Heterodyne Sensing CMOS Array with High Density and Large Scale: A 240-GHz, 32-Unit Receiver Using a De-Centralized Architecture

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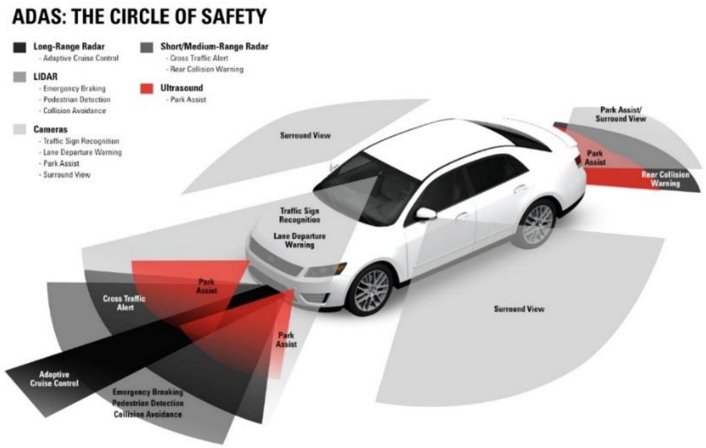
Outline

- Introduction
- Array Architecture
- Multi-functional Heterodyne Pixels
- Phase Locking Circuitry
- Measurement Results
- Conclusion

Terahertz Radar as an Important Sensing Mode



[Source: roboticsandautomationnews.com]

[Source: Getty Images]

- Multiple sensing modes are needed in navigation applications where safety is a priority
  - Examples: self-driving cars, unmanned aerial vehicles, etc.

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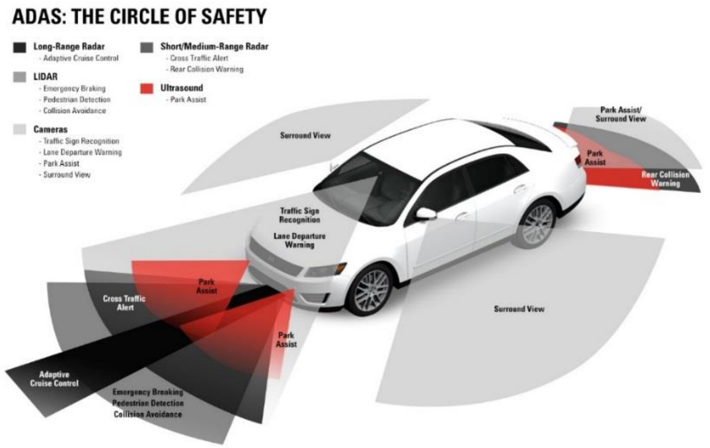

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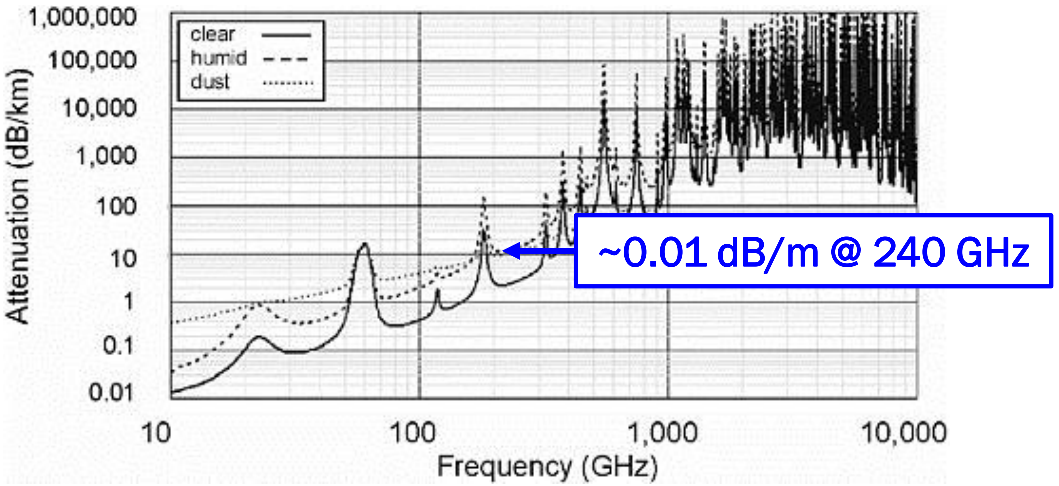

[National Research Council, Assessment of Millimeter-Wave and Terahertz Technology for Detection and Identification of Concealed Explosives and Weapons, 2007]

[Source: Getty Images]

- Multiple sensing modes are needed in navigation applications where safety is a priority
  - Examples: self-driving cars, unmanned aerial vehicles, etc.
- Terahertz sensing is an important complement to light-based sensing (e.g. LiDAR)
  - Sub-THz waves have much lower propagation loss than light

Possible Path Towards Sharp THz Beam

- If we use a single heterodyne receiver array,
  - to obtain 1° beam width, an area of 6cm x 6cm (~ 10,000 units) is needed at 240 GHz

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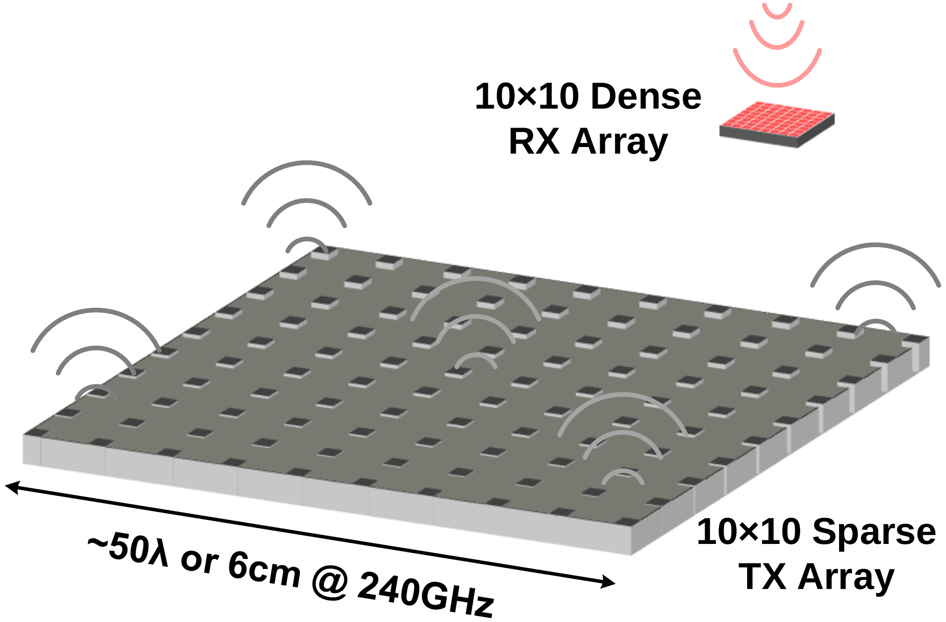
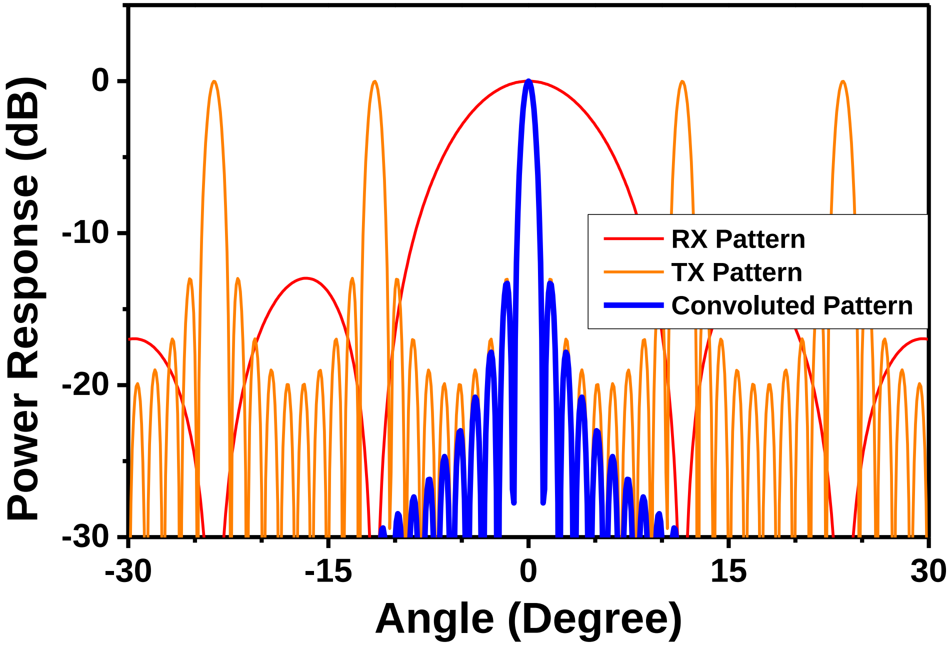
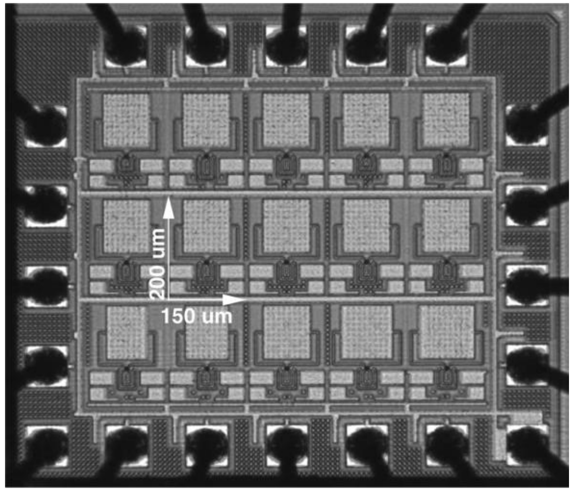




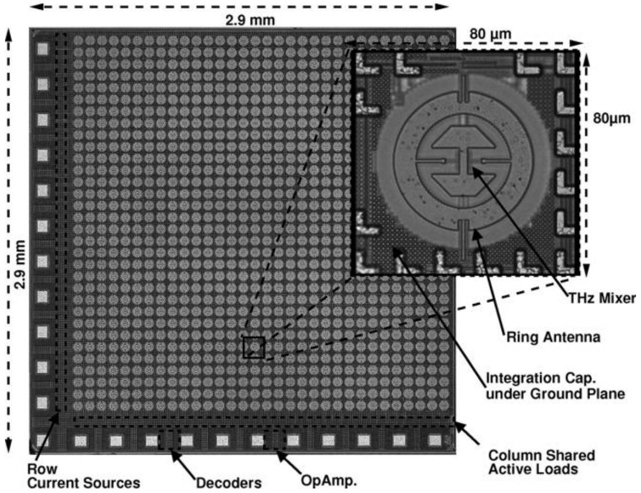
- One possible solution is based on the two-way array pattern
  - On-board sparse TX array generates sharp beams
  - On-chip dense RX array synthesizes single beam to filter out TX sidelobes -- with relaxed, but still high, scale requirement

Review of Previous On-Chip THz Sensing Arrays

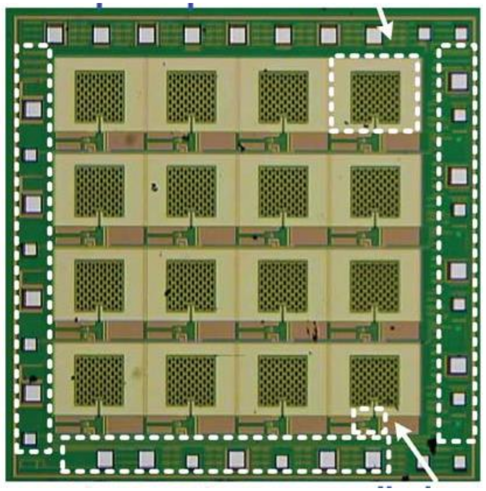
- **Direct (Square-Law) Detector Arrays (large scale)**



[E. Öjefors, et al., JSSC, 2009]



[R. Al Hadi et al., JSSC, 2012]

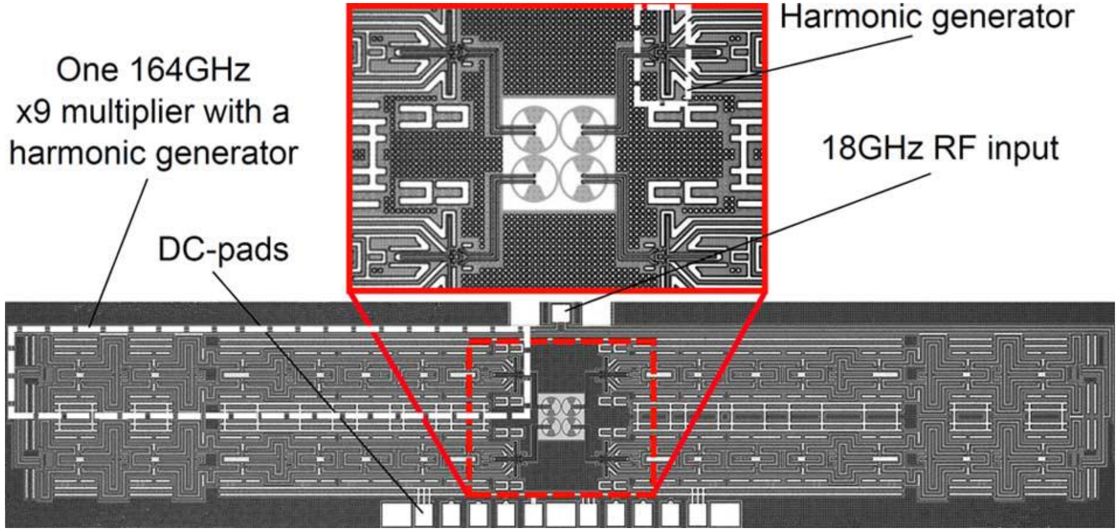


[R. Han et al., JSSC, 2013]

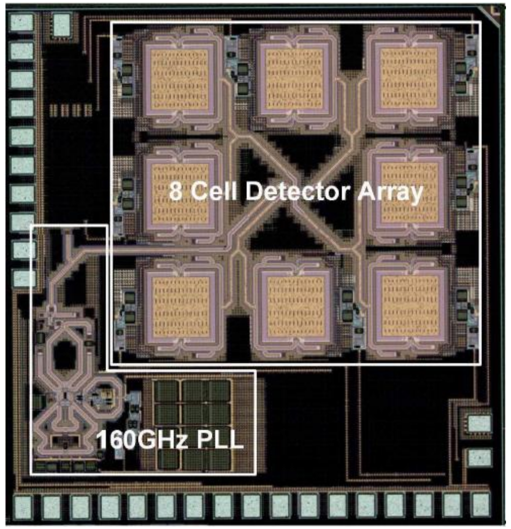
- Techniques of building large-scale direct detector arrays have become mature
- Limitations of direct detection
  - ☹ Low responsivity and low SNR, due to limited received RF power ($P_{IF} \propto P_{RF}^2$)
  - ☹ Coherence of RF signals is lost, thus unable to perform beam-forming (electrical scanning)

