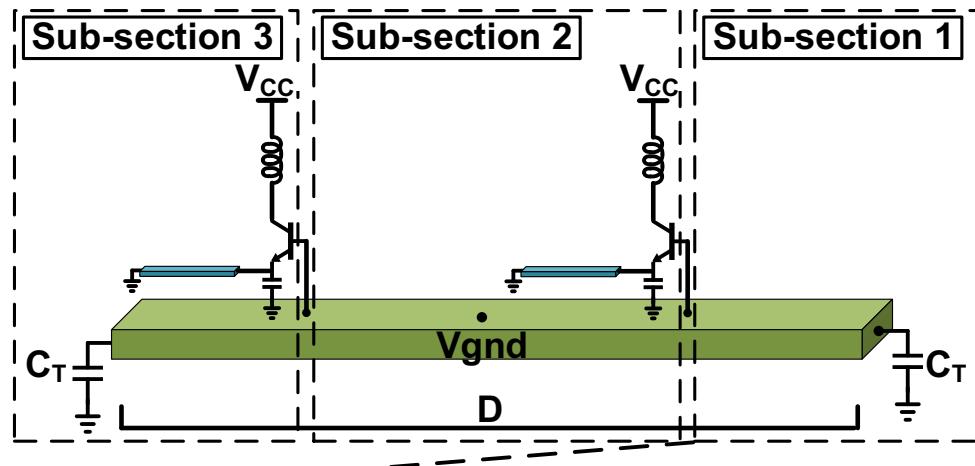


Radiation Structure Simulation



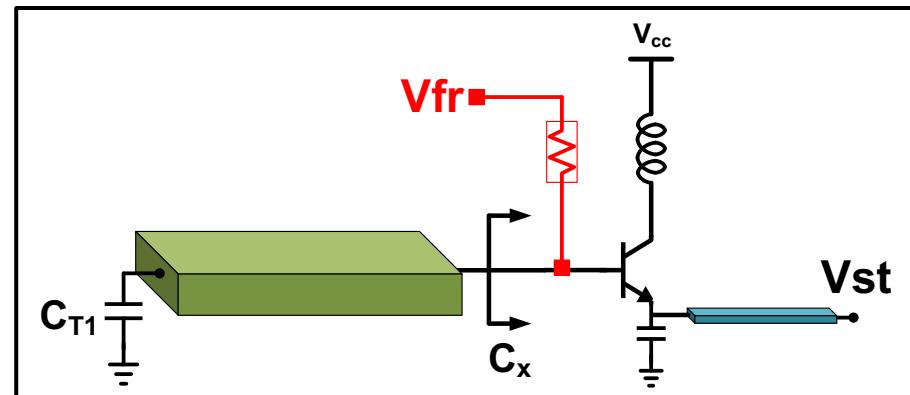
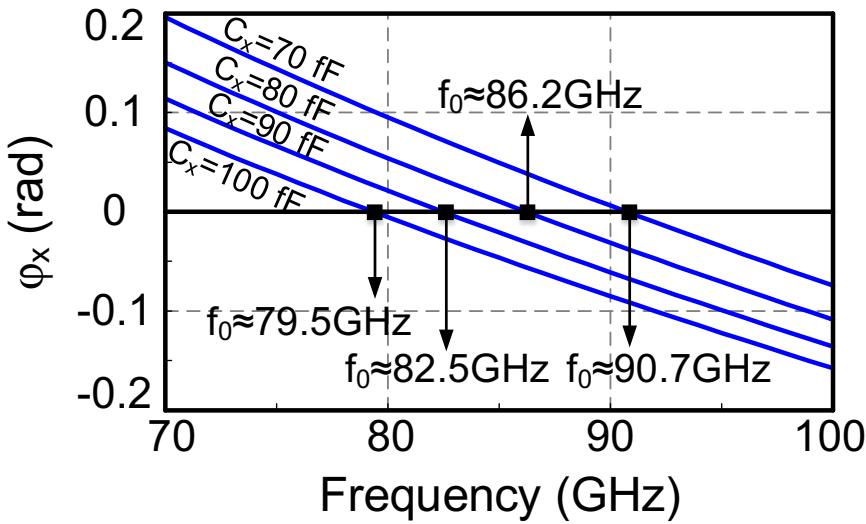
SWO Frequency Tuning

- Frequency of operation determined by the “phase condition”

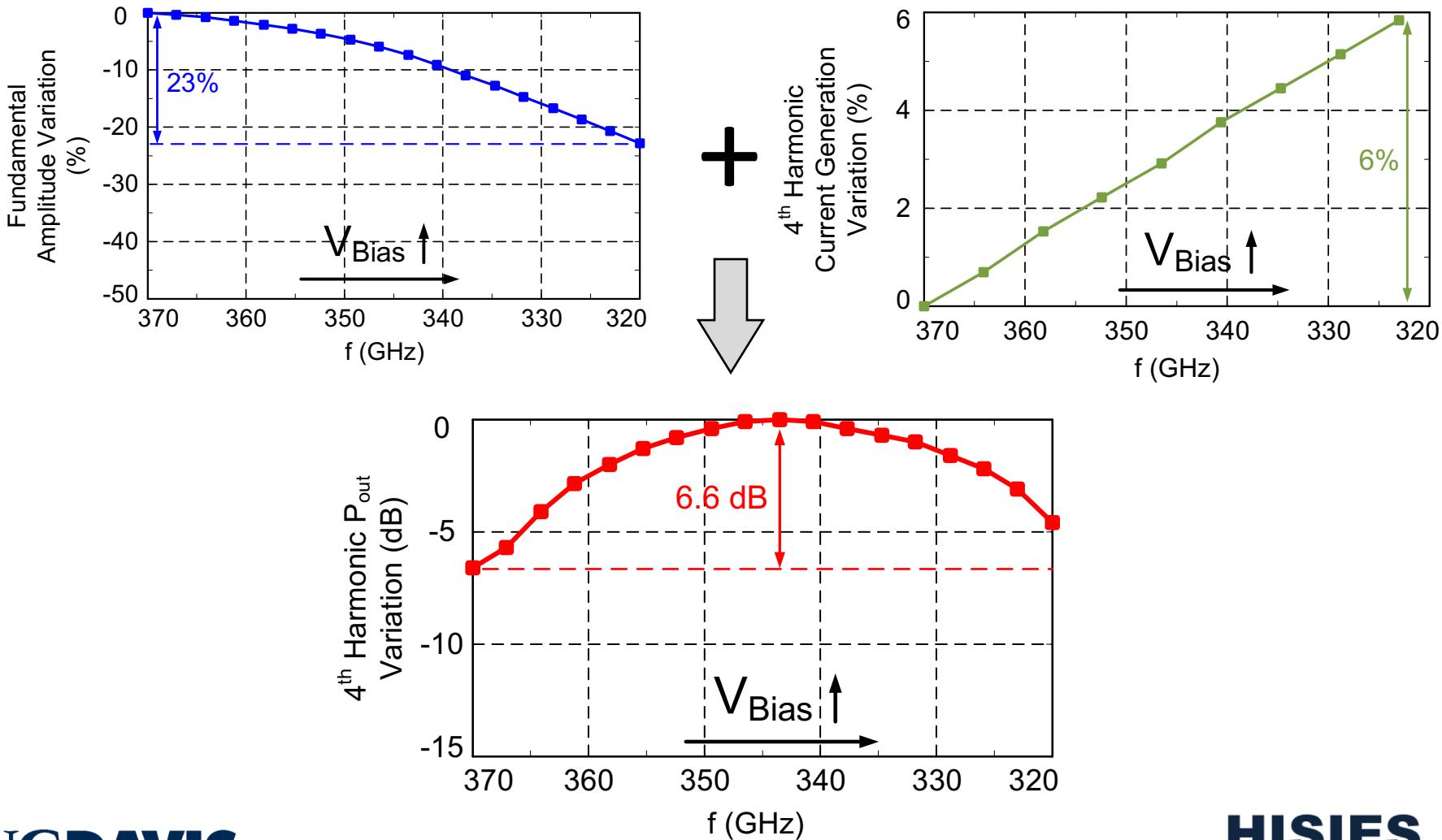


SWO Frequency Tuning

- Transistor as lossless active variable capacitor
- C_x determines termination phase shift
- Freq. variation by controlling termination cap with V_{fr}

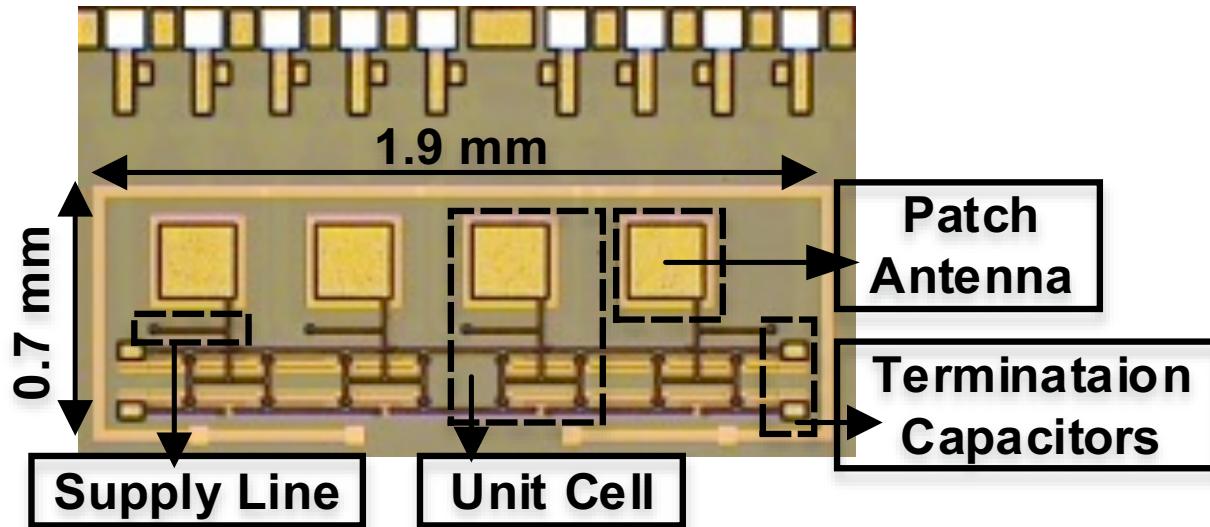


Power Variation within T.R.



