CMOS Terahertz Integrated Circuits and Systems

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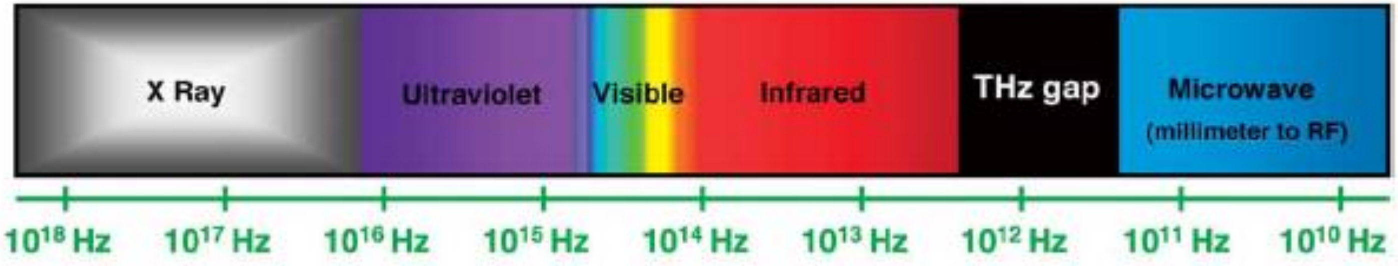
Outline

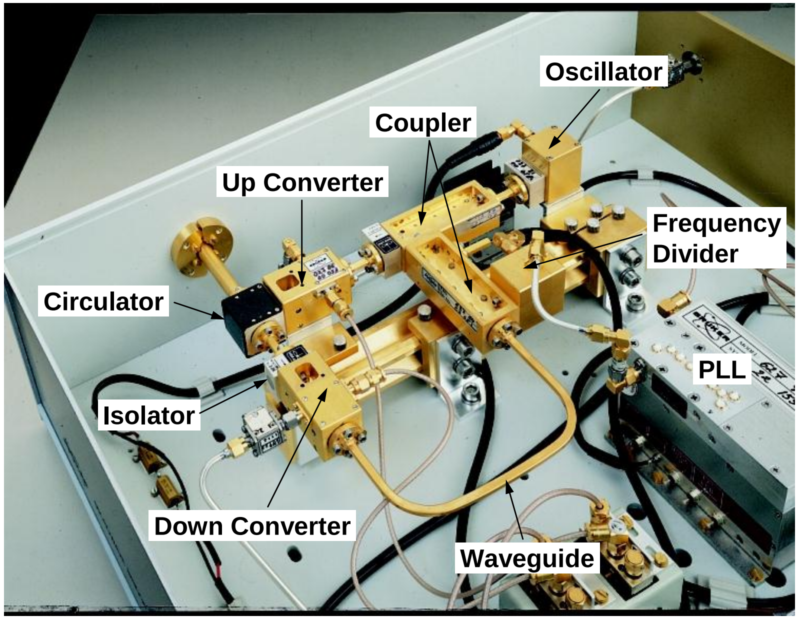
- Introduction
- CMOS Integrated Circuits and Systems
  - Imaging
  - Spectroscopy
  - High data rate wireline communication
- Conclusions