Review of Previous On-Chip THz Sensing Arrays

- **Heterodyne Detector Arrays (small scale)**



2 x 2 array [K. Statnikov, et al., TMTT, 2015]



8-unit array [C. Jiang, et al., JSSC, 2016]

- **Strengths of heterodyne detection**
  - ☺ High responsivity and high SNR, by leveraging high LO power ($P_{IF} \propto P_{LO} \cdot P_{RF}$)
  - ☺ Coherence of RF signals is preserved, thus inherently capable of beam-forming
- **There are still challenges of designing large-scale heterodyne detector arrays to form sharp beam**

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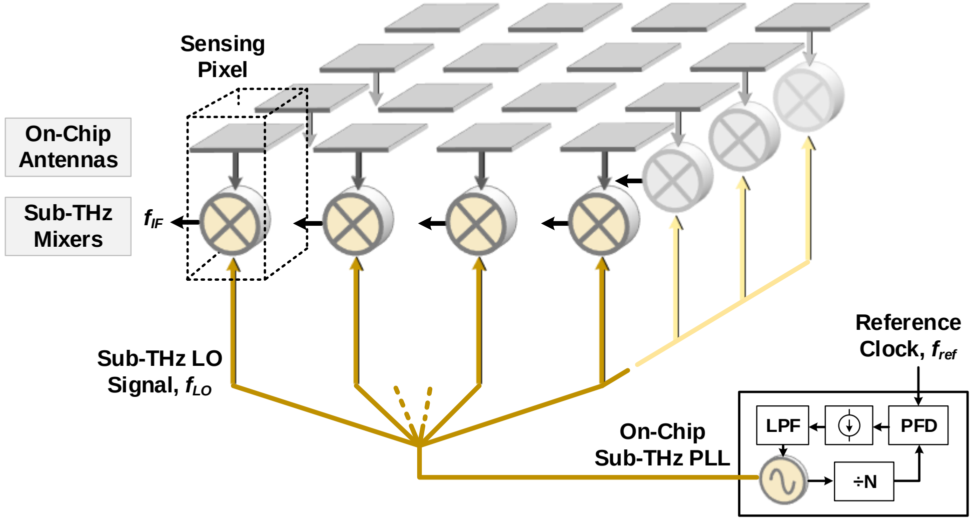
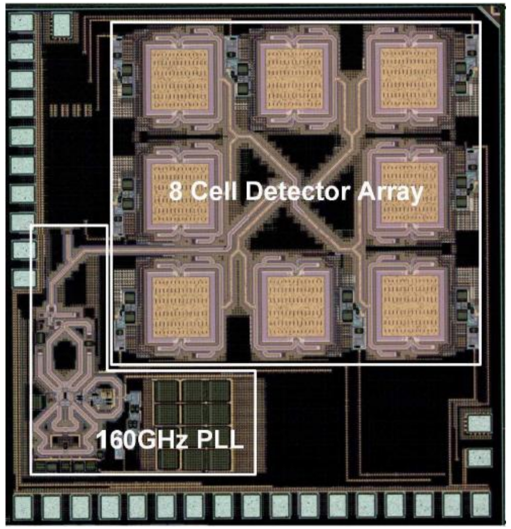
RX Chip: Centralized vs. De-Centralized Arrays



- Centralized array relies on a single LO source, however,
  - ☹ LO power of each unit scales down as array scales up
  - ☹ Long LO feed lines are lossy and hard to route

- Example



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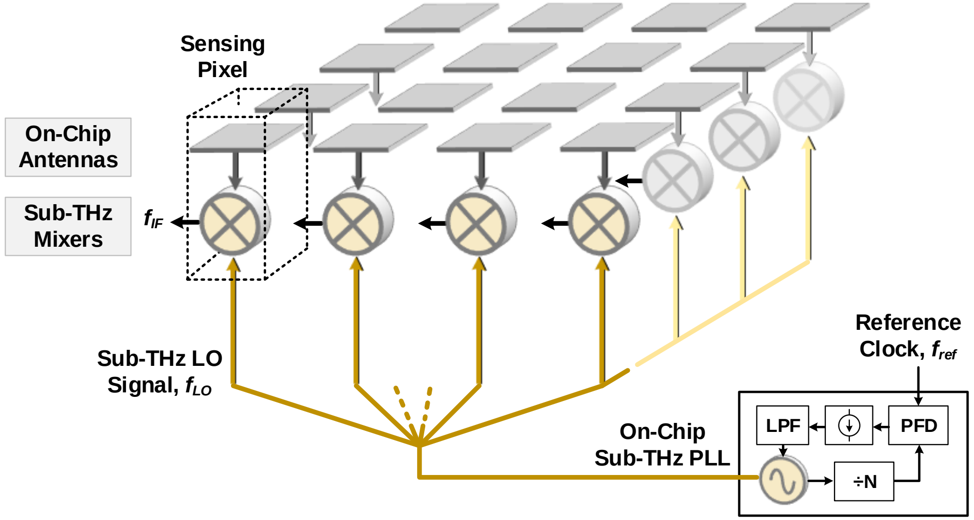
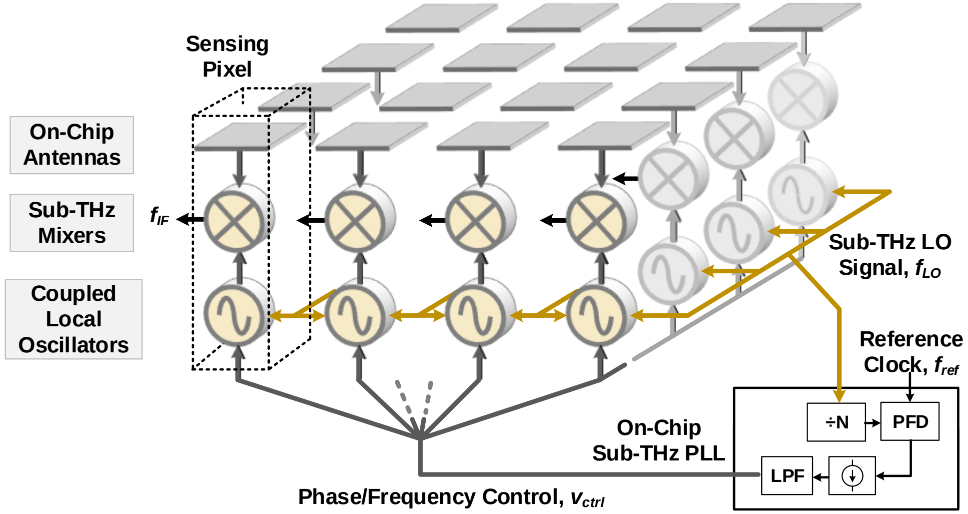
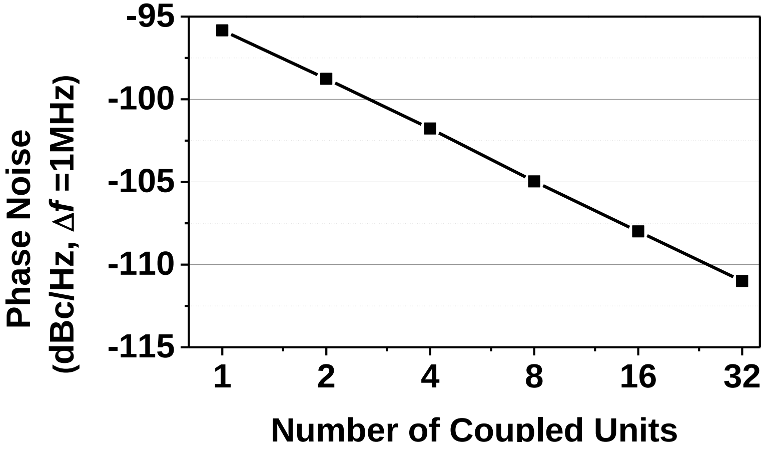


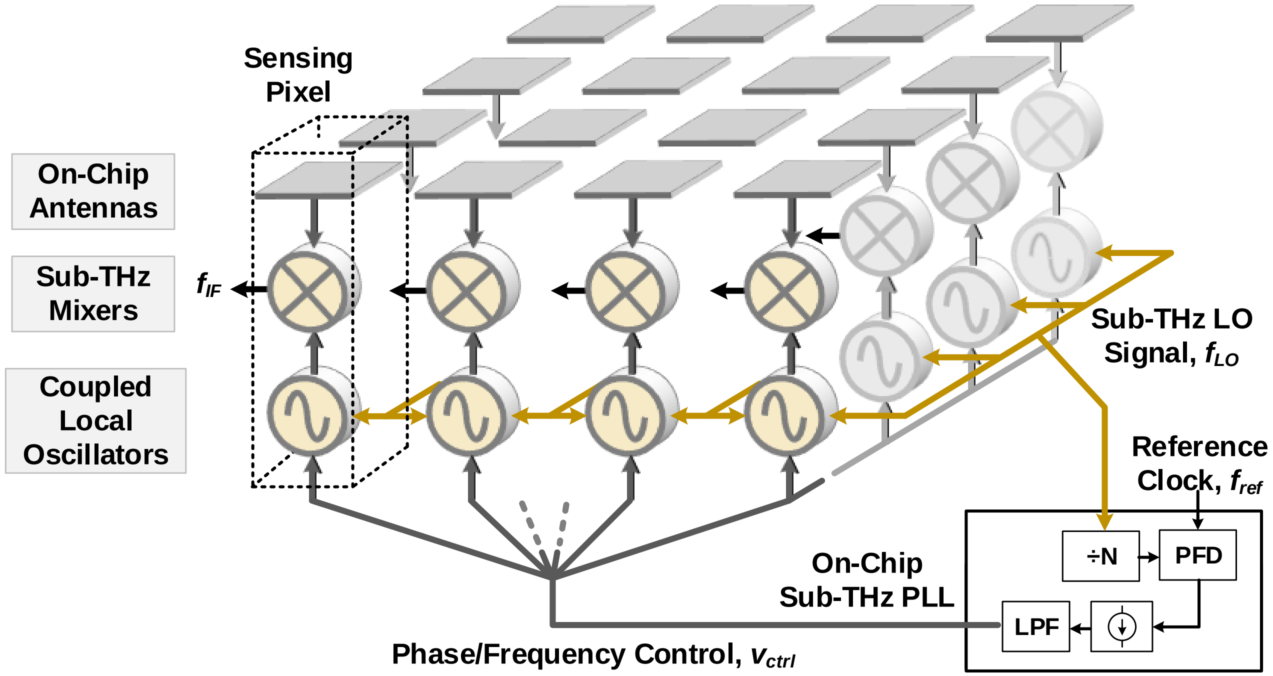


- **Centralized array relies on a single LO source, however,**
  - ☹ LO power of each unit scales down as array scales up
  - ☹ Long LO feed lines are lossy and hard to route

- **De-Centralized array ensures every unit having an LO source**
  - ☺ LO sources are coherently coupled; corporate feed is thus eliminated
  - ☺ Oscillator power requirement is relaxed
  - ☺ Bonus: LO phase noise improves as more units are coupled



Challenges of Scaling and Our Solutions



- **Density challenge:**
  - – Within $\lambda/2 \cdot \lambda/2$ area, antenna, oscillator, mixer, coupler etc. needs to be incorporated

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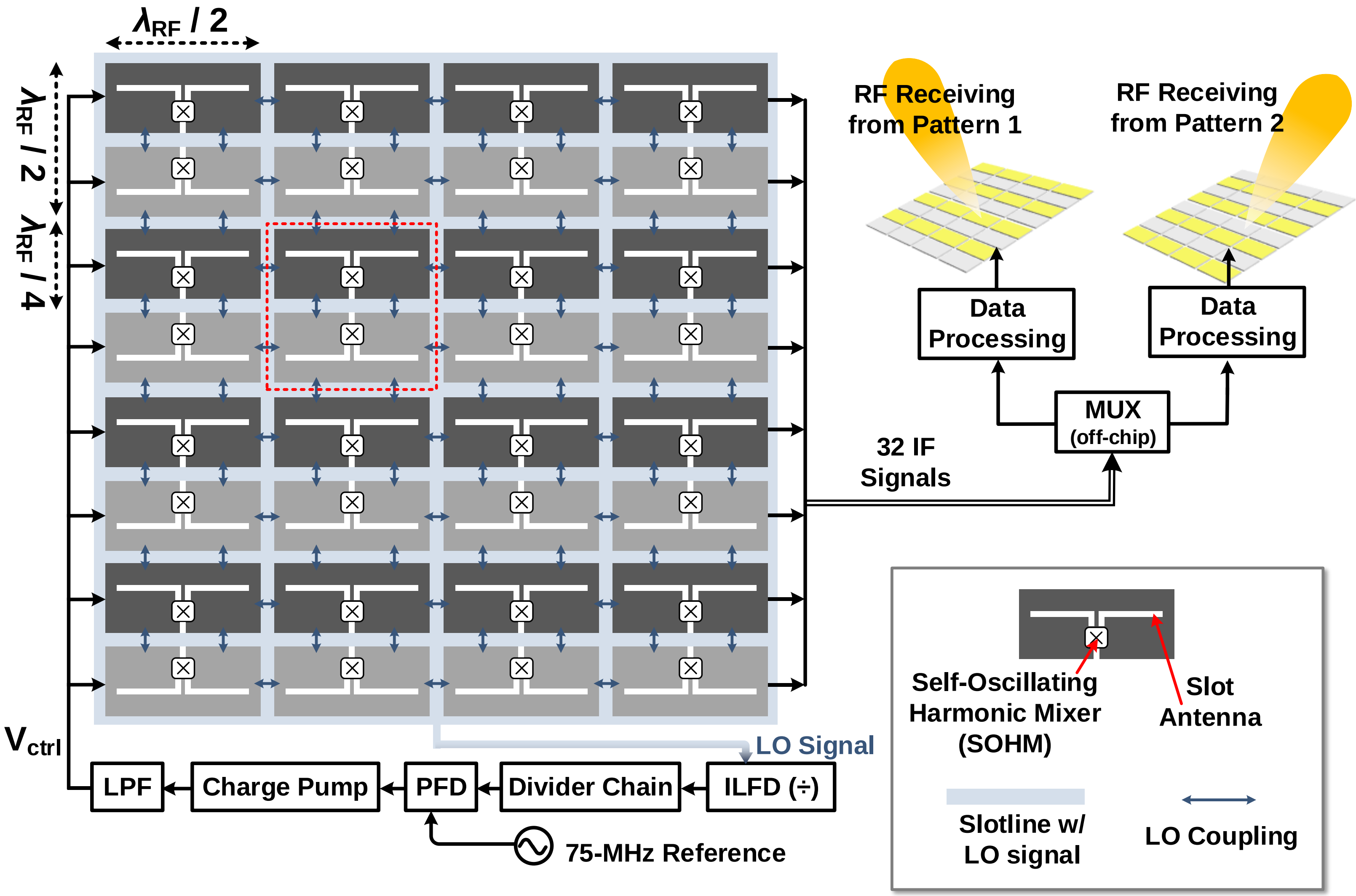