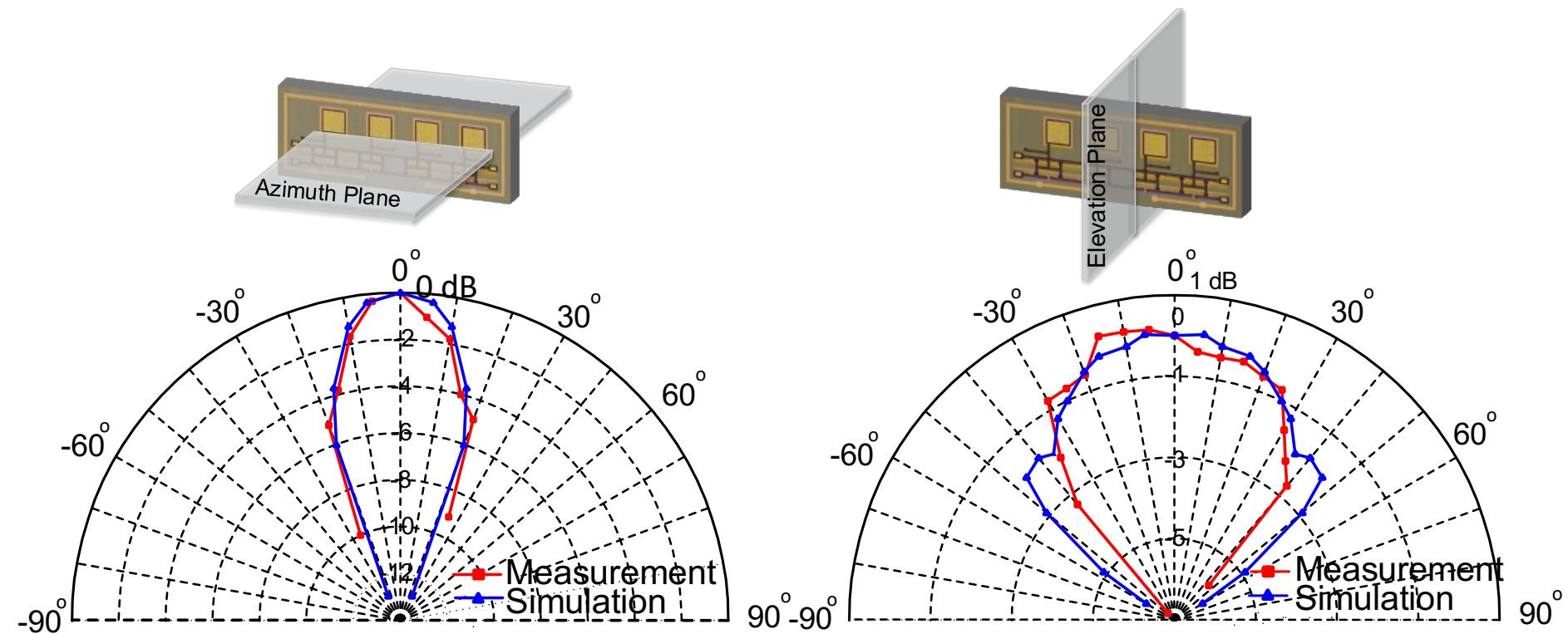
Fabrication

- Fabricated in 130nm BiCMOS, 215GHz f_{\max}
- Whole structure characterized in HFSS 3D EM simulator
- No post-processing or silicon lens used



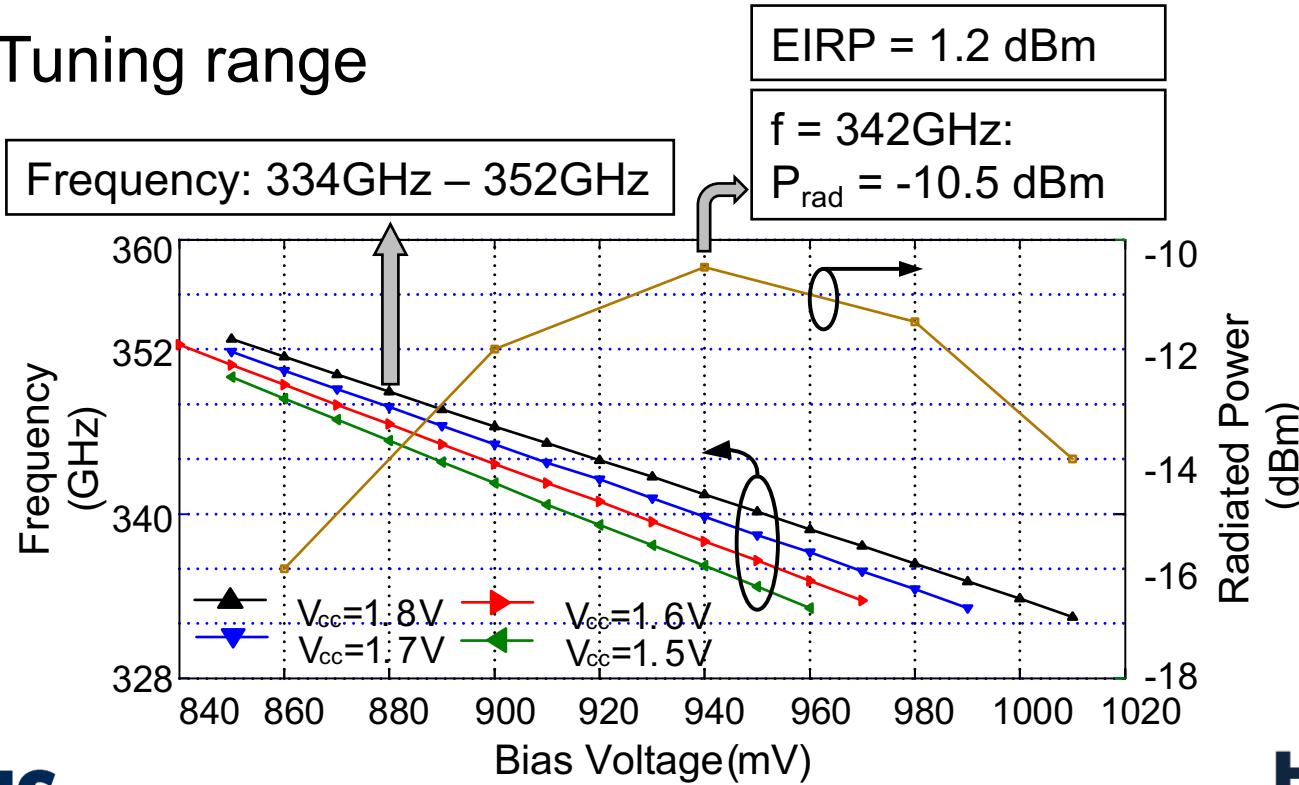
Radiation Pattern

- HPBW's: $15^\circ/40^\circ$ in azimuth/elevation planes
- Measured Directivity = 11.3 dBi



Frequency and Power

- 5.5 dB power variation from 334GHz to 352GHz
- -10.5 dBm total radiated power
- 5.9% Tuning range

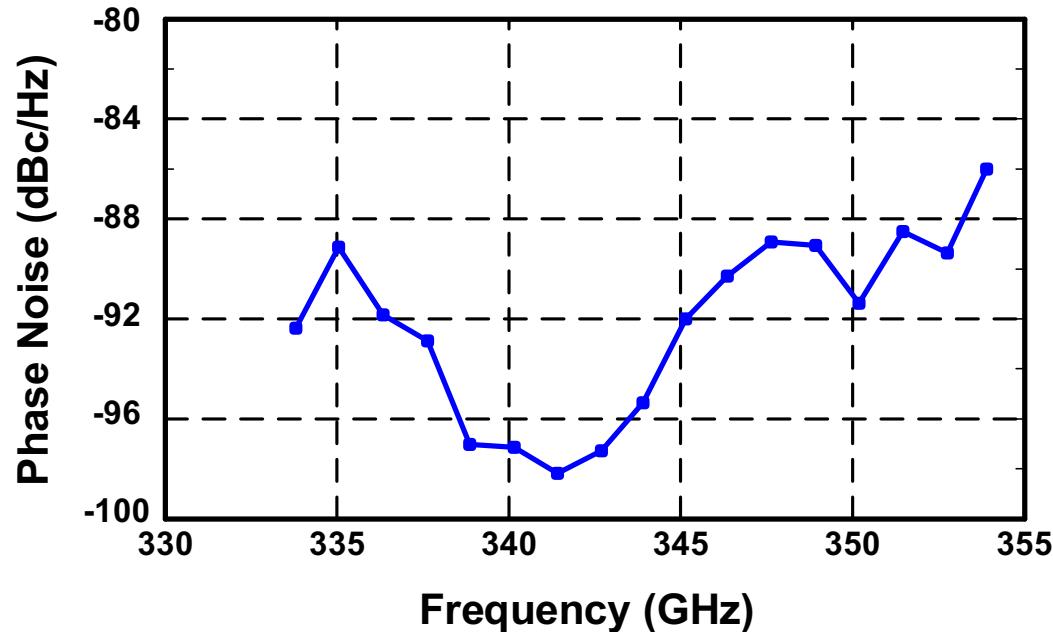


Phase Noise

□ -98.2 dBc/Hz phase noise at 10MHz offset at center freq.

- Including the noise added by the receiver

**Measured Phase Noise vs. Frequency
@ 10MHz Offset**



Performance Summary

	Freq.	Technology	f_{\max} (GHz)	Size	Si Lens	Tuning Range (%)	P_{rad} (dBm)	$P_{\text{rad}}/\text{Cell}$ (dBm)	EIRP (dBm)	DC Power (W)
This work	342	130nm SiGe	215	1x4	No	5.9	-10.5	-16.5	1.2	0.425
[1]	320	130nm SiGe	280	4x4	No	N/A	0.9	-11.1	13.9	0.61
					Yes		5.2	-6.8	22.5	
[2]	338	65nm CMOS	250	4x4	No	2.1	-0.9	-13	17.1	1.54
[3]	530	130nm SiGe	500	4x4	Yes	3.2	0	-12	25	2.54
[4]	280	CMOS 45nm SOI	N/A	4x4	No	3.2	-7.2	-19.2	9.4	0.81

