Student Paper Finalist

RTU2B-2

Fully-Scalable 2D THz Radiating Array: A 42-Element Source in 130-nm SiGe with 80-µW Total Radiated Power at 1.01THz

Zhi Hu and Ruonan Han
MIT, Cambridge, MA, USA
Massachusetts Institute of Technology

Outline

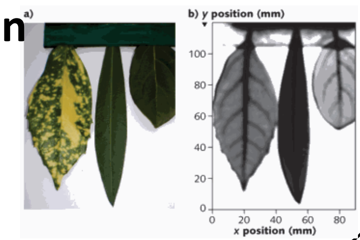
- Motivation and Challenges
- Design of Oscillator
- Formation of 1-THz Oscillating-Radiating Array
- Measurement Results
- Conclusions

Pushing Frequency and Power Limit of THz Radiator

Applications of high-power high-frequency THz source

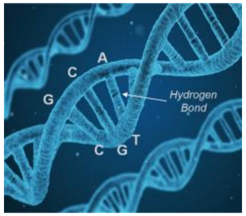
High-Resolution Imaging

[F. Schuster et al., *ISSCC*, 2011.]



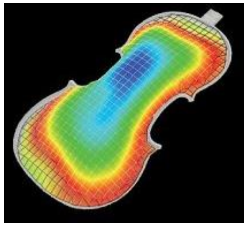
Bio-Molecule Spectroscopy

[T. Globus et al., *Convergent Science Physical Oncology*, 2016.]

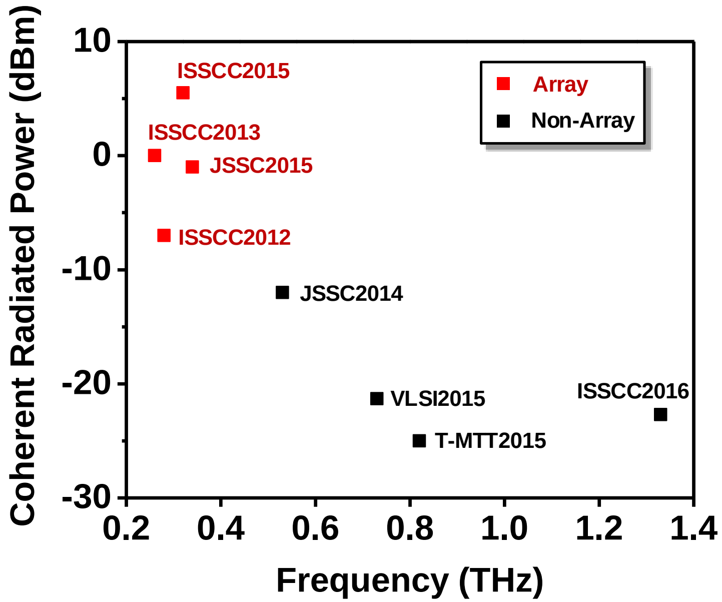


High-Precision Vibrometry

[G. Bissinger, D. Oliver, *Sound & Vibration*, 2007.]



Path to high-power 1-THz radiator



- **Building coherent radiating array at higher frequency is more challenging**

Why Building 1-THz Radiating Array Is Difficult?

1 THz > f_{max} of all silicon-based transistors (fastest: 450 GHz in IHP S13G2)

→ Efficient high-order harmonic generation and radiation

Antenna array requires λ/2 spacing

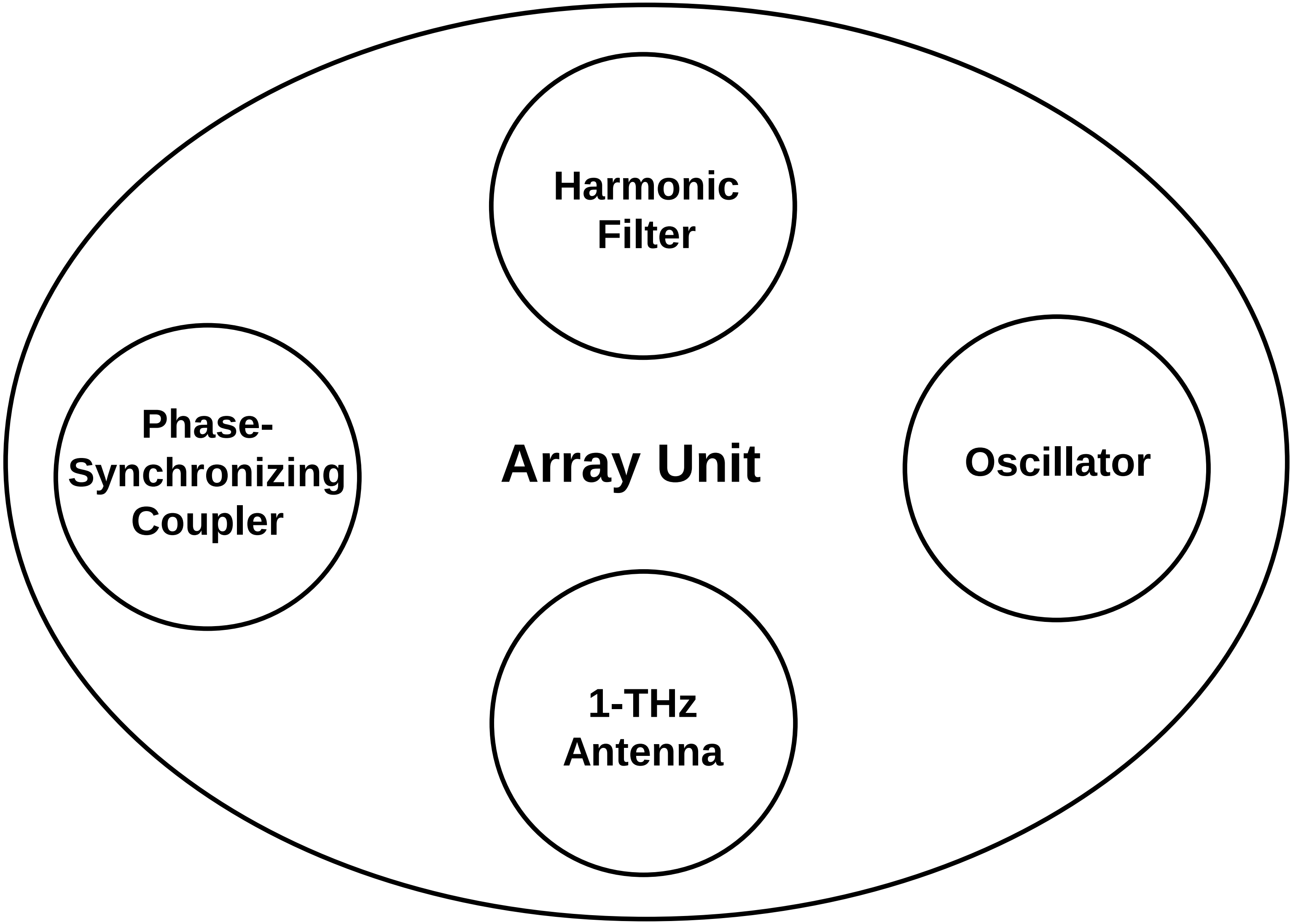
→ ~70μm x 70μm for each radiating unit

→ Very limited area to fit in all necessary components

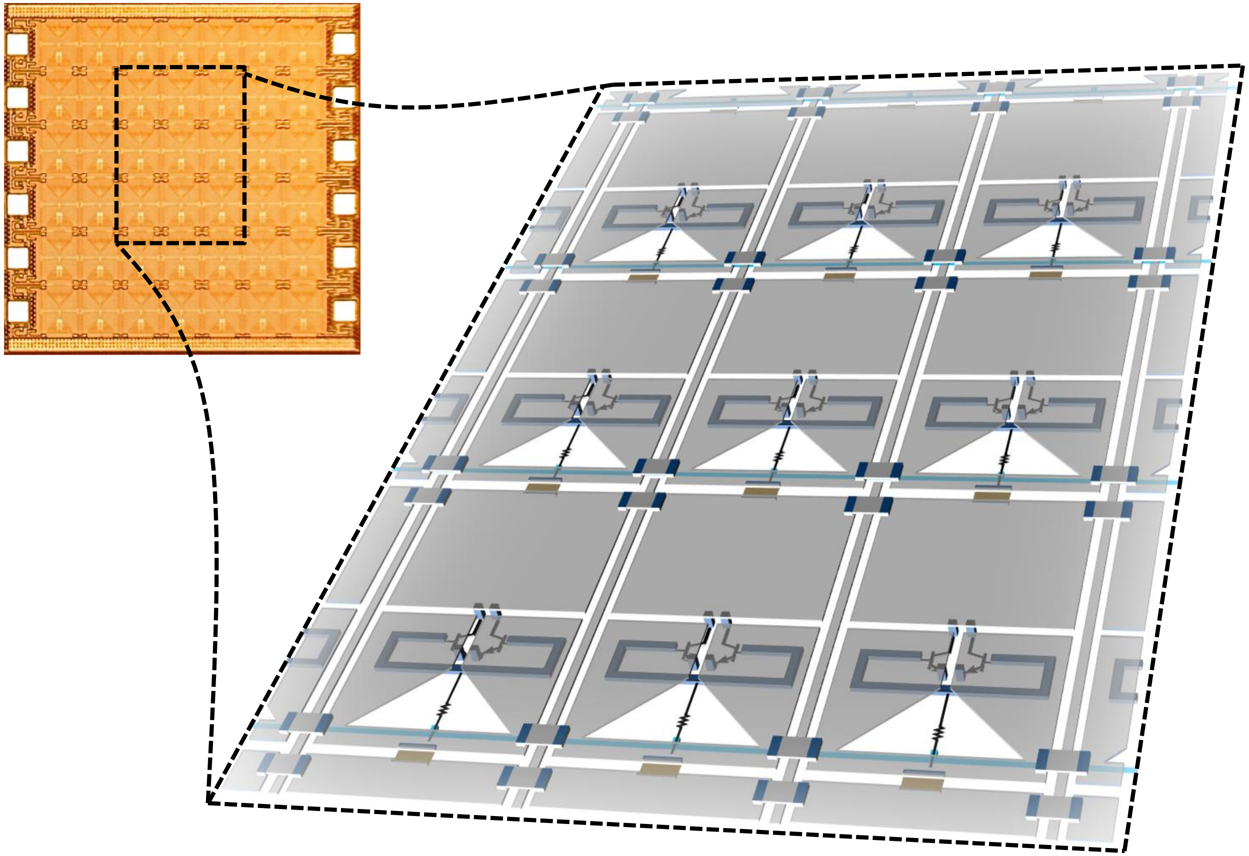
Array scale can be very large

→ Accumulation of phase error between units due to inter-unit injection can cause severe beam tilting