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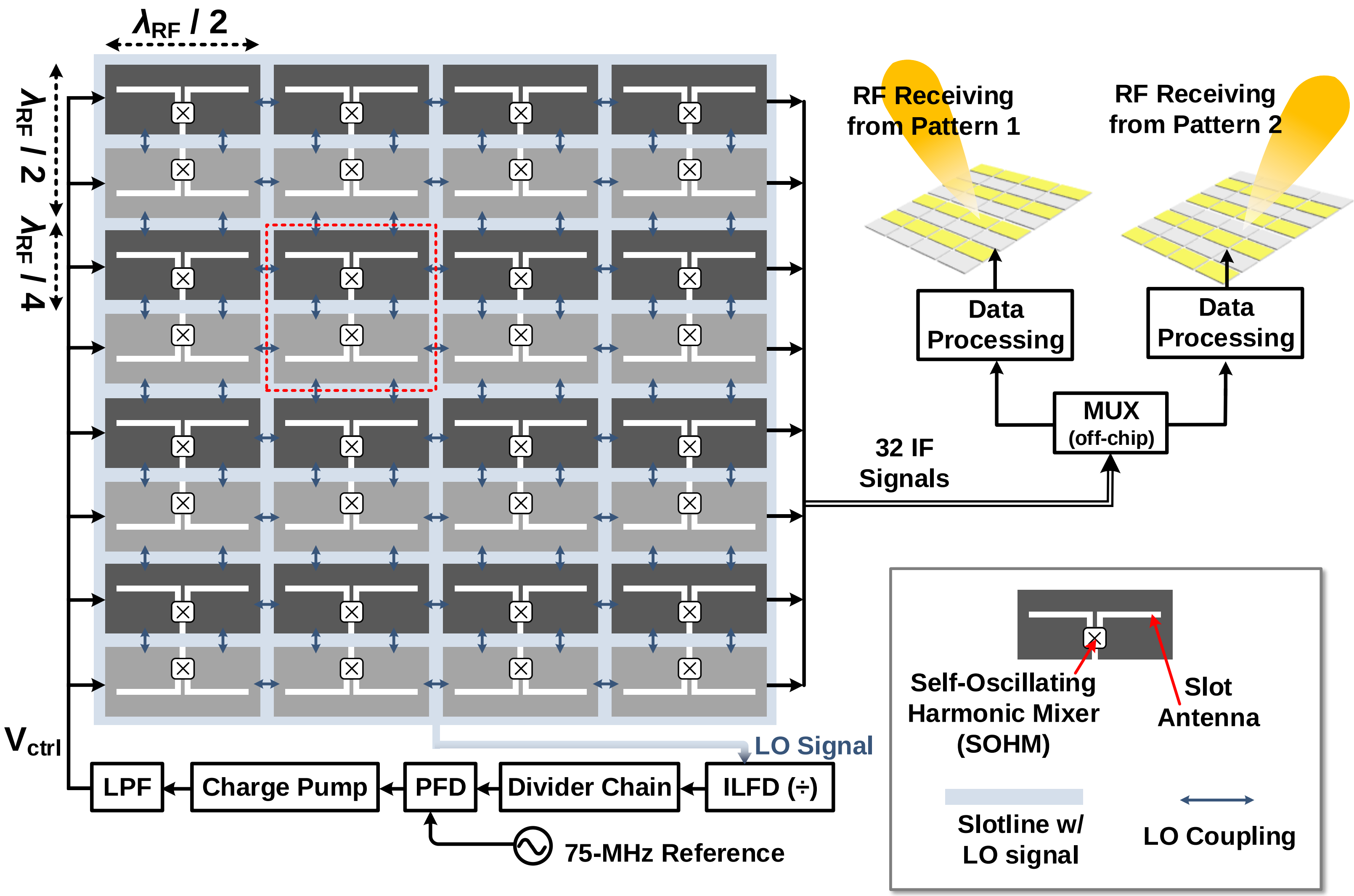

- Density challenge:
  - Within $\lambda/2 \cdot \lambda/2$ area, antenna, oscillator, mixer, coupler etc. needs to be incorporated

- Self-Oscillating harmonic mixer (SOHM) employed
  - Oscillator and mixer condensed into one component
- Slotline-resonator-based oscillator coupling employed
- Two interleaved 4x4 array integrated ($A_{unit} = \lambda/2 \cdot \lambda/2$)

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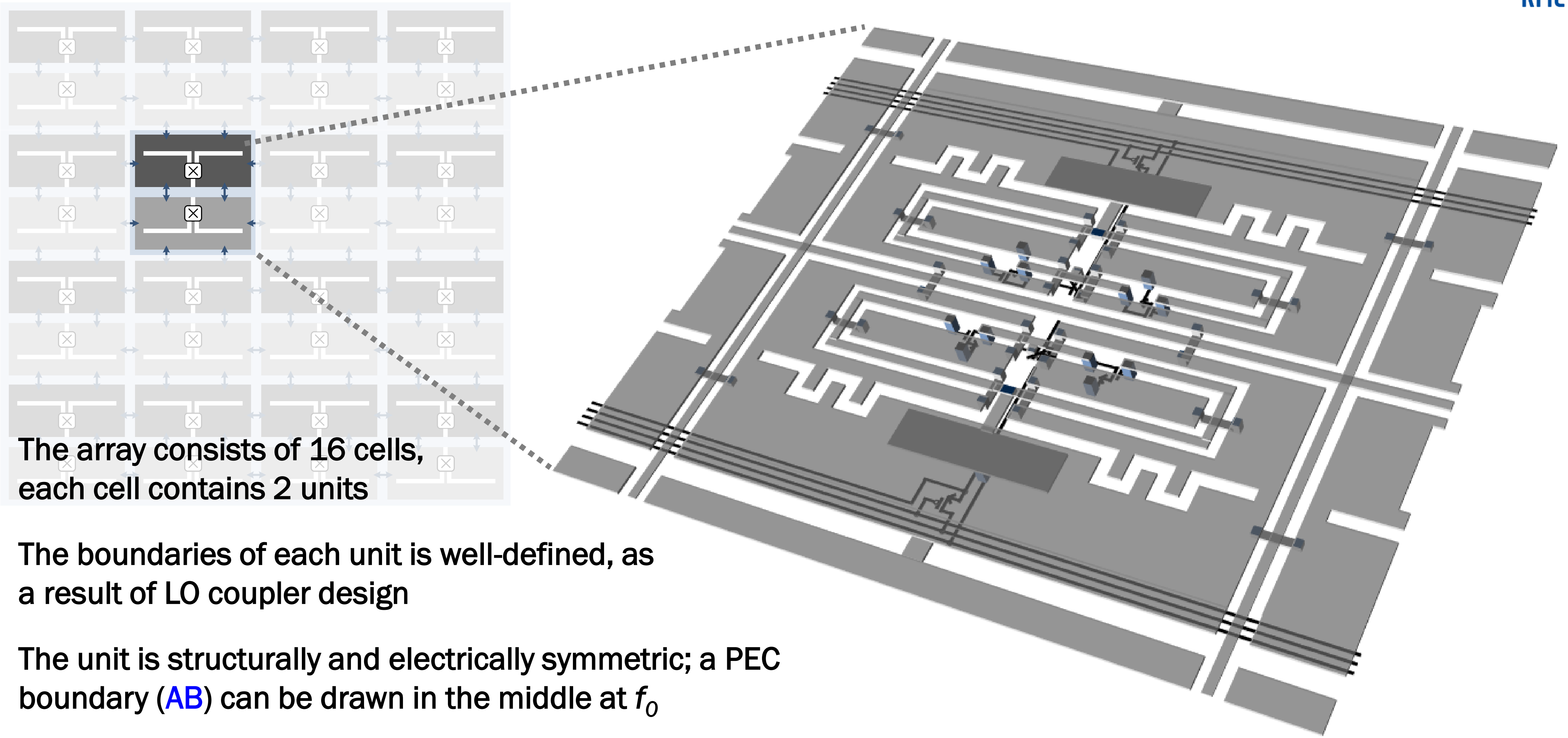
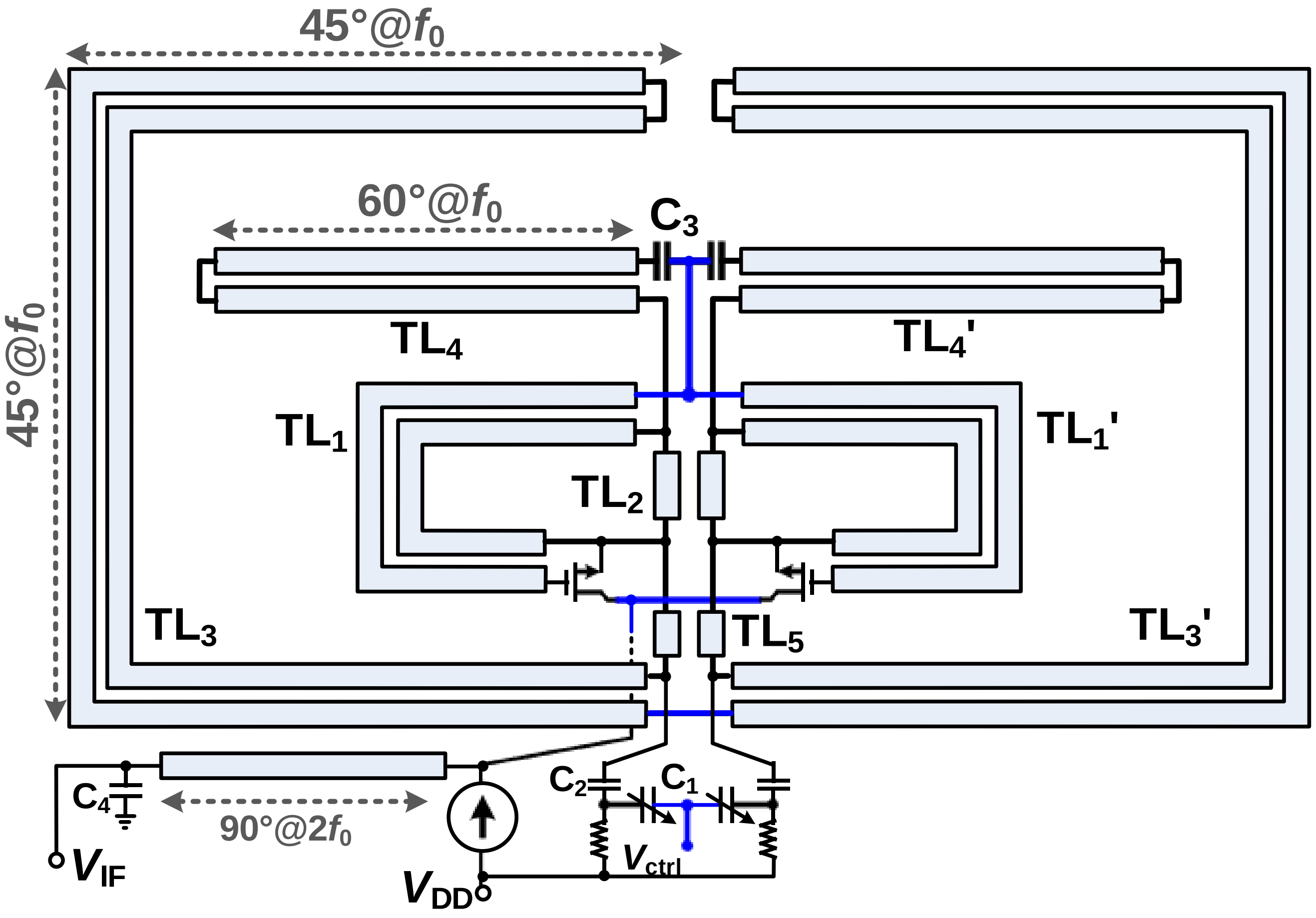
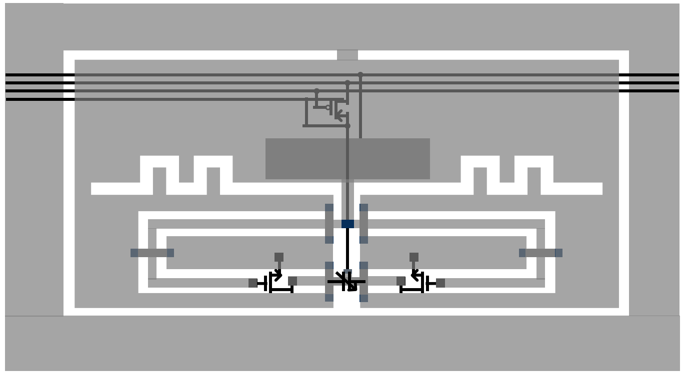
EM Structure of a Single Cell



- The array consists of 16 cells, each cell contains 2 units
- The boundaries of each unit is well-defined, as a result of LO coupler design
- The unit is structurally and electrically symmetric; a PEC boundary (AB) can be drawn in the middle at f_0

Highlight I: Multifunctional Structures





EM structure as reference

- TL_4 and TL_4' are slot antennas
- TL_3 and TL_3' are resonator and coupler of oscillators
- TL_1, TL_1', TL_2, and TL_5 are integral components of oscillators

