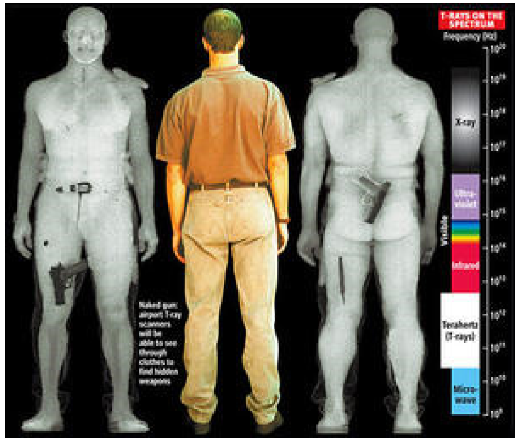
Outline

- Introduction
  - THz Applications
  - Harmonic THz oscillators concept
- Proposed Oscillator-Radiator Array
- Measurement Results
- Conclusion

THZ for Imaging

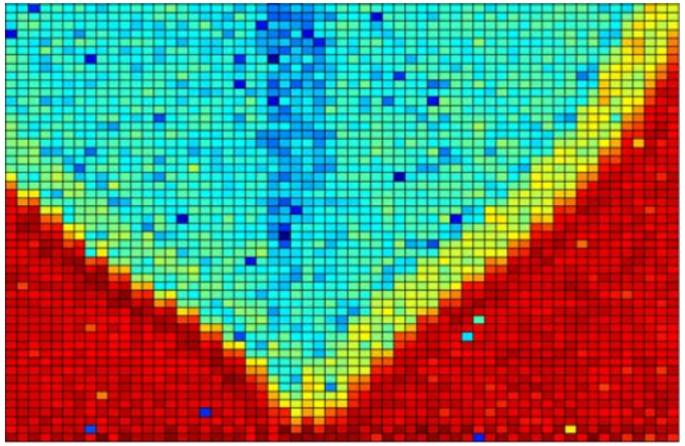
- THz radiation can pass through dielectrics and is non-ionizing.

Security



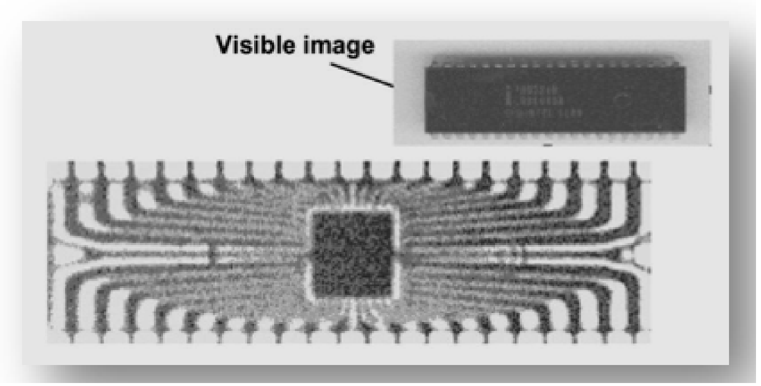
[Source: dailymail.co.uk]

Biological



[Steyaert W. et al., JSSC, 2014]

Industrial



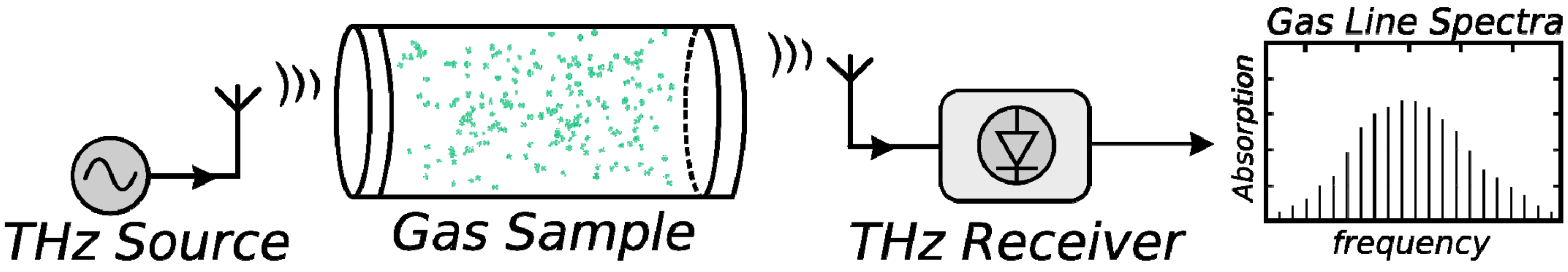
[B.B. Hu et Al, Optics Letters, 1995]

- Resolution is limited by wavelength. $$Resolution \propto \frac{1}{\lambda} \propto f$$

- Higher frequency allows smaller pixel-size. $$N_{Pixels} \propto \frac{1}{\lambda} \propto f$$

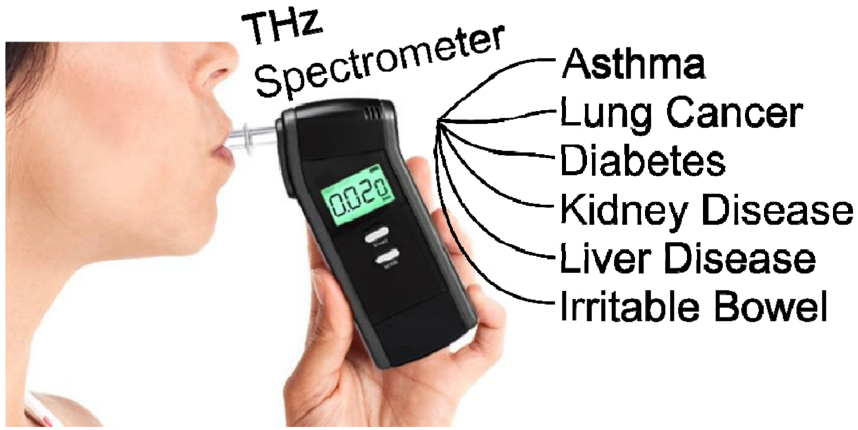
THz for Spectroscopy

- Low-pressure gasses exhibit high-Q absorption lines in THz range

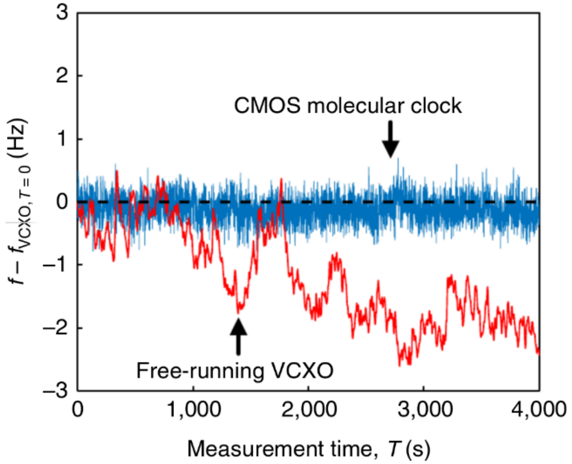


Gas Detection

Medical



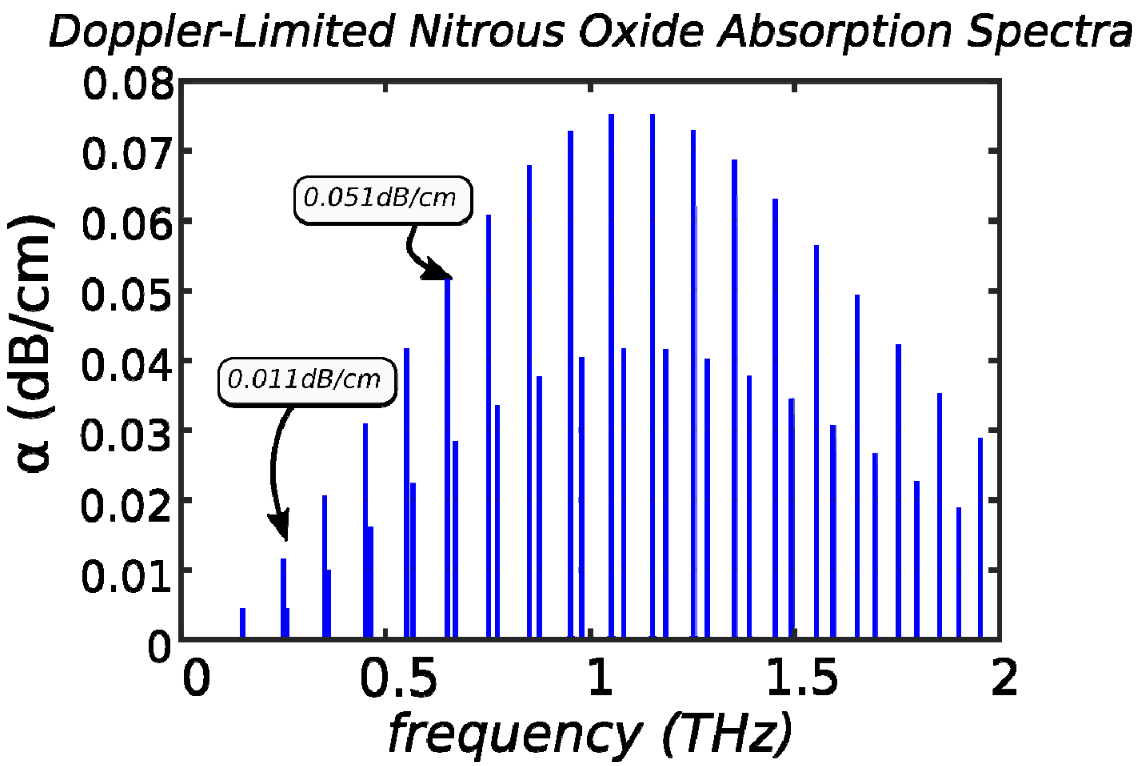
Frequency Reference



[C. Wang et al., VLSI, 2018]

Higher Frequencies in Spectroscopy

- Maximum absorption of rotational modes at ambient temperature occurs on the middle terahertz range for many molecules.



For $P_T = 0dBm, NF = 20dB, N_{BW} = 10Hz$

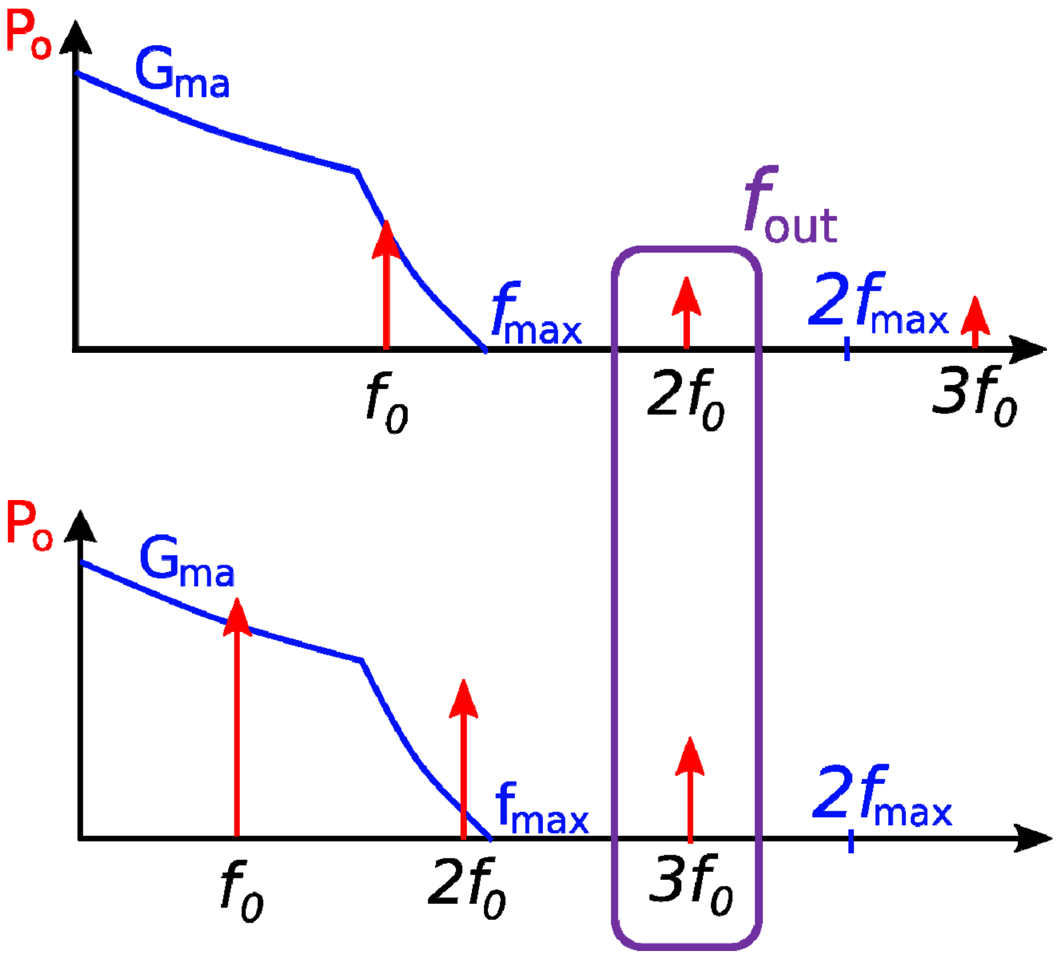
$L_{chamber} = 0.5m, wg_{loss} = 0.05dB/cm$

- $SNR_{250GHz} = 106.3\ dB$
- $SNR_{650GHz} = 118.9\ dB$

18X More Sensitive!