Call for Compact Multi-Functional Array Unit



Our Slotline-Bound-Array Solution

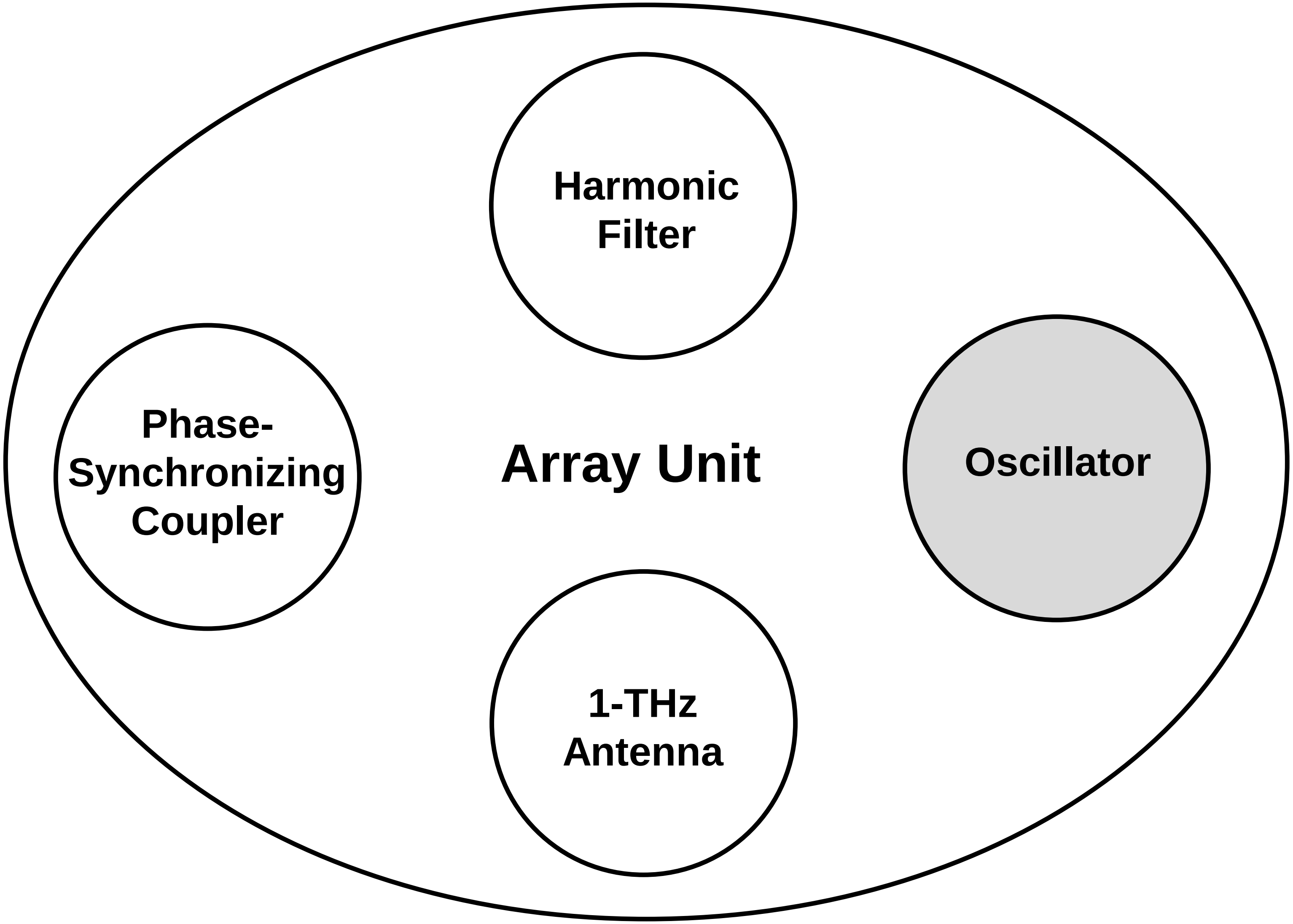


- **Differential oscillators plus slotlines accomplish all tasks**
  - Each unit oscillates at f_0 = 250 GHz and radiates $4f_0$ = 1 THz

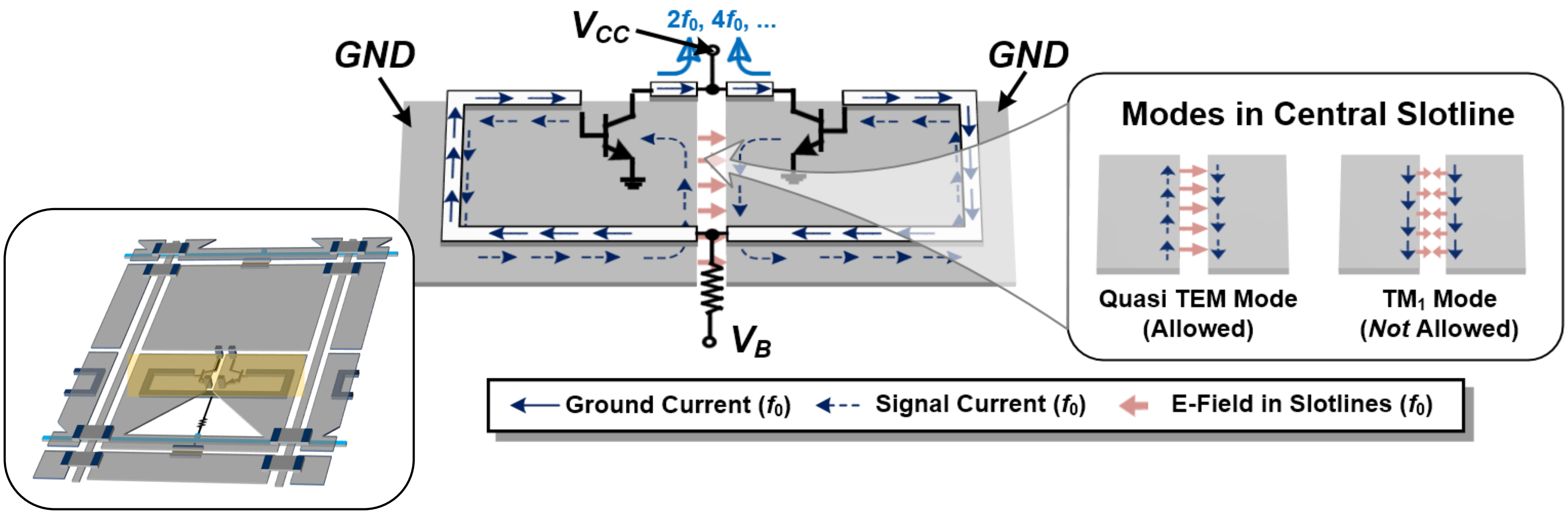
Outline

- Motivation and Challenges
- **Design of Oscillator**
- Formation of 1-THz Oscillating-Radiating Array
- Measurement Results
- Conclusions

Multi-Functional Array Unit

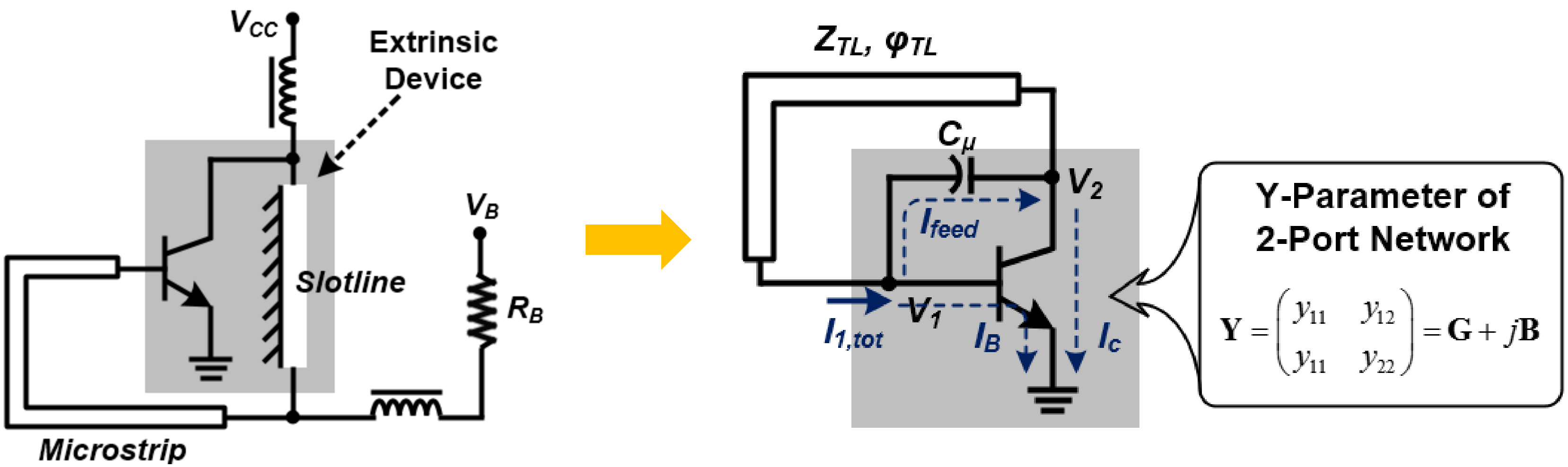


Oscillator Pair Capable of Efficient Harmonic Generation



- **At f_0 (250 GHz), two oscillators are forced to oscillate differentially**
- **For even-order harmonics from two oscillators, including $4f_0$ = 1 THz**
  - They are in-phase, hence repelled from slotline (feedback loop)
  - No dissipation at base, more power is delivered outwards

Maximize Oscillation at f_0 in Single Oscillator

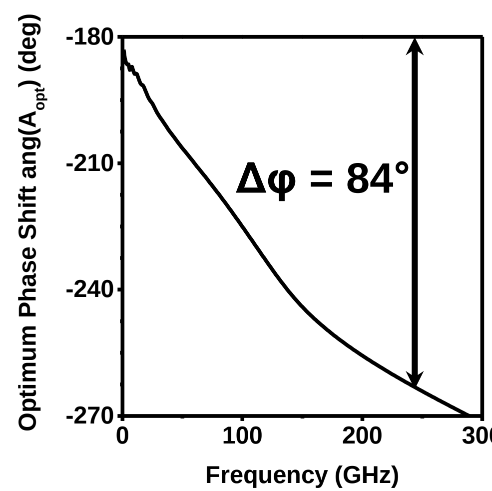


- **Phase delay of V_2 should be compensated**
  - Intrinsic delay of I_C
  - Undesired feed-forward current I_{feed}
- **Use self-feeding topology to adjust phase**

$$\angle A_{opt} = \angle V_2 / V_1 = -\left(y_{21} + y_{12}^*\right),$$

$$\varphi_{TL} = \arcsin\left(Z_{TL} \cdot \left(g_{11} + \mathrm{Re}\left(A_{opt} \cdot y_{12} / \mathrm{Im}(A)\right)\right)\right)^{-1}$$

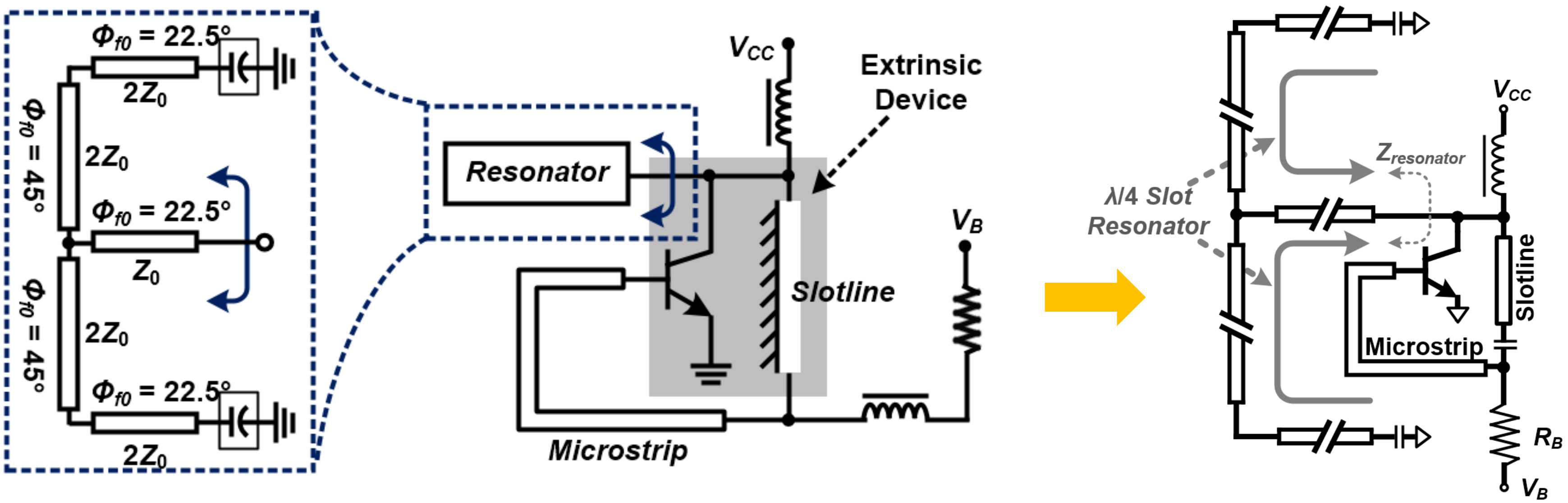
[R. Spence, Linear Active Networks, 1970.]