THz or Sub-millimeter Wave

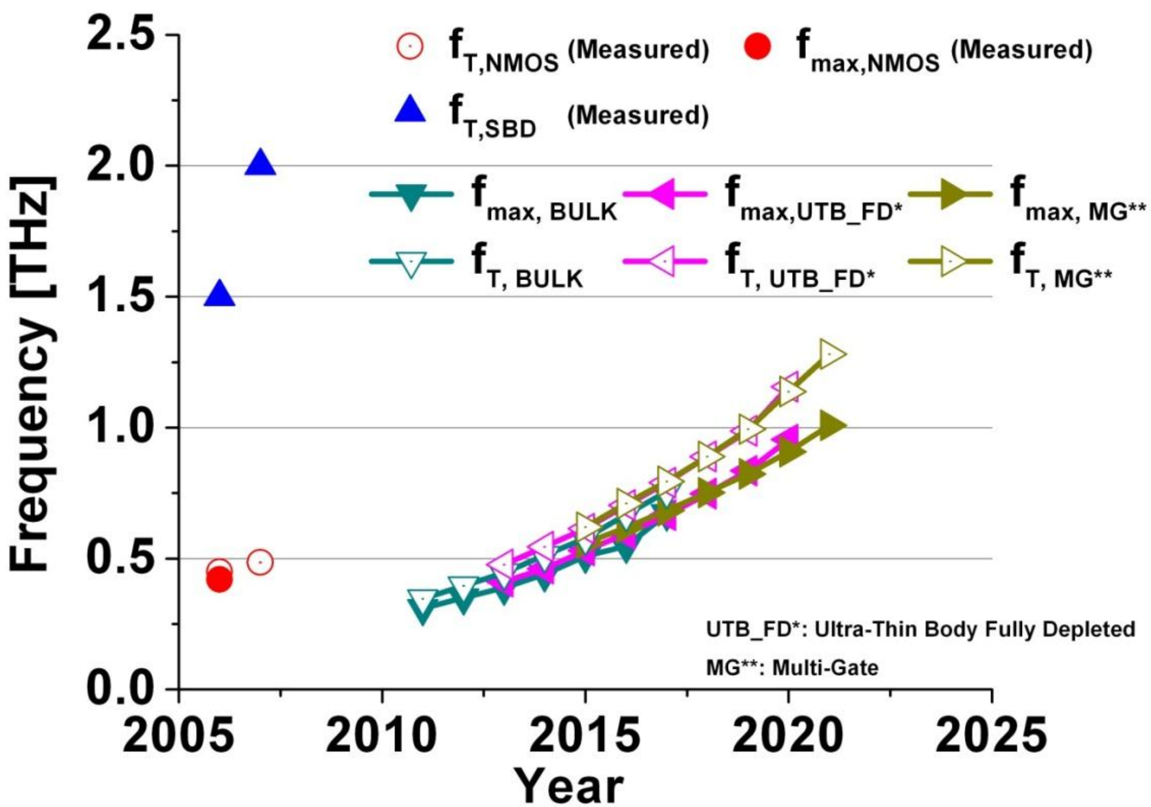


D. L. Woolard et al., "Terahertz Frequency Sensing and Imaging, a Time of Reckoning Future Applications?" IEEE Proceedings, vol. 93, no. 10, pp. 1722 – pp. 1743, Oct. 2005.

- THz or Sub-millimeter wave: 300 GHz – 3 THz.
- Information rich. 98% of photons emitted since the Big Bang fall in this and far-IR region.
- THz Gap: Difficult to reach using electronic and photonic means.
- Costly (100's of thousands) and bulky.
- Largely limited to scientific studies.



Projected NMOS Transistor Requirements



- Interests for THz CMOS gained by the scaling of CMOS technology.
- f_T and f_{max} are 485 and 420 GHz for CMOS transistors.

- According to 2011 ITRS, NMOS transistors with f_{max} of 500GHz are projected to be required by 2015. ??
- Schottky diodes with measured cut-off frequency of ~2THz.
- Other nonlinear passive devices are possible.

CMOS Approach

- **Integration of millimeter wave or sub-millimeter wave circuits with baseband analog and digital subsystems – Higher level of integration will lead to smaller size and simplification of high frequency interconnections.**
- **High yield.**
- **Digital subsystems and calibration can be used to correct the imperfections for higher yield and better performance.**
- **Somebody else is paying to for the technology development.**
- **Potentially low cost: 100's of thousands to 100's of dollars for THz systems.**
- **Large chip area (>2cm x 2cm). Well suited for 2-D arrays with a large number of elements. Silicon technology is the only that could make such systems practical.**