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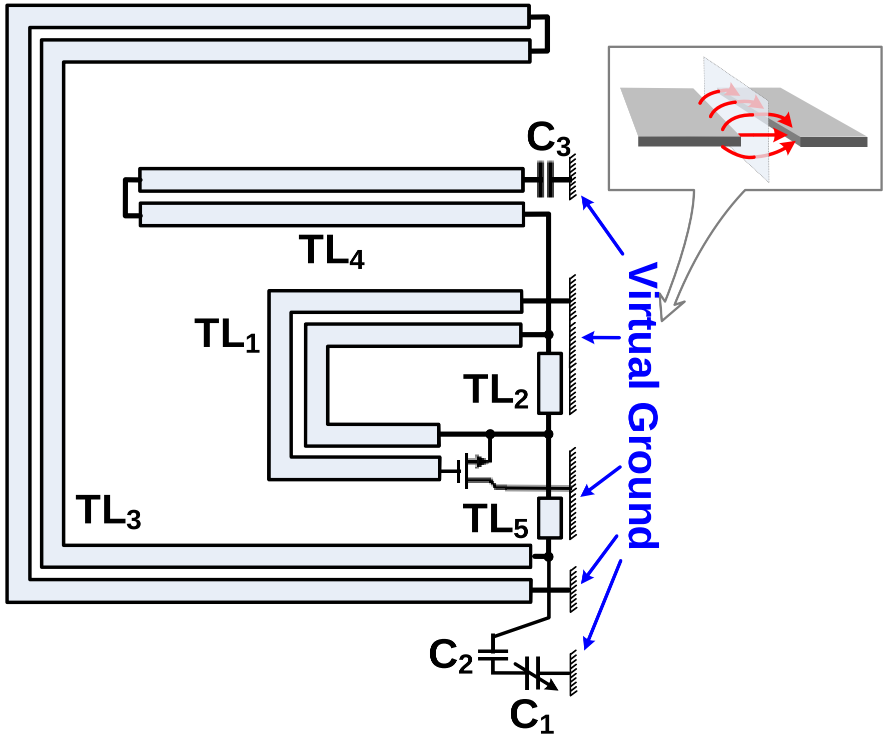

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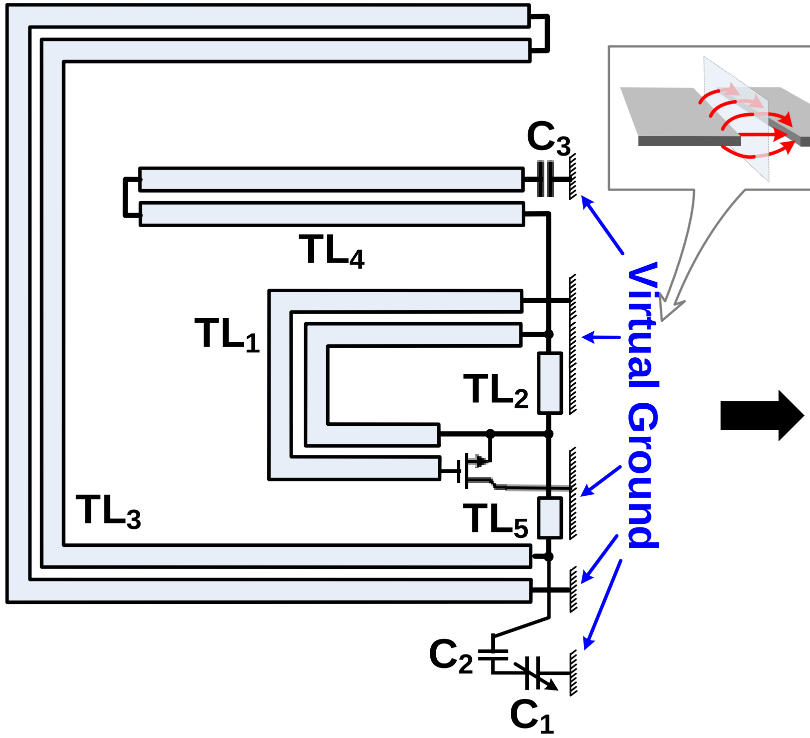
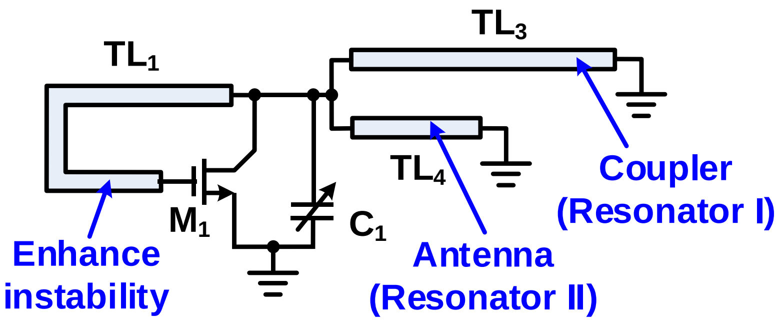


Self-Feeding Oscillator



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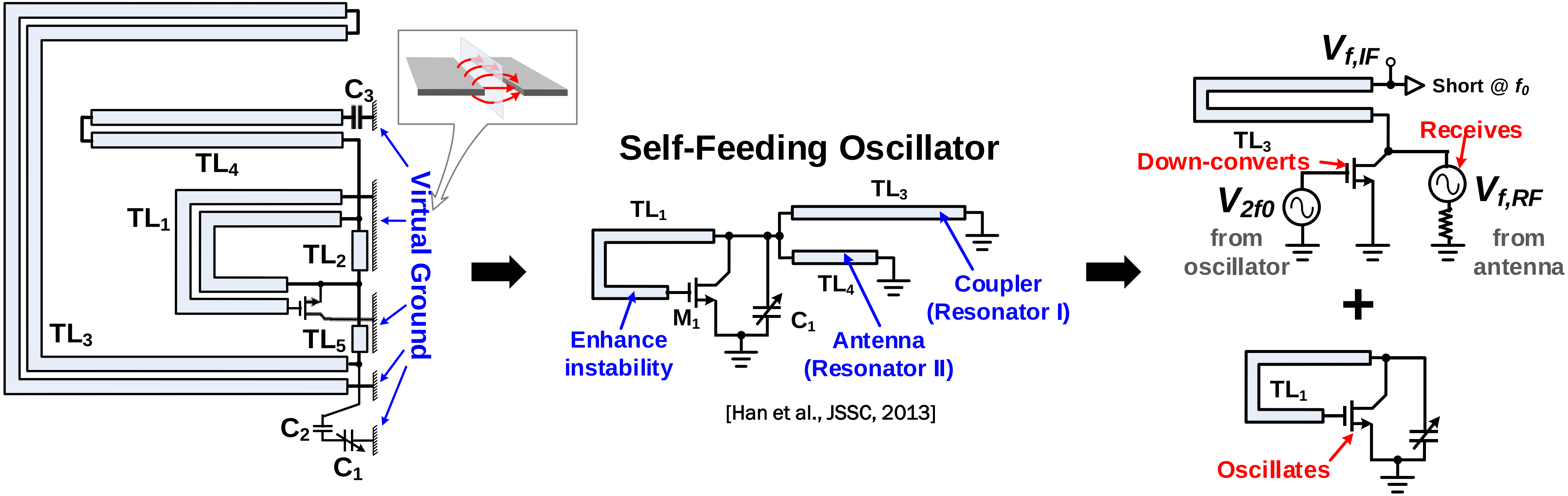

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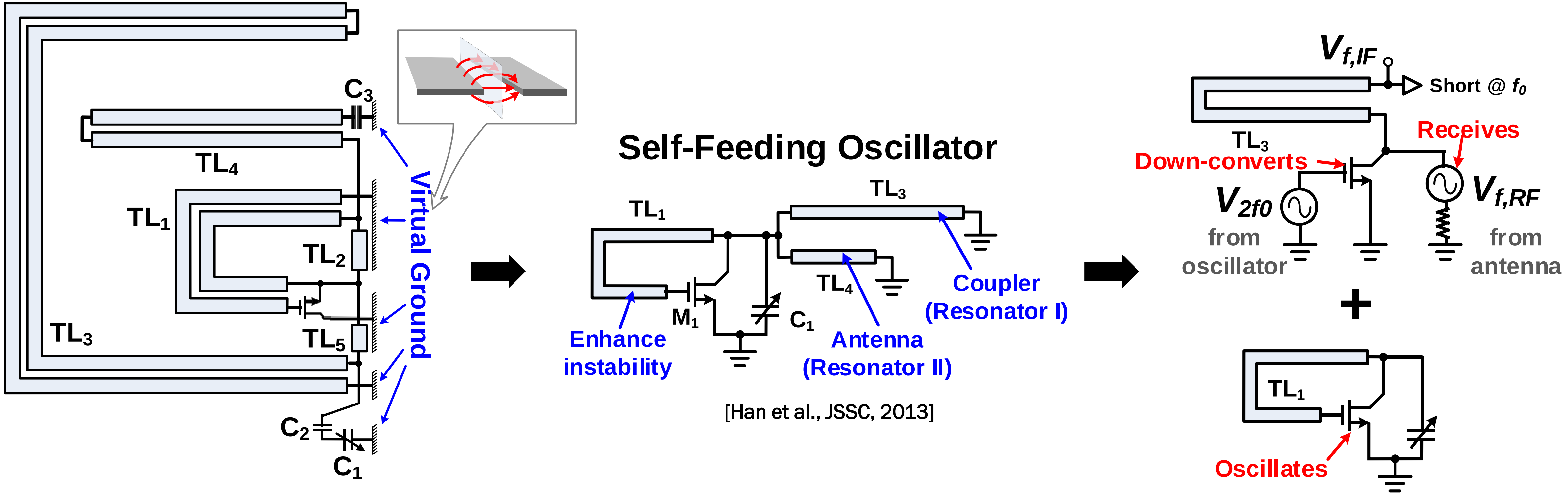
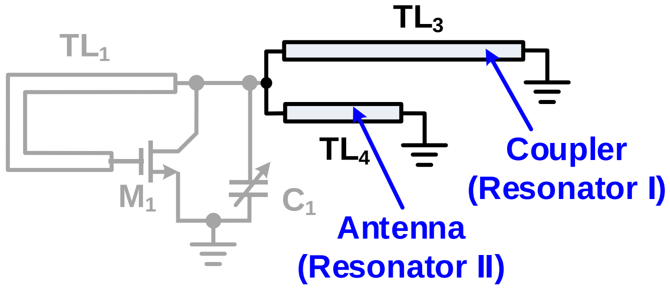


[Han et al., JSSC, 2013]

- Self-oscillating harmonic mixer (SOHM) can be regarded as an oscillator that
  - **Oscillates** at f_0 = 120 GHz and simultaneously generates LO signal $f_{LO} = 2f_0$ = 240 GHz
  - **Receives** RF power from resonator (TL_4, Resonator II)
  - **Down-converts** RF to IF, i.e. $f_{IF} = f_{RF} - 2f_0$ (using the non-linearity of the transistor)
- Oscillator is optimized to the optimal phase condition by choosing proper Z_{TL1} and φ_{TL1}

Highlight II: Near-field Interference

- Resonator I and II are for coupling and radiation cancelling
- For explanation, E-field distributions are needed



Highlight II: Near-field Interference at f_0

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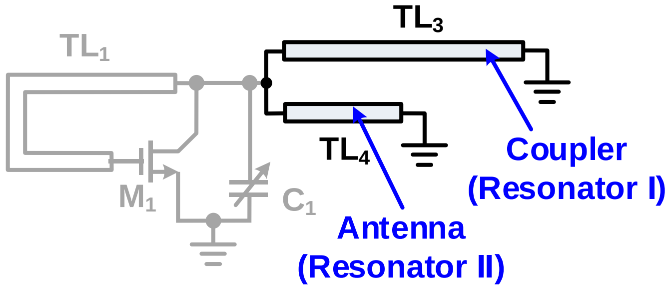
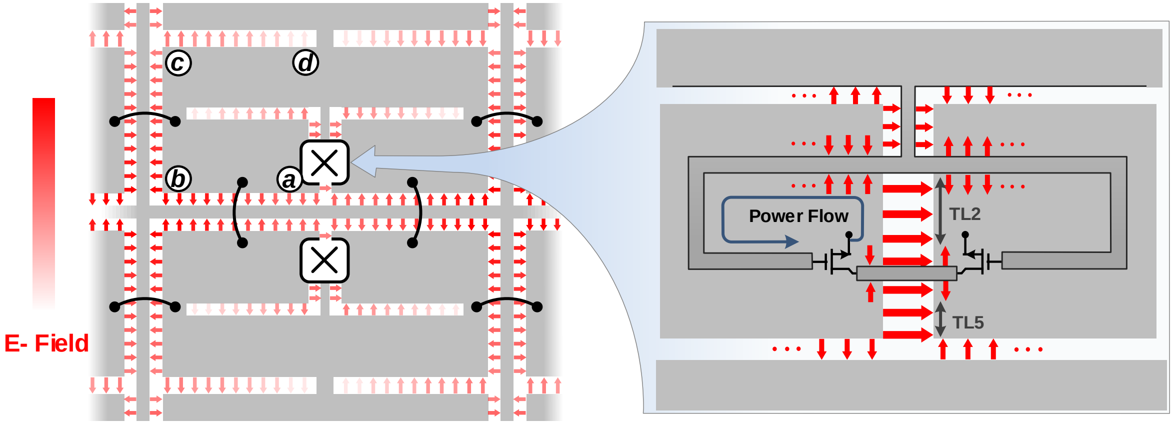
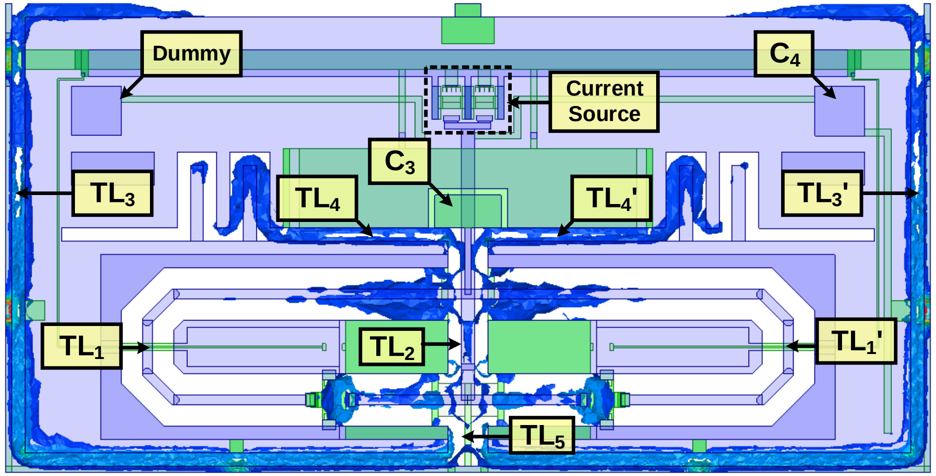


- At $f_0 = f_{LO}/2$, waves in TL_3 induce coupling between oscillators
- E-Field polarizations in TL_3 and TL_4 of adjacent units ensure radiation cancellation at f_0

- Theoretical prediction



- Full-wave Simulation (ports at drains are driven)