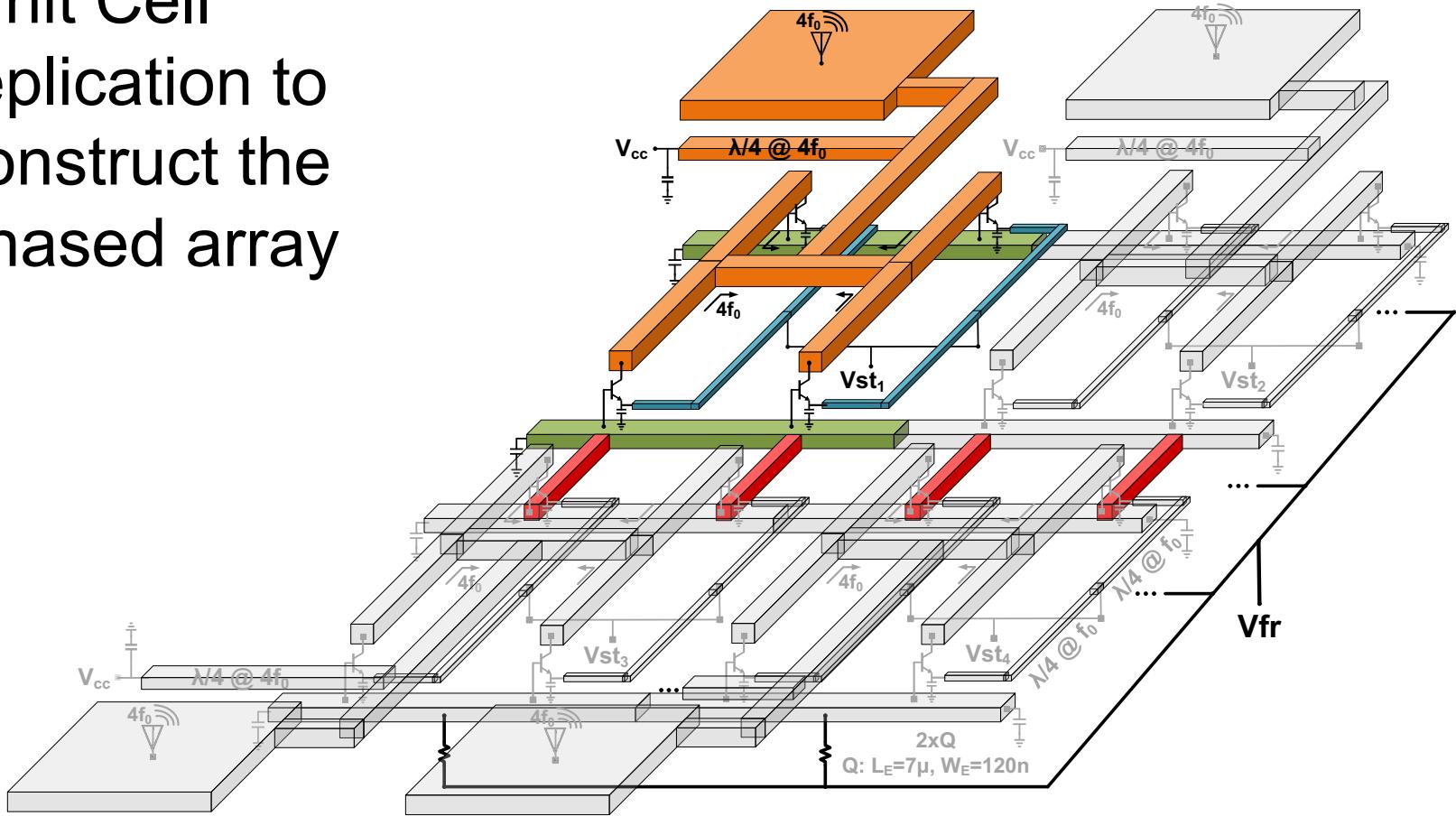
□ At the time of publication this is the largest tuning range reported for a radiating array above 300GHz

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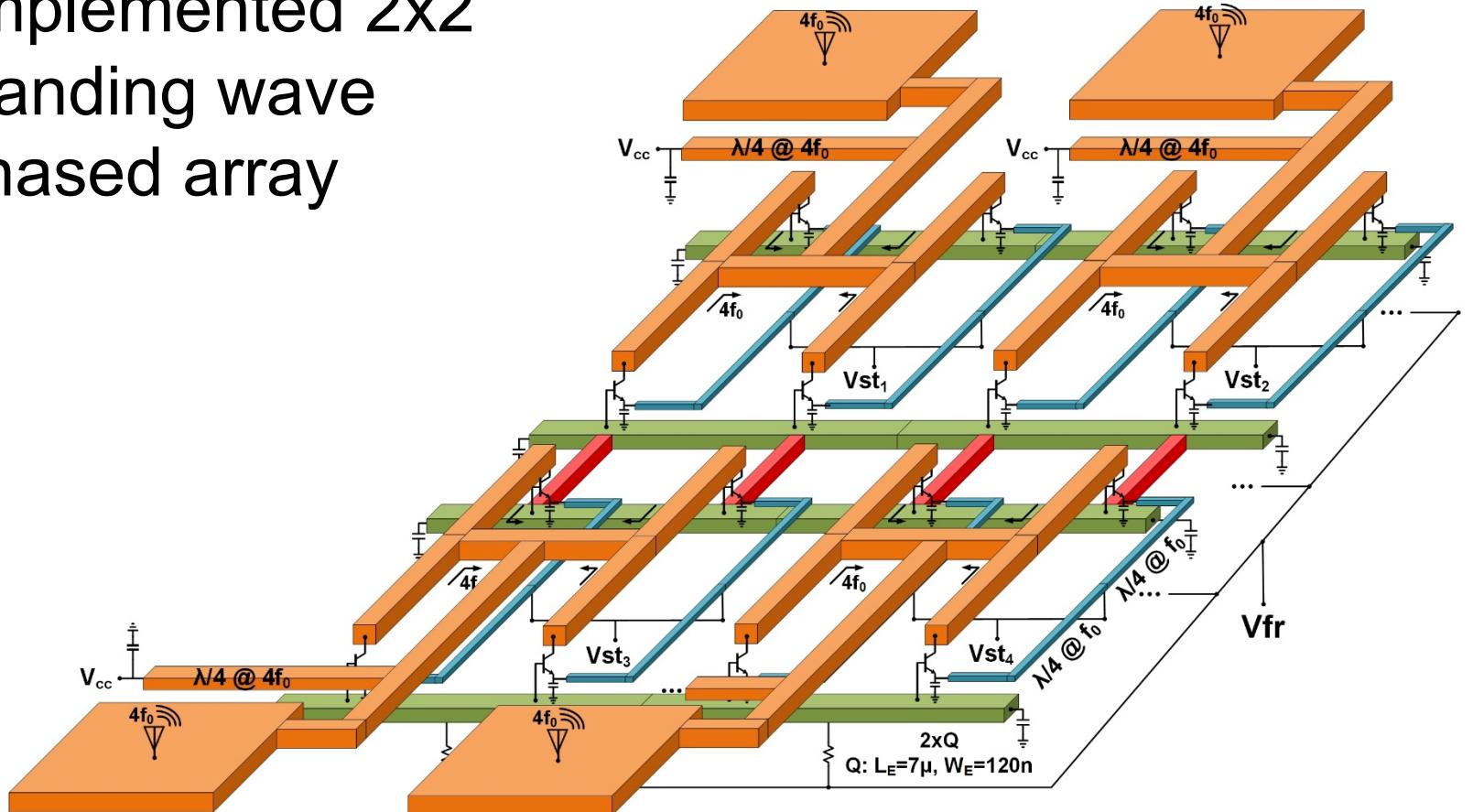
2x2 SW Phased Array