Outline

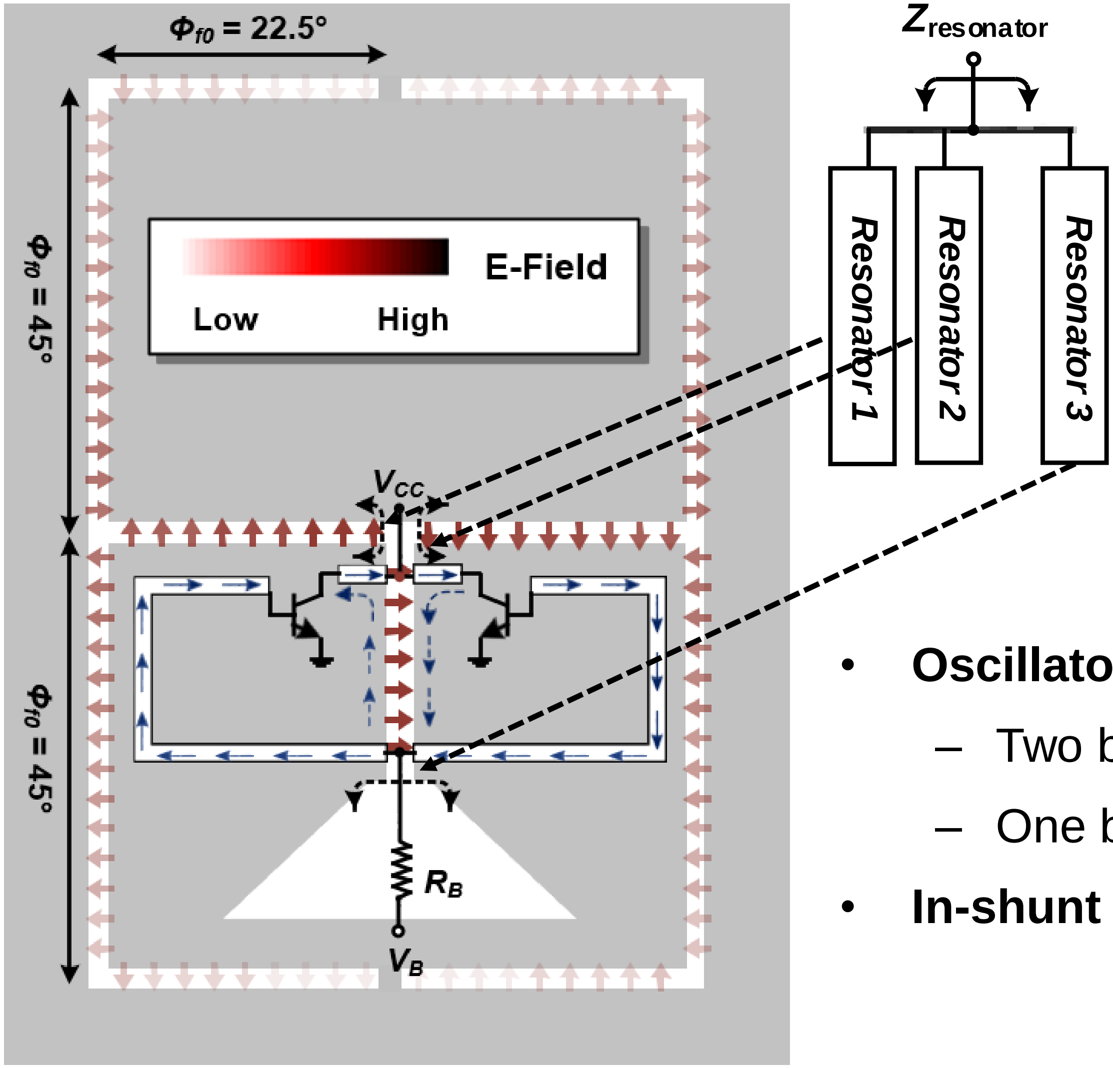
- Motivation and Challenges
- Design of Oscillating Unit
- **Formation of 1-THz Oscillating-Radiating Array**
- Measurement Results
- Conclusions

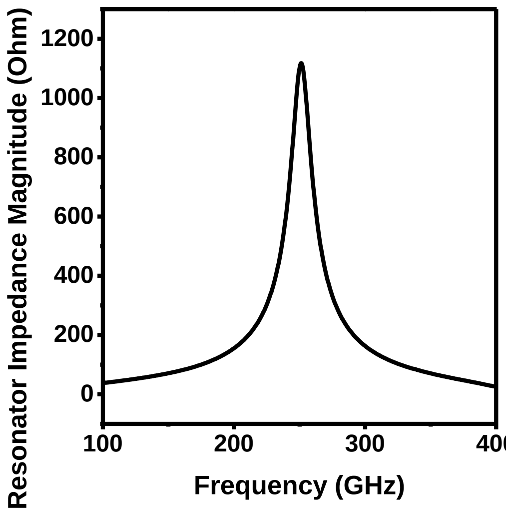
Expose Oscillation Using Branched Resonator



- Two *λ*/4 @ f_0 transmission lines (short → open)
- E-shaped pattern composes the boundary of oscillating unit
- Resonator is implemented by slotlines

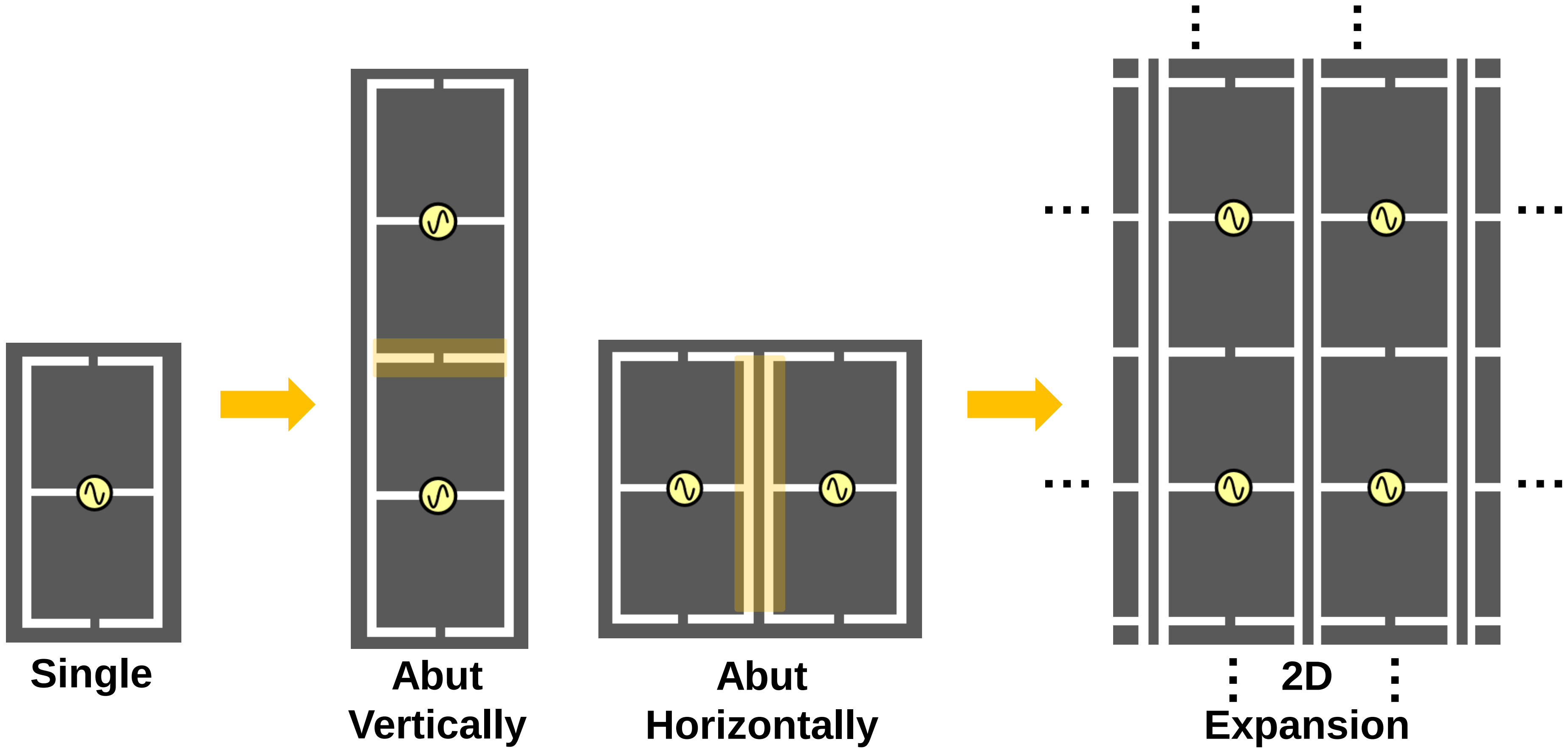
Structure of a Complete Oscillating Unit





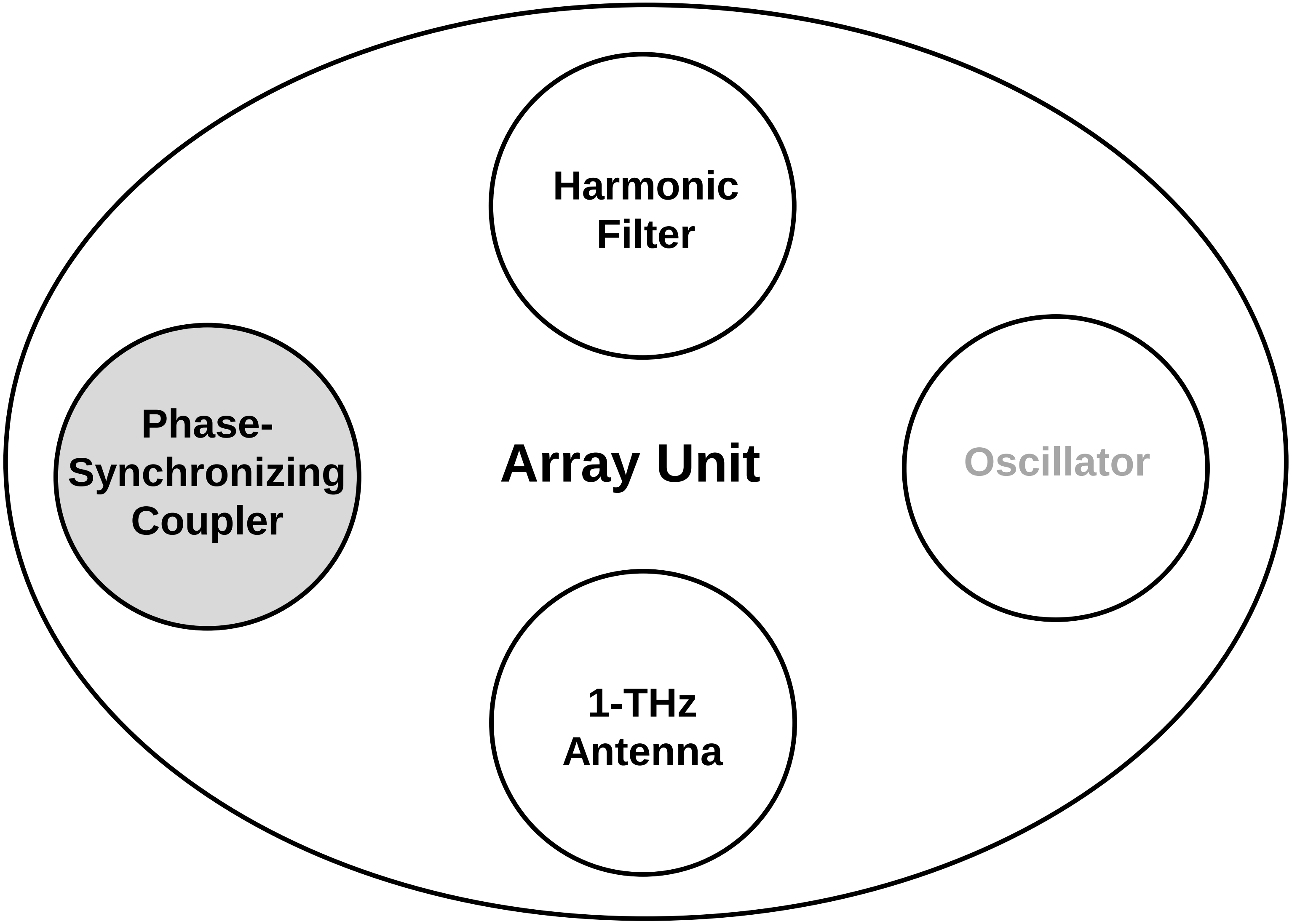
- **Oscillators sealed by three resonators**
  - Two branched resonators
  - One broadband open
- **In-shunt resonators present Q = 18**