Highlight II: Near-field Interference at $2f_0$

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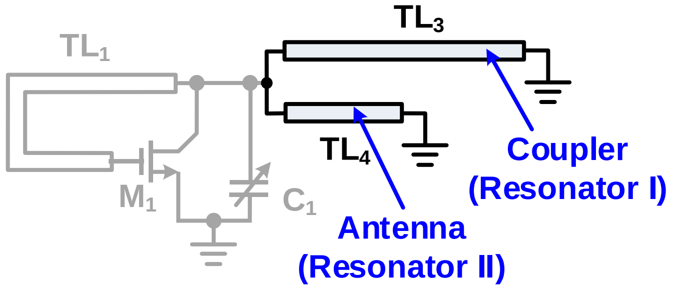

- At $2f_0 = f_{LO}$, waves are largely confined within the transistor
- Potential radiation is cancelled due to polarizations

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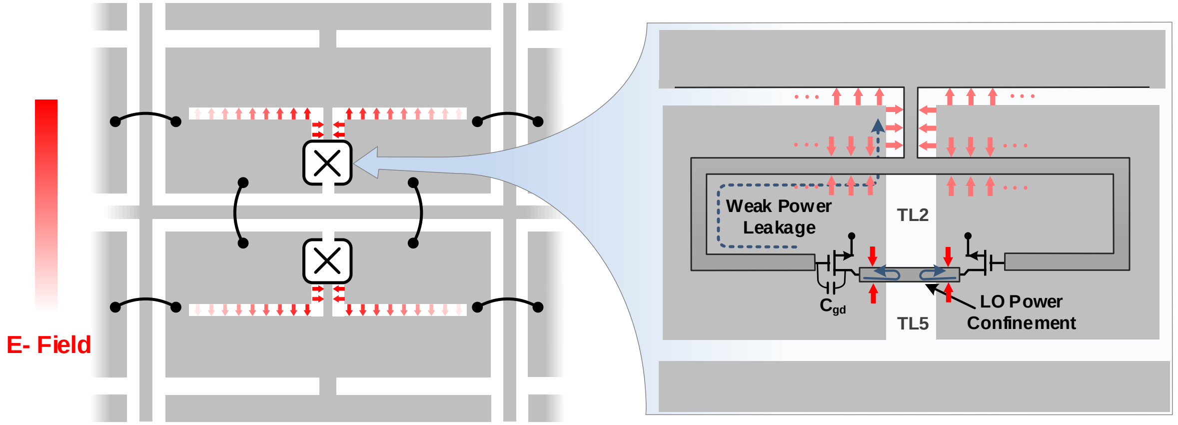

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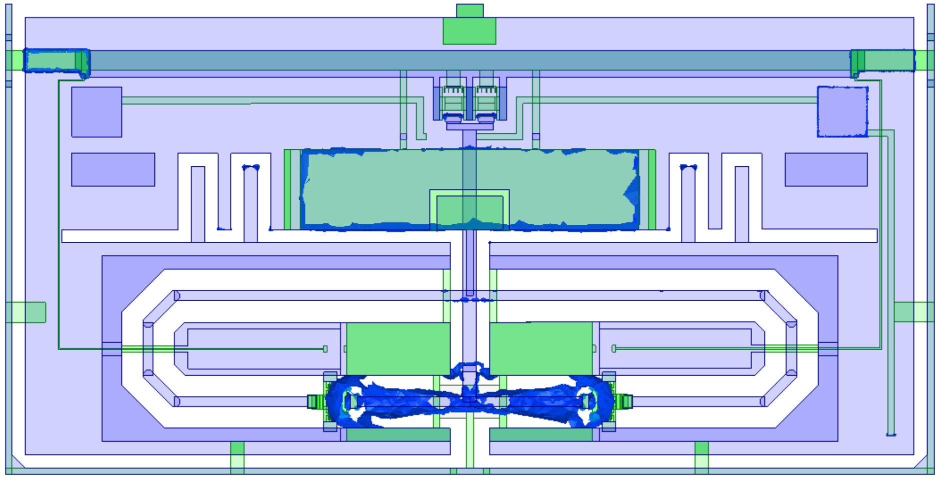

Highlight II: Near-field Interference at f_{RF}

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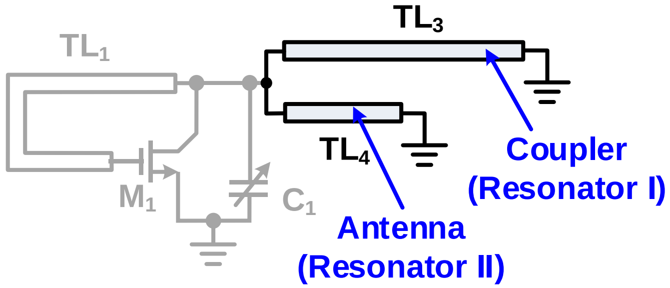
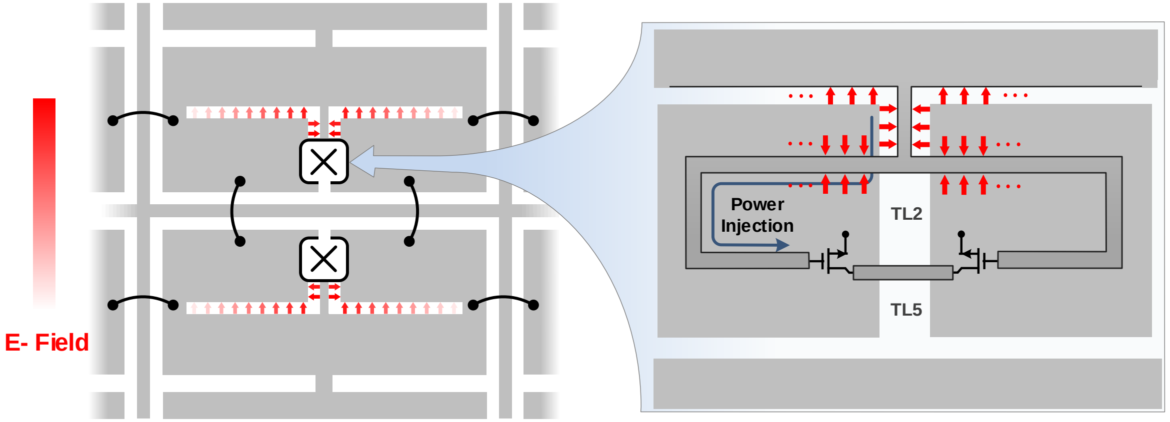


- At f_{RF}, waves are received by antennas since they are from a far-field source with the same polarization
- Down-converted IF signals are thus out-of-phase

- Theoretical prediction



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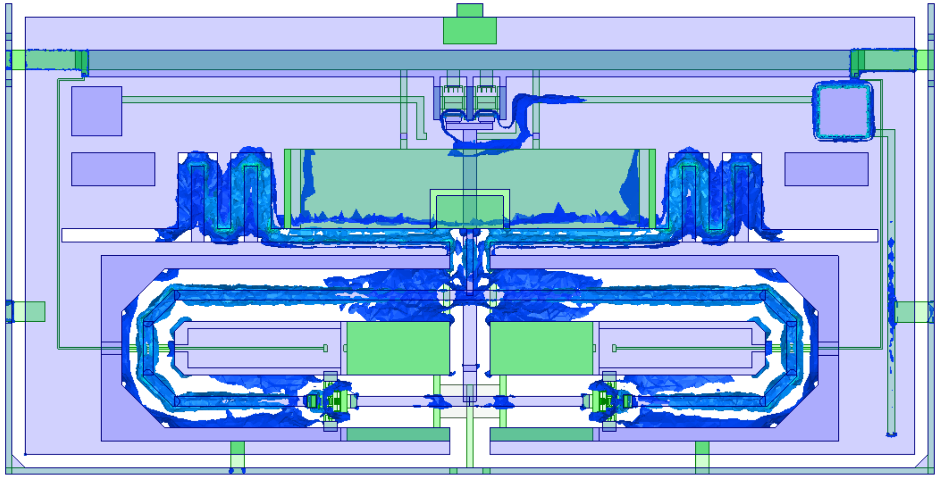
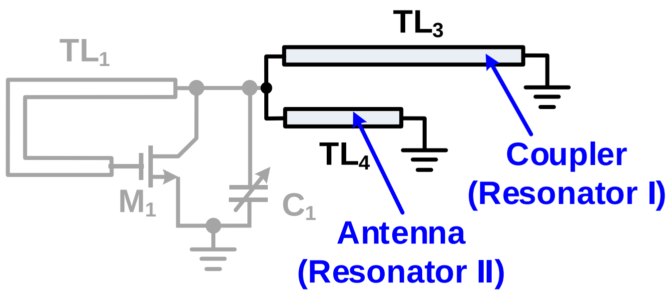


Recap: Multi-functionality + Near-field Interference

- Resonator I and II are for coupling and radiation cancelling
- For explanation, E-field distributions are needed



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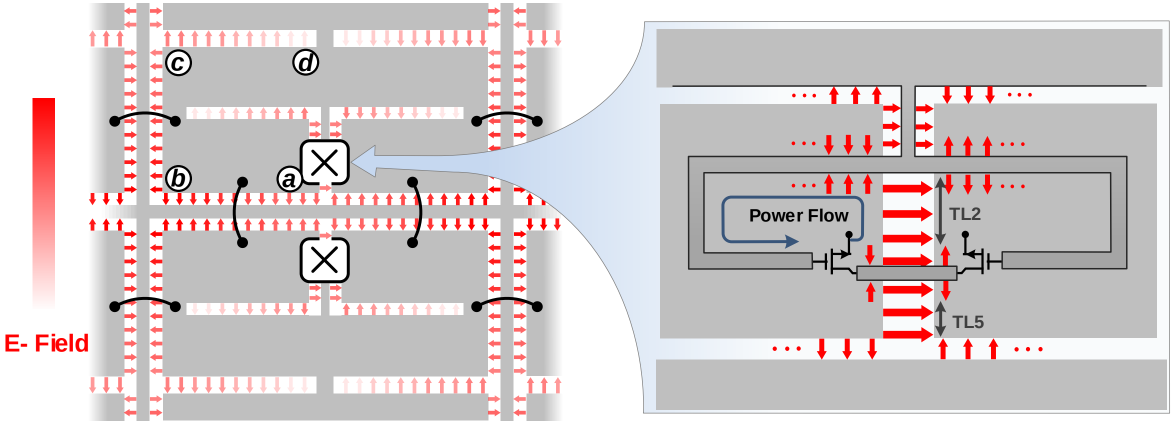

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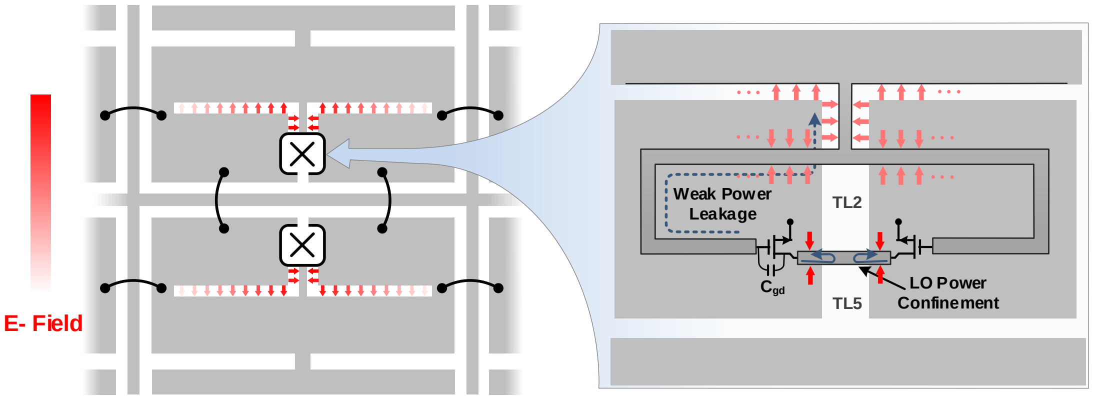

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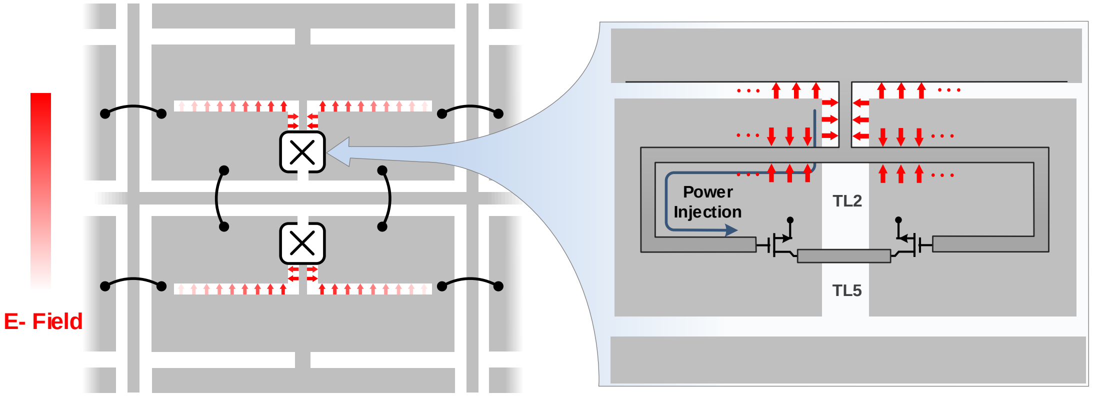
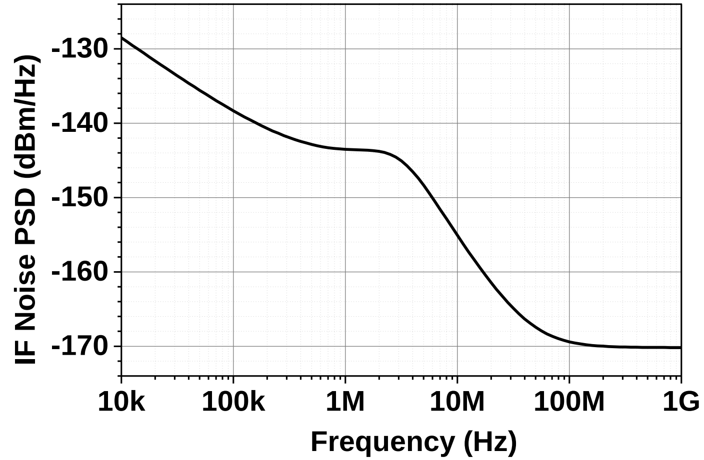
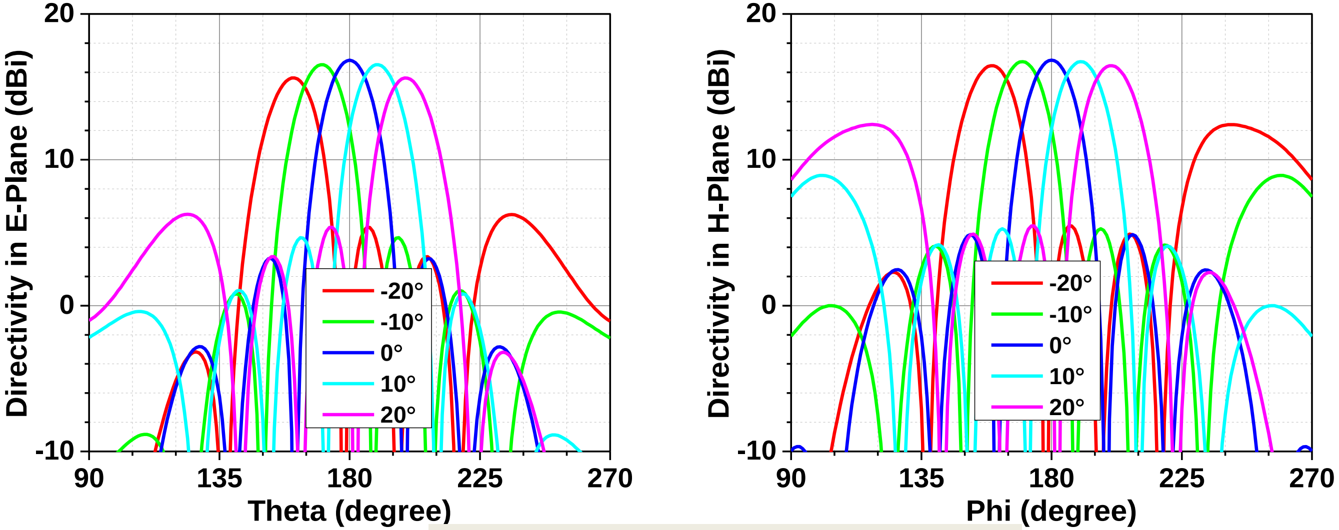