□ Unit Cell
replication to
construct the
phased array

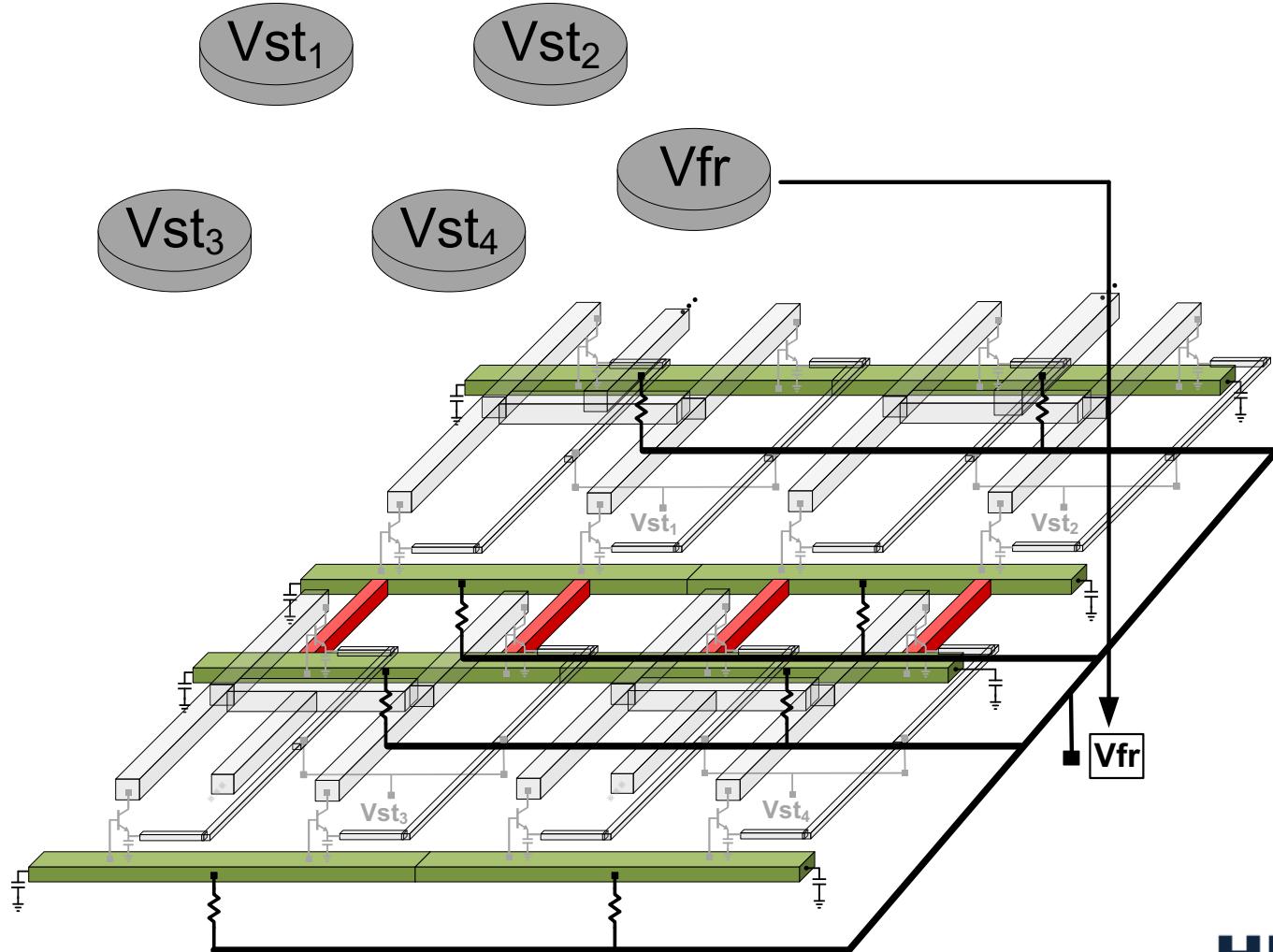


2x2 SW Phased Array

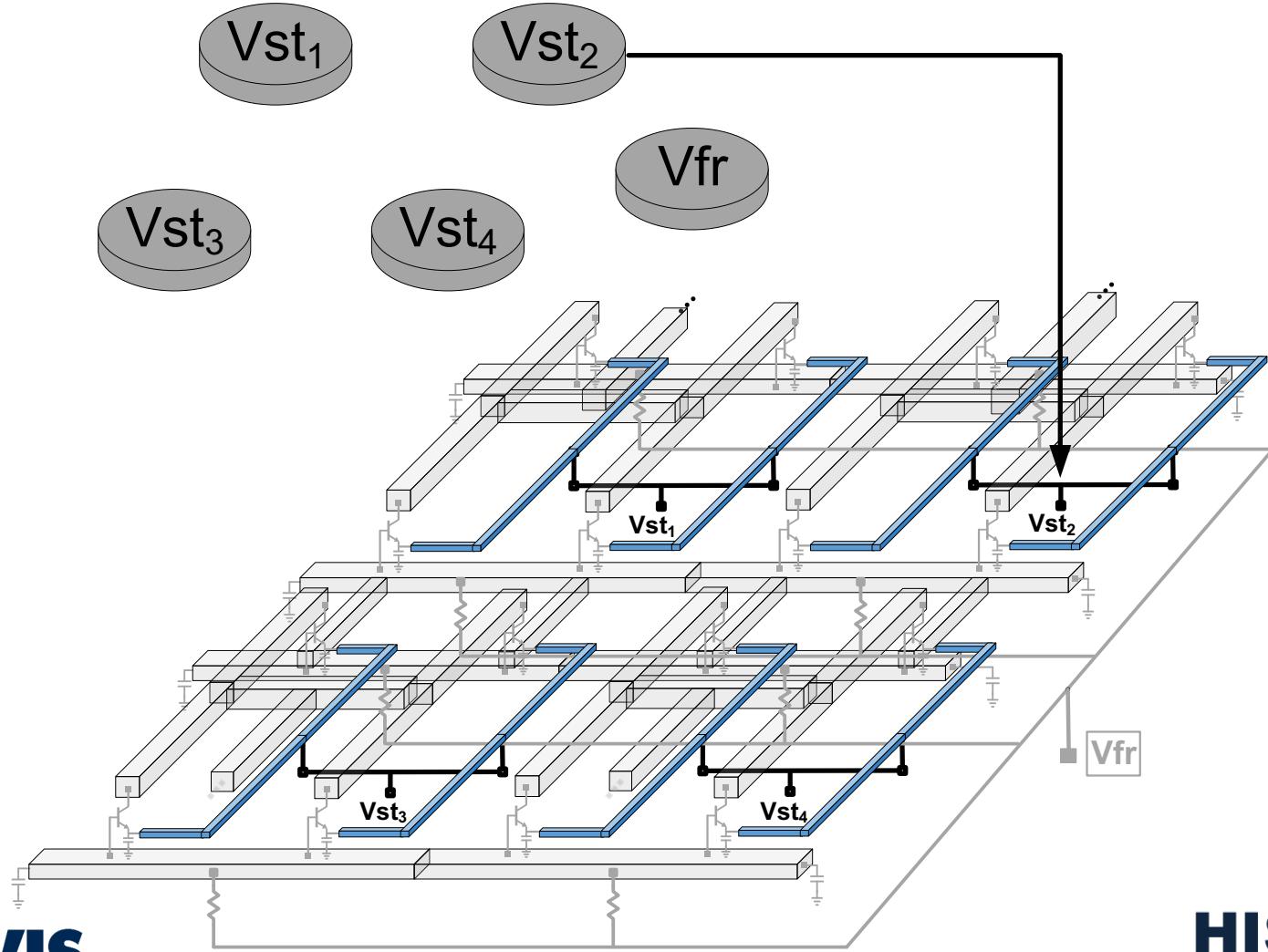
□ Implemented 2x2 standing wave phased array