Interface Adjacent Units Using Branched Resonator

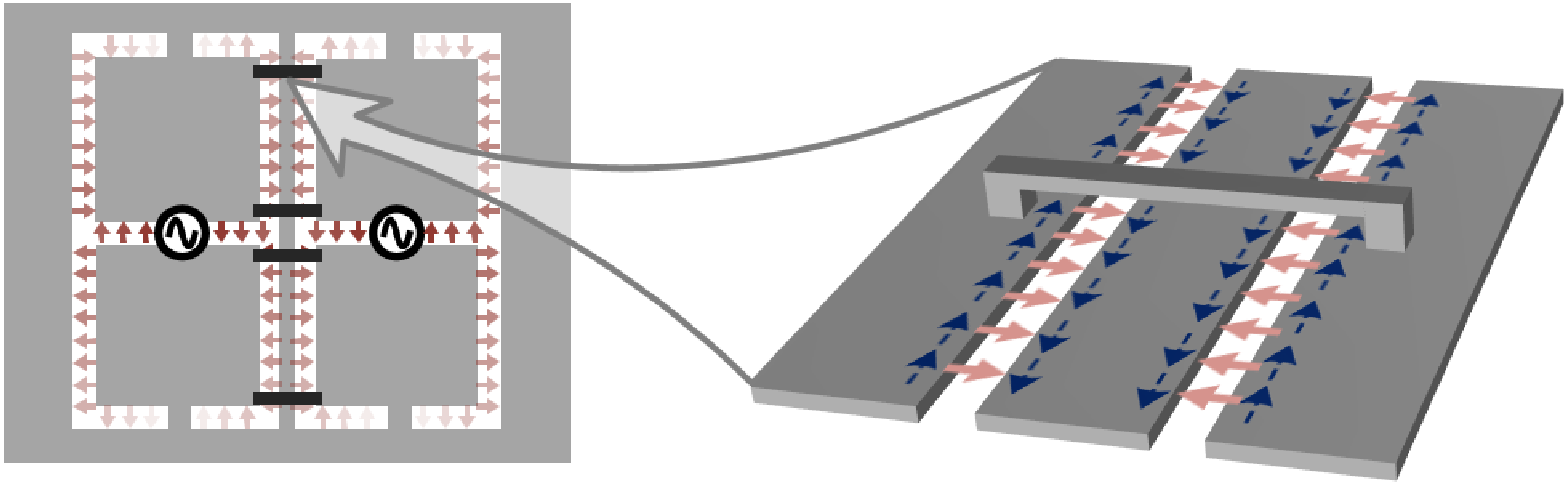


- Horizontal slotlines on the border (2x1 case) are merged
- Vertical slotlines on the border (1x2 case) run parallel

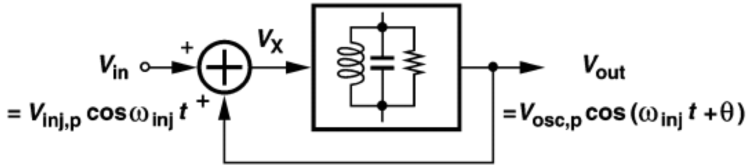
Multi-Functional Array Unit



Coupling (at f_0) between Horizontally Adjacent Units

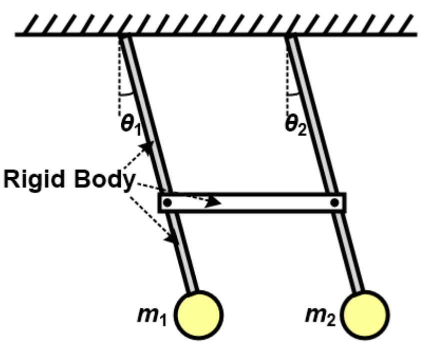


Single-Node Injection vs. Distributed Phase Synchronization



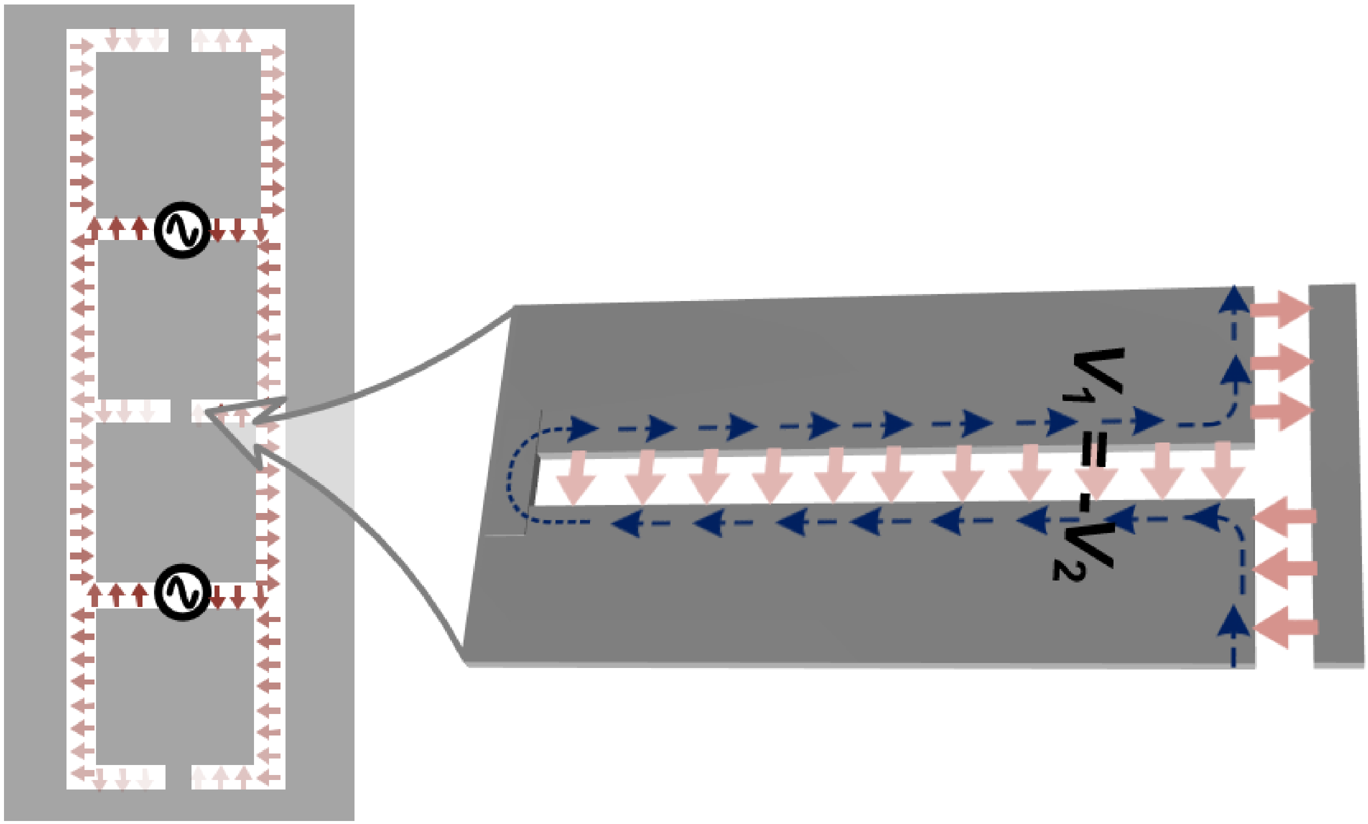
$$\frac{d\theta}{dt} = \omega_0 - \omega_{inj} - \frac{\omega_0}{2Q} \cdot \frac{V_{inj,p}}{V_{osc,p}} \sin\theta$$
$$= \omega_0 - \omega_{inj} - \omega_L \sin\theta.$$

[B. Razavi, JSSC, 2004.]



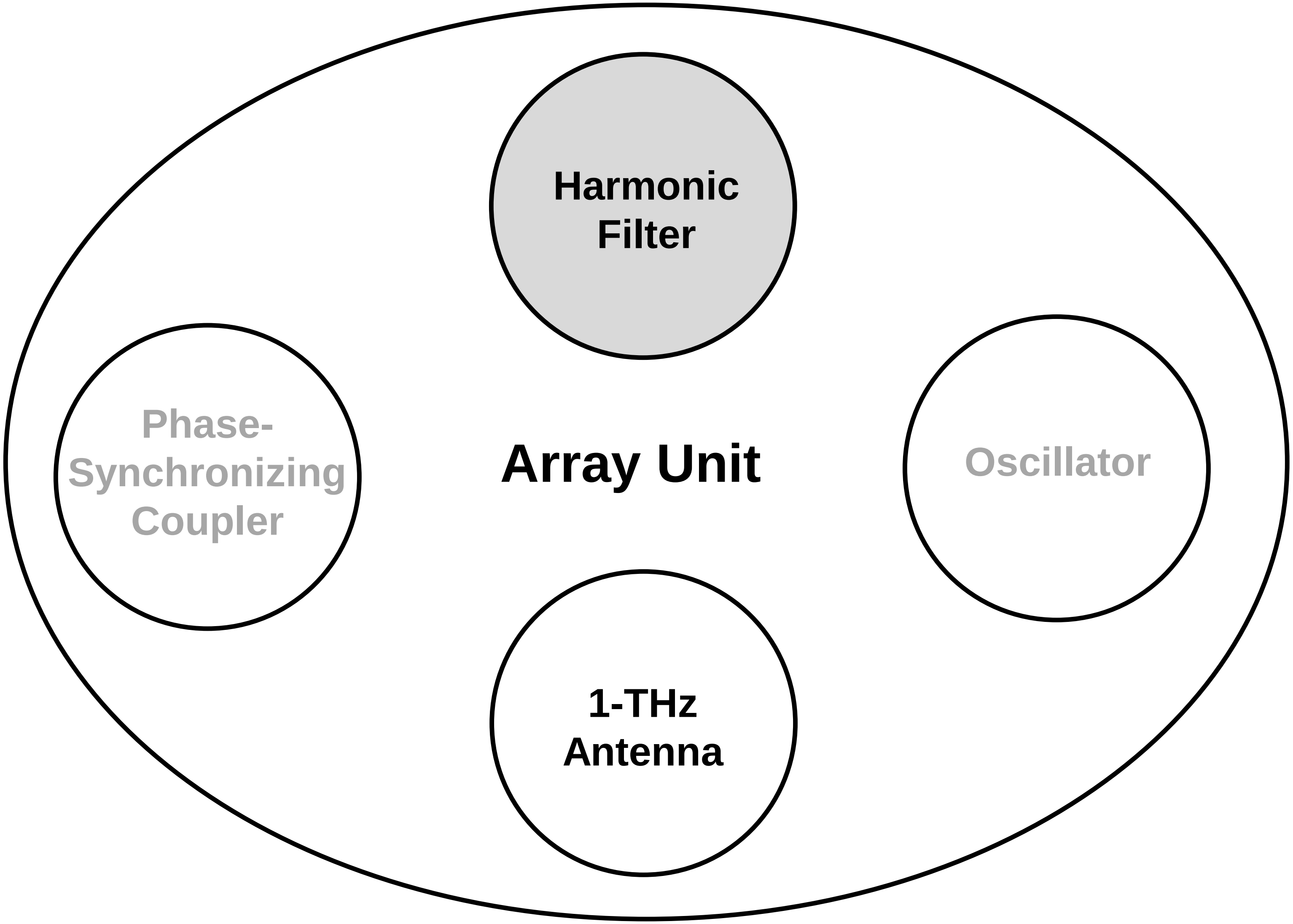
Phase at every point is synced, even if there is mismatch of ω_0

Coupling (at f_0) between Vertically Adjacent Units

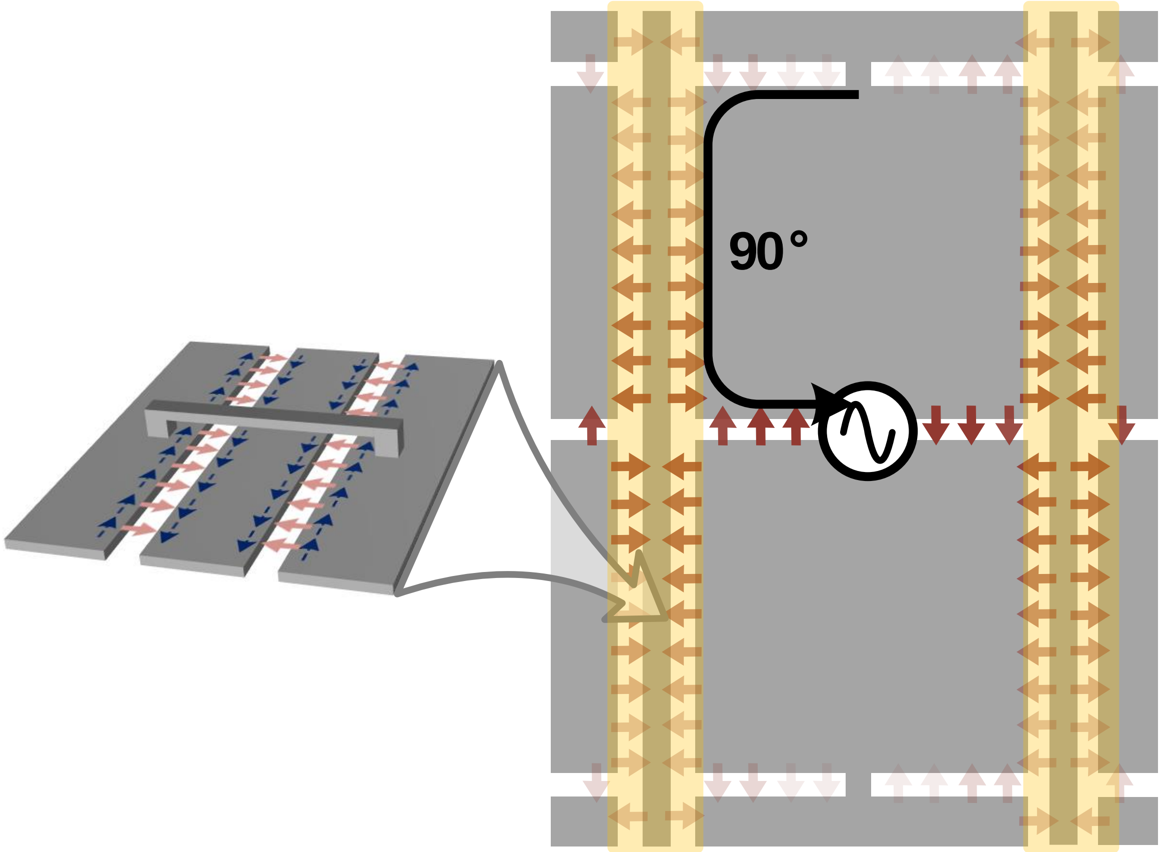


- **Branched resonator shared → phase relationship determined**
- **Use slotline for the purpose of array-wide in-phase radiation (discuss later)**