Simulation Results of SOHM Performance

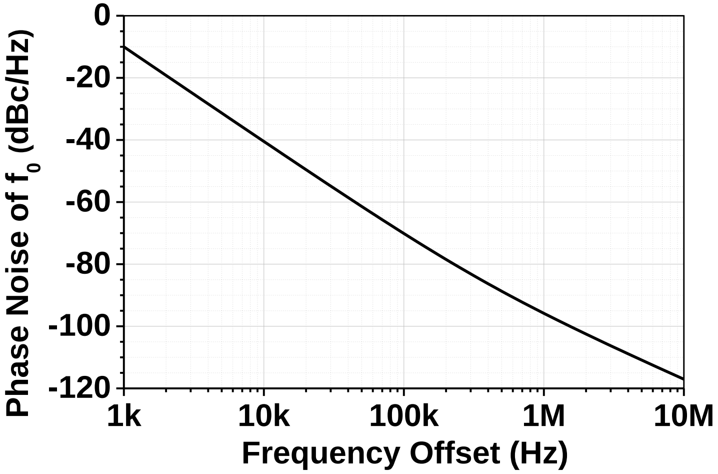
- DC Power per unit: 43.2 mW
- Conversion loss (CL): 16 dB (with 50-Ω output load)
- Noise figure (NF): 46.5dB at f_{IF} =5 MHz; 19.3 dB at f_{IF} =100 MHz
- Antenna peak directivity: 4.8 dB; antenna efficiency: 40 %



Simulated IF noise floor



Simulated beam-steering results



Simulated f_0 phase noise

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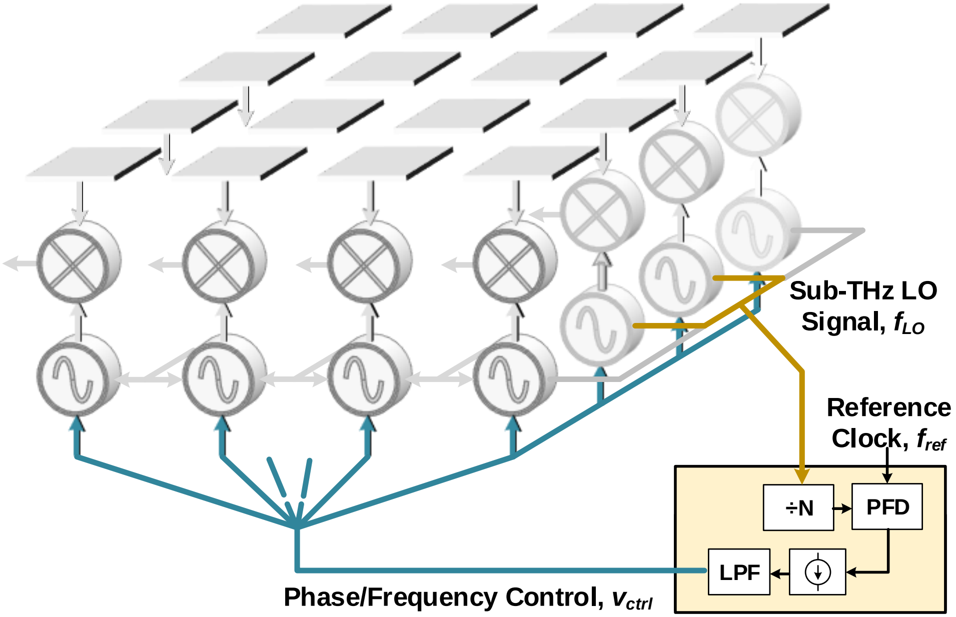
Overview of the Phase Locking Circuitry



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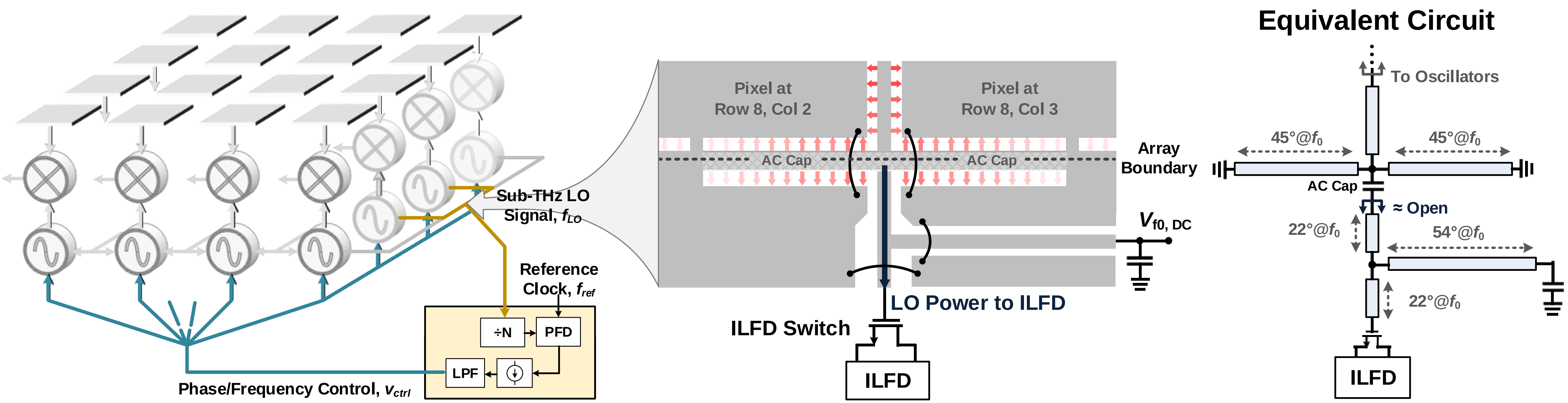
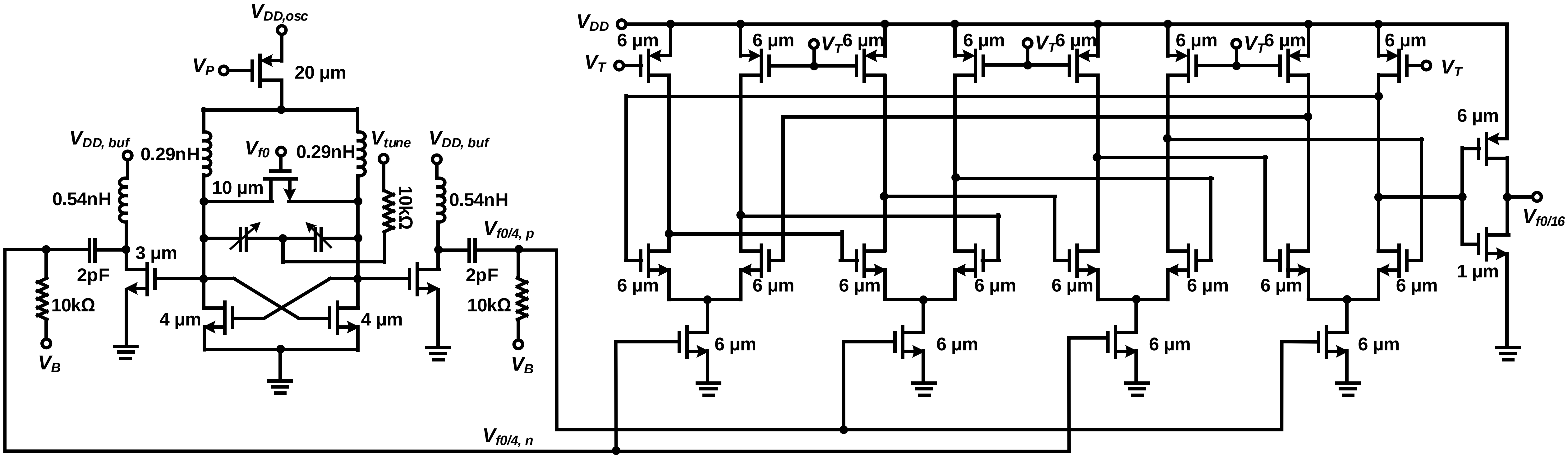


- Bottom two pixel units inject a small amount of waves at f_0 = 120 GHz into the divider
- PLL components generate the VCO control voltage for the entire array
- Due to array-wide coupling, all units are locked

Design of the 120-GHz Divide-by-16 Divider



- 1^{st} stage: div-by-4 ILFD, based on $f_{inj} = 4f_{osc}$ mixing with $3f_{osc}$
- 2^{nd} stage: div-by-4 ILFD, based on injected signals modulating the current sources of the ring oscillator
- Total DC power consumption: 10.5 mW

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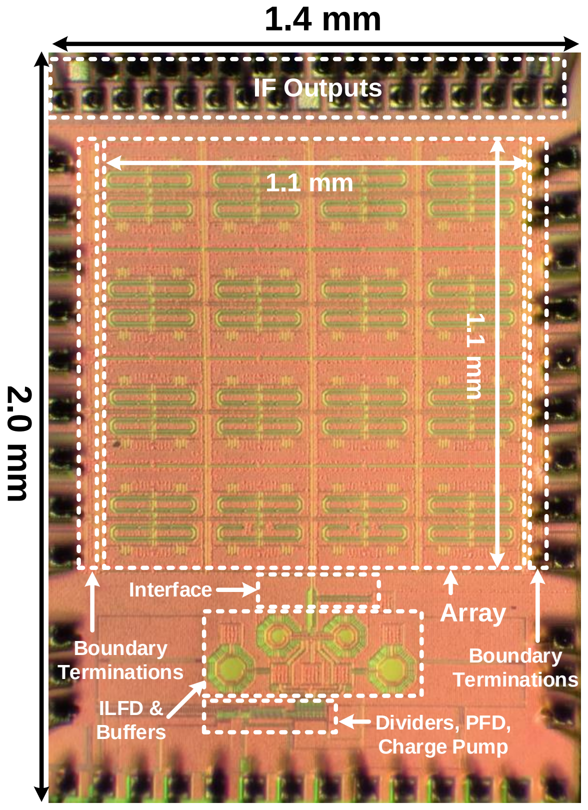
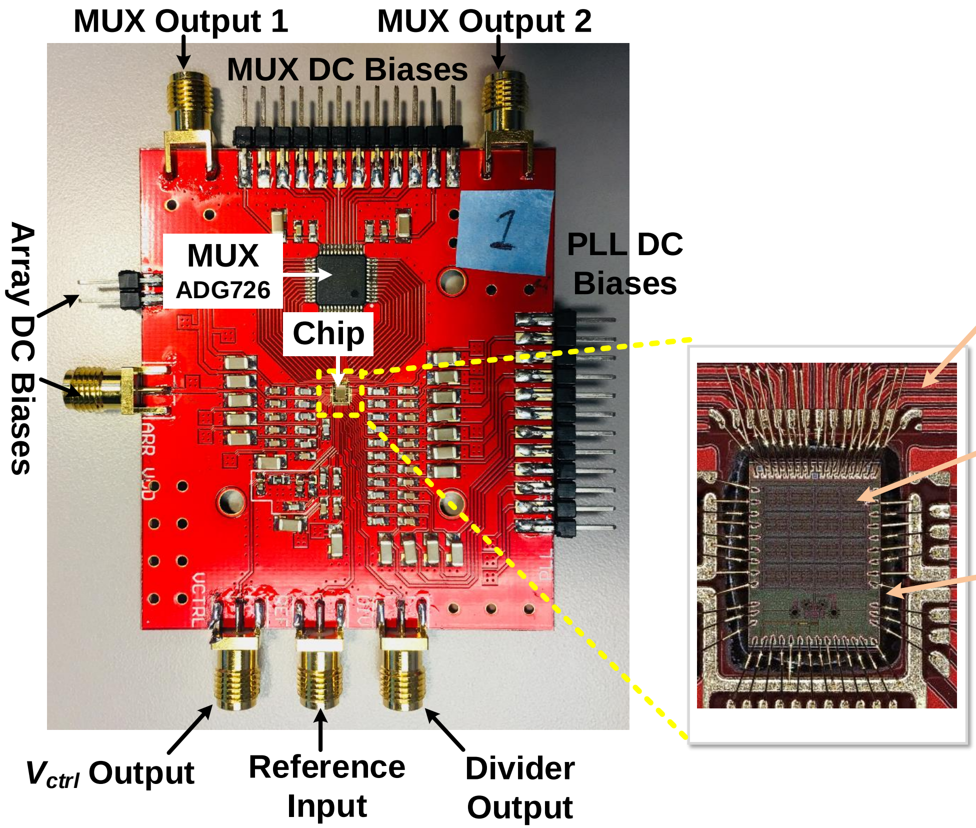
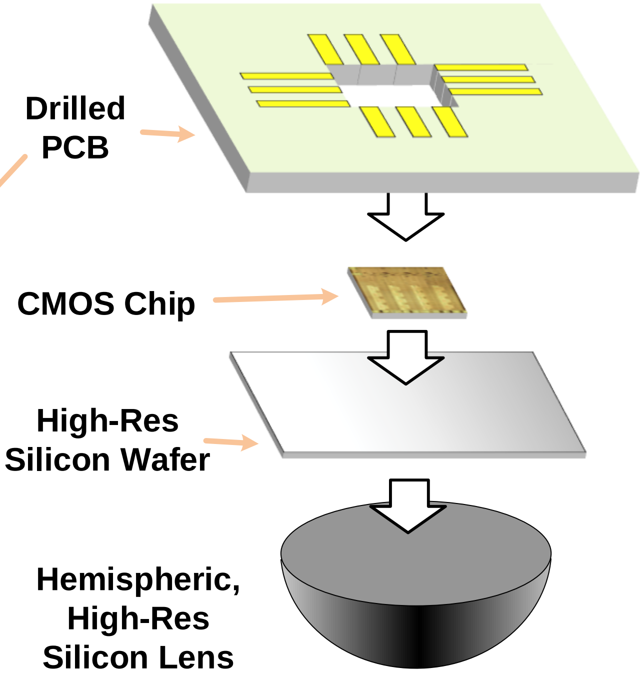
Die Photo and Chip Packaging Details