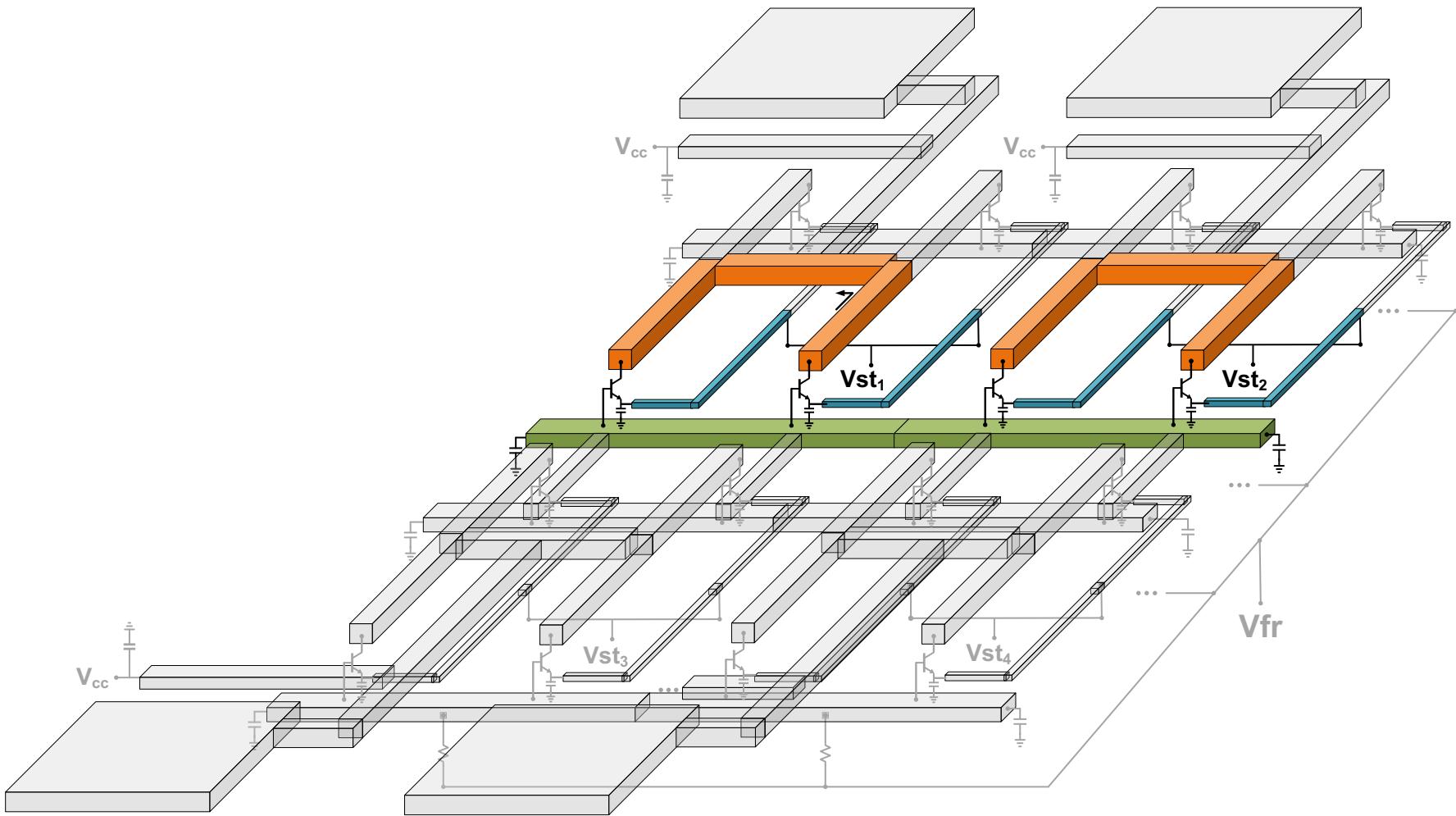
V_{fr} for Frequency Control



V_{st} for Steering Control

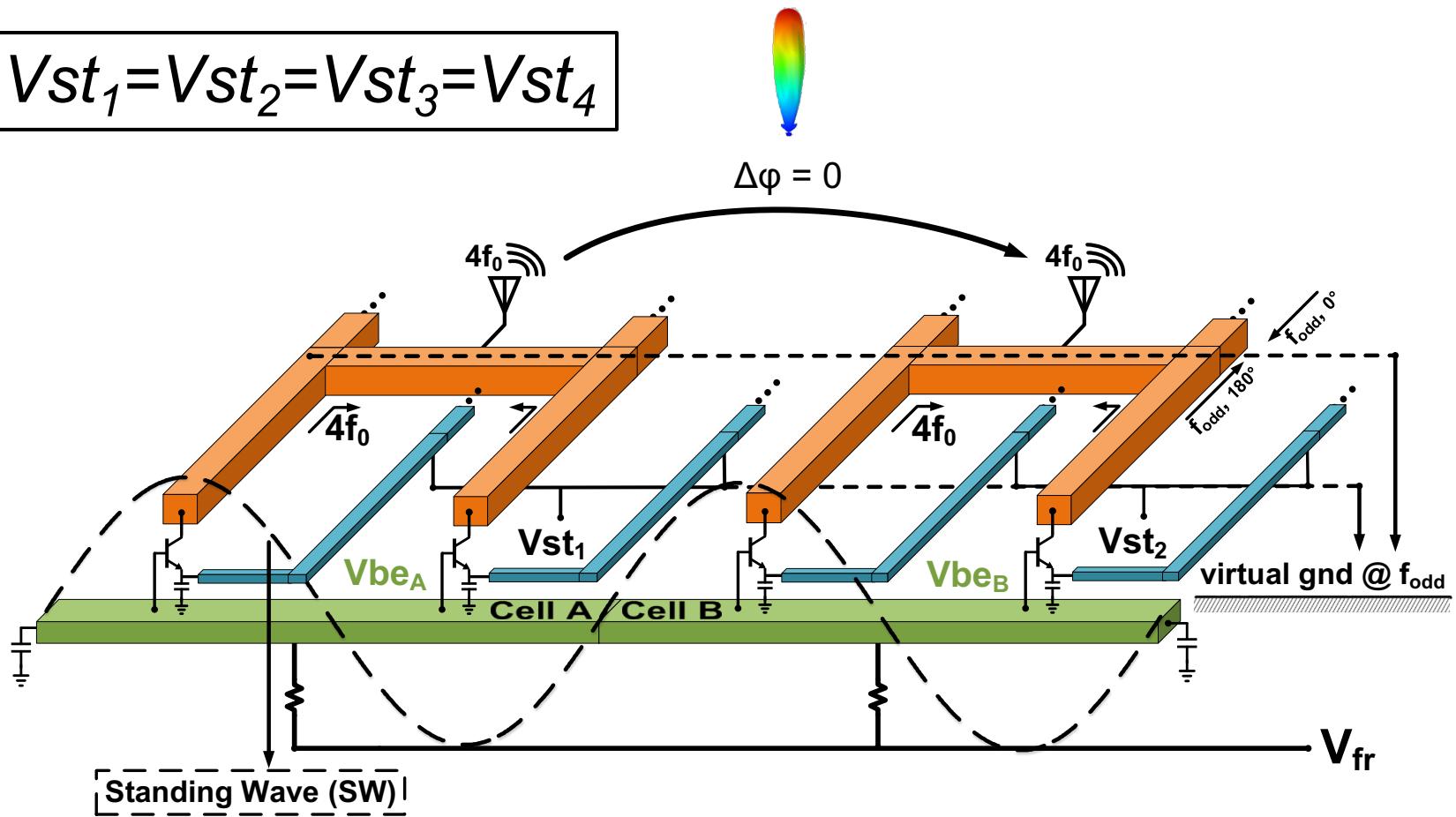


X-Steering

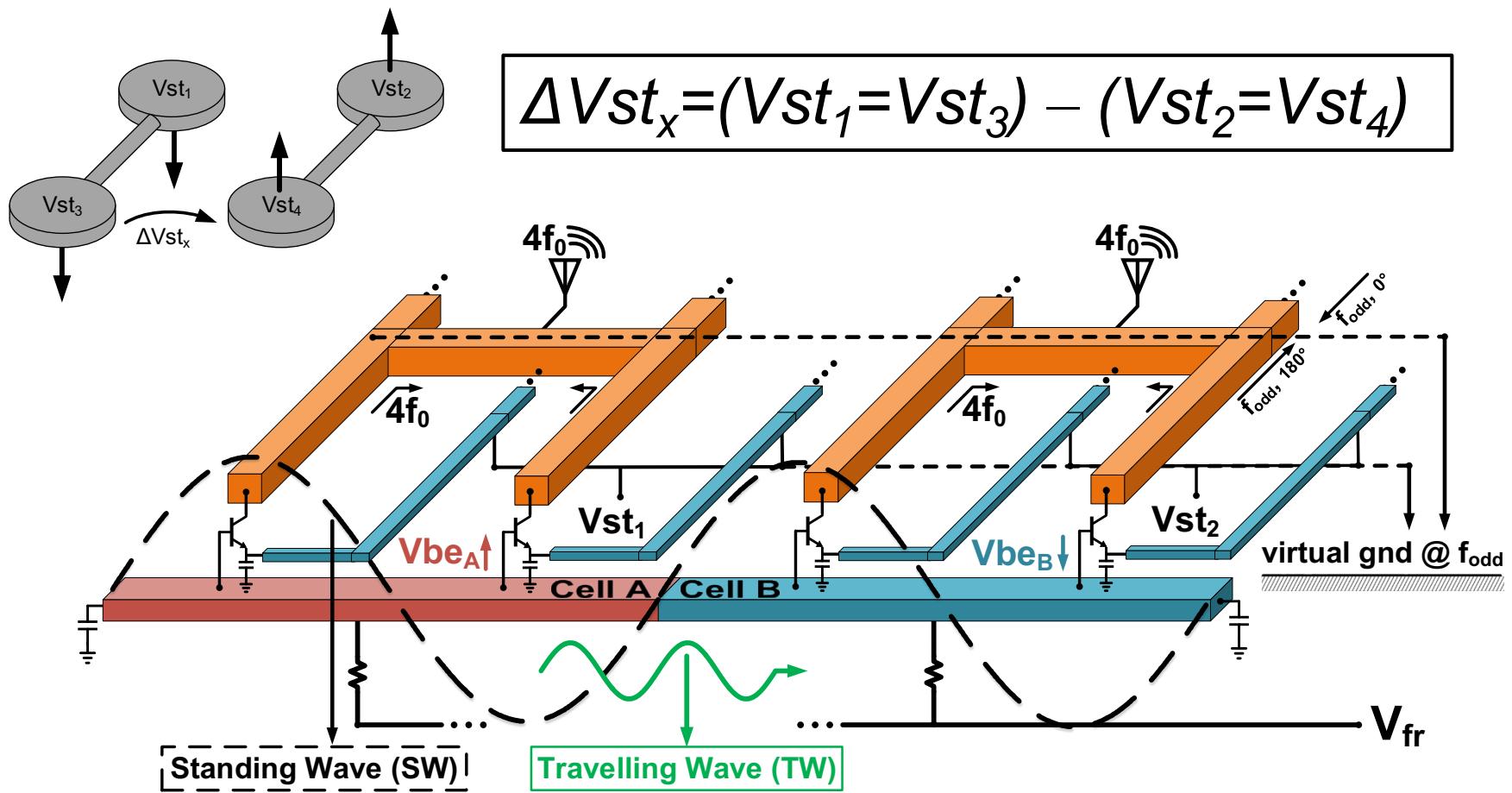


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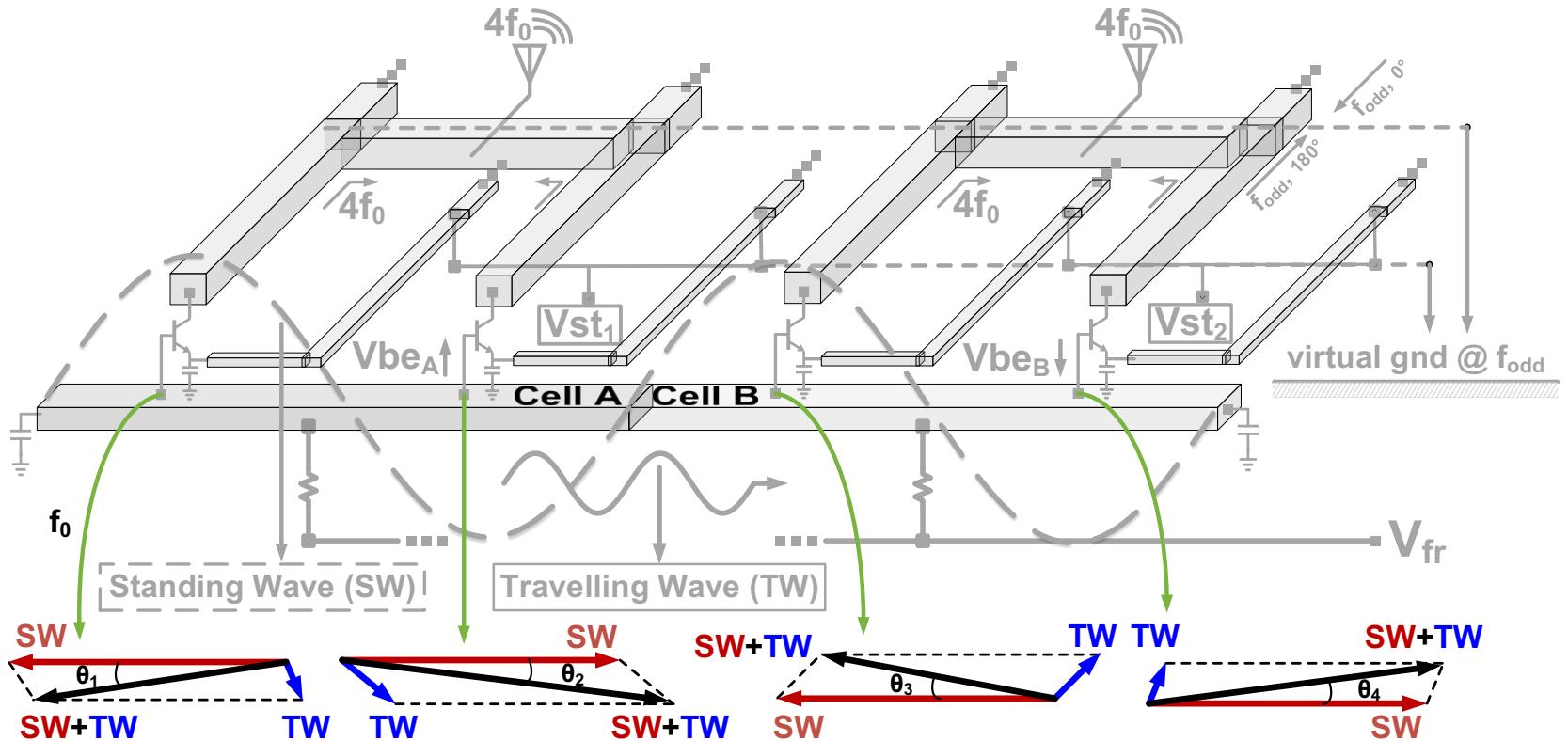
$$Vst_1 = Vst_2 = Vst_3 = Vst_4$$