Multi-Functional Array Unit

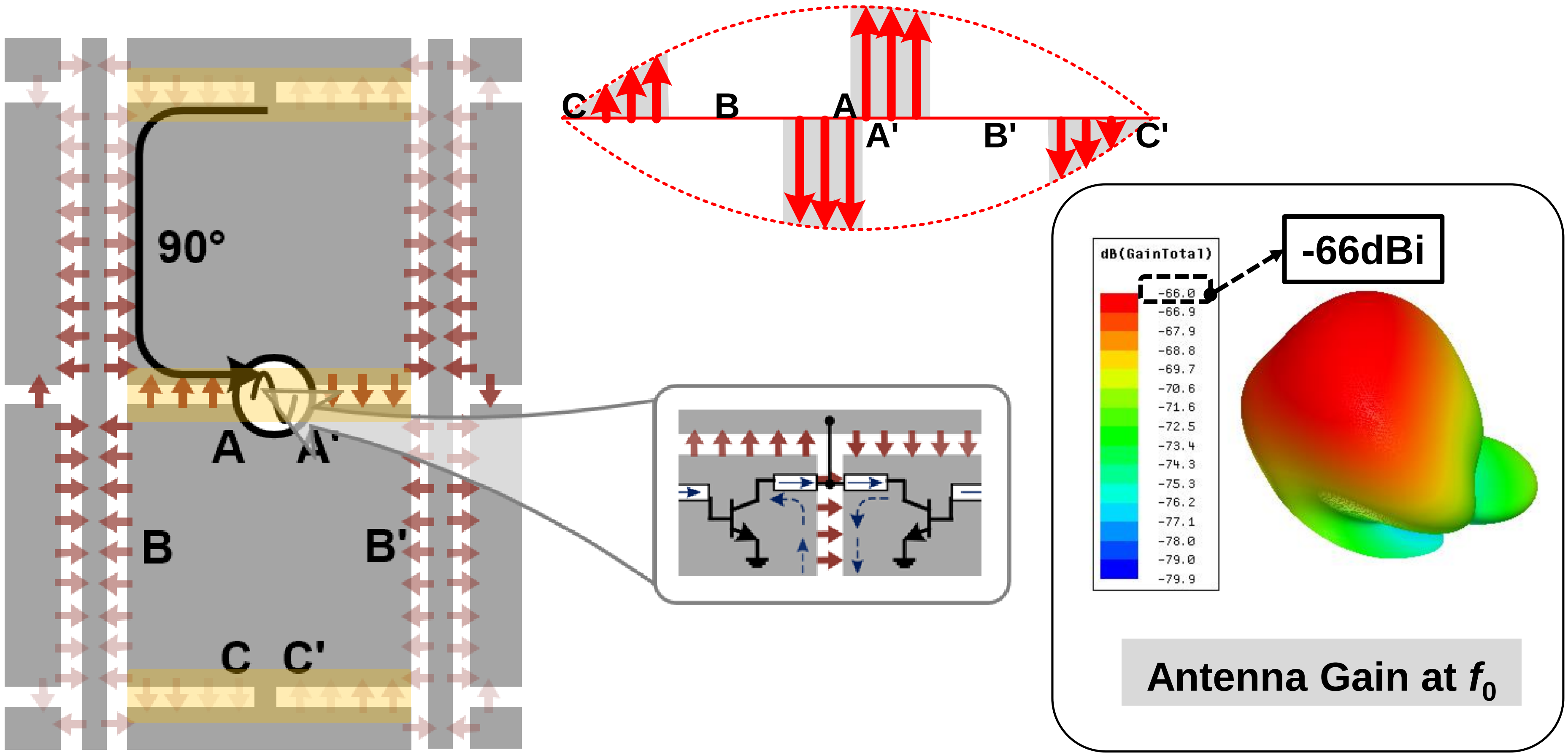


Radiation Cancellation at f_0 (250 GHz): Vertical



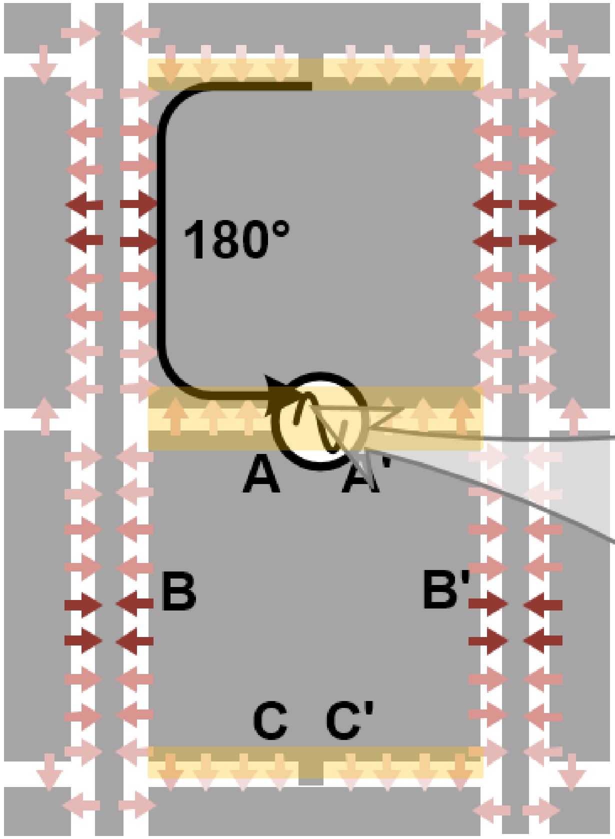
- **Vertical slotlines pairs do not radiate**
  - E-field in left and right slotlines balance out

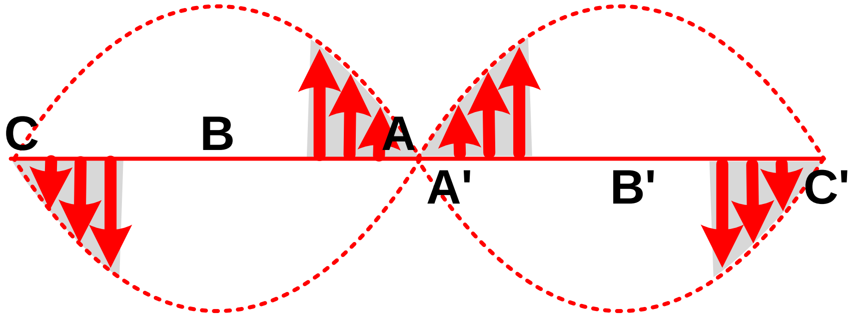
Radiation Cancellation at f_0 (250 GHz): Horizontal

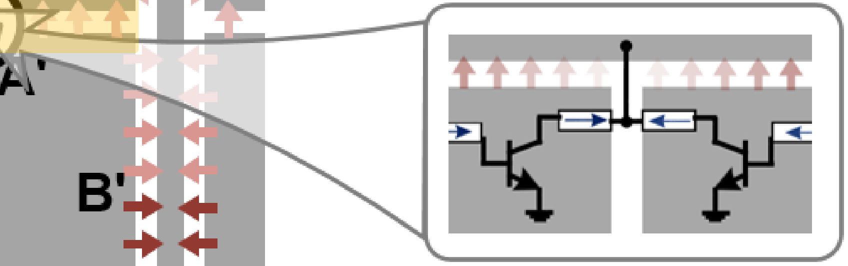


- **Horizontal slotlines pairs do not radiate**
  - E-field in left and right slotlines balance out

Radiation Cancellation at $2f_0$ (500 GHz): Horizontal

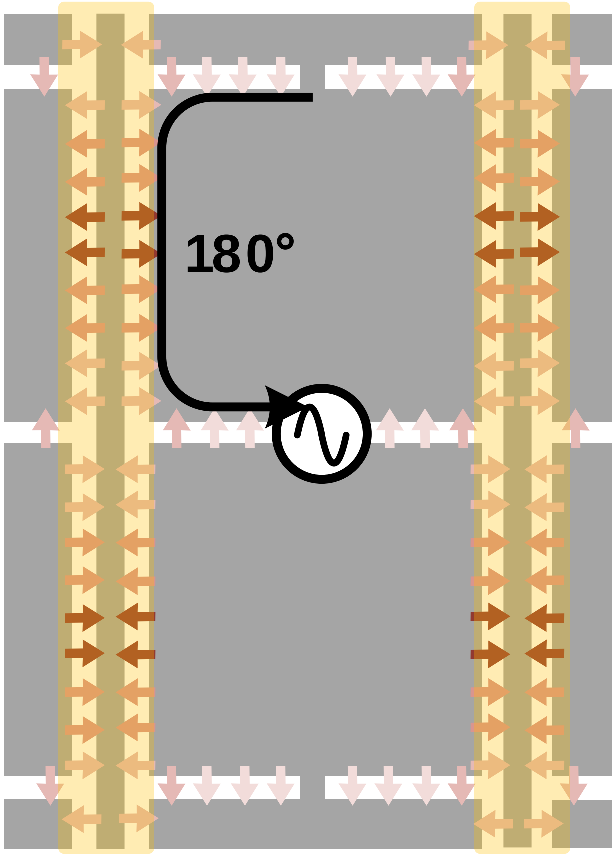


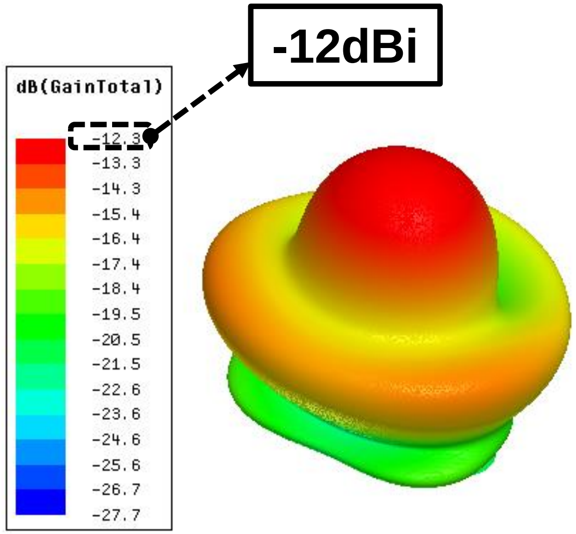




- **Horizontal slotlines do not radiate**
  - E-field in central slotlines balance out with top/bottom slotlines