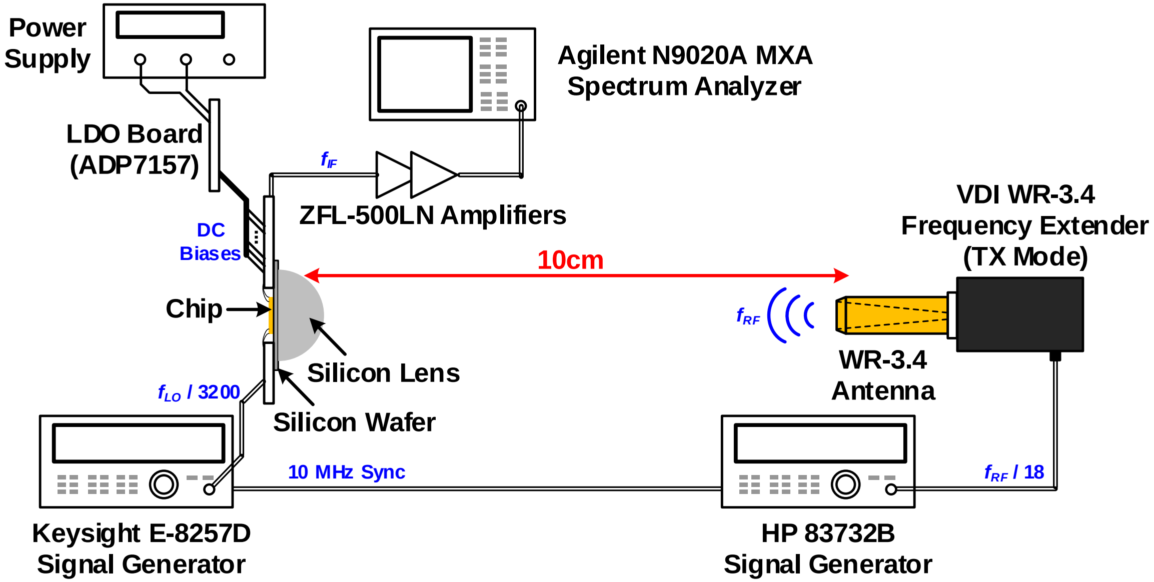


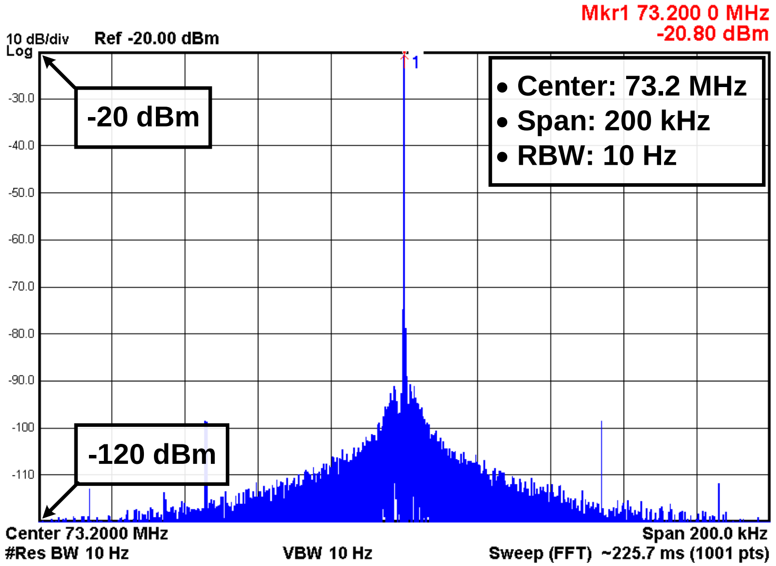




- Technology: 65nm CMOS; chip area 2.8 mm^2 (1.21 mm^2 for the array)
- Silicon lens is attached to the backside of the chip (backside radiation)
- Off-Chip multiplexer is used to select the desired IF signal from 32 outputs

Overview of the Chip Measurement

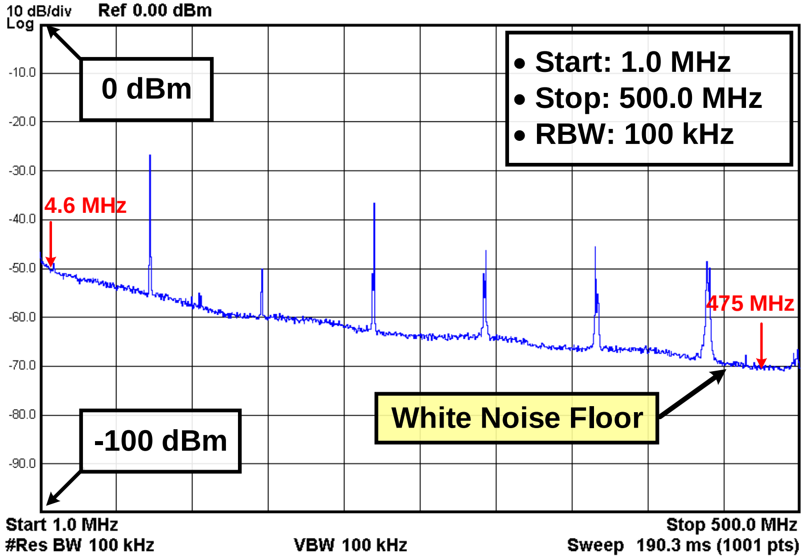




Spectrum of the divider output

- VDI WR-3.4 extender is used as the RF source
- Frequency reference of the chip and the VDI source are synchronized
- Locking range of the array (obtained from divider output): 232.96 GHz – 234.88 GHz

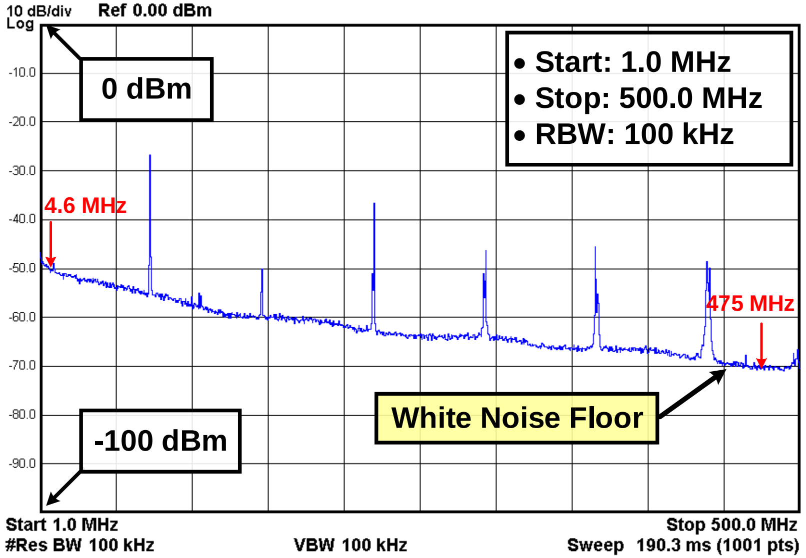
Measured IF Spectra at Low/High Frequencies



IF noise spectrum (from spectrum analyzer)

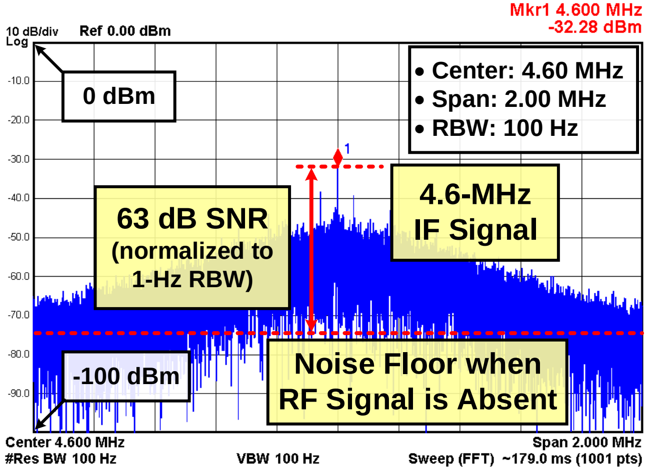
- Flicker noise dominates until ~ 450 MHz (IF amp BW = 500 MHz)

Measured IF Spectra at Low/High Frequencies

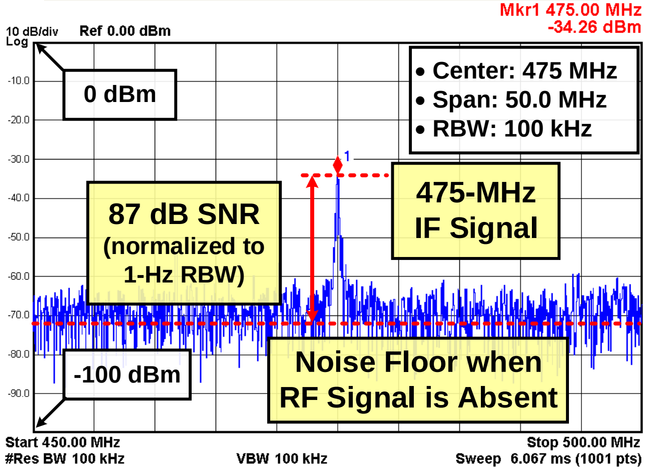


IF noise spectrum (from spectrum analyzer)

- Flicker noise dominates until ~ 450 MHz (IF amp BW = 500 MHz)
- At 4.6 MHz (below corner frequency), SNR = 63 dB (RBW = 1Hz)
- At 475 MHz (beyond corner frequency), SNR = 87 dB (RBW = 1Hz)
- Other pixels are also locked; they have similar responses, and their f_{IF} all shifts simultaneously as f_{ref} shifts

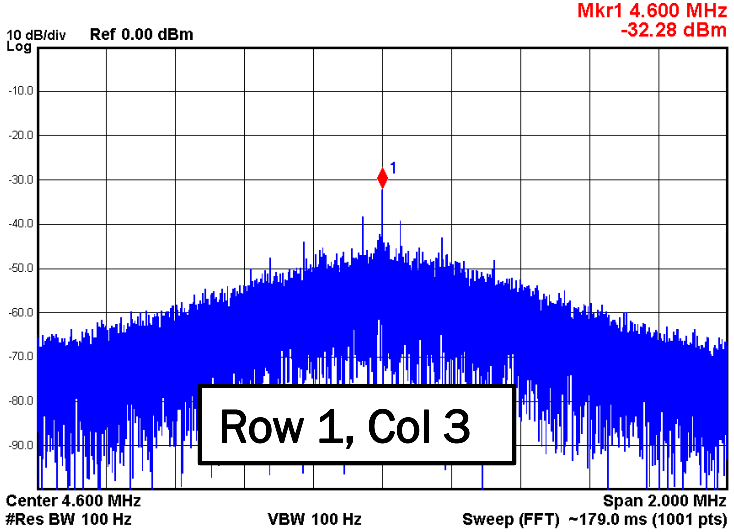


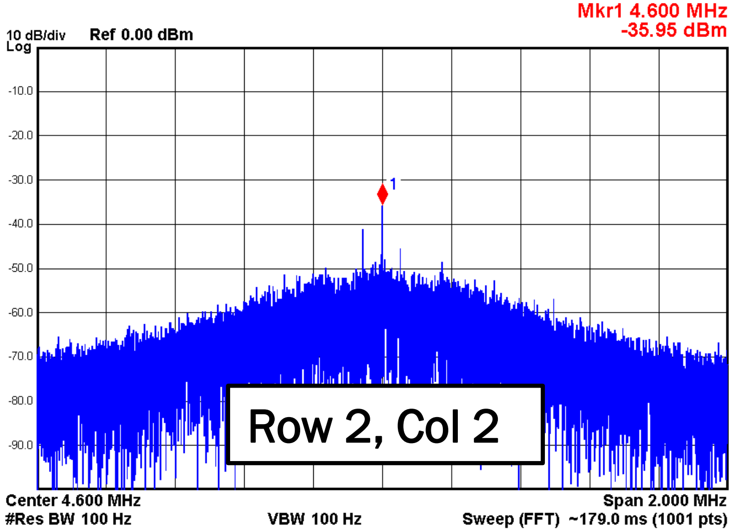
IF spectrum (f_{IF} = 4.6 MHz)