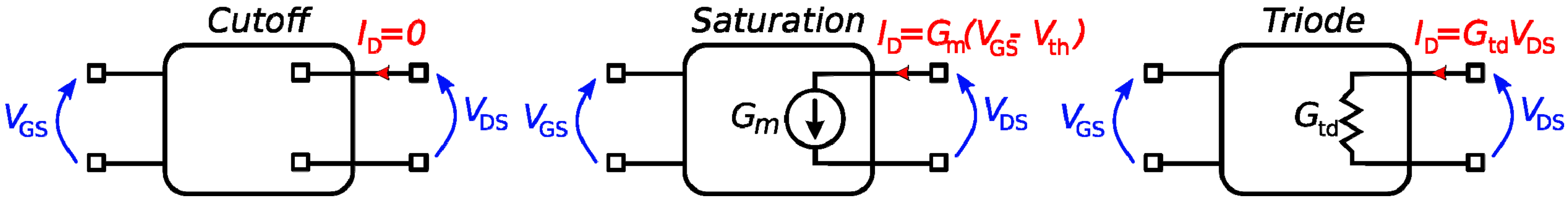
f_{max} Limitation for THz Oscillation

- At f_{max}, oscillation is impossible.
- Generate power through non-linearity
  - Depends on Harmonic number N and voltage swing.
  - Second harmonic limits your frequency below $2f_{max}$.



Transistor Harmonic Currents

- Large nonlinearity from change of transistor operating condition



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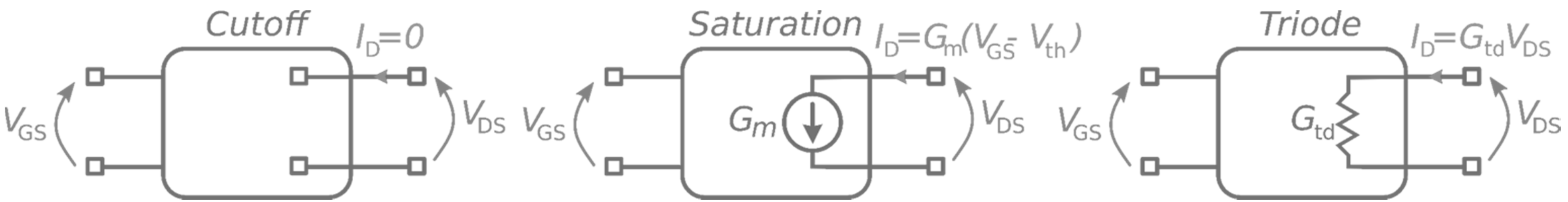
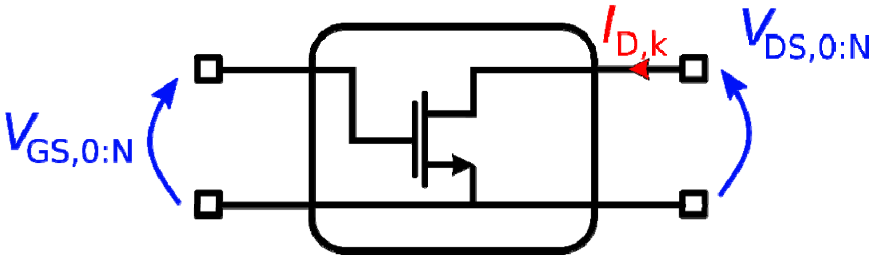


- $I_{D,n}$ is function of harmonic components of V_{GS} and V_{DS}.

$$I_{D,n} \approx \sum_{m=1}^{N} T_{nm}\ (*)$$



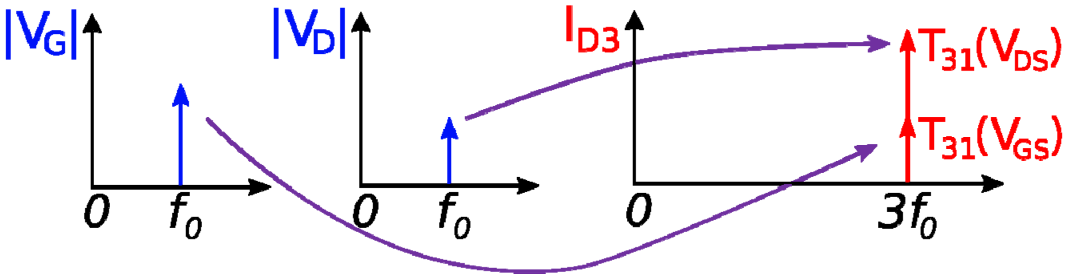
[Kananizadeh R., Momeni, O., JSSC, 2018]

***In-Phase to quadrature translations are ignored for simplicity.**

$$T_{nm} = \frac{V_{GS,m} G_m}{\pi} \int_{Saturation} \cos(m\theta)\cos(n\theta)\, d\theta + \frac{V_{DS,m} G_{td}}{\pi} \int_{Triode} \cos(m\theta)\cos(n\theta) d\theta$$

Transistor Harmonic Translations

- $T_{31} \rightarrow$ Biggest contributor to $I_{D,3}$
  - $T_{31}(V_{DS})$ has same sign as $T_{31}(V_{GS})$
  - *Maximize* $V_{DS,1}$



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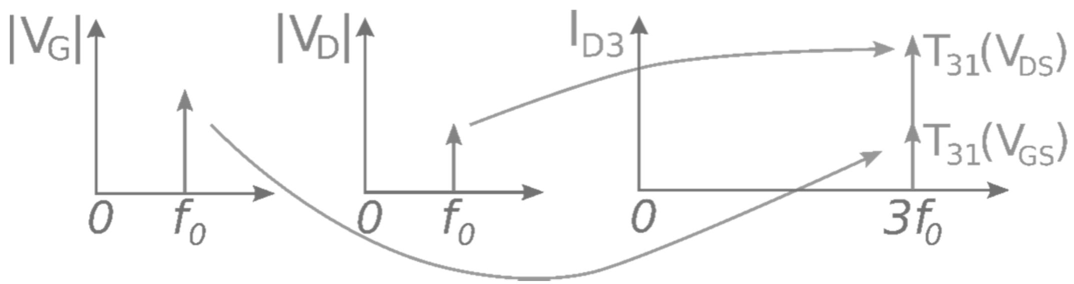
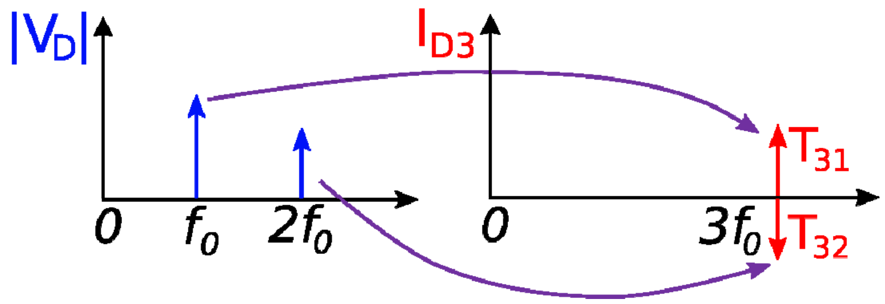


- $T_{32} \rightarrow$ Contribution opposite to T_{31}
  - Minimize $V_{DS,2}$



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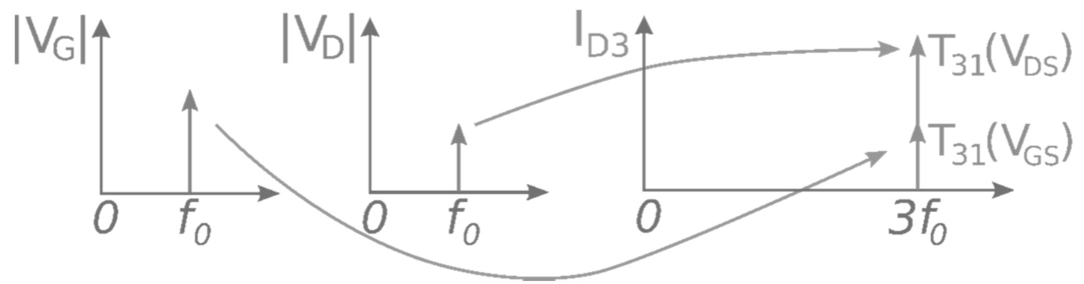

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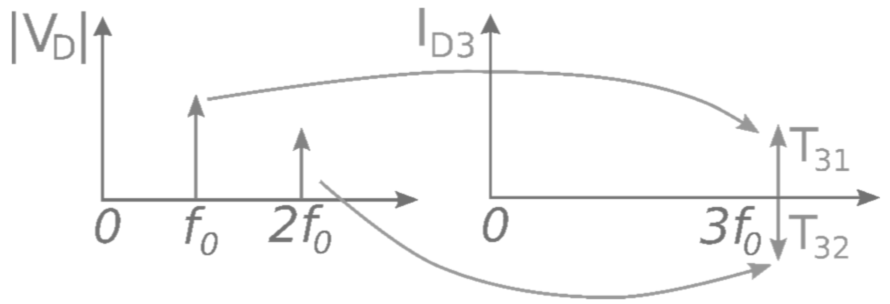
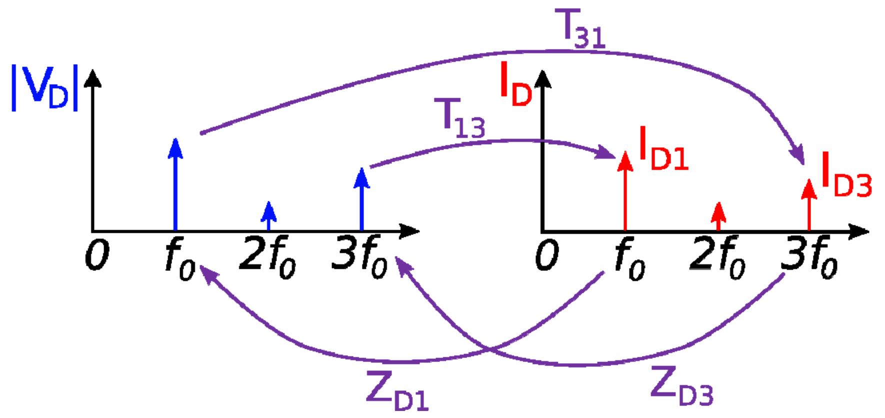
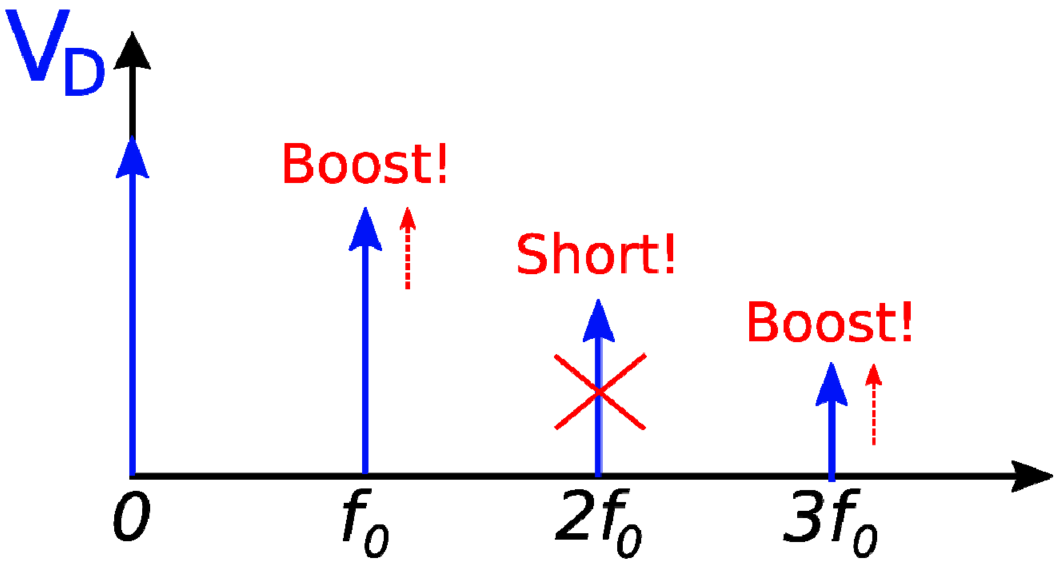


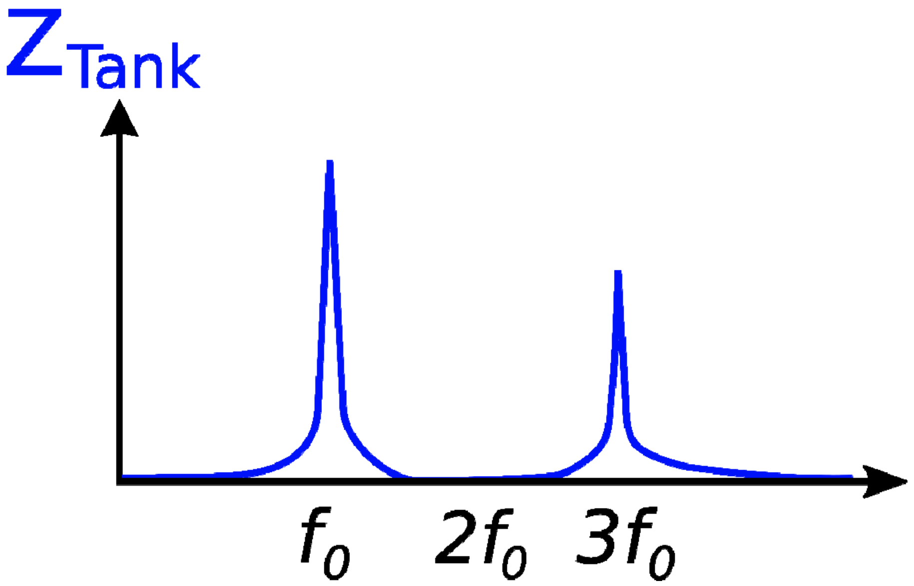
- $T_{13} \rightarrow$ Increases $I_{D,1}$ that turns into $V_{D,1}$
  - Creates "Harmonic Feedback"
  - Suppresses $I_{D,2}$



Optimum Drain Impedance

- Using the previous insights:





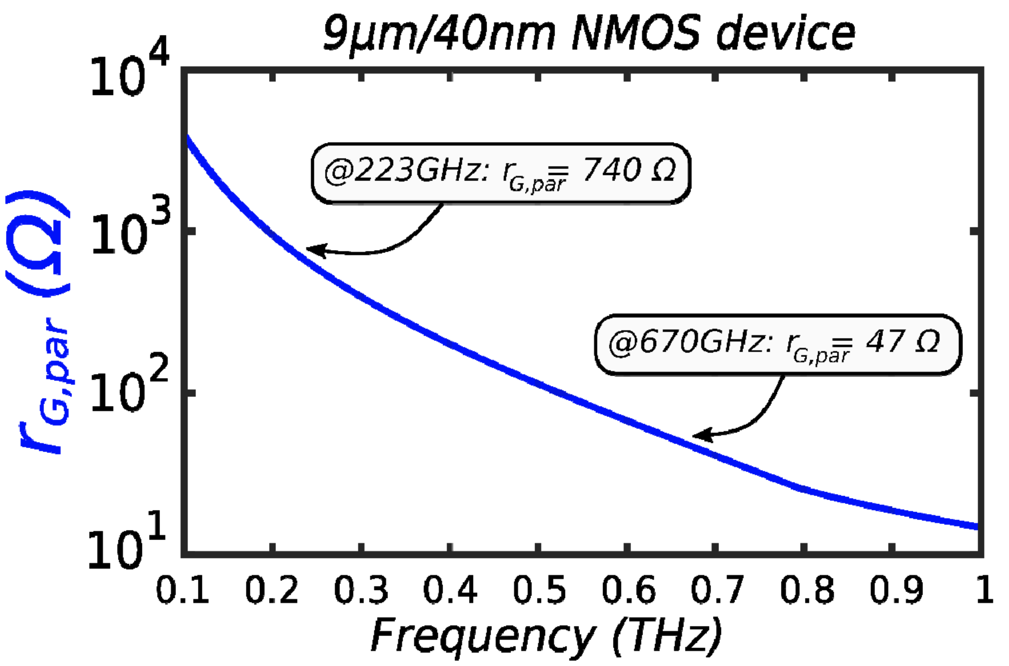
- It's a class-F oscillator!
  - Third harmonic voltage improves ISF and phase-noise performance.