Radiation Cancellation at $2f_0$ (500 GHz): Vertical

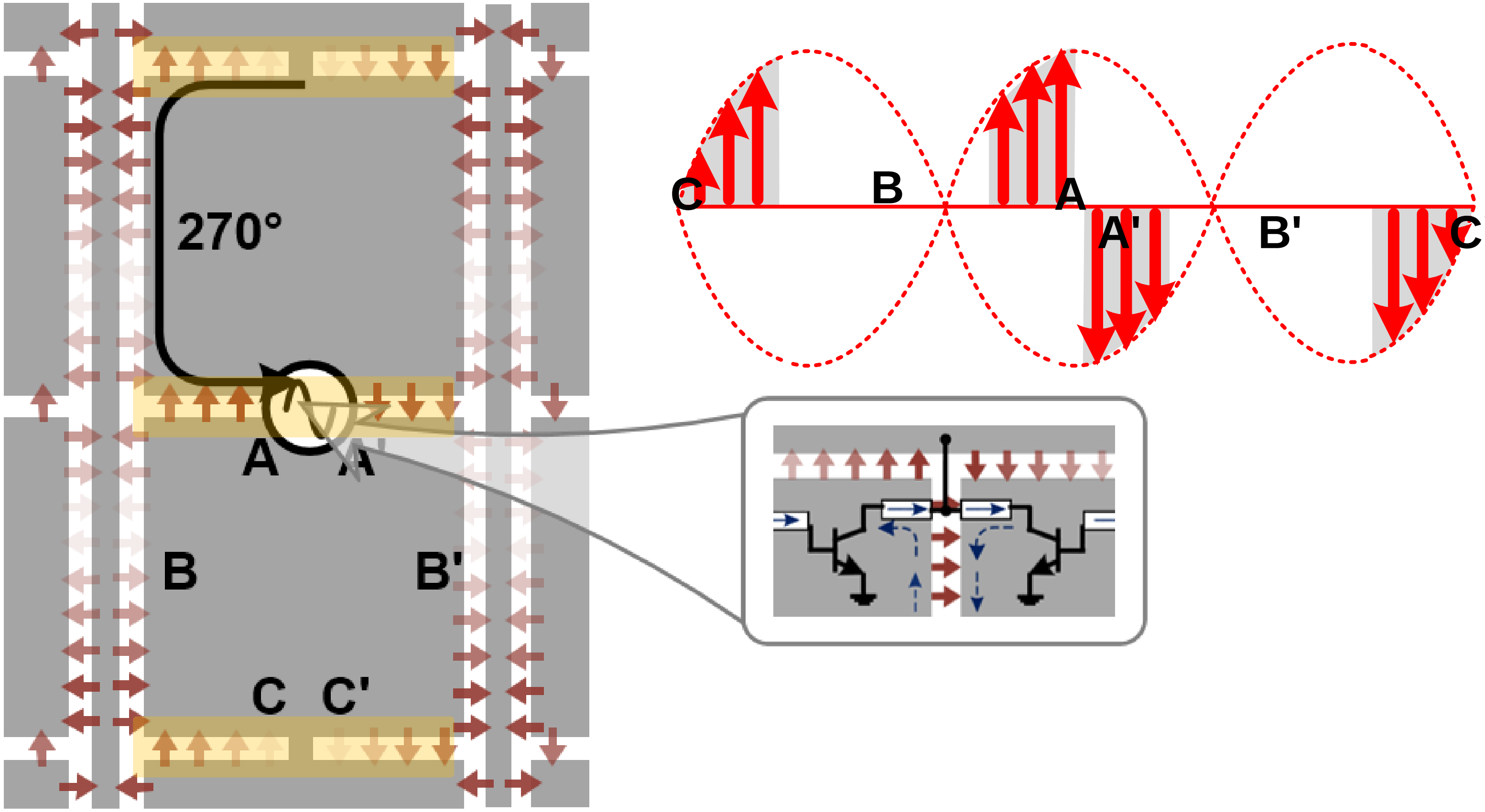




Antenna Gain at $2f_0$

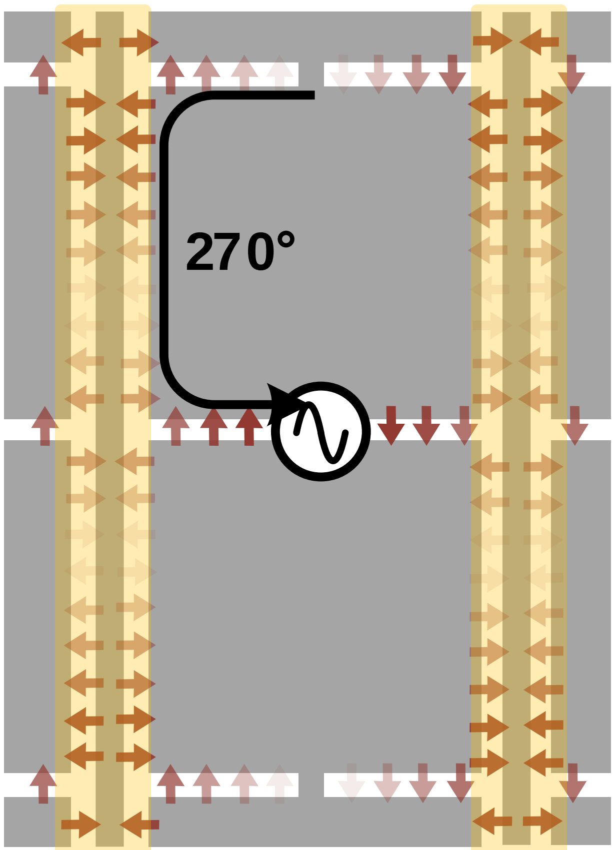
- **Vertical slotlines pairs do not radiate**
  - E-field in left and right slotlines balance out

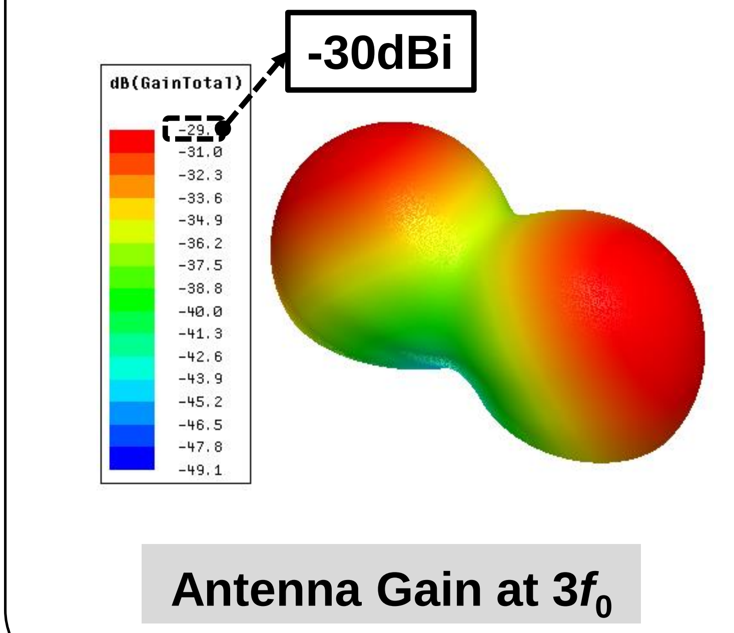
Radiation Cancellation at $3f_0$ (750 GHz)



- **Horizontal slotlines pairs do not radiate**
  – E-field in left and right slotlines balance out

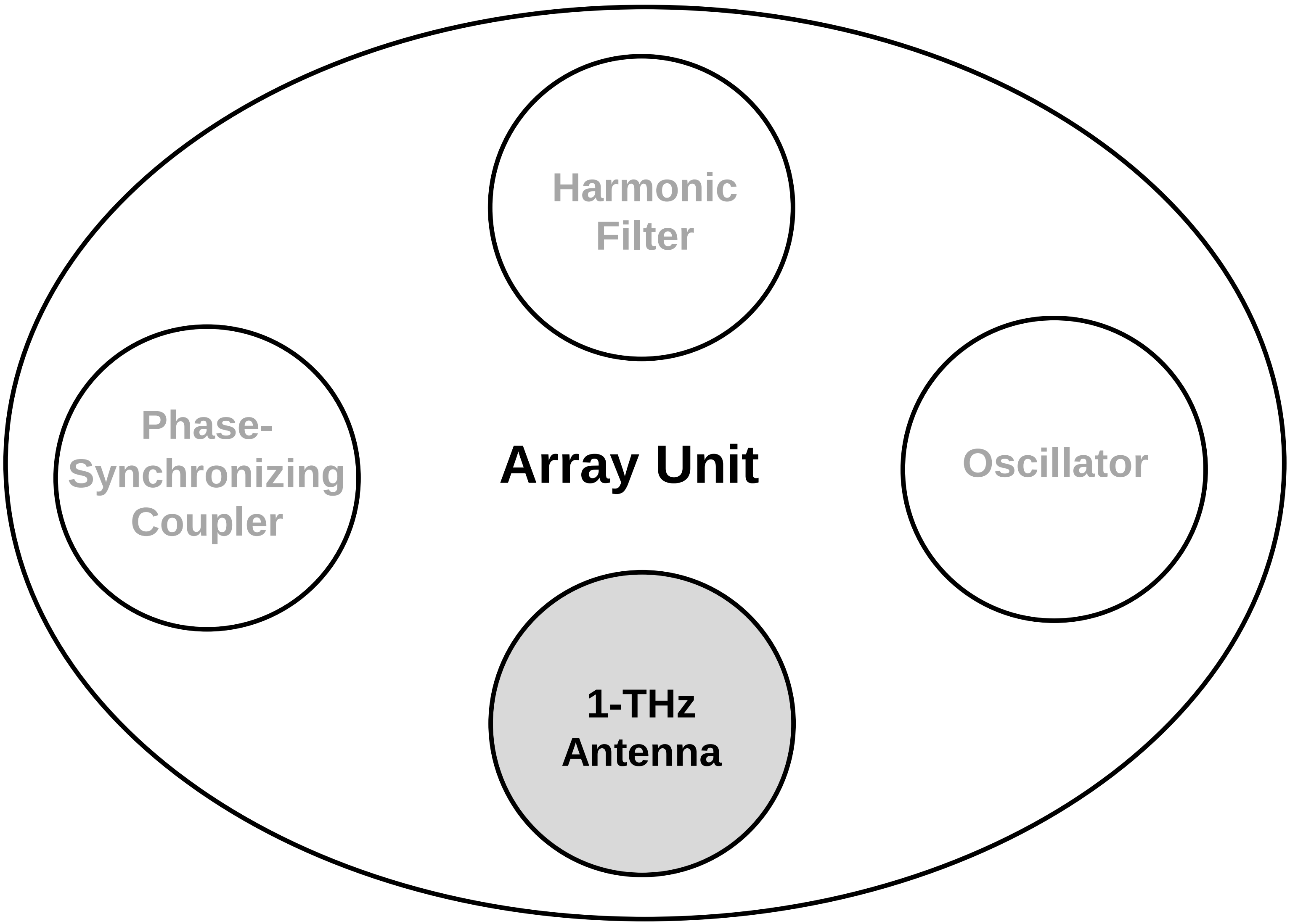
Radiation Cancellation at $3f_0$ (750 GHz)



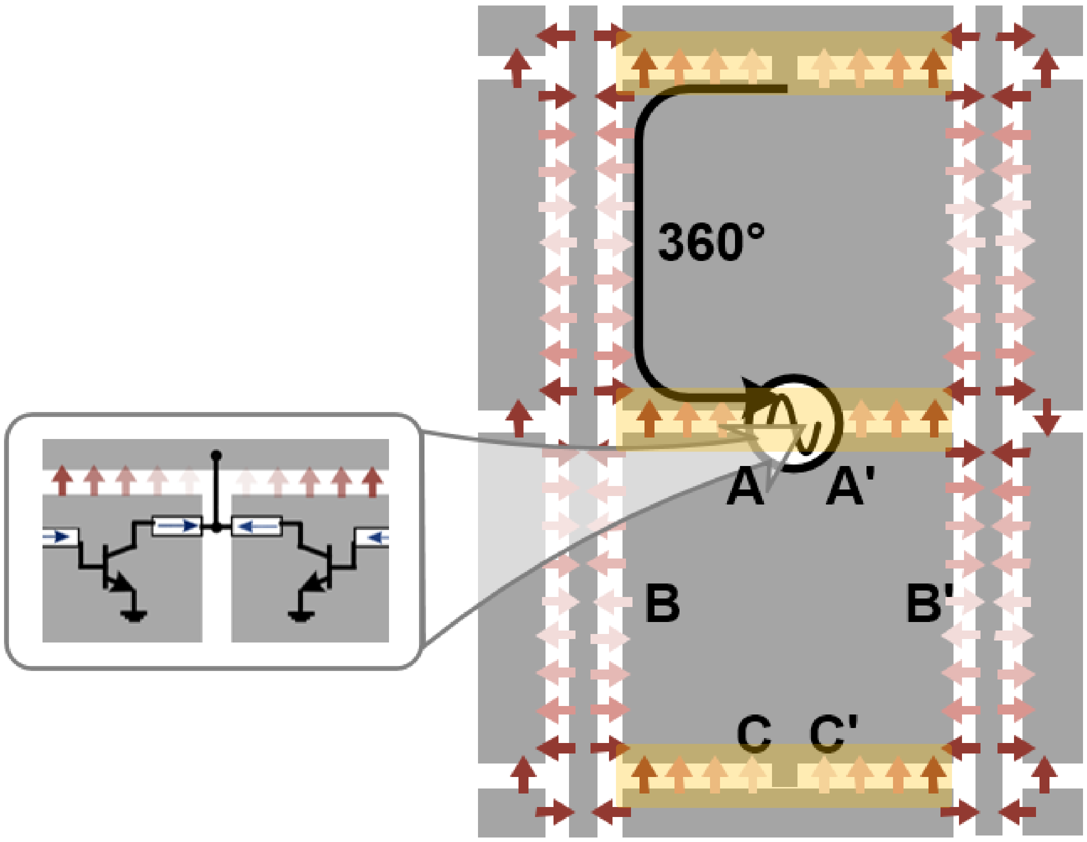


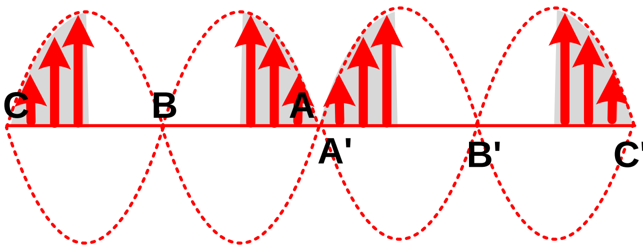
- **Vertical slotlines pairs do not radiate**
  - E-field in left and right slotlines balance out