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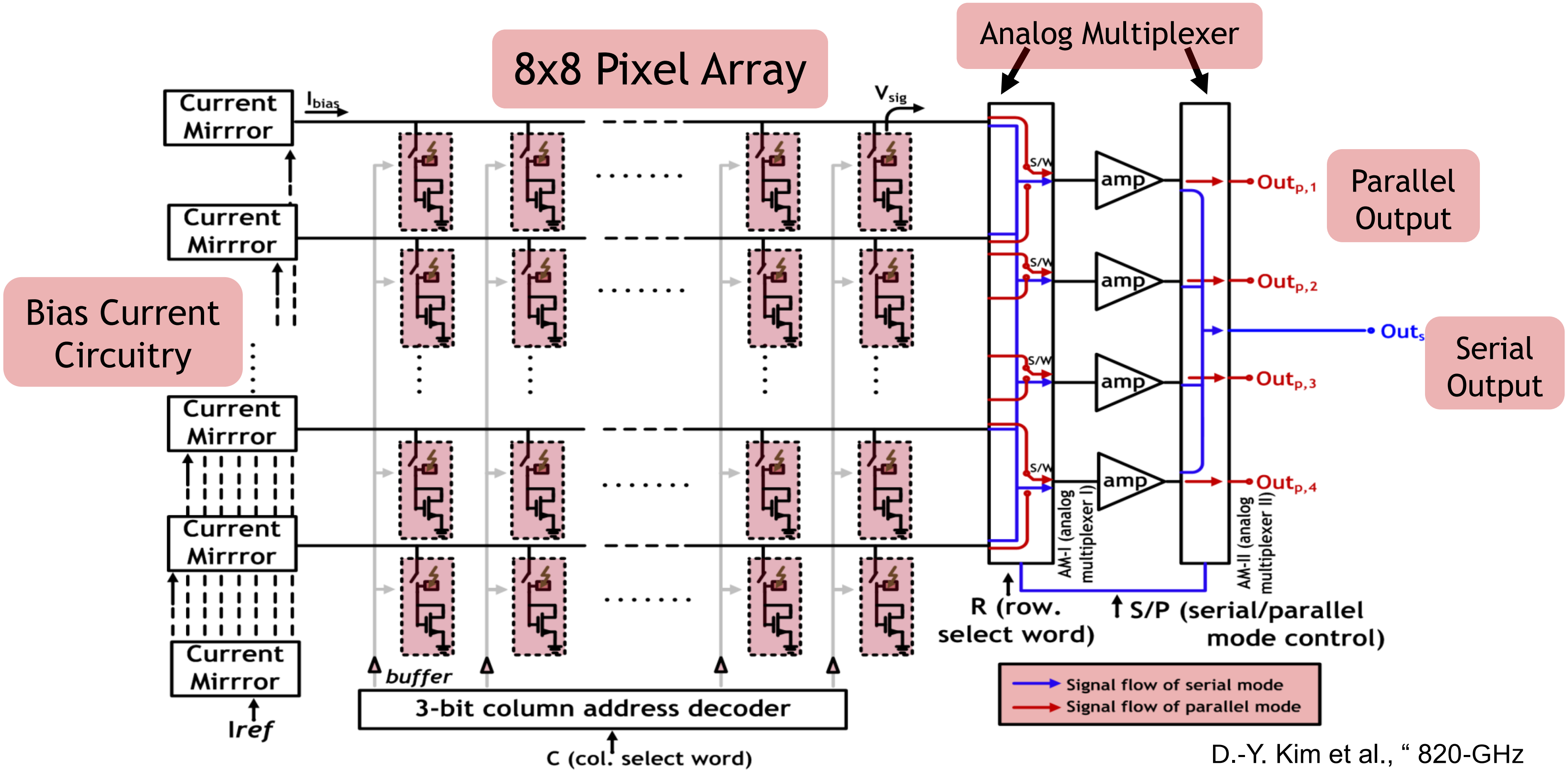
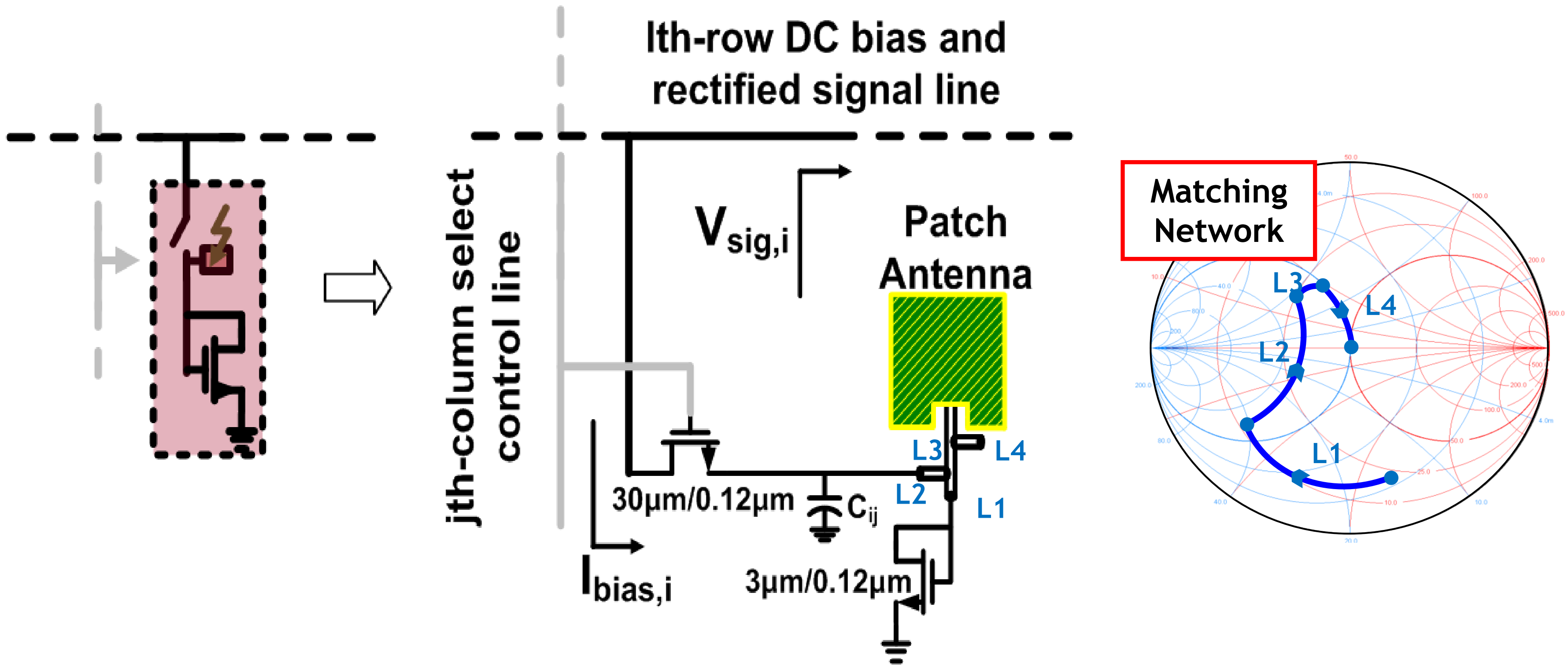
820-GHz 8x8 Imaging Array