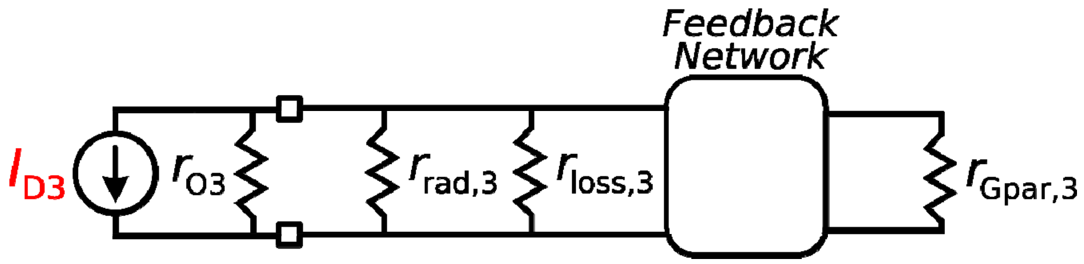
[Babaie M., Staszeswki R., JSSC, 2013]

Gate Loading

- Transistor Gates are very lossy beyond f_{max}.
  - Dissipates oscillator harmonic power.
  - Dampens Drain third harmonic resonance.

- Feedback network must isolate Gate from Drain at harmonic frequency.





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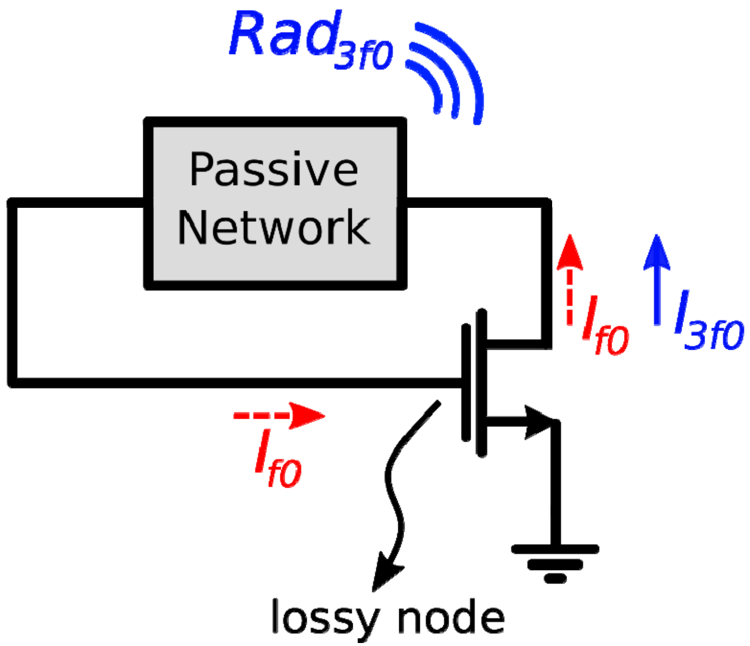
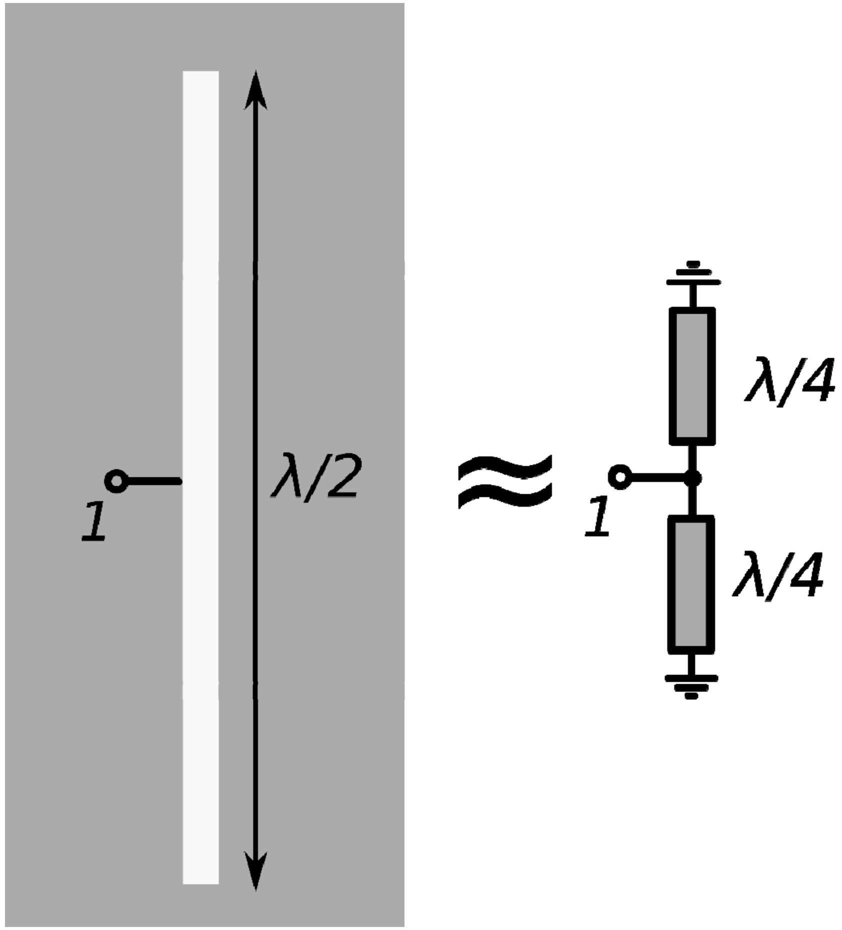
Building A Filtering Oscillator Cell

- $223GHz$ Fundamental frequency.
  - Multi-harmonic tank.
  - Feedback must filter third harmonic ($670GHz$).
- Built-in coupling mechanisms to adjacent cells.
  - No additional coupling circuitry.
- $\lambda/2$ spacing at $670GHz$.
  - Radiate into silicon substrate.



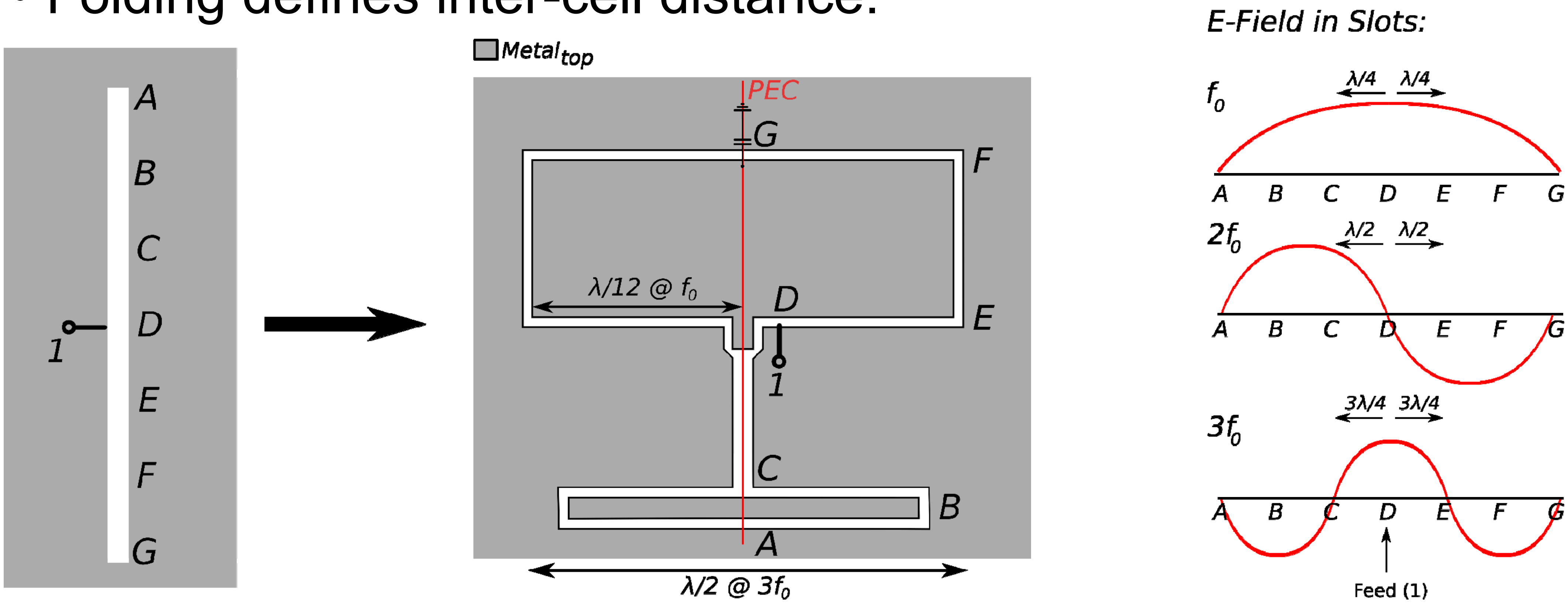
Tank Implementation

- $\lambda/4$ stub resonator provides us with optimum impedances "intrinsically".
- Slotlines radiate more signal into the the substrate.
  - Power that goes into infinite substrate proportional to $\epsilon_{Sub}^{3/2}$.
  - Require two $\lambda/4$ stubs in parallel.



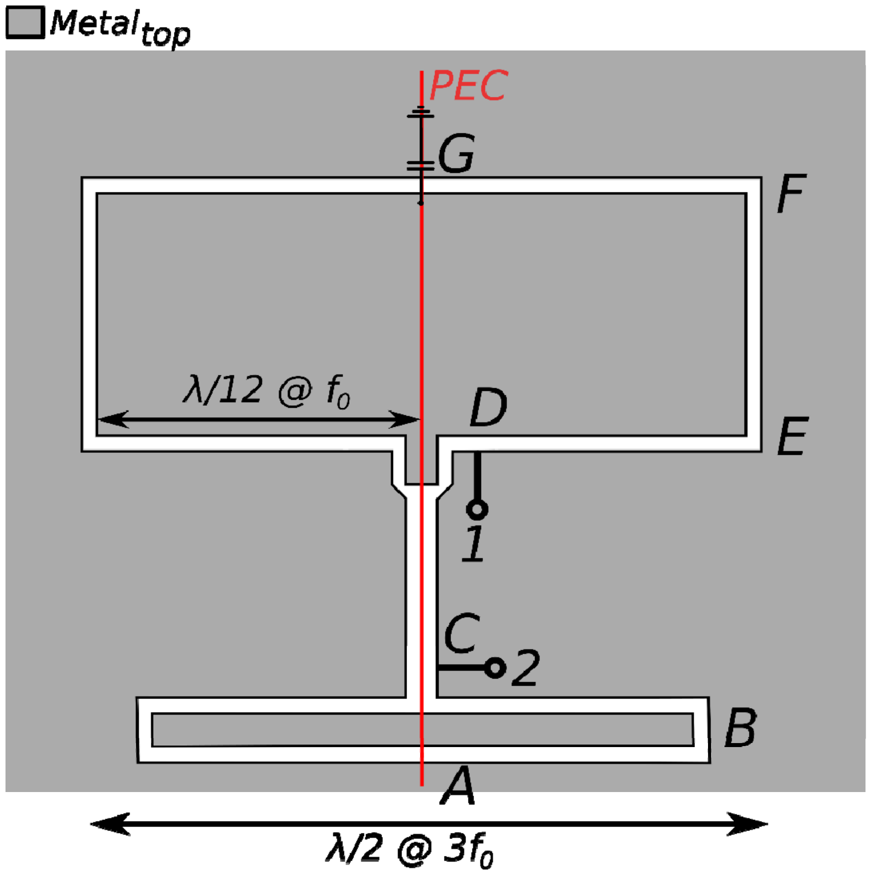
Tank Implementation

- Folding slots prevents radiation at fundamental.
  - Higher fundamental Q.
- Folding defines inter-cell distance.



Tank Implementation

- Feedback from virtual ground point at third harmonic.