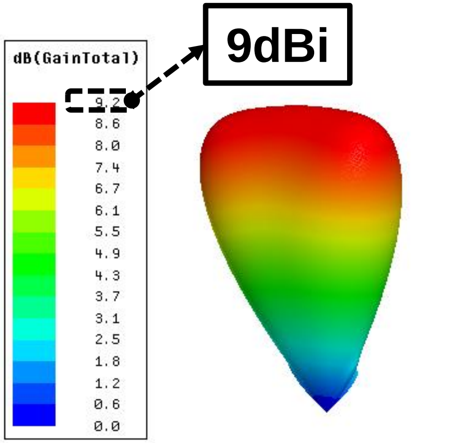
Multi-Functional Array Unit



Radiation at $4f_0$ (1 THz) from Single Unit



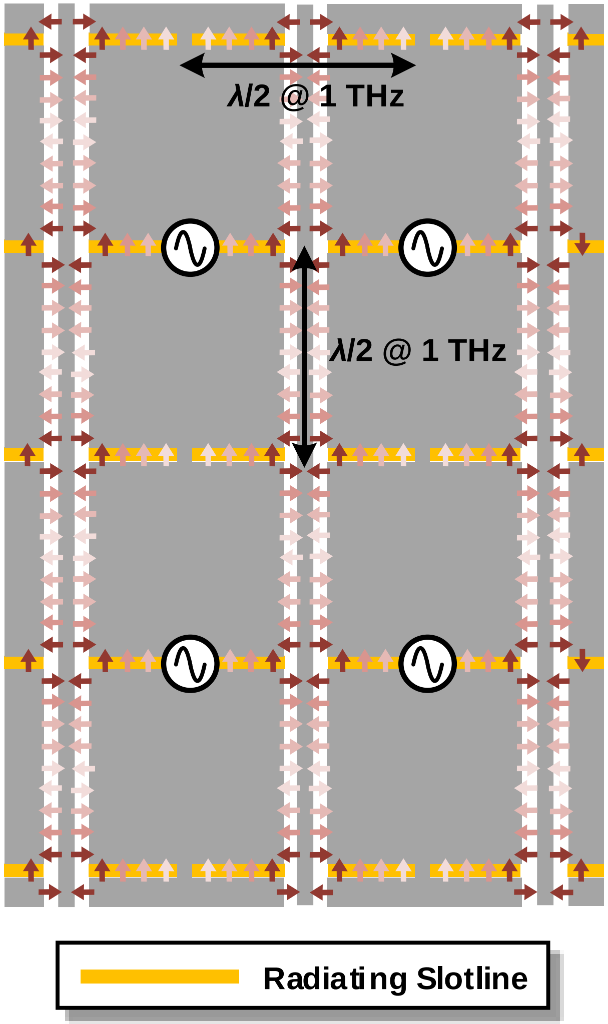




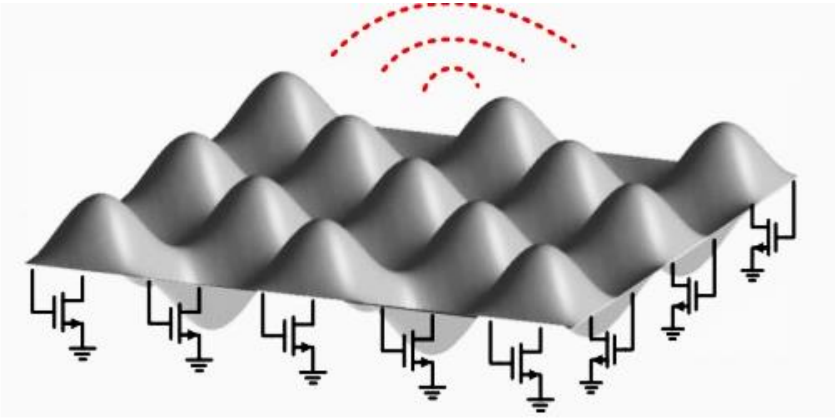
Antenna Gain at $4f_0$

- All horizontal slotlines pairs radiate in-phase
- Vertical slotlines do not radiate

1-THz Radiating Array



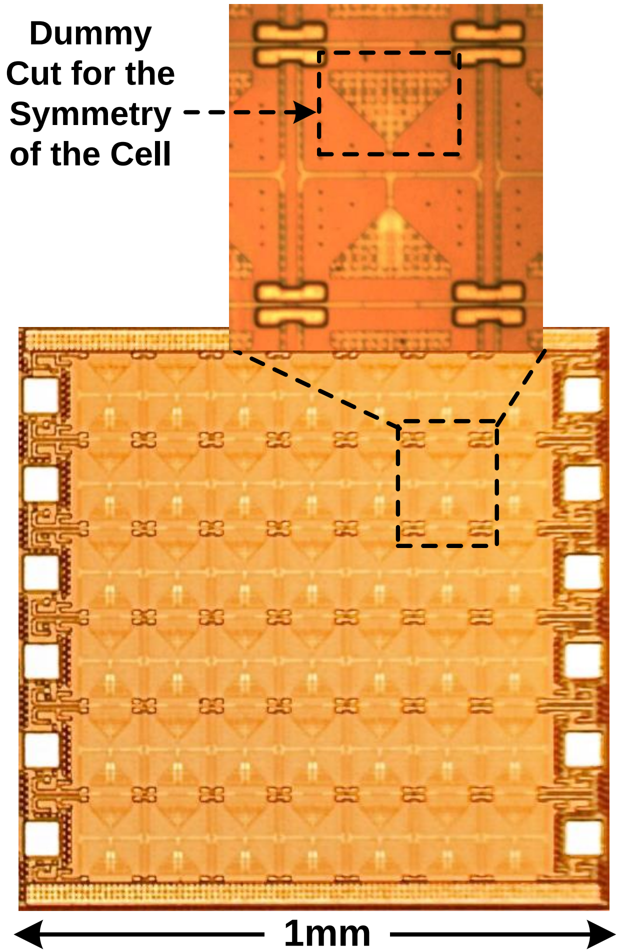
- In-phase radiation from all units is achieved by CPW and slotline coupling
- 1-THz antennas are spaced by *λ*/2 in both horizontal and vertical directions
- Equivalently, the array is like an "active planar wave front" with big aperture underpinned by transistors



Outline

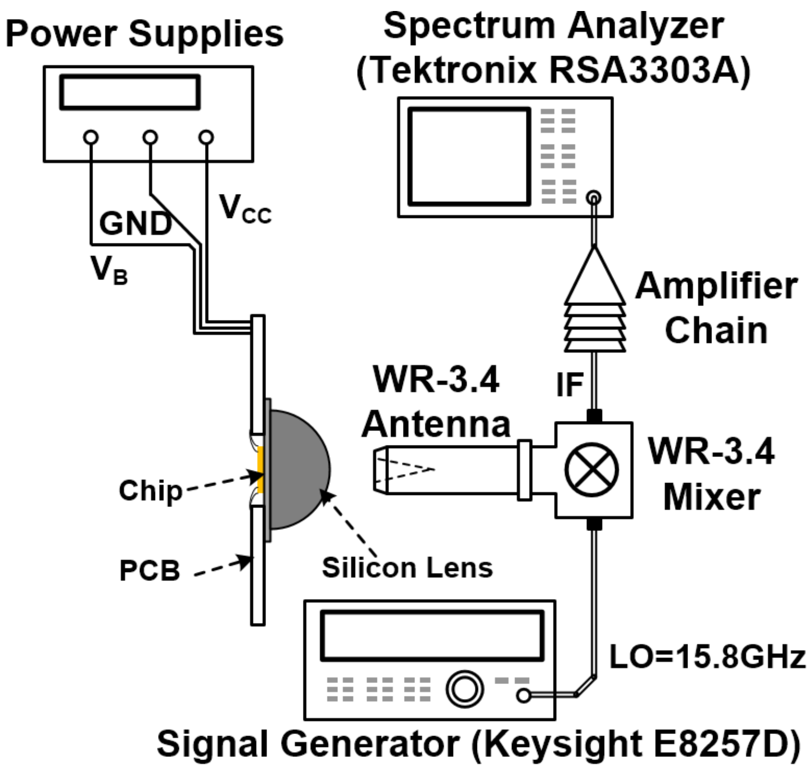
- Motivation and Challenges
- Design of Oscillator
- Formation of 1-THz Oscillating-Radiating Array
- **Measurement Results**
- Conclusions

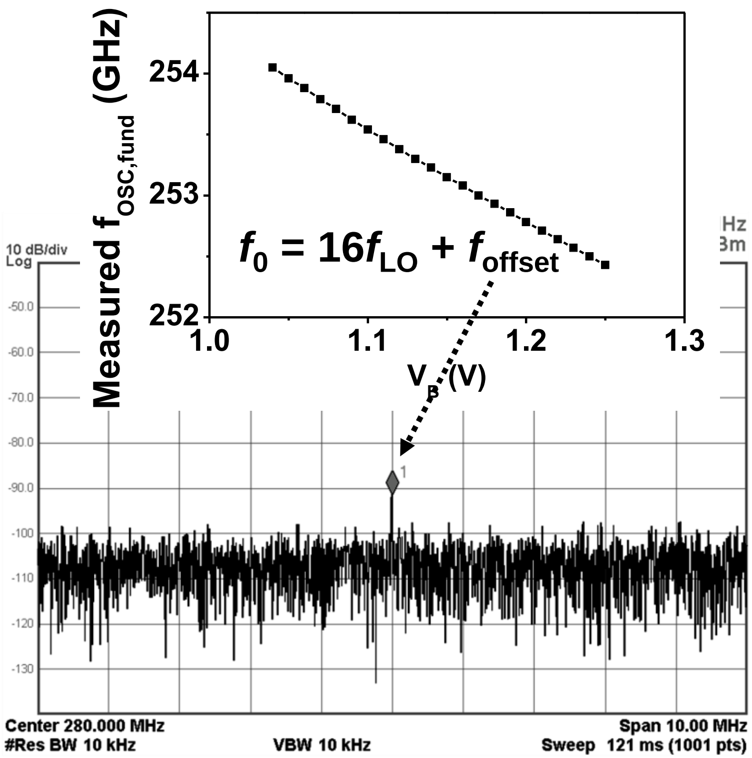
SiGe Chip Prototype



- **Technology: IHP S13G2 SiGe BiCMOS**
  - f_{max} = 450 GHz
- **Area: 1 mm^2**
- **Array scale**
  - 42 units
  - 91 antennas
- **DC Power: 1.1 W**

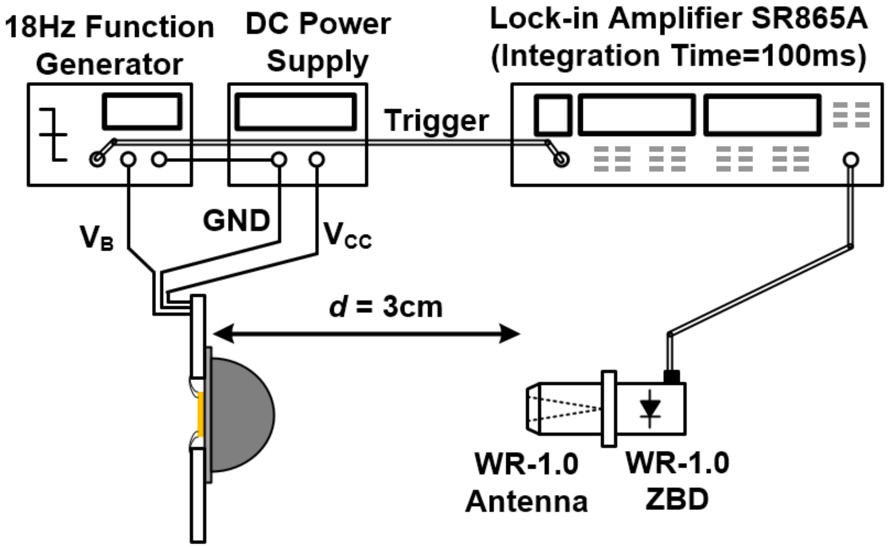
Measurement of Spectrum of Leaked Fundamental