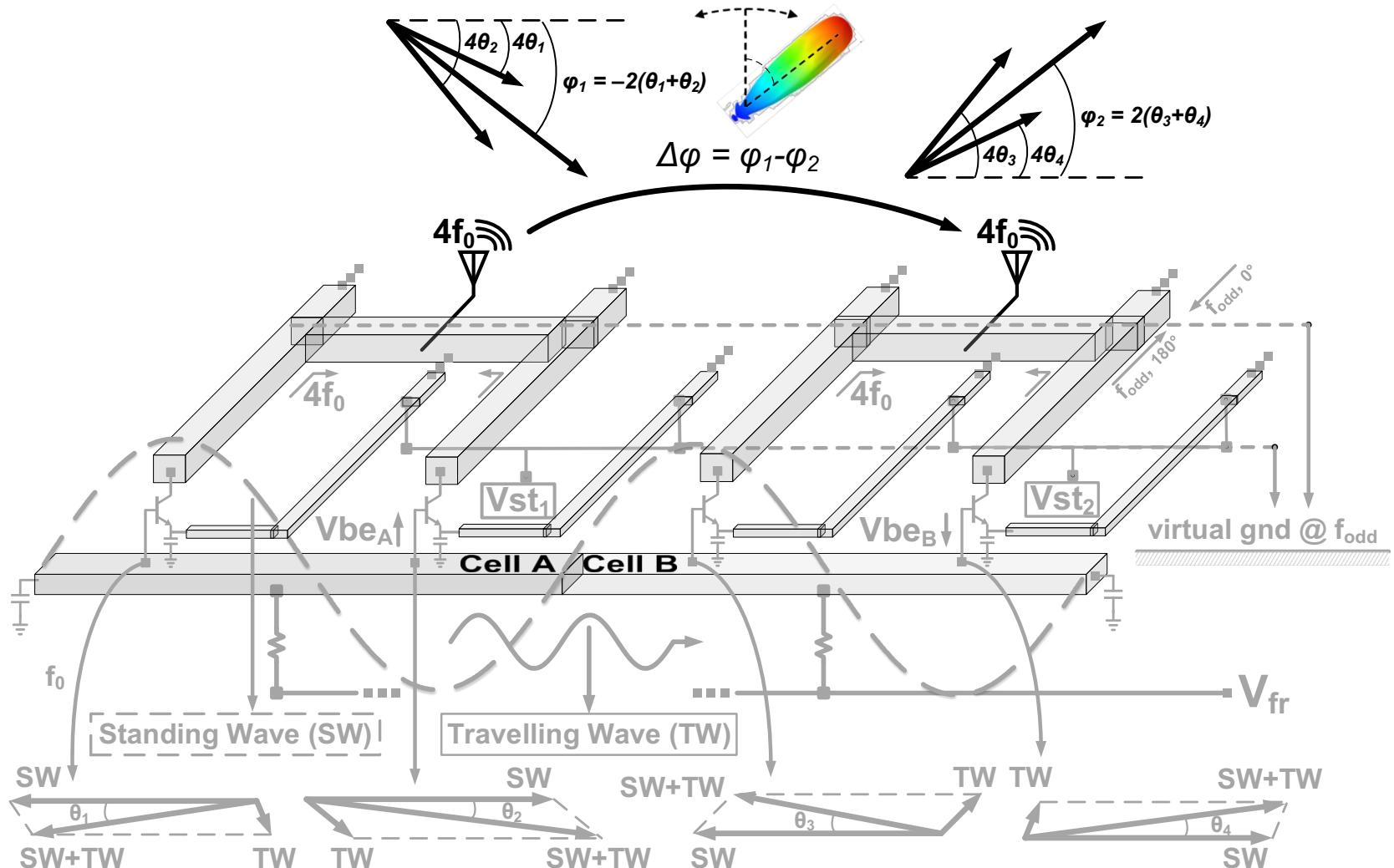
X-Steering



X-Steering

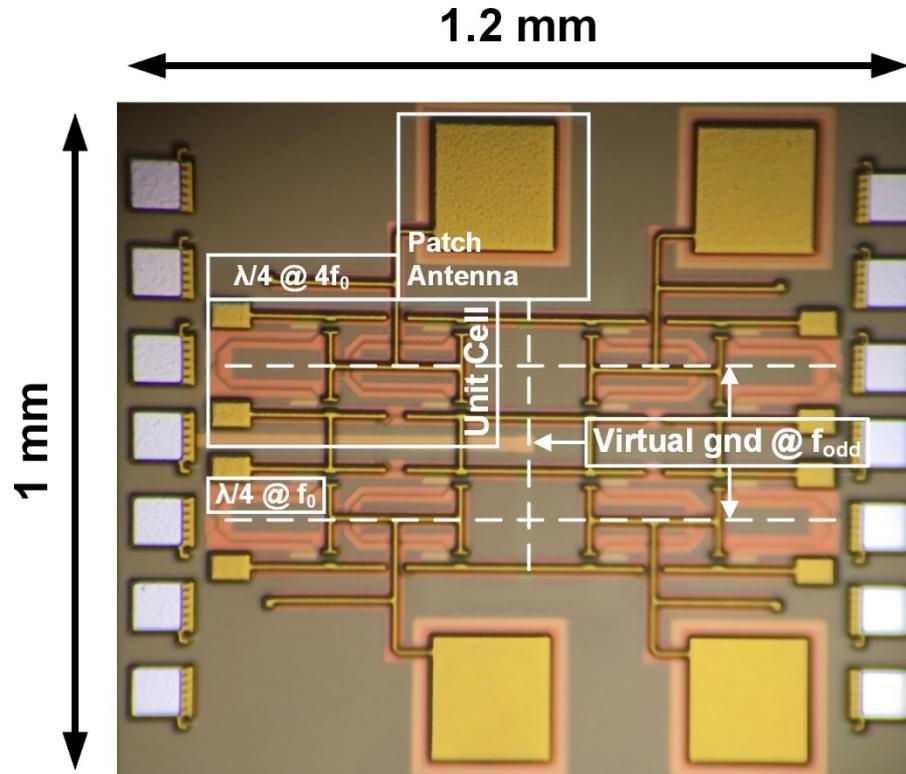


X-Steering



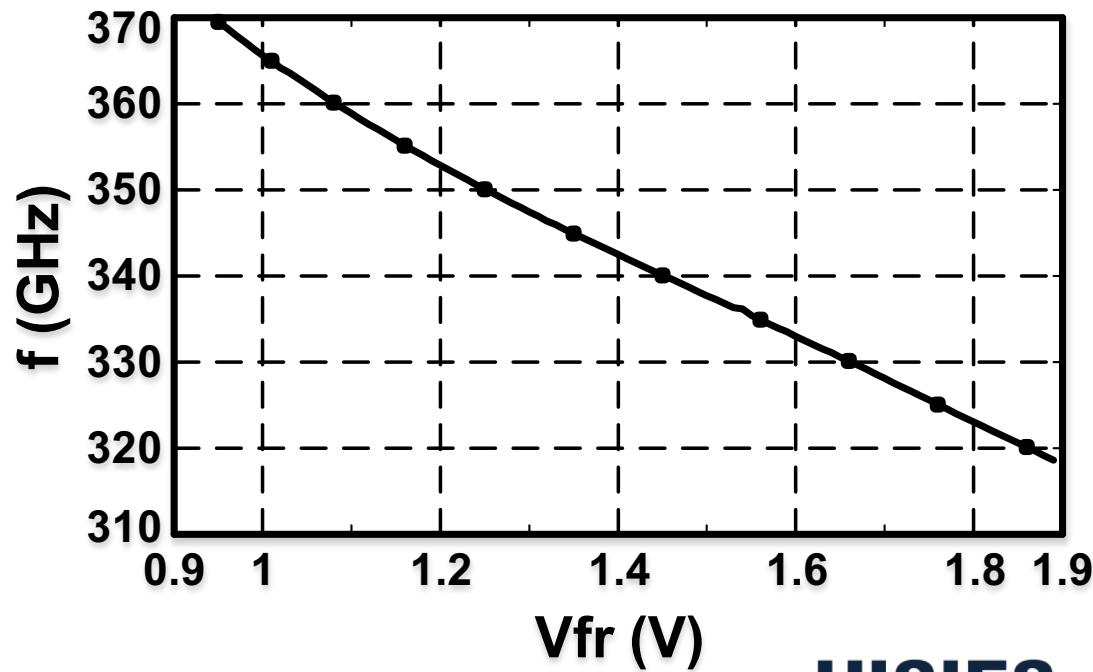
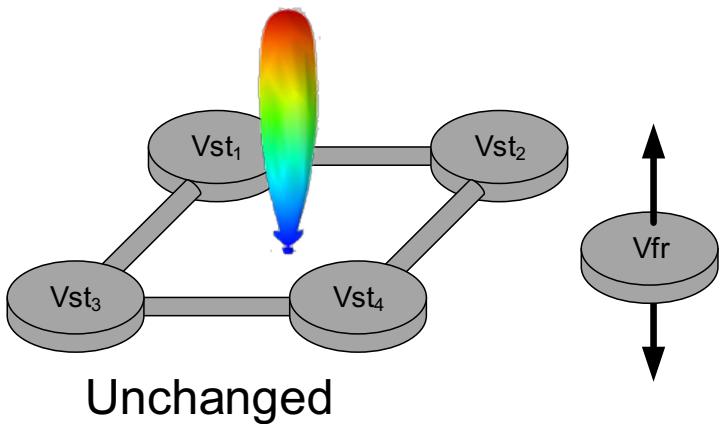
Fabrication

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- No post-processing or silicon lens used