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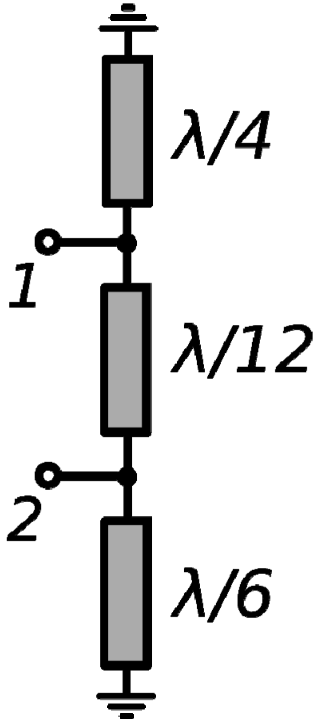
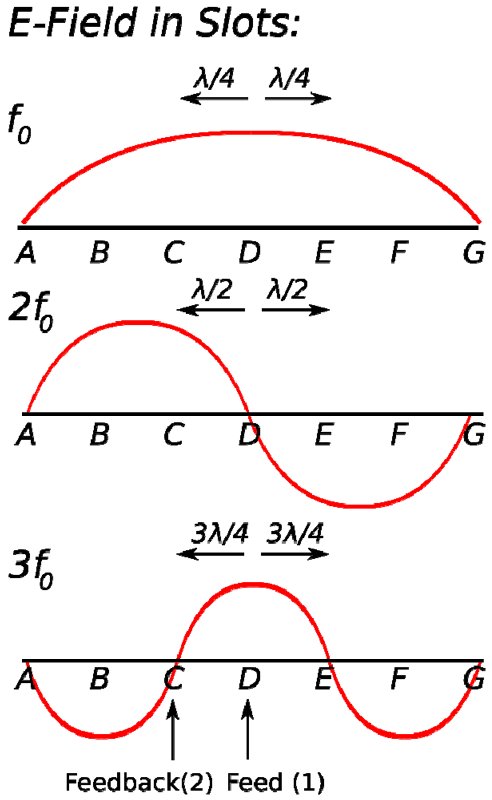
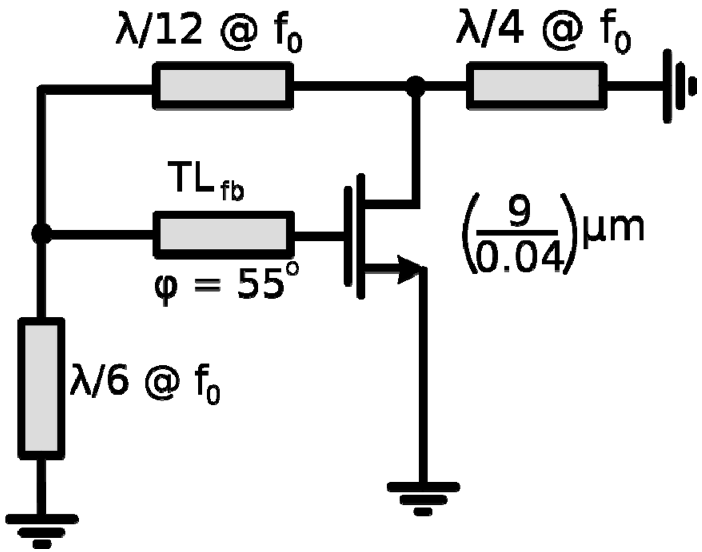
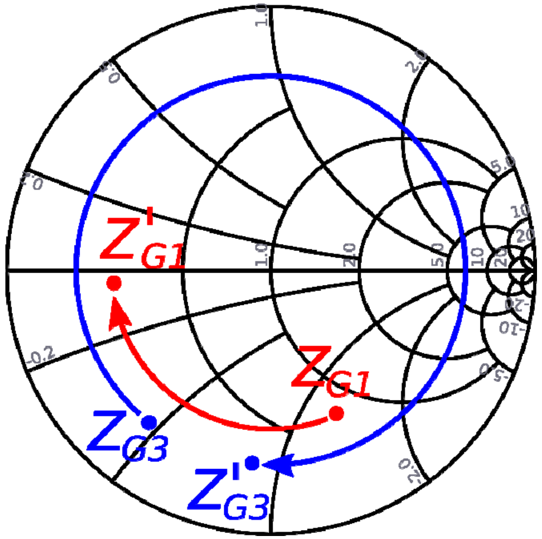




Feedback Line

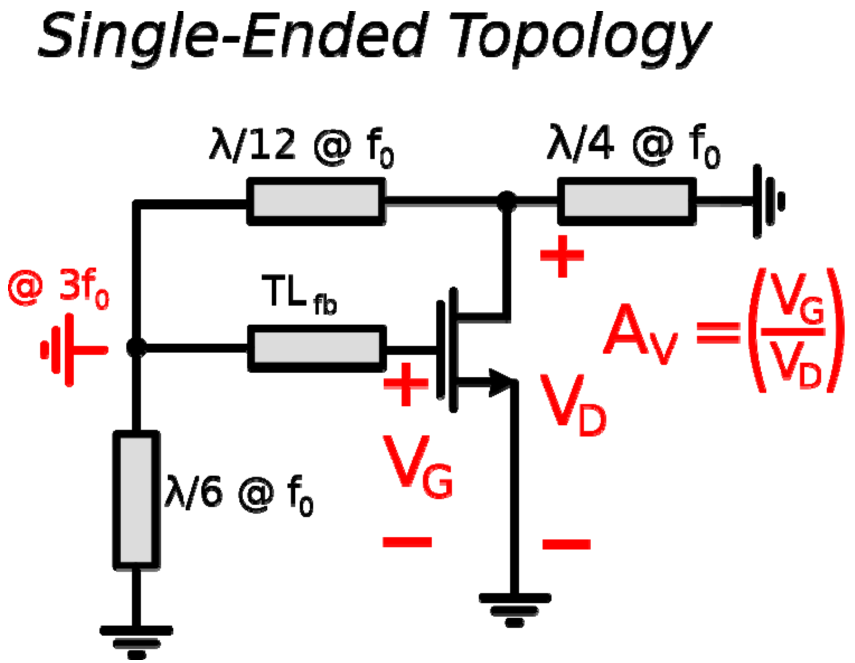
- We need a transmission-line to connect the transistor Gate to port 2.
  - Couple slotline to microstrip-line at lower-metal.
  - Transform the gate impedance to real at fundamental.
- Small transistor is required due to lumped drain parasitics.

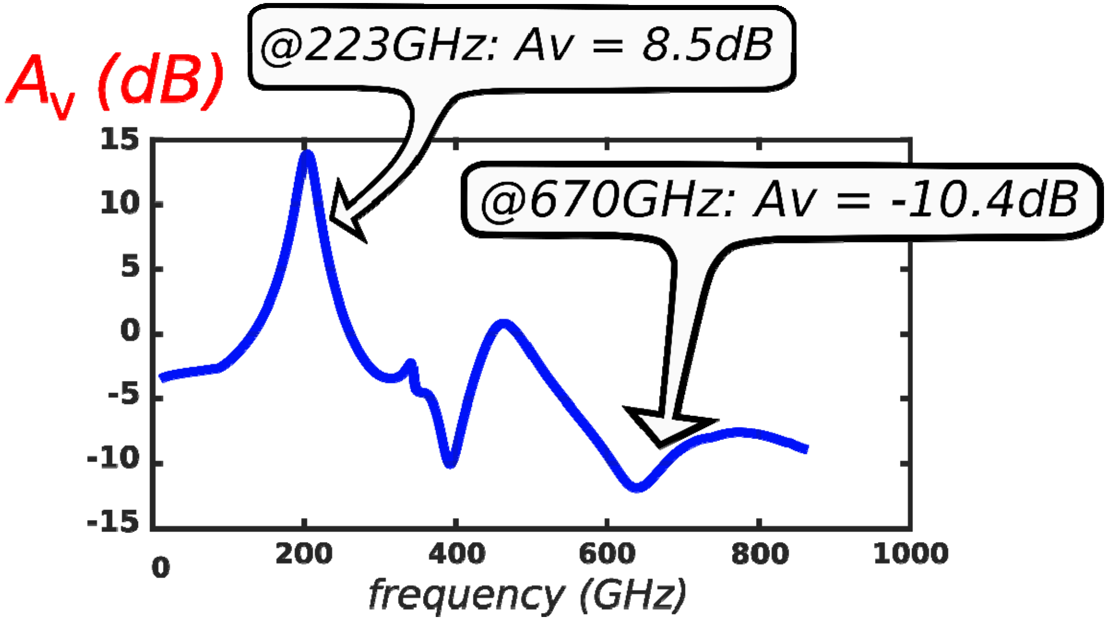




Cell Half-Circuit and Filtering

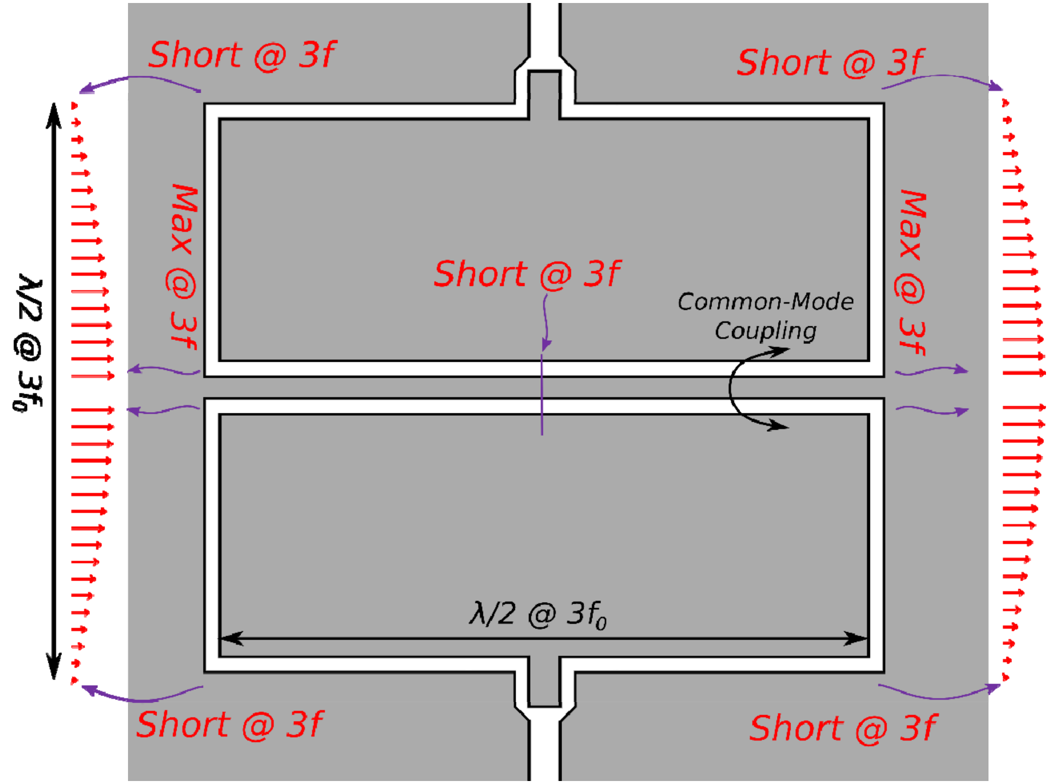
- The filtering mechanism can be seen by looking at the ratio of drain to gate voltage in a closed-loop circuit.
  - All transistors parasitics taken into account.



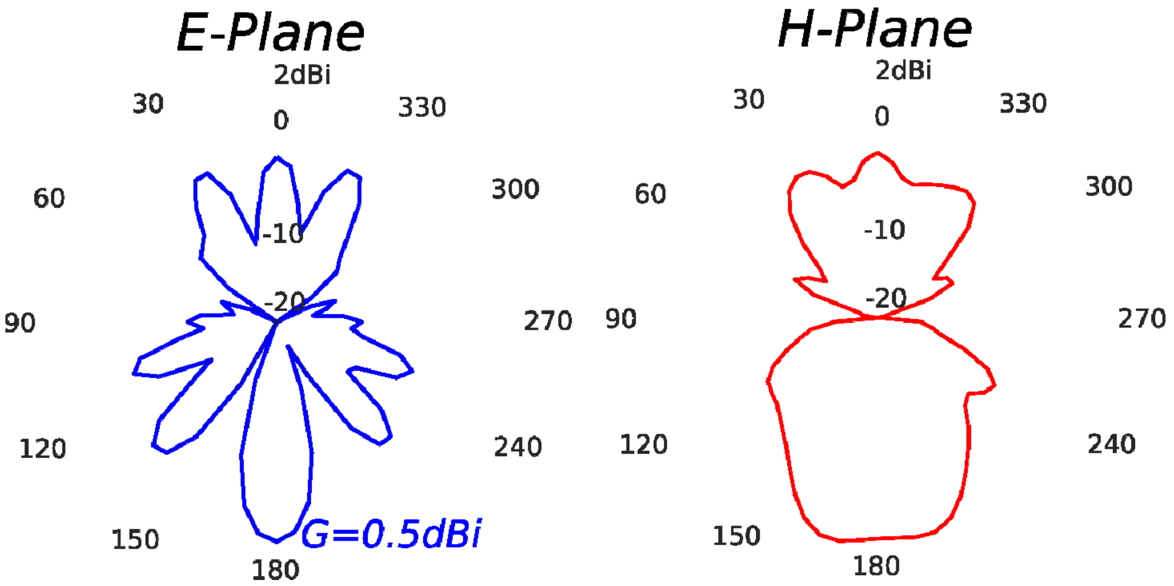


Radiation at $3f_0$.

- The fields of two cells build up a radiative pattern.
  - Two optimally-spaced $\lambda/2$ slot antennas at $3f_0$.