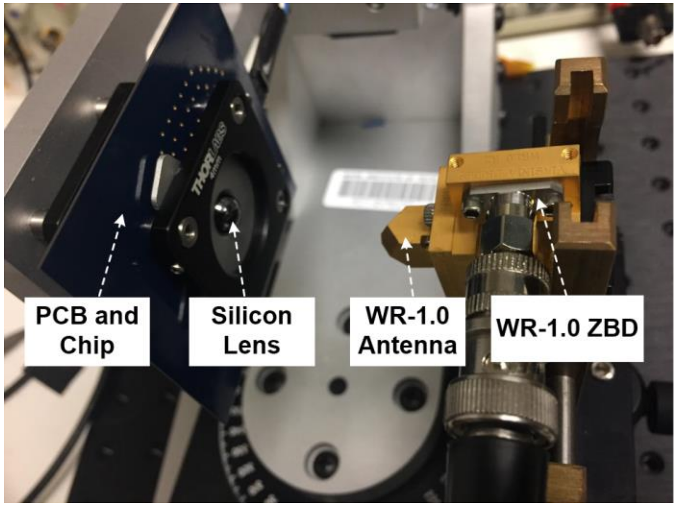




- **Chip is attached to a half-ball silicon lens and radiates into backside**
- **Due to device mismatch, there will be little of f_0 wave leaking out, with which we can confirm f_0 and hence $4f_0$**

Measurement of Total Radiated Power

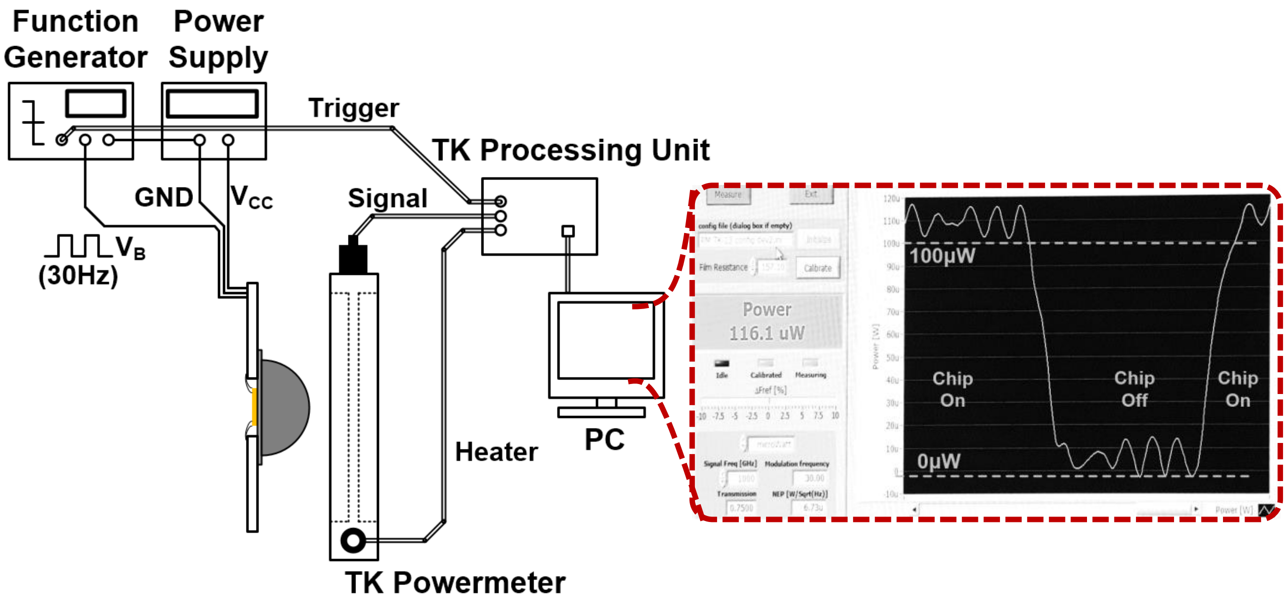


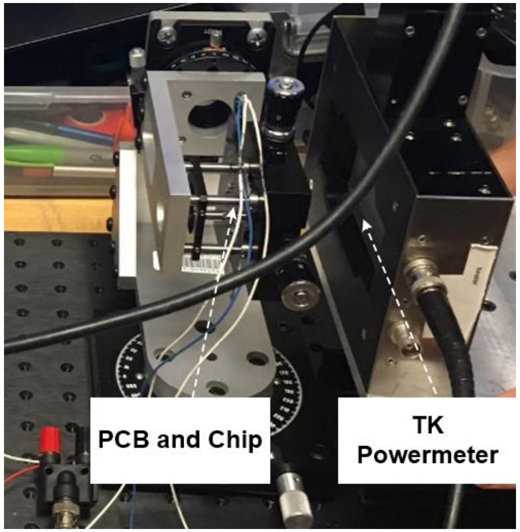


Measurement using VDI WR-1.0 zero-bias diode detector

- **Total radiated power of 1 THz (from ZBD): 80μW (-11dBm)**

Measurement of Total Radiated Power

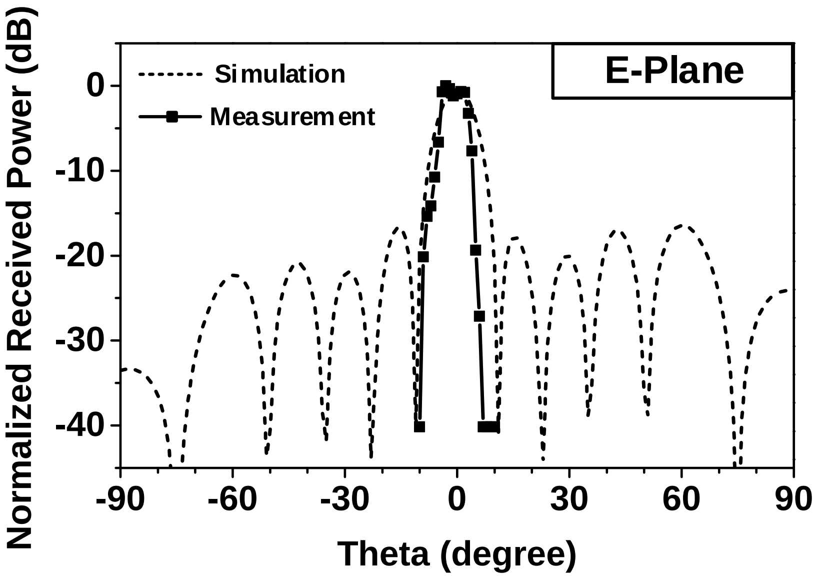


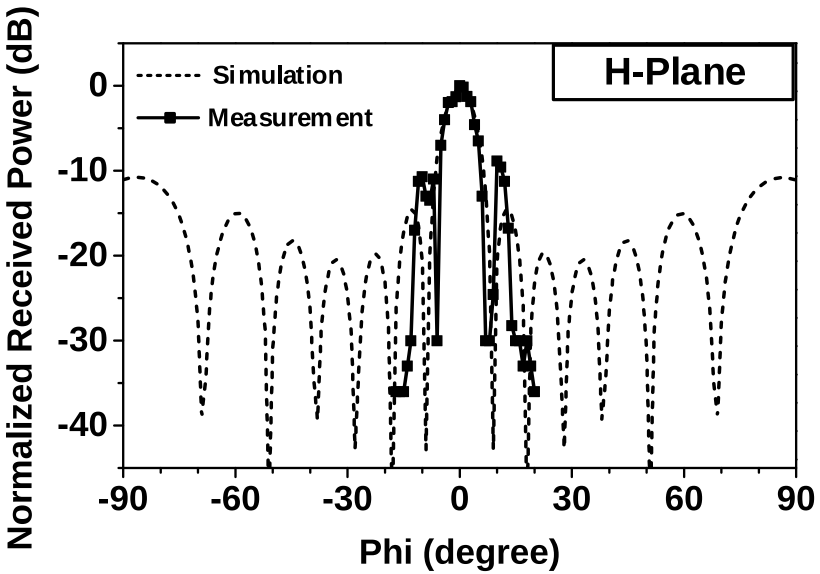


Measurement using large-aperture Thomas Keating photo-acoustic powermeter

- **Total radiated power of 1 THz (from ZBD): 80μW (-11dBm)**
- **Total radiated power of all harmonics (from TK): 100μW**

Measurement of Radiation Pattern





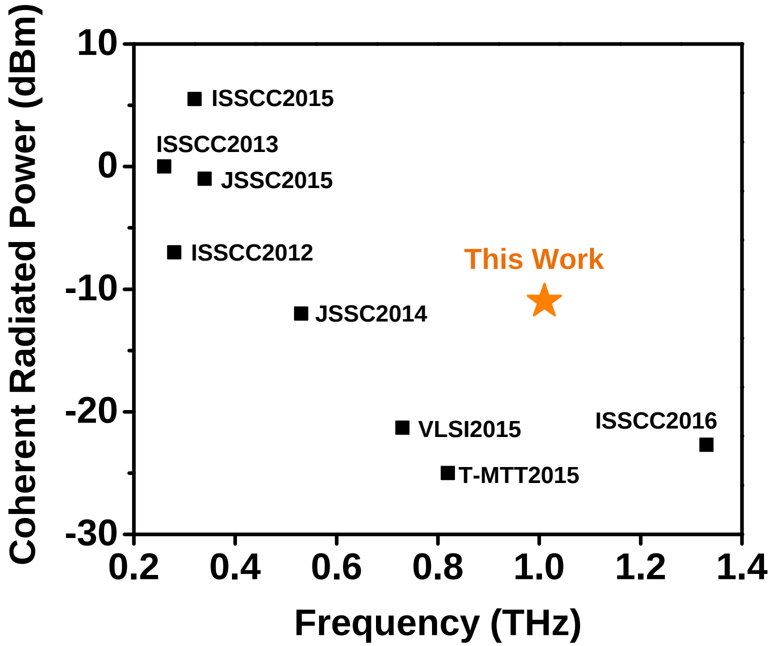
- **Measured using zero-bias diode detector**
- **Peak directivity: 24dBi**
- **EIRP: 13dBm**

Performance Comparison

Reference	This Work	MTT2015	ISSCC2011	ISSCC2016	VLSI 2015
Circuit Type	Oscillator Array (4f_0)	Active Multiplier (6f_0)	Active Multiplier (5f_0)	Passive Multiplier (10f_0)	Passive Multiplier (5f_0)
Output Frequency (THz)	1.01	0.99	0.82	1.33	0.73
Radiated Power (dBm)	-10.9	N/A	N/A	-22.7	-21.3
EIRP (dBm)	13.1	-37	-17	-13	-22.2
Input RF Power (dBm)	N/A	8	14	18	13.8
DC Power (W)	1.1	4	3.7	0	0
Chip Area (mm^2)	1.00	3.28	3.22	0.36	0.26
Technology	0.13µm SiGe	0.25µm SiGe	0.25µm SiGe	65nm CMOS	65nm CMOS

- Highest total radiated power
- Highest EIRP

Conclusions



- **A high-power 1-THz radiator featuring 2D-coupled array architecture**
  - Large array scale
  - Directive radiated beam
- **Compact multi-functional structure will be an important component in future THz circuits**

Acknowledgements

- Analog Devices Inc.
- MIT/MTL GaN Energy Initiative
- MIT Center for Integrated Circuits and Systems (CICS)
- Singapore-MIT Alliance for Research and Technology (SMART)
- Prof. Qing Hu at MIT for chip testing support
- Dr. Mehmet Kaynak at Leibniz-Institut für innovative Mikroelektronik (IHP) for chip fabrication support

Student Paper Finalist

RTU2B-2

Fully-Scalable 2D THz Radiating Array: A 42-Element Source in 130-nm SiGe with 80-μW Total Radiated Power at 1.01THz

Zhi Hu and Ruonan Han
MIT, Cambridge, MA, USA

Massachusetts Institute of Technology