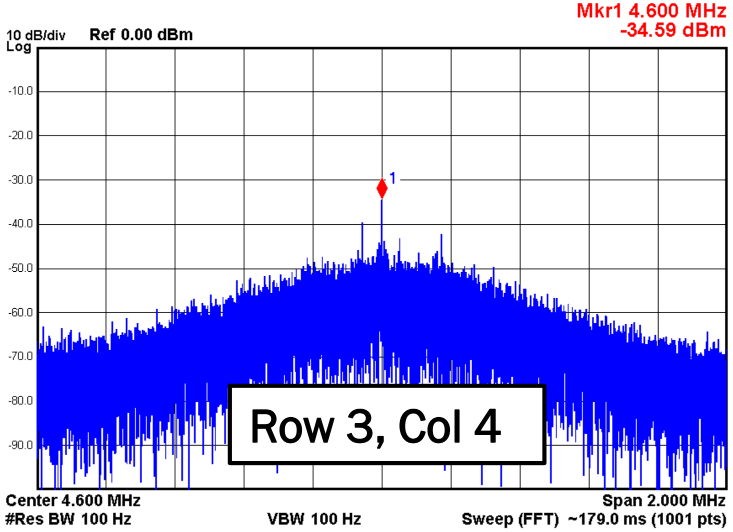


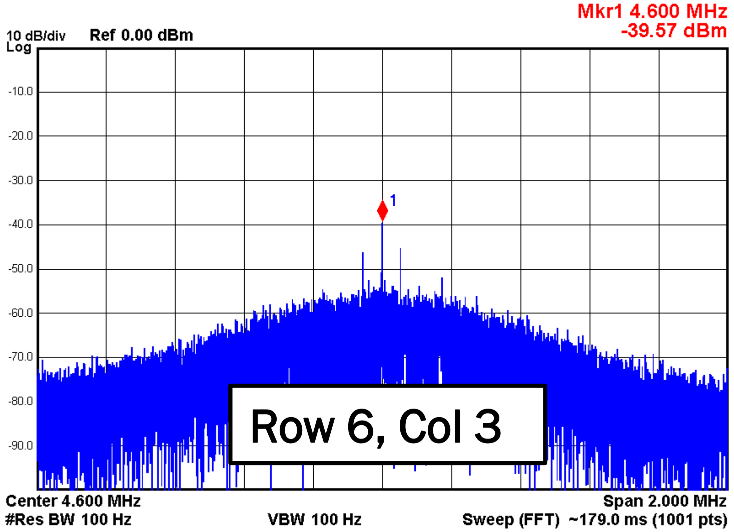
IF spectrum (f_{IF} = 475 MHz)

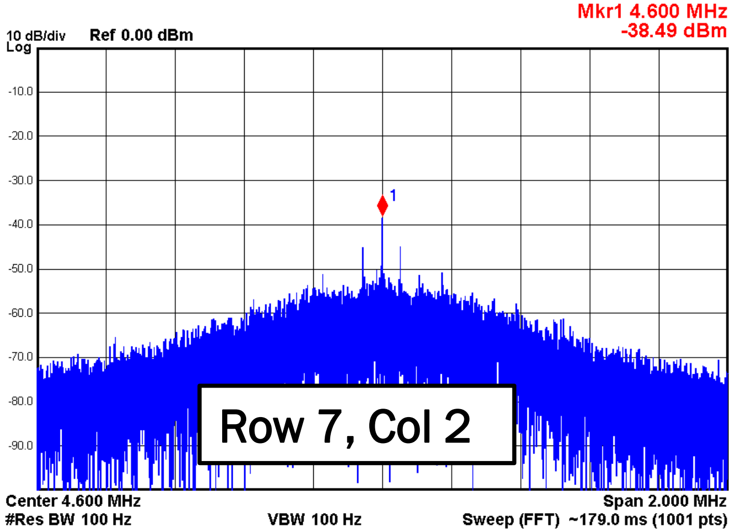
Measured 4.6-MHz IF of Some Other Units

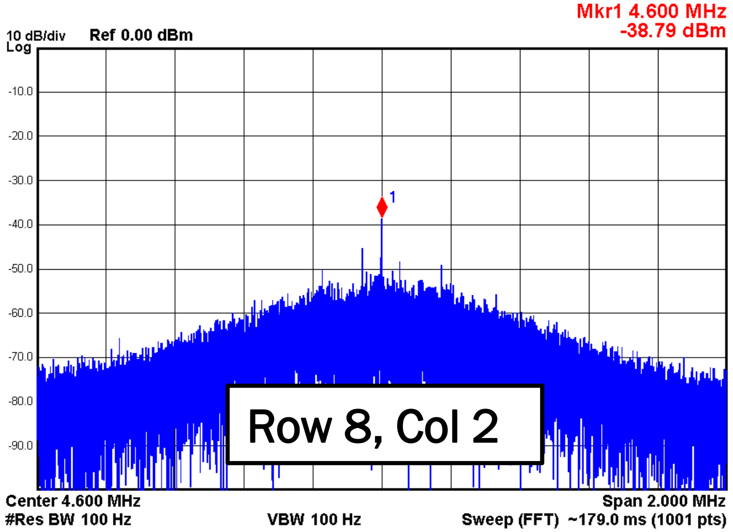




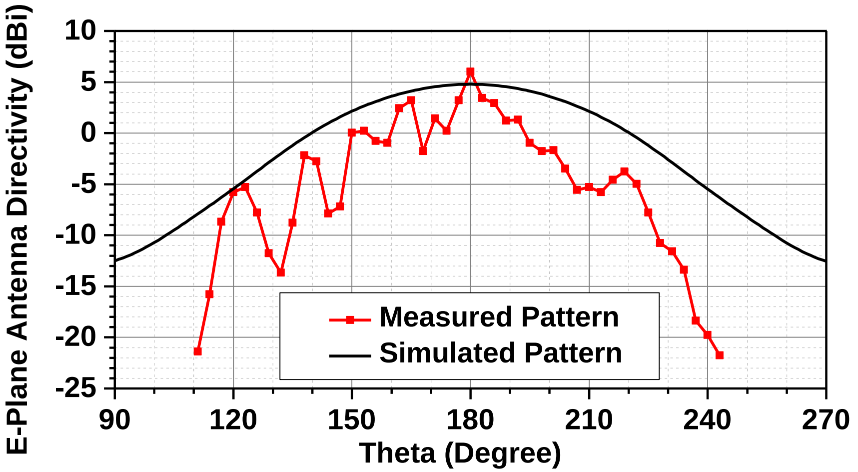




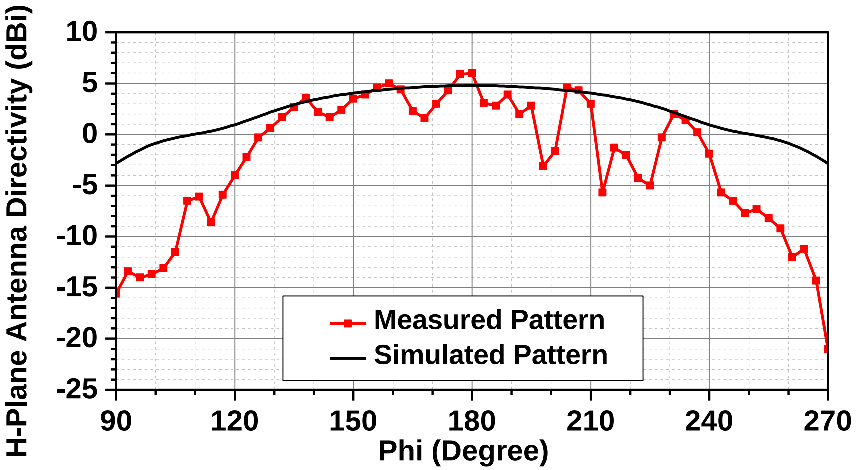




Antenna Pattern and Performance Evaluation



Measured and simulated antenna patterns (E-Plane)



Measured and simulated antenna patterns (H-Plane)

- Conversion gain (dB)

  $CG = P_{IF} - P_{RF}$, where

  $P_{IF} = P_{IF,\,analyzer} - G_{amp}$, and

  $P_{RF} = P_{RF,\,TX} + D_{TX} + G_{RX} - 20\log_{10}(\lambda/(4\pi d))$

- Noise figure (dB)

  $NF = P_{noise} - (-174\text{ dBm}) - CG$, where

  $P_{noise} = 10\log_{10}(10^{(Pnoise,\,analyzer\,-\,Gamp)/10} - 10^{-17.4})$

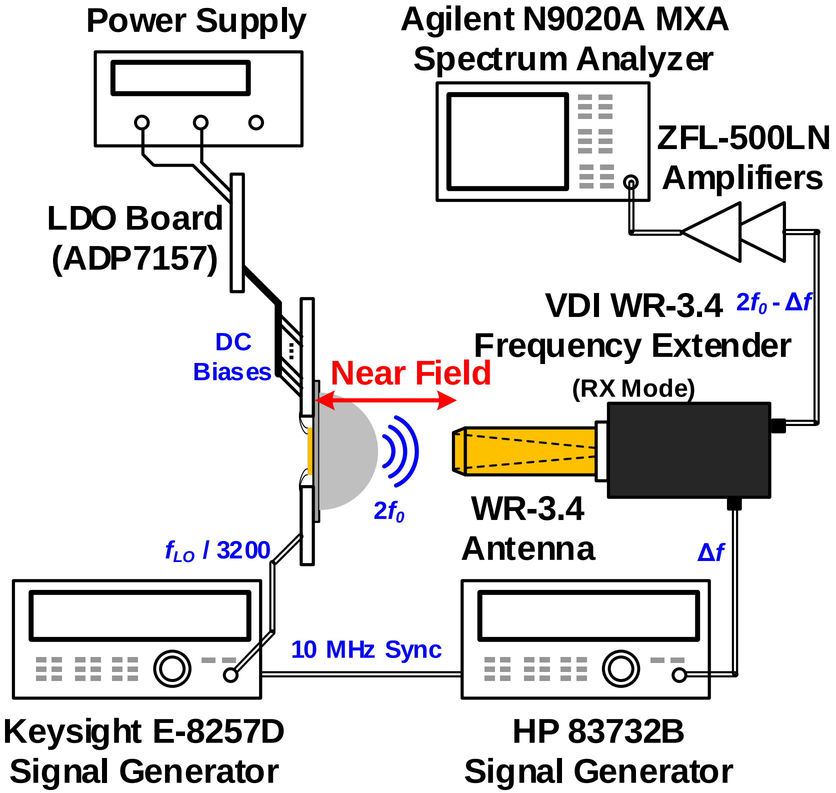
  (considering $NF_{amp} = 3\text{dB}$)

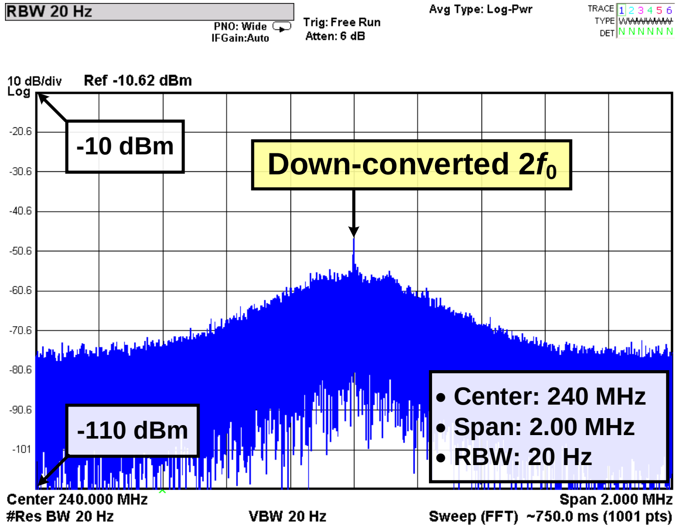
- Here, we have $G_{amp} = 49$ dB, $P_{RF,TX} = -7.1$ dBm, $D_{TX} = 24$ dBi, $D_{RX} = 6.0$ dB, $\eta_{RX} = 40$ % (simulated), $\lambda = 1.28$ mm, $d = 0.1$ m

- For $f_{IF} = 475$ MHz (beyond corner frequency), $CG = -42.4$ dB, $NF = 44.2$ dB

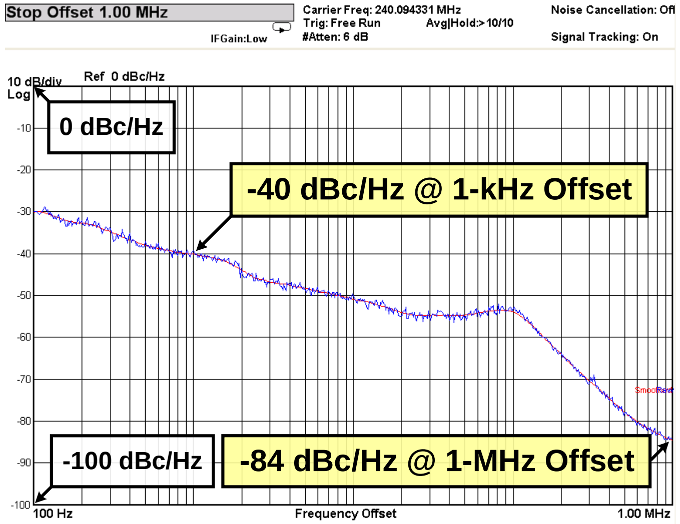
Define *Sensitivity* = *NEP* · √1000Hz = -174 dBm + *NF* + 30dB; for f_{IF} = 475 MHz, *Sensitivity* = 0.105 pW

Measured Phase Noise of the LO Signal





Spectrum of the leaked $2f_0$ signal



Measured phase noise of the $2f_0$ signal

- VDI extender is placed very close to the chip to capture the leaked near-field radiation at $2f_0$
- Measured $2f_0$ phase noise at 1 MHz offset is -84 dBc/Hz

Performance Comparison

References	This Work	[5]	[1]	[2]	[3]
Detection Method	Heterodyne Detection		Square-Law (Direct) Detection		
Array Size	4x8	8	4x4		
Array Scalability	Yes	No	Yes	Yes	Yes
RF Frequency (GHz)	240	320	280	320	280
Sensitivity (pW)	0.105 †	71.4	917	1080	250
DC Power (mW)	980	117	6	38	180
Chip Area (mm^2)	2.80	3.06	5.76	6.76	6.25
Technology	65nm CMOS	130nm SiGe	130nm CMOS	180nm SiGe	130nm SiGe

Notes:

† Calculated based on P_{IF} and P_{noise} at f_{IF} = 475 MHz

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Outline

- Introduction
- Array Architecture
- Multi-functional Heterodyne Pixels
- Phase Locking Circuitry
- Measurement Results
- Conclusion

Conclusion

- For the first time, heterodyne receiver array has achieved large scale and high density that are comparable to those of square-law detector arrays
- Our array improves the sensitivity by ~680x compared with the 8-unit heterodyne receiver array, and by ~2400x compared with the best square-law detector arrays
- Scalability and sensitivity improvements make sub-THz array technology a more promising candidate for the implementation of high-resolution beam-forming imagers in the future

Acknowledgement

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  - Guo Zhang, Jack Holloway and Dr. Xiang Yi at MIT for technical discussions
  - Dr. Andrew Westwood and Kathleen Howard at Keysight Inc. for their support to the experimental instruments

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  - Taiwan Semiconductor Manufacturing Company (TSMC)
  - The Singapore-MIT Research Alliance

RTu1B-4

Heterodyne Sensing CMOS Array with High Density and Large Scale: A 240-GHz, 32-Unit Receiver Using a De-Centralized Architecture

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