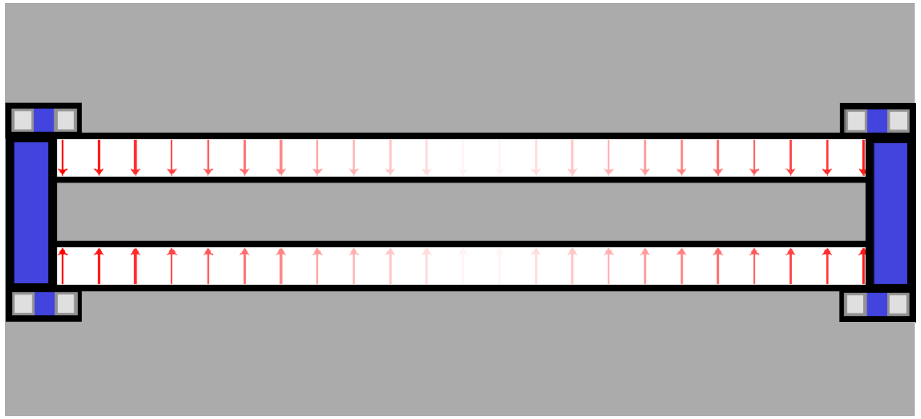


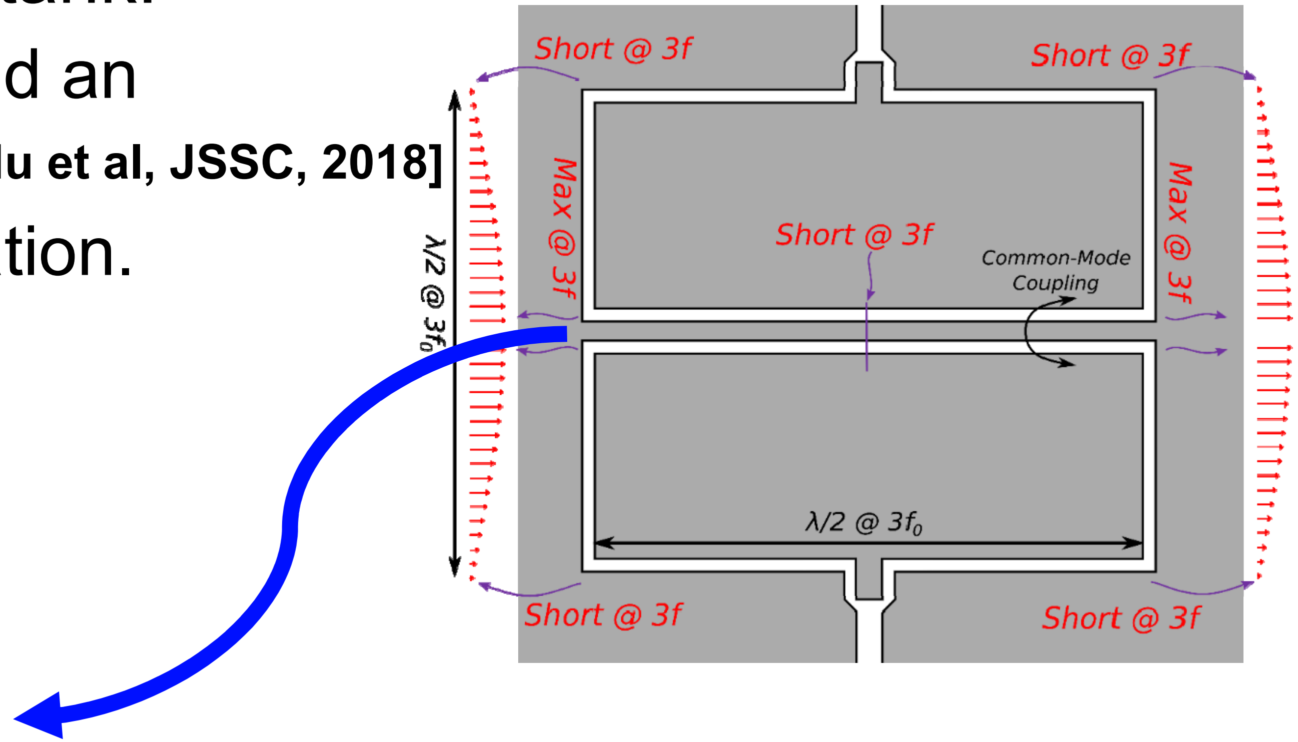
Simulated radiation pattern



Shorted Slotline Coupling

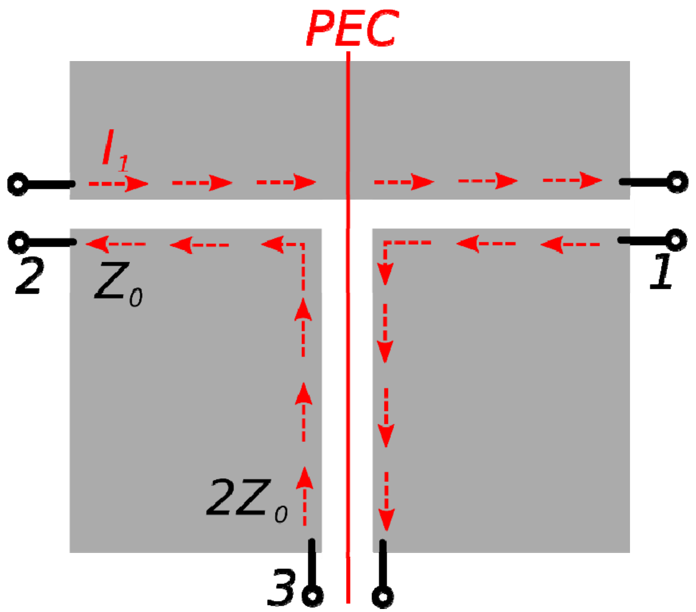
- Just shorting two lines in the tank:
  - Short in differential-mode and an open in common-mode.**[Zhi Hu et al, JSSC, 2018]**
  - Force common-mode oscillation.
- Mode similar to CPW.
  - Fields cancel in far-field.





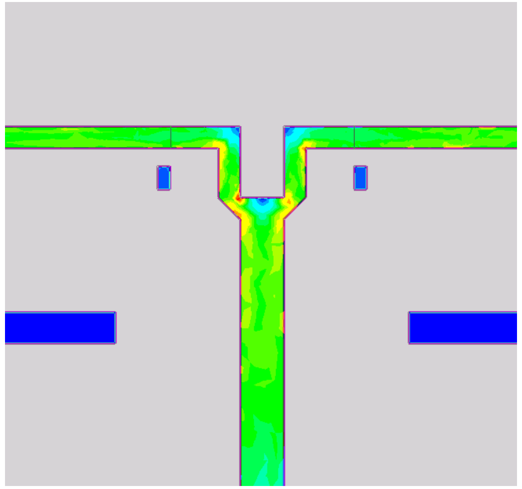
Shared Slotline Coupling

- Shared slotline act as an open for common-mode signal.
  - Forces differential-mode oscillation within cell.
  - Couple cells adjacent to each other.
- Shared slot is radiative.

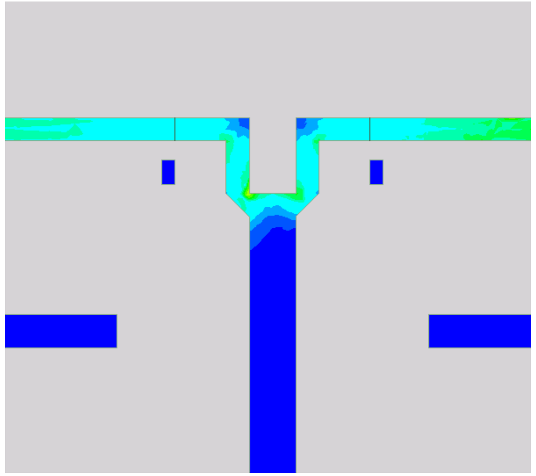


[Zhi Hu et al, JSSC, 2018]

Differential Mode:

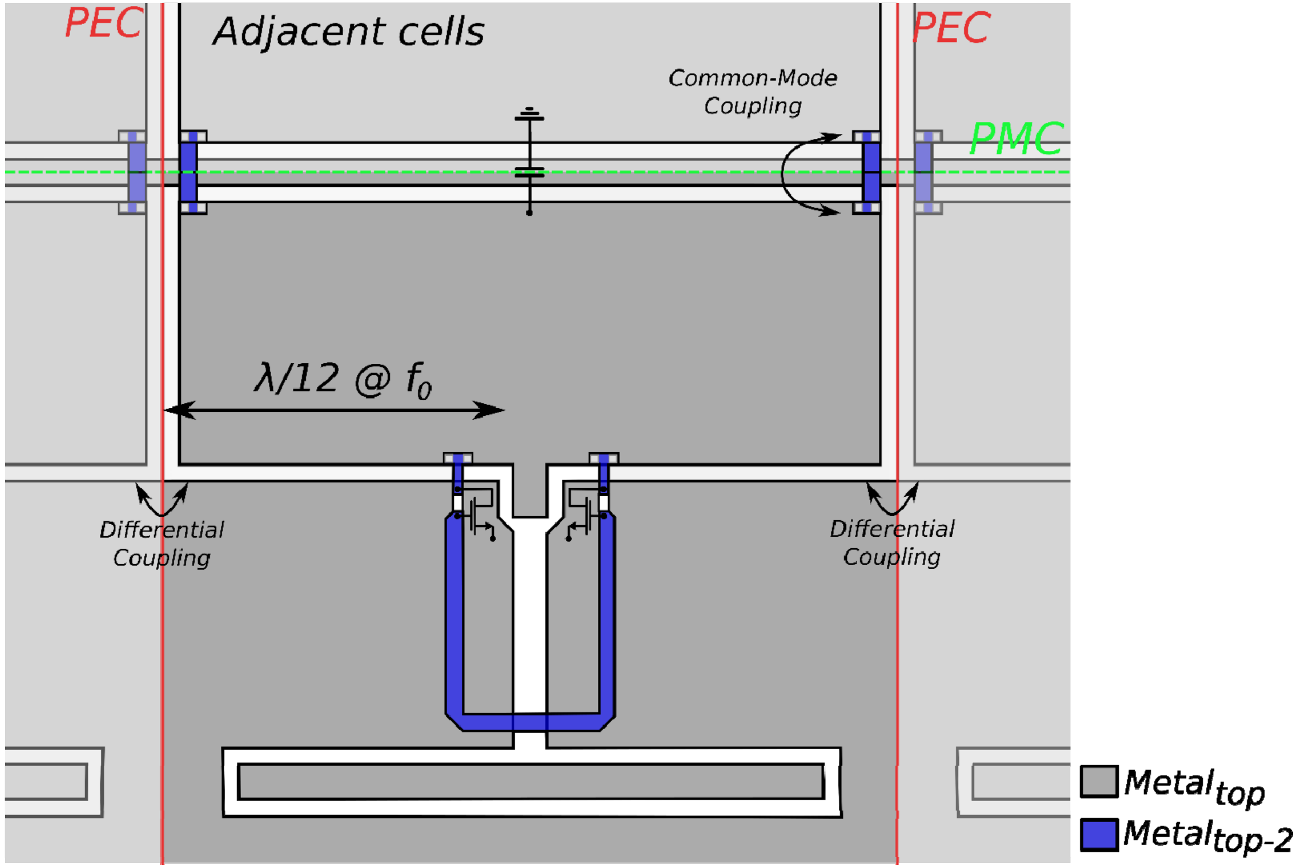


Common Mode:



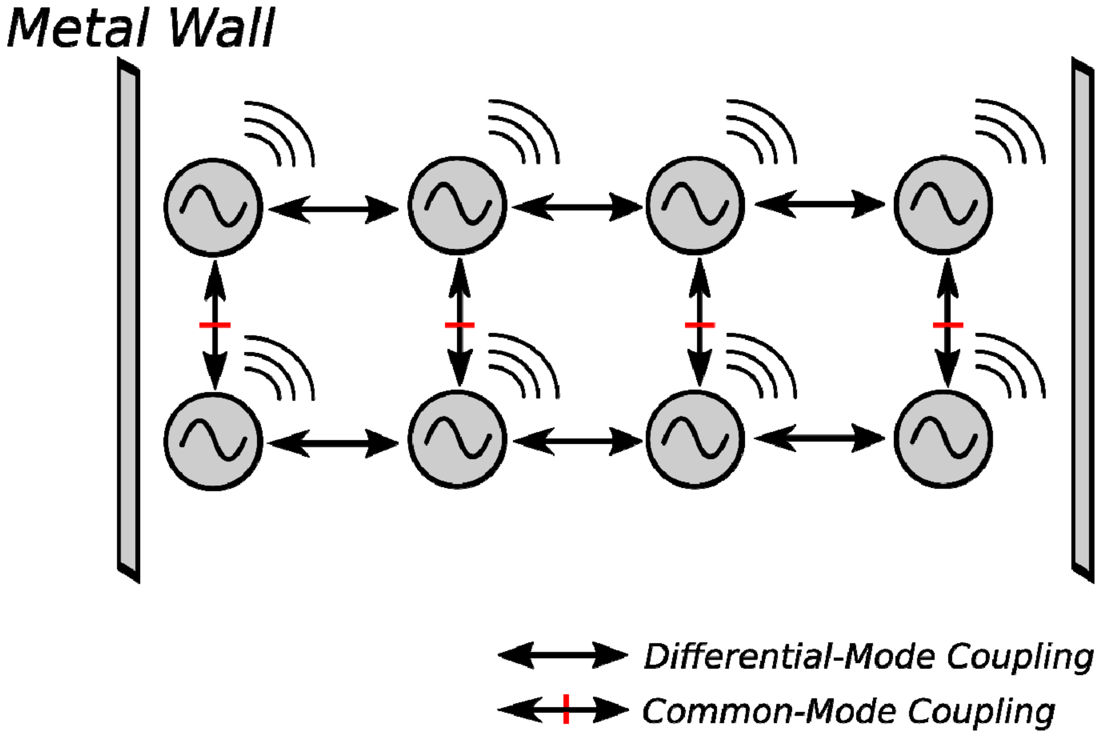
Full Cell Layout

- Cell mosaic is built to form array.