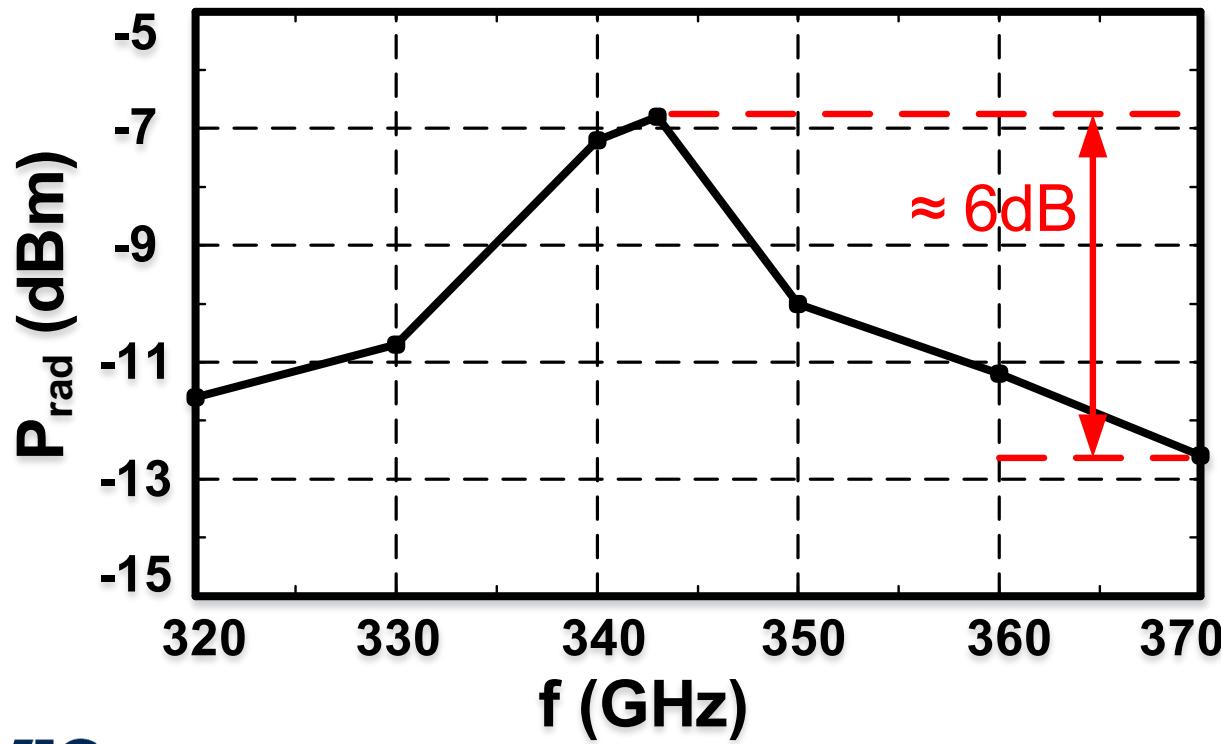
Frequency Tuning

- Frequency range: 318-to-370GHz
- 15.1% Tuning Range



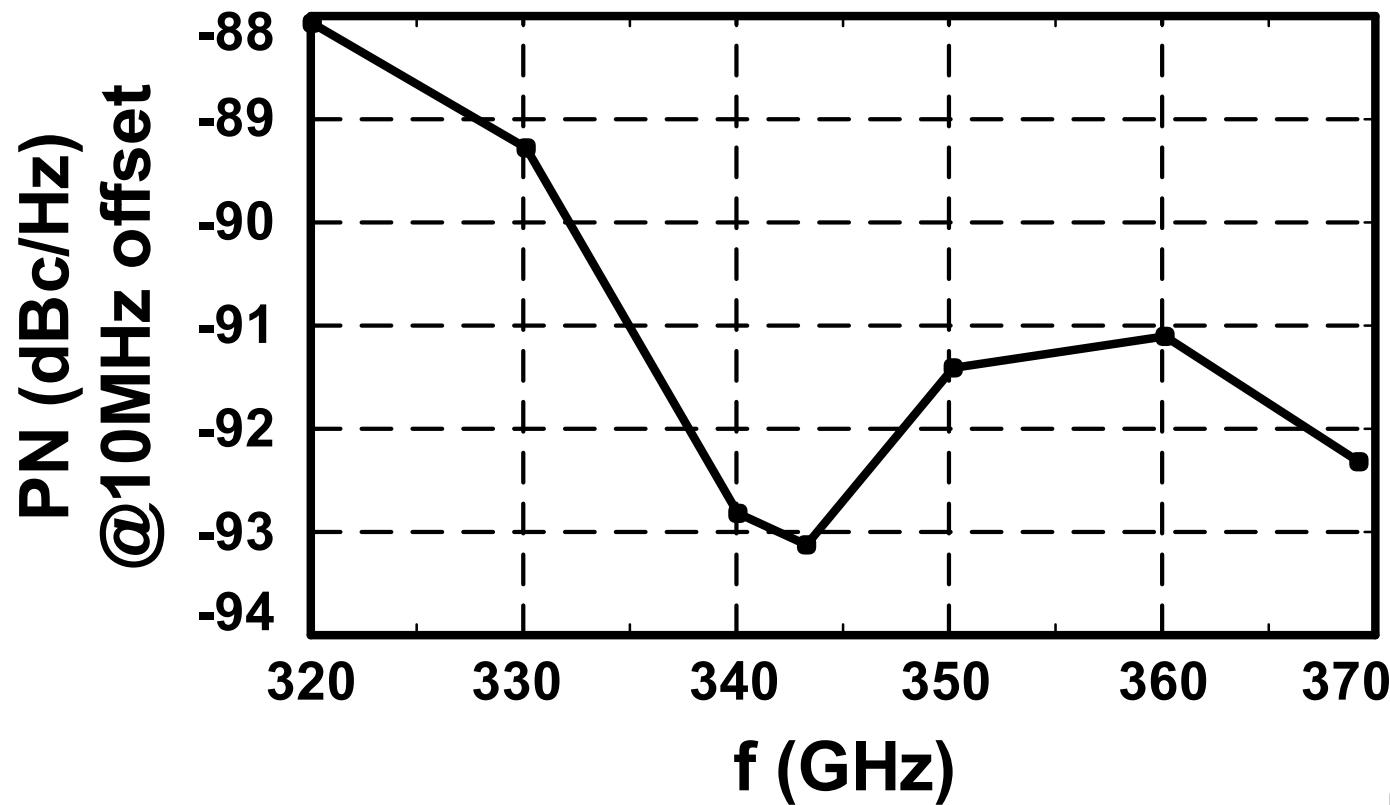
Radiated Power

- -6.8 dBm total radiated power at $f_c=344$ GHz
- Maximum 6 dB variation across tuning range

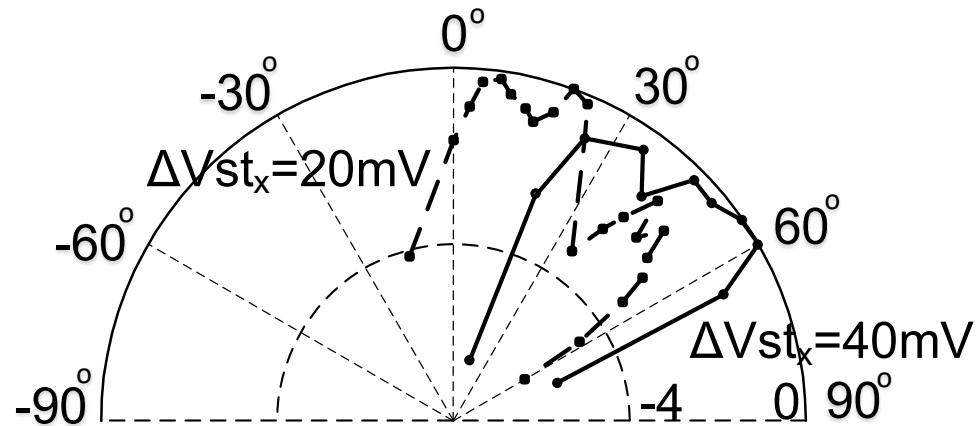
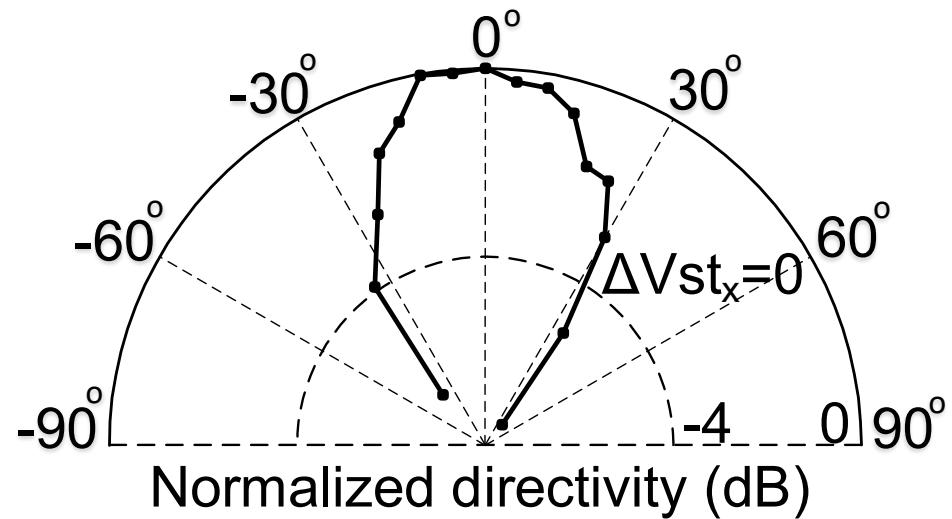
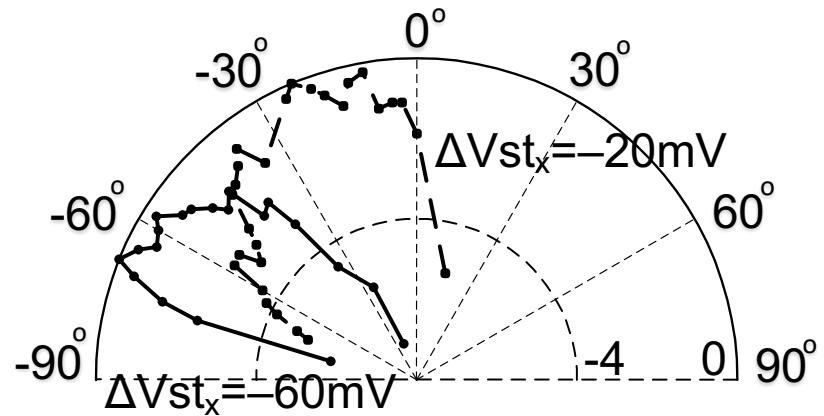
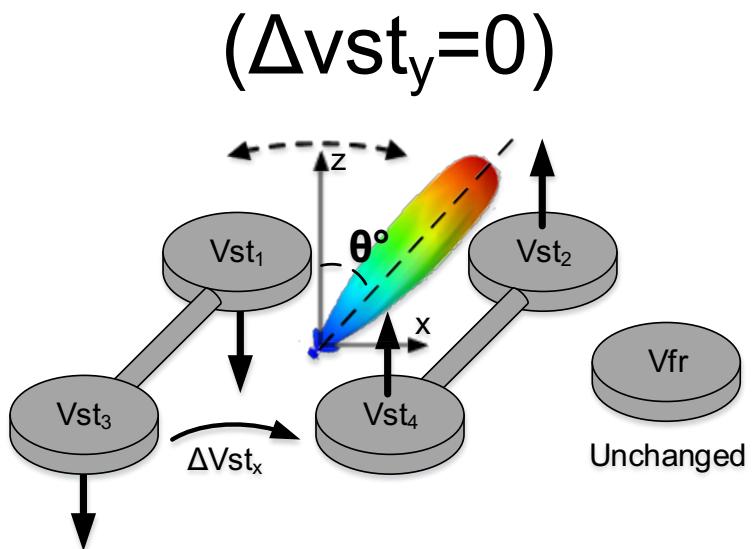


Phase Noise

□ -93.1 dBc/Hz at 10MHz offset at $f_c=344$ GHz

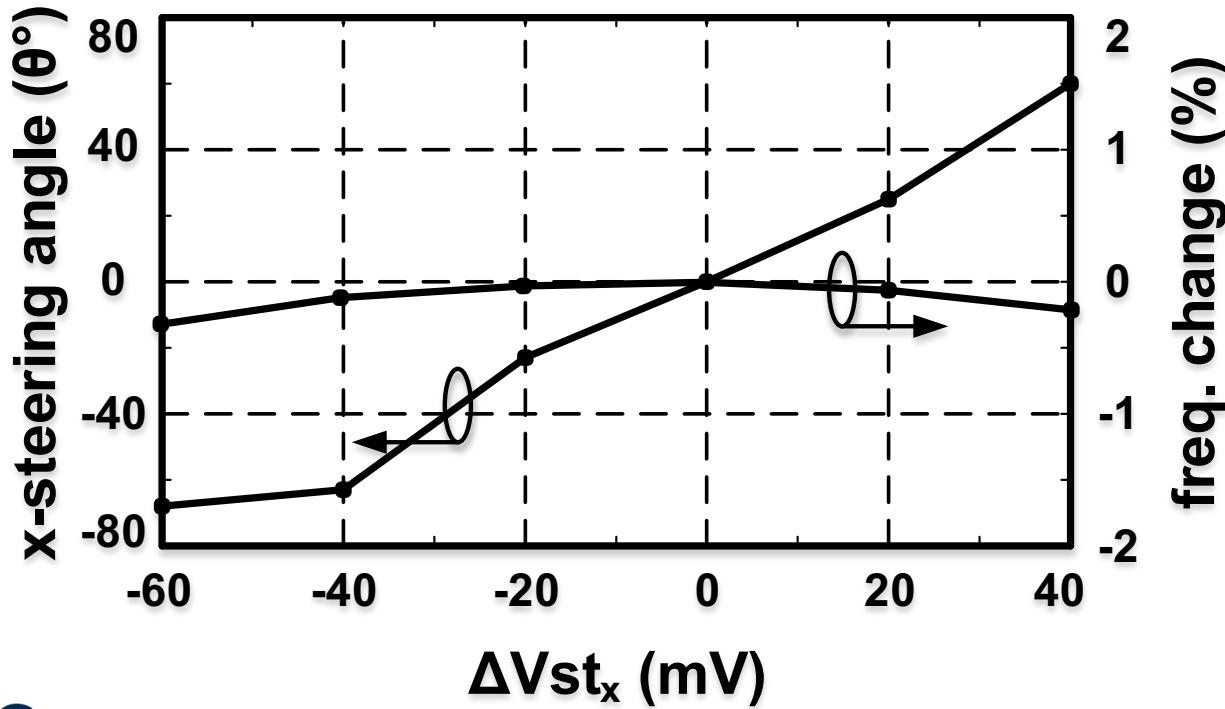


Beam Steering (E-Plane)