D.-Y. Kim et al., " 820-GHz Imaging Array Using Diode-Connected NMOST's," 2013 *Symposium on VLSI Circuits*.

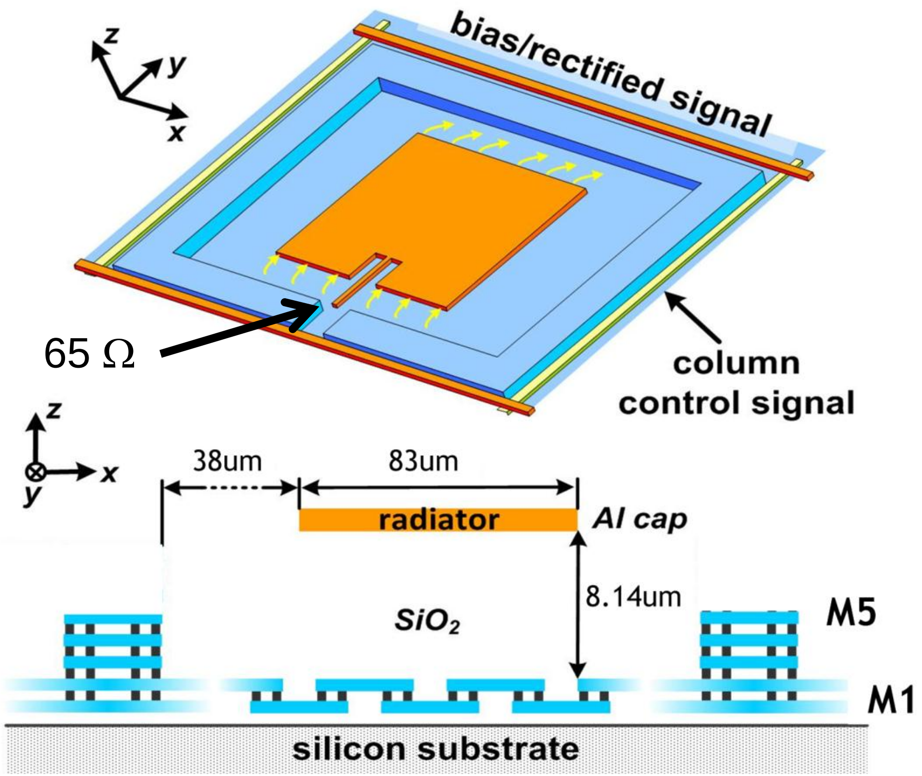
- **Diode connected NMOS detectors in 130-nm CMOS.**
- **Column and row decoders for selection of pixel(s).**
- **Reference current is distributed to each row for diode biasing.**
- **On-chip low noise baseband amplifiers**
- **Two scanning modes: 2X4 parallel or one output/amplifier sharing**