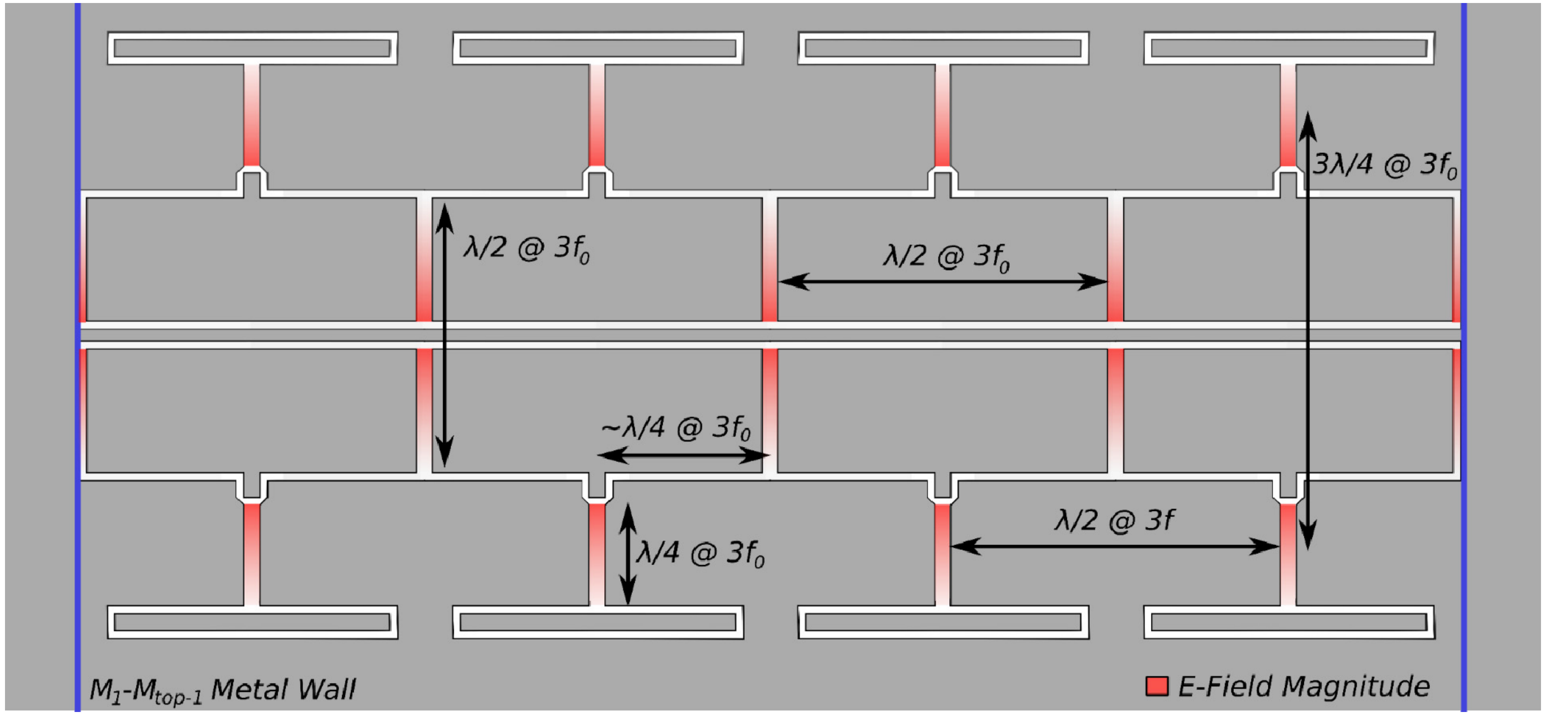
Array Architecture

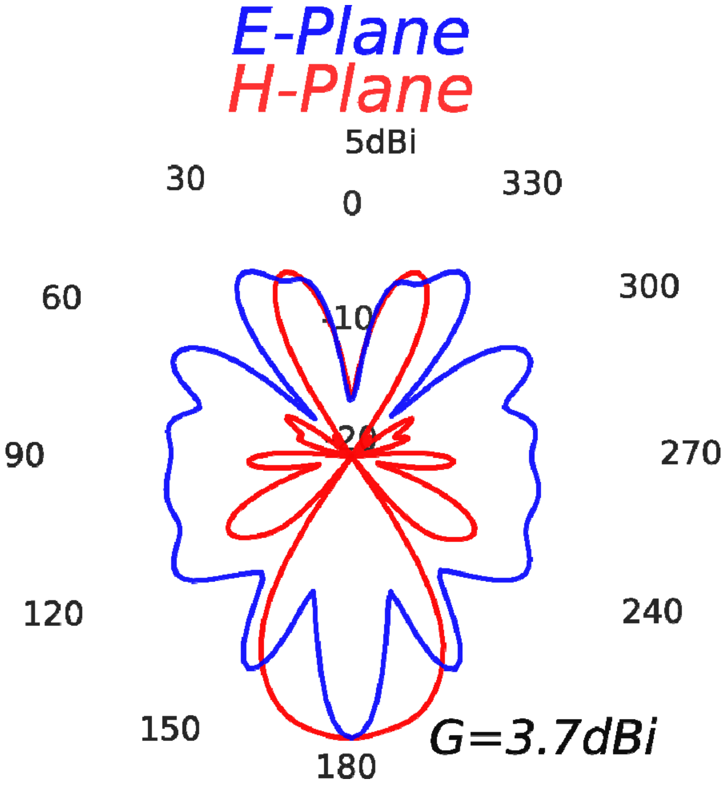
- A 4x2 Array of self-oscillating radiators at $670GHz$.
  - $165\ \mu m$ lateral pitch.
- Metal-wall added on boundaries to emulate anti-phase cells.
  - Better free-running frequency match.
- Cells radiate through substrate into silicon lens.



Array E-Field Magnitude and Spacing

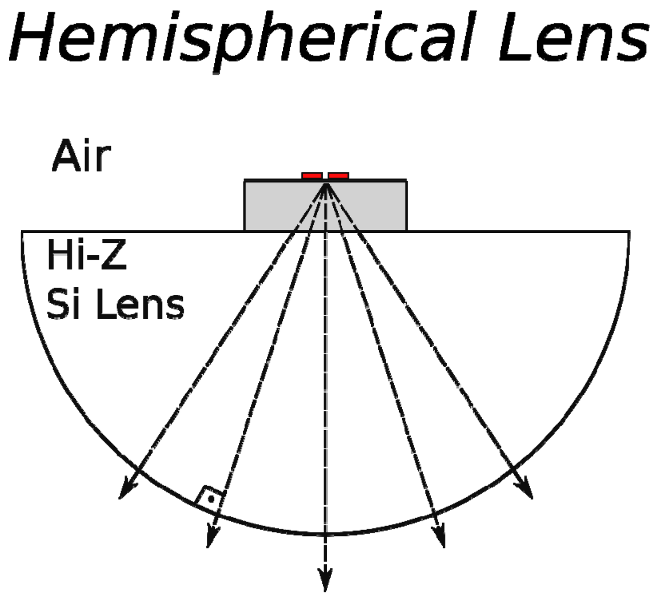
- Linear Array of 5 Slot antenas.
  - Simulated Directivity over inifinite Hi-Z Si: 6dBi

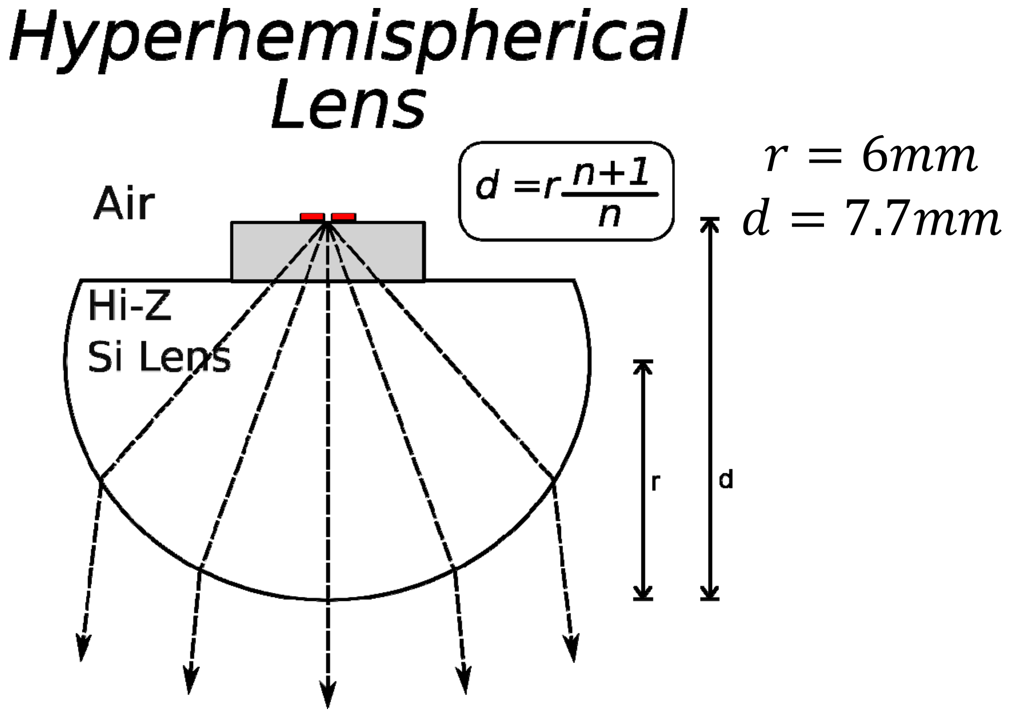




Hyperhemispherical Silicon Lens

- We can design the lens to increase the Directivity.



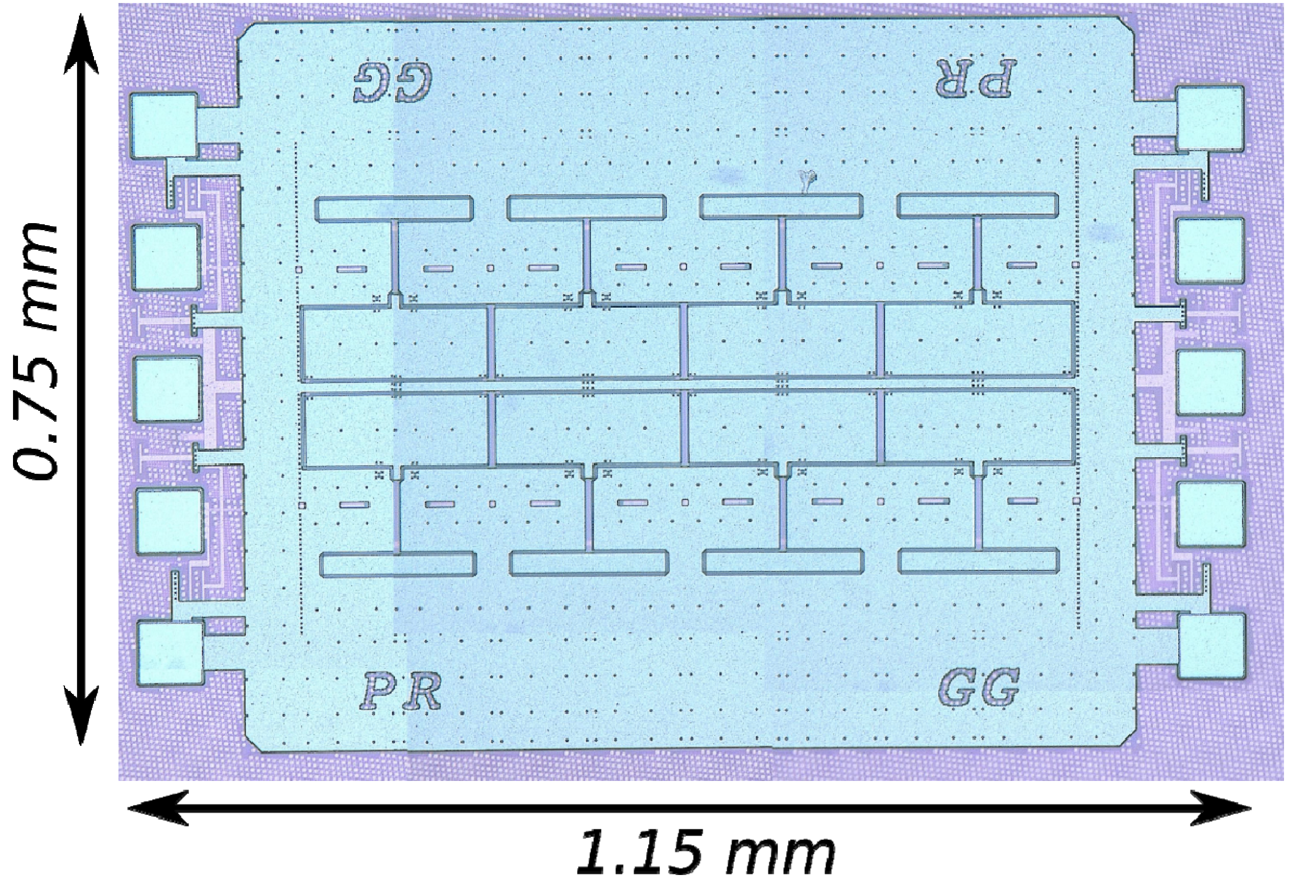


- Emulates infinite substrate.
- No gain improvement.

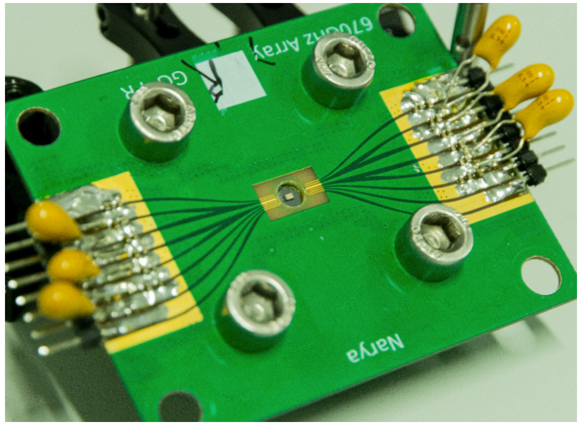
- Large directivity improvement.
- Not viable to simulate for large lenses.