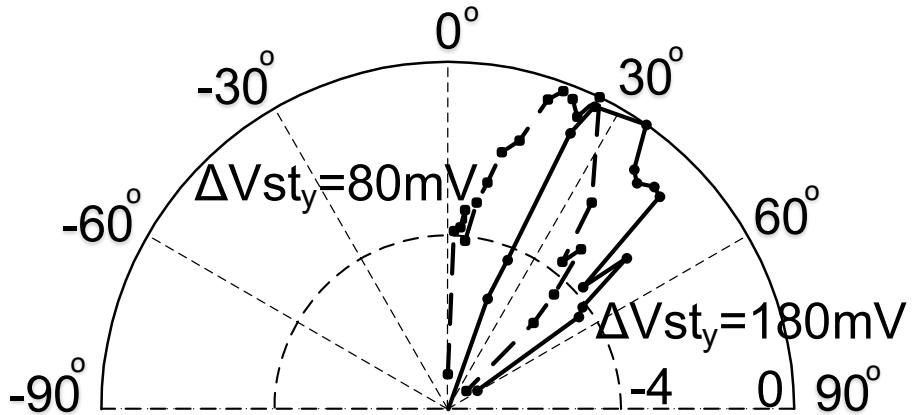
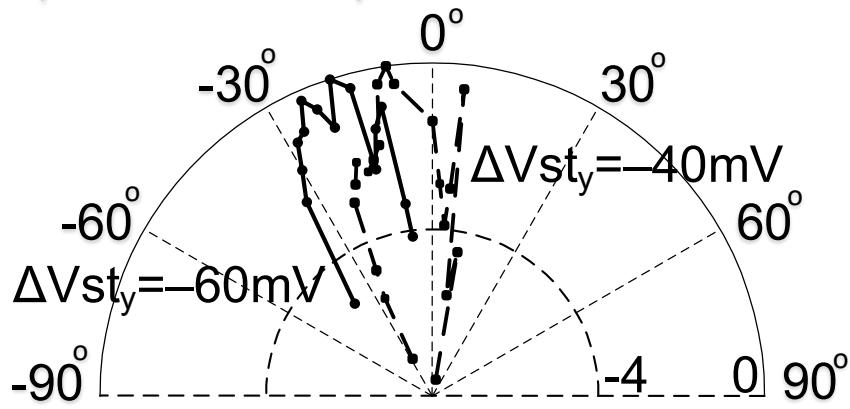
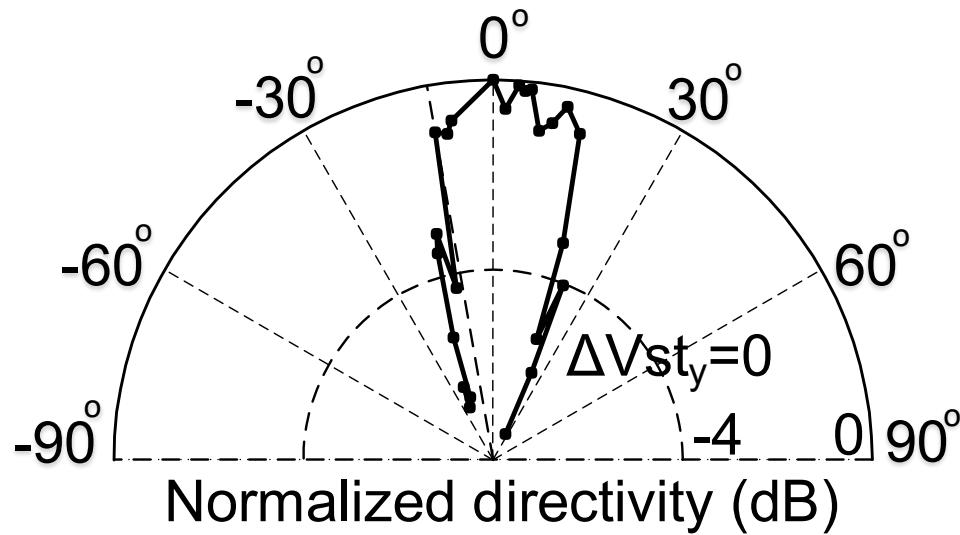
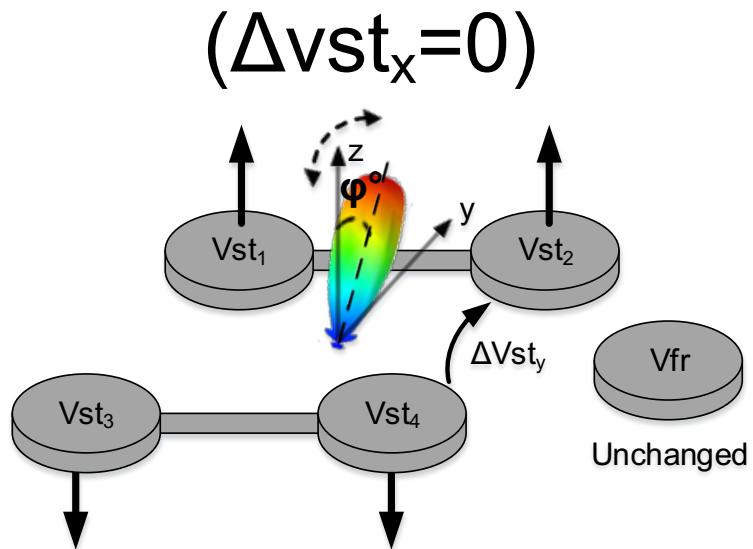


Beam Steering (E-Plane)

- 128° E-plane beam steering range
- Maximum 0.3% freq. change while steering

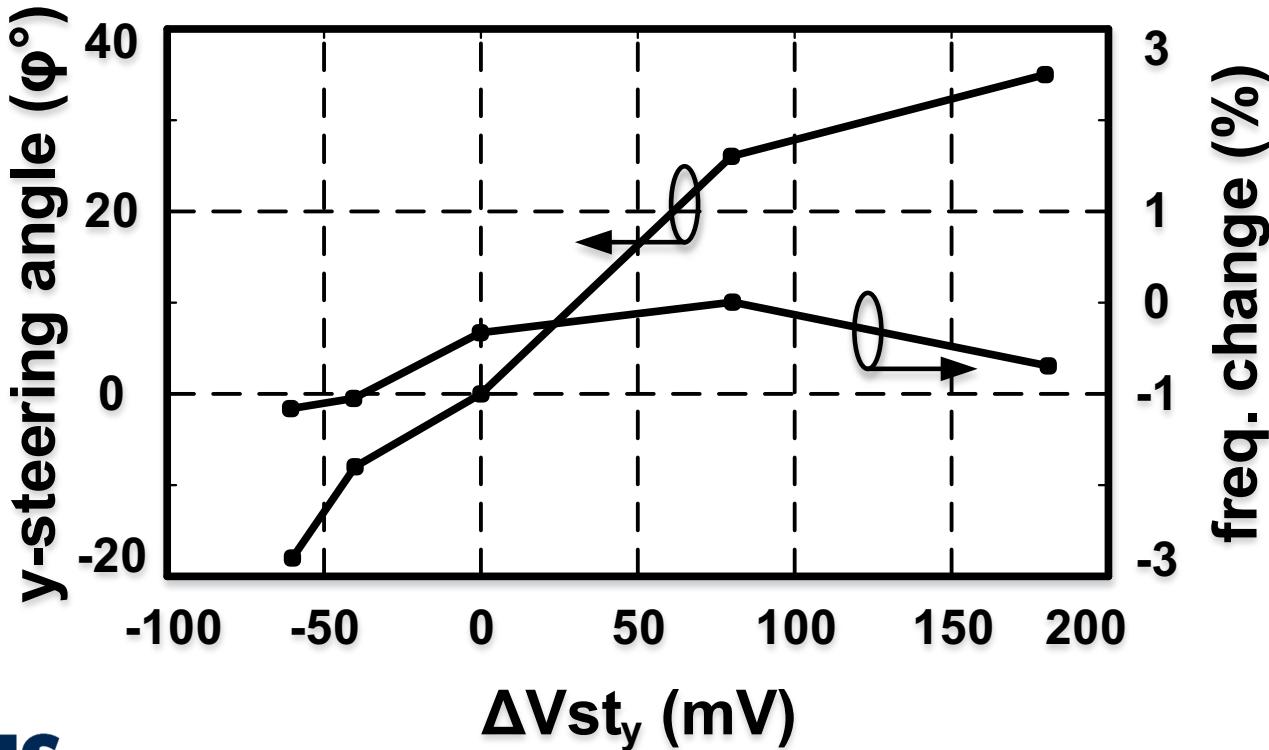


Beam Steering (H-Plane)



Beam Steering (H-Plane)

- 53° H-plane beam steering range
- Maximum 1.2% freq. change while steering



Results Summary

	This Work	[1]	[2]	[3]	[4]	
Frequency	344	338	280	530	320	
Array Size	2x2	4x4	4x4	4x4	4x4	
Frequency Tuning (%)	15.1	2.1	3.2	3.2	N/A	
Beam Steering E/H (°)	128/53	45/50	80/80	Fixed	Fixed	
Peak Rad. Power (dBm)	-6.8	-0.9	-7.2 ²	0 ¹	0.9	5.2 ¹
Radiation/Ant. (dBm)	-12.8	-12.9	-19.2 ²	-12 ¹	-11.1	-6.8 ¹
Phase Noise (dBc/Hz)	-93.1 (10MHz offset)	-93 (1MHz offset)	N/A	N/A	-79 (1MHz offset)	
DC Power (W)	0.31 to 0.64 ³	1.54	0.81	2.54	0.61	
Technology	130nm SiGe	65nm Bulk CMOS	45nm SOI CMOS	130nm SiGe	130nm SiGe	
f _{max} (GHz)	215	250	N/A	500	320	
Area (mm ²)	1.2	3.9	7.2	4.2	2.1	

1 Hemispheric Si lens used

2 Substrate thinning used

3 For frequencies 370 to 318 GHz

Conclusion

- Strong signal generation and radiation is perhaps the most challenging part of any THz system. Without it these systems can not reach the potentials that are envisioned for them.
- Individual oscillator or amplifier blocks have limited output power and it is essential to enable scalable array structures for higher output power.
- We have shown a scalable radiator array at THz frequencies that takes advantage of standing wave properties.
- We have also shown a phased array system at THz frequencies with record breaking tuning range and beam steering angle.

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