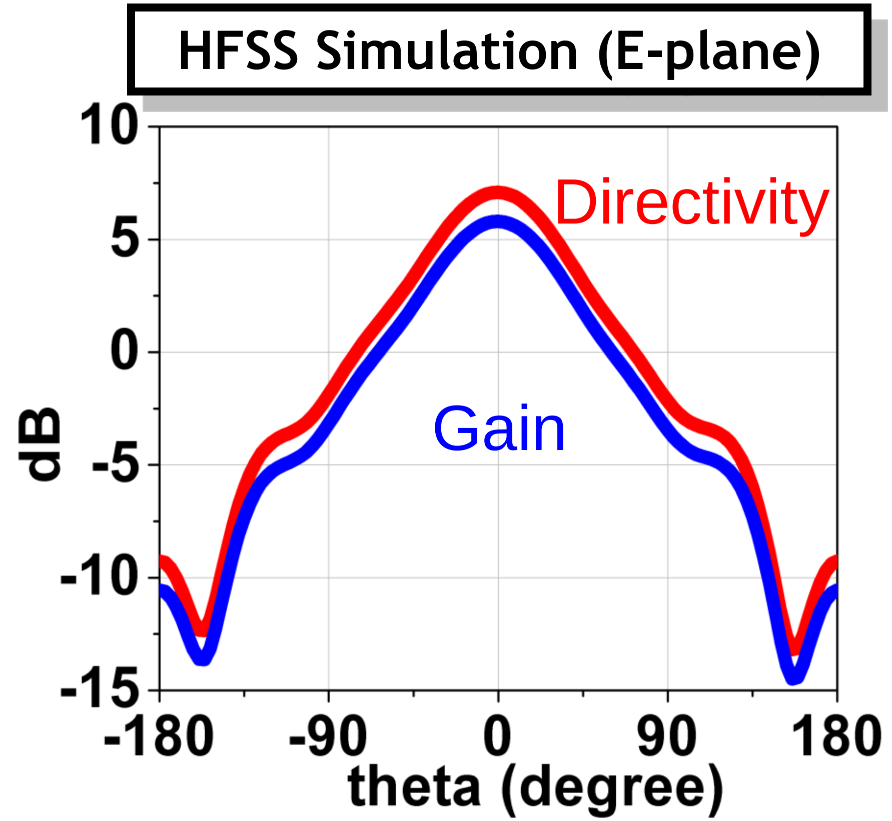
820-GHz Passive Pixel



- Integrated patch antenna, matching network and bus control.
- Only one interconnect for each row and column is required.