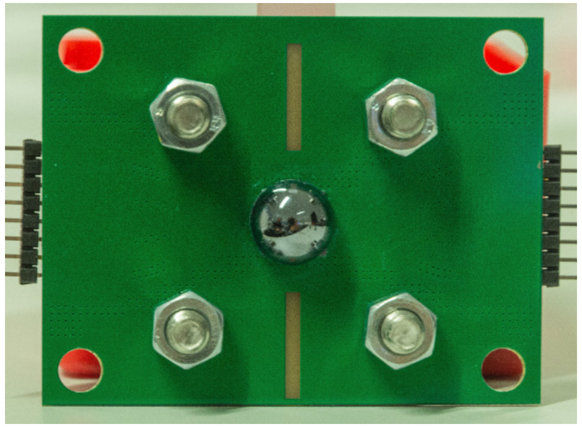
Die Micrograph

- Chip fabricated in 40nm Bulk CMOS.



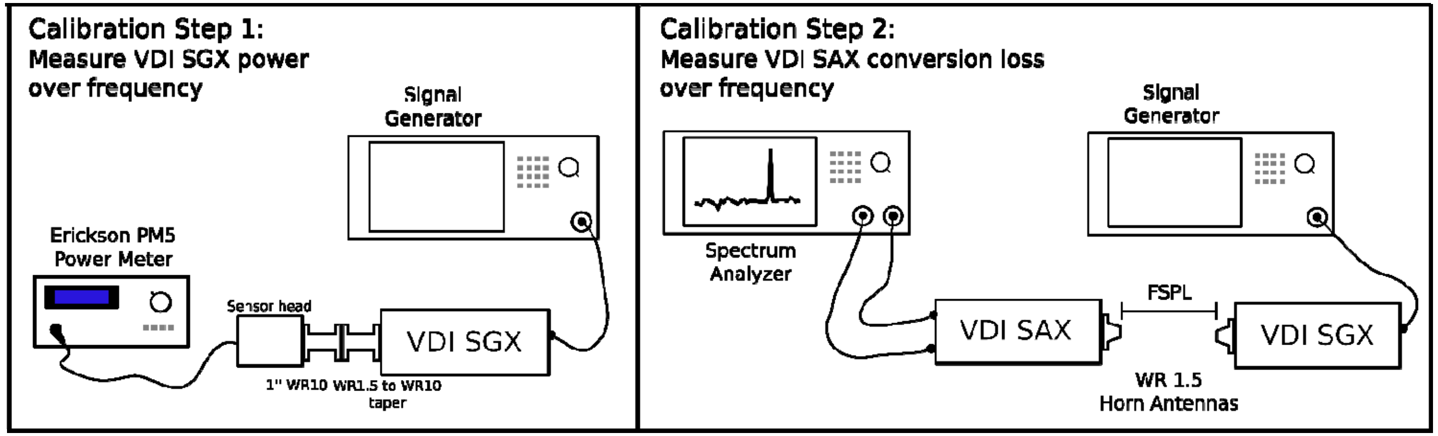
- Chip Assembly



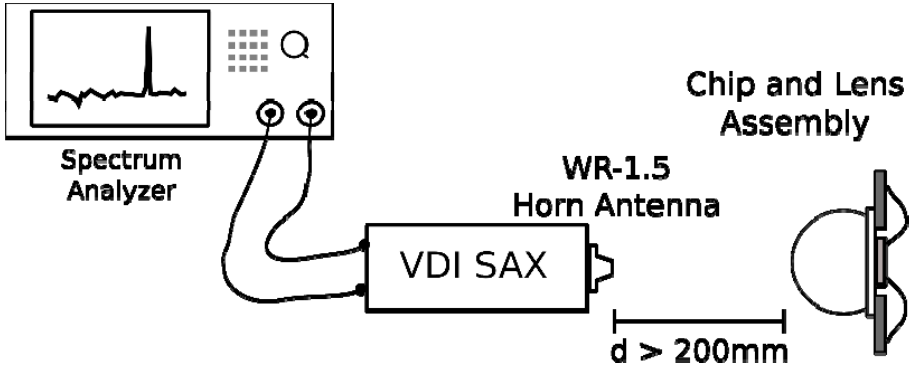


Measurement Setup

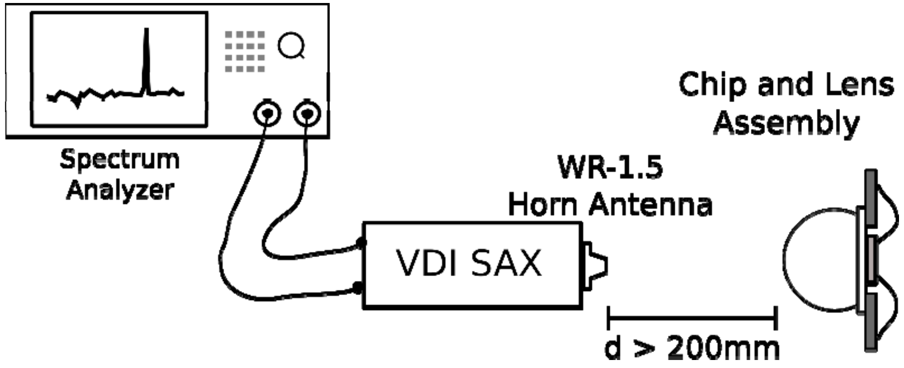
- Two-Step calibration:

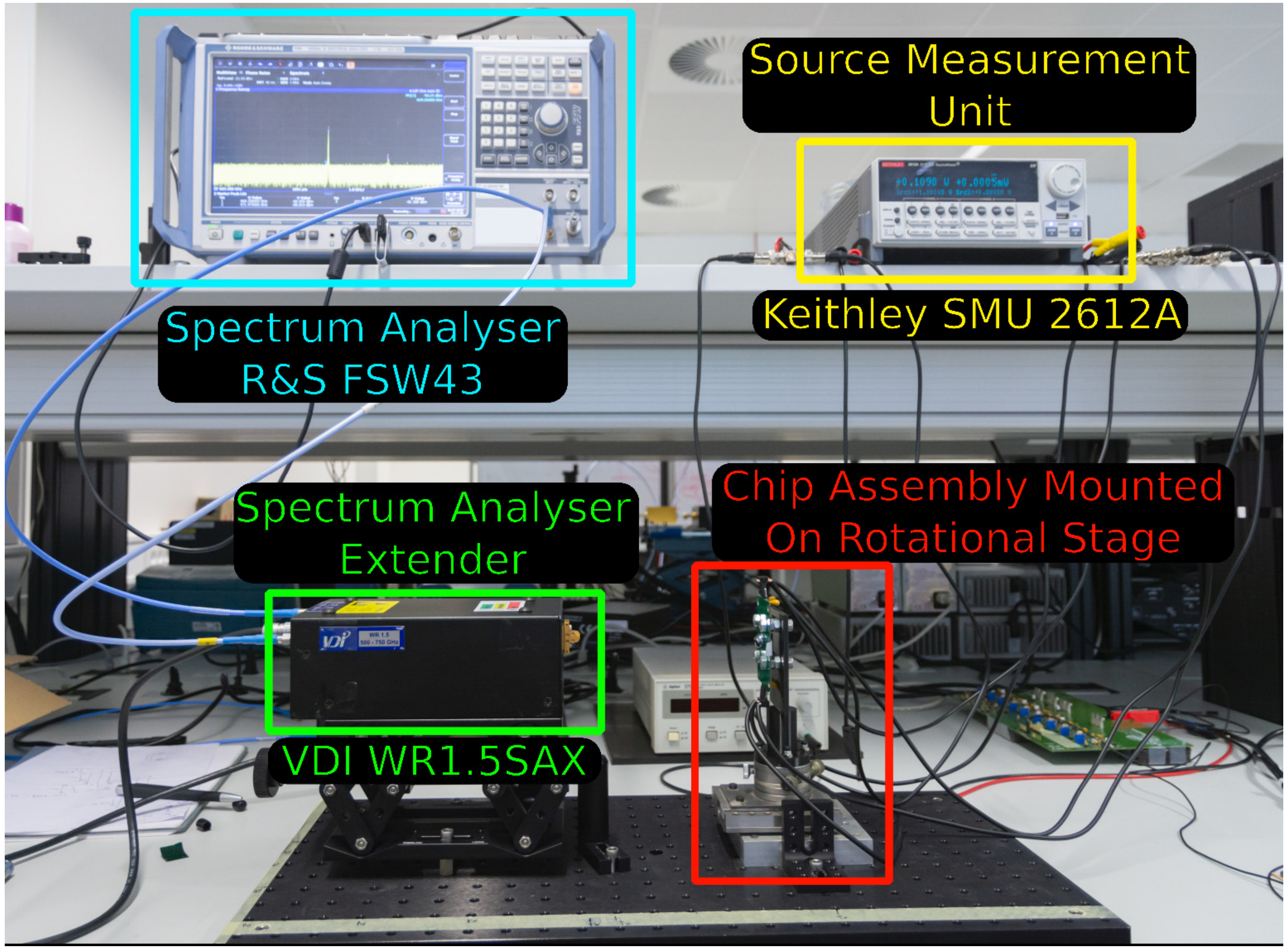


- Spectrum measurement setup:

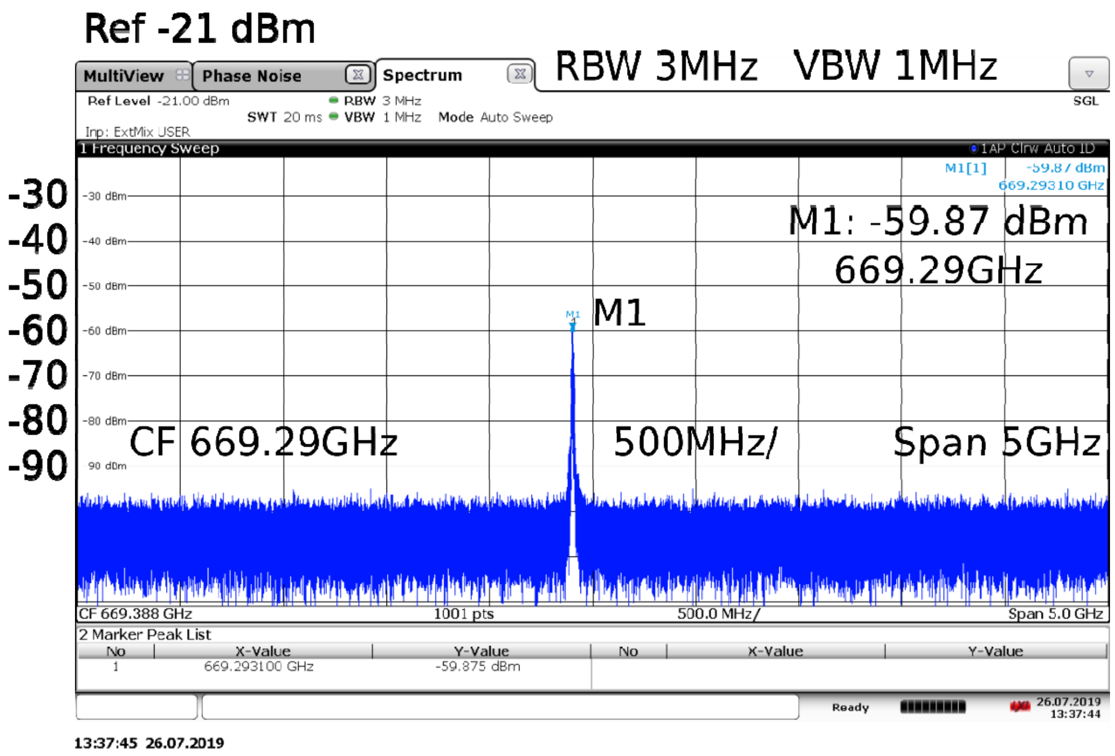


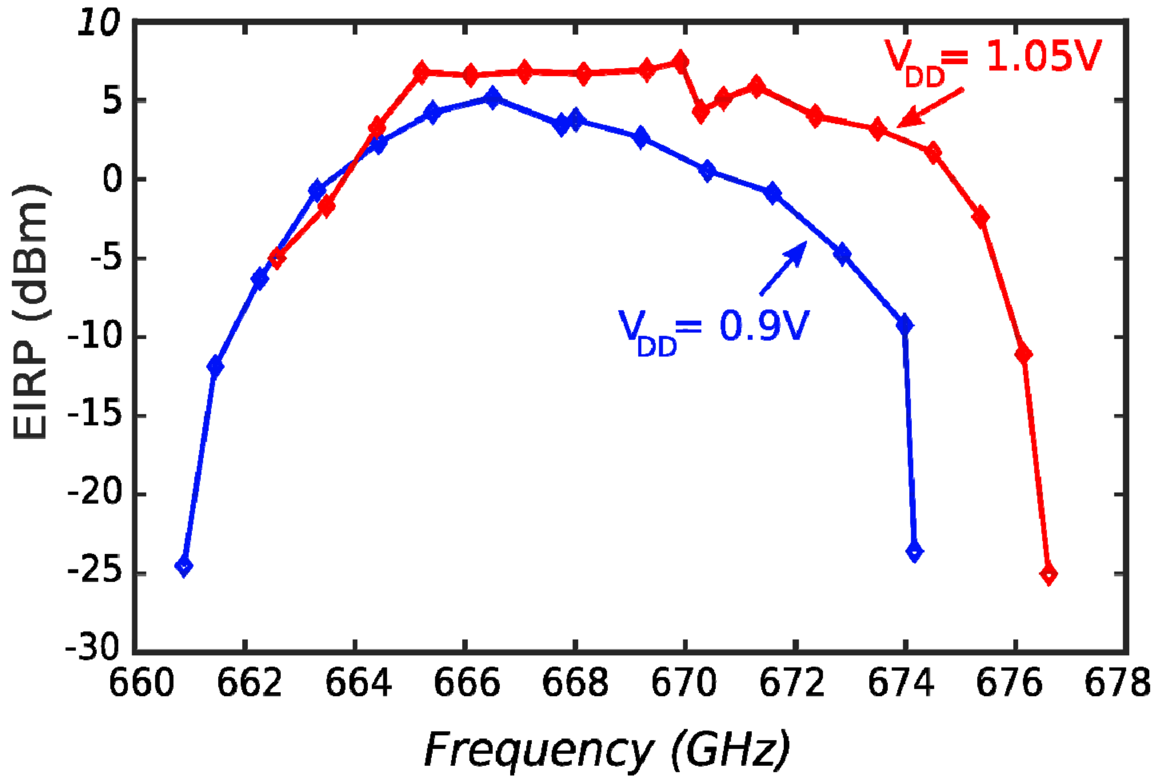
Measurement Setup





Measured Spectrum and EIRP

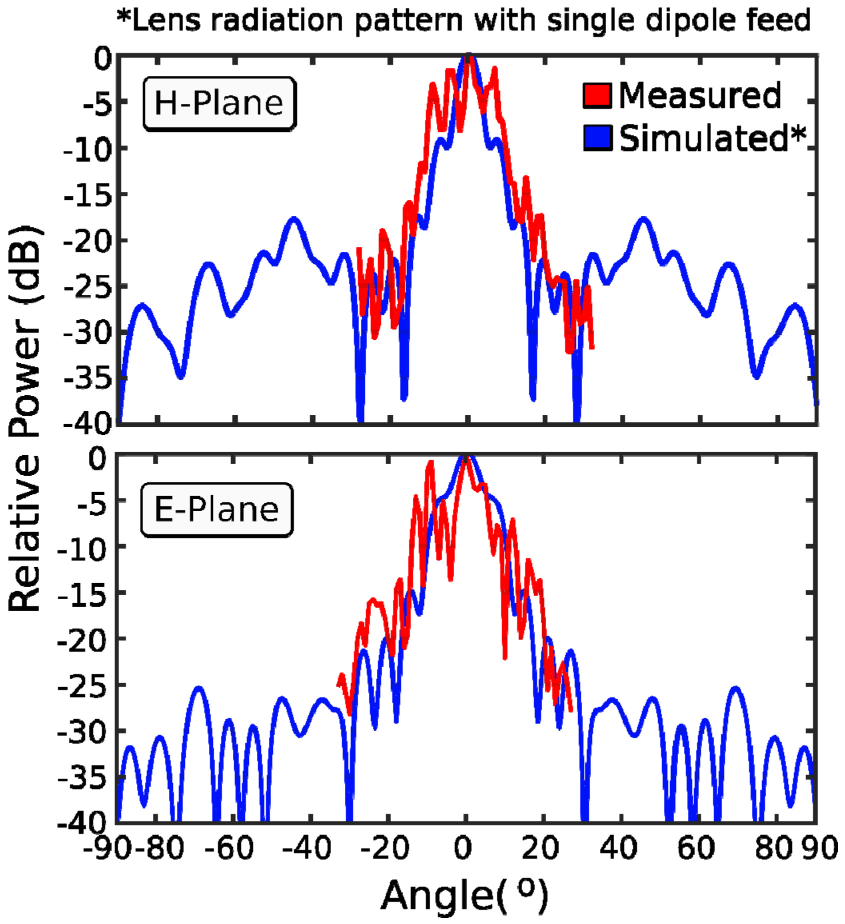




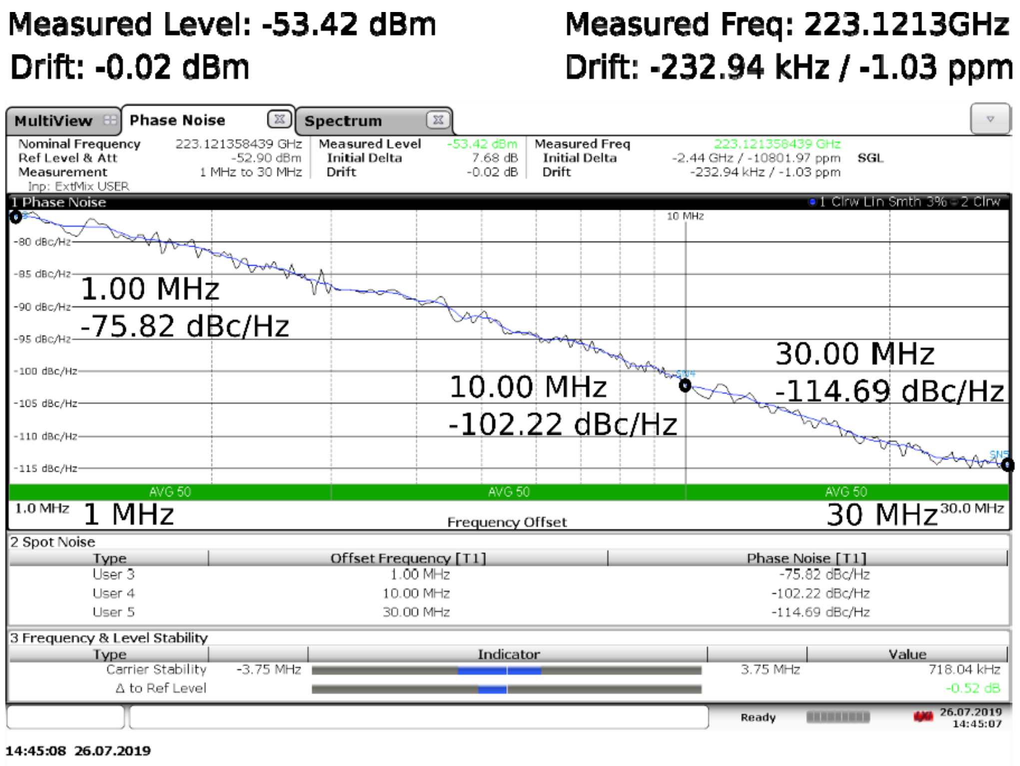
- Maximum measured EIRP is 7.4dBm at 670GHz

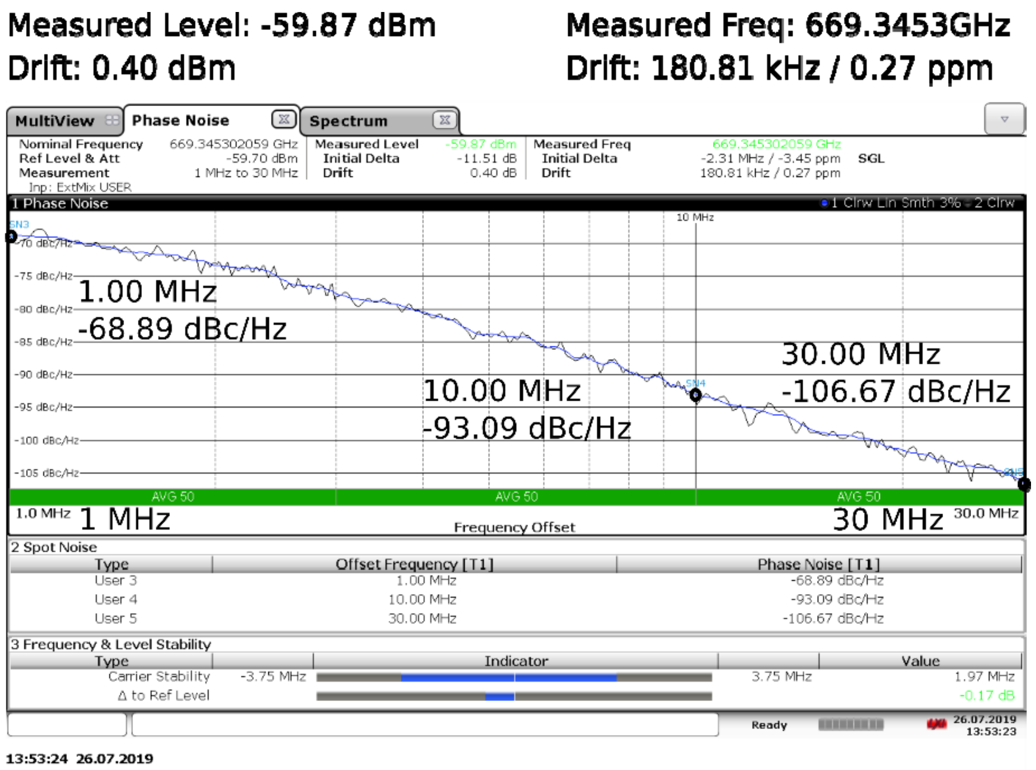
Measured Radiation Pattern

- Measurement angle limited by setup SNR.
- Array non-negligible size causes higher sidelobes than a dipole-source.
- Measured directivity is: $23.5dBi$
  - Lens + point source simulation: $24.7dBi$
  - Total radiated power of: $-16.1dBm$



Phase Noise





- Phase Noise of free-running oscillator measured using frequency and level tracking.

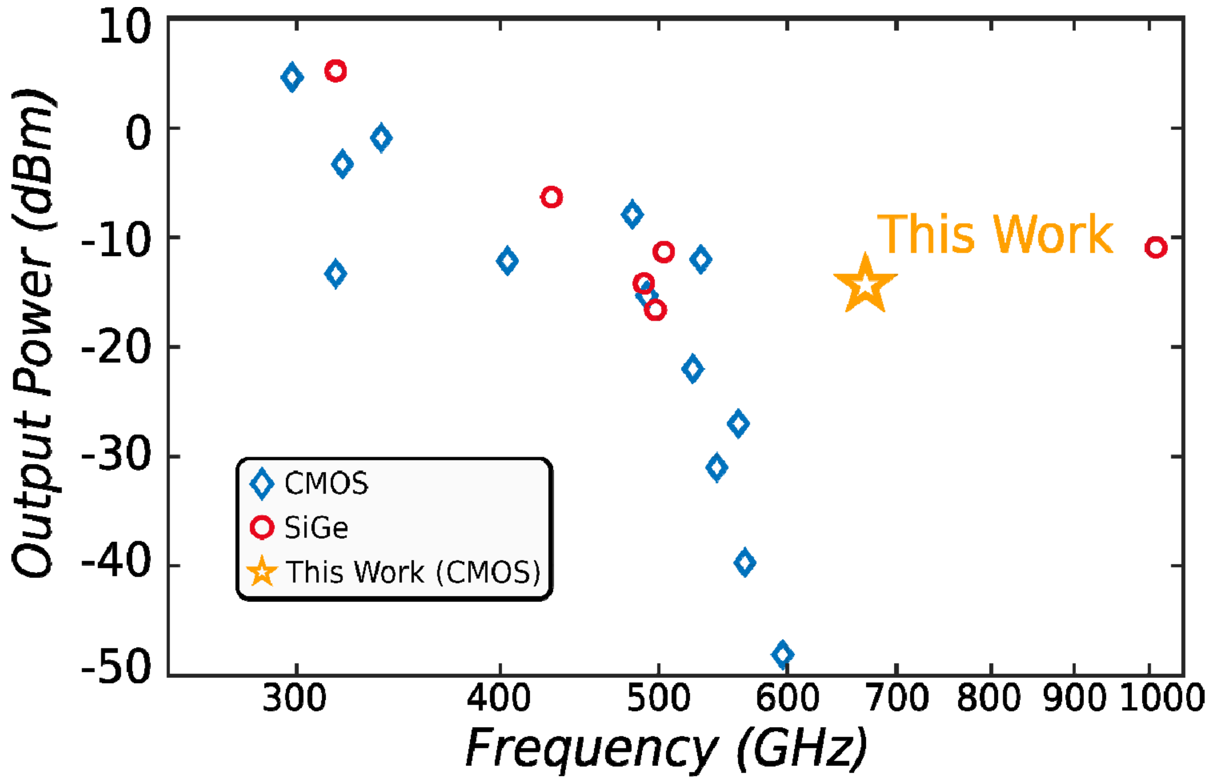
Performance Summary

	This Work	JSSC'2019[5]	ISSCC'2016[6]	ISSCC'2018[7]	ISSCC'2015[3]	JSSC'2018[4]	JSSC'2015[8]
Technology (fmax)	40nm CMOS (300GHz)	40nm CMOS (300GHz)	65nm CMOS (280GHz)	130nm SiGe BiCMOS (280GHz)	130nm SiGe BiCMOS (280GHz)	130nm SiGe BiCMOS (500GHz)	130nm SiGe BiCMOS (350GHz)
Source Type	4x2 Oscillator Array	1x4 Injection-Locked Oscillator Array	PLL Oscillator	PLL Oscillator	PLL + 4x4 Oscillator Array	7x6 Oscillator Array	Injection-Locked Oscillator
Frequency (GHz)	660.8-676.6	531.5	538.7-559.9	302-332	317	1010	485-511
Phase-Noise (dBc/Hz) @1MHz Δf	-69	-98*ǂ	-74	-78.5	-79	—	-87
Phase-Noise (dBc/Hz) @10MHz Δf	-93	-105*ǂ	-85	-97*	—	—	—
EIRP (dBm)	7.4	2.3	—	—	22.5	13.1	—
Output Power (dBm)	-16.1 (Radiated)	-12 (Radiated)	-27 (Radiated)	-13.9 (Probed)	5.2 (Radiated)	-10.9 (Radiated)	-16.6 (Probed)
Die Size (mm x mm)	1.15 x 0.75	1.71 x 1.46	1.8 x 1.55	1 x 0.85	1.6 x 1.3	1 x 1	0.72 x 0.7 (core)
DC Power (mW)	99.7	260	172	51.7	610	1100	388

* Value estimated from graph

ǂ Phase-Noise from oscilator injection locked to external signal generator

State-of-the-Art of silicon-based THz sources



Conclusion

- An analysis for the optimum impedances for third-harmonic power generation in a harmonic oscillator was presented. It was shown that gate impedance loading was a limiting factor for third-harmonic power generation.

- A frequency-filtering feedback topology was proposed for a high-power third-harmonic THz scalable array.

- The topology was demonstrated in a 670GHz arrayed signal source in 40nm CMOS that achieves state-of-the-art output power and phase-noise.

Acknowledgements

- Colleagues in MICAS for interesting and entertaining discussions on circuit design.

A 490GHz 32mW Fully Integrated CMOS Receiver Adopting Dual-Locking FLL

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