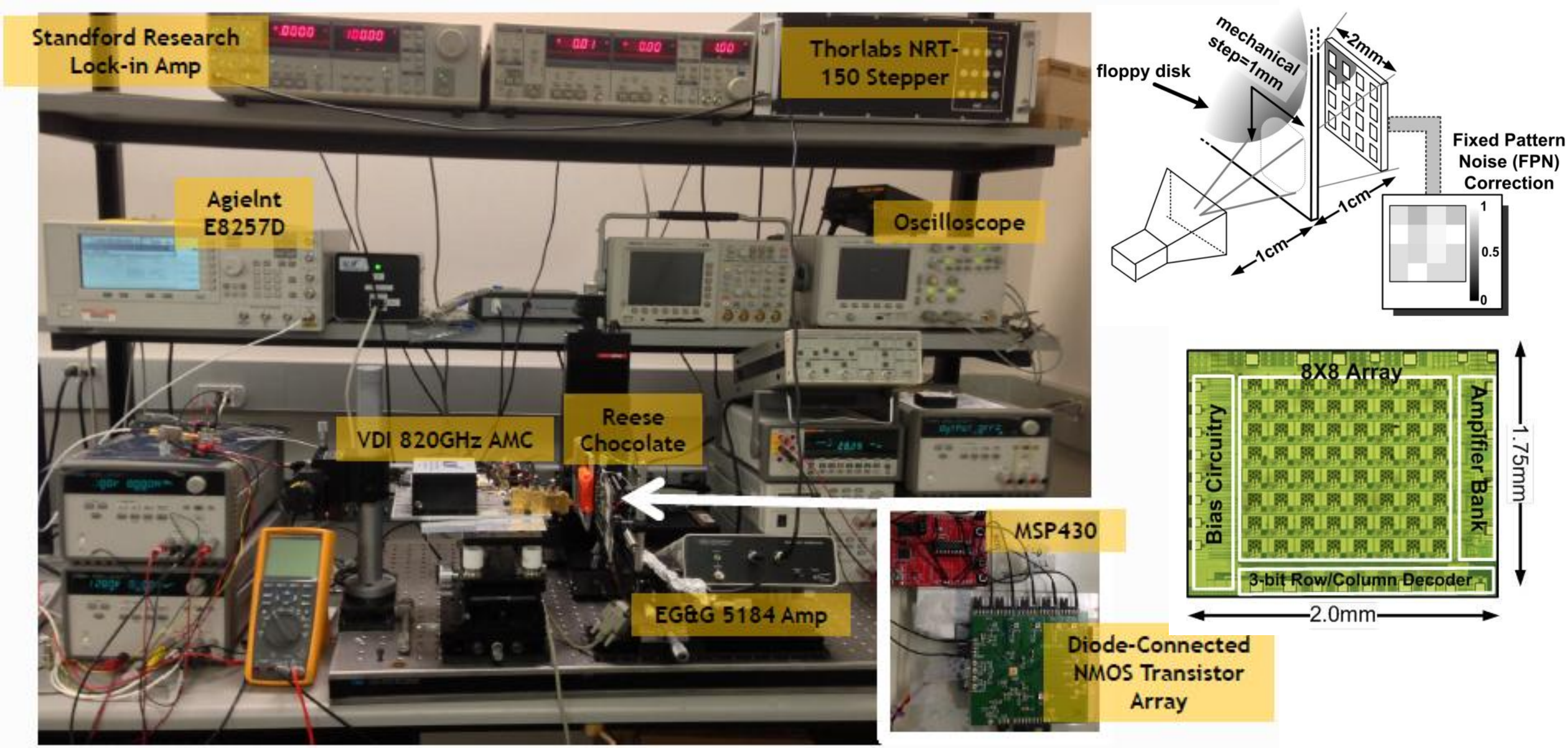
On-Chip Antenna





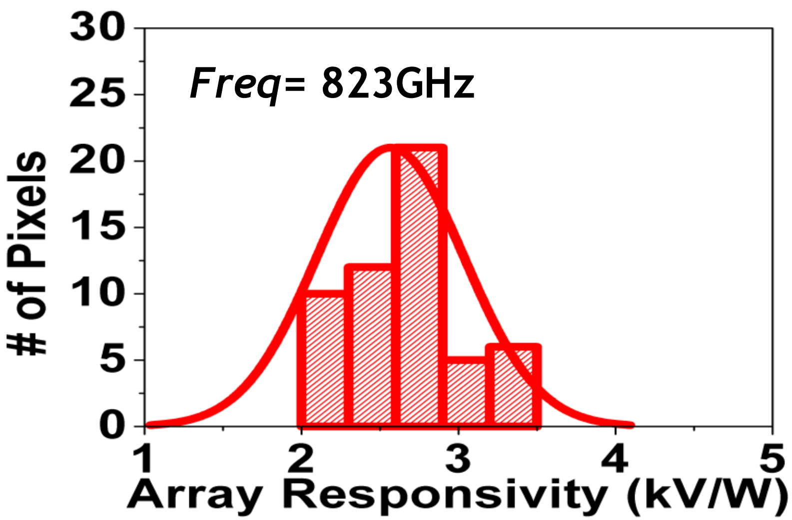
- **Patch on Al bond pad layer with a size of 83×83μm^2.**
- **Ground plane using shunted Metal 1 and 2 layers.**
- **Ground walls for isolation of bus lines.**
- **Simulated antenna directivity is 7.0dBi and efficiency is 74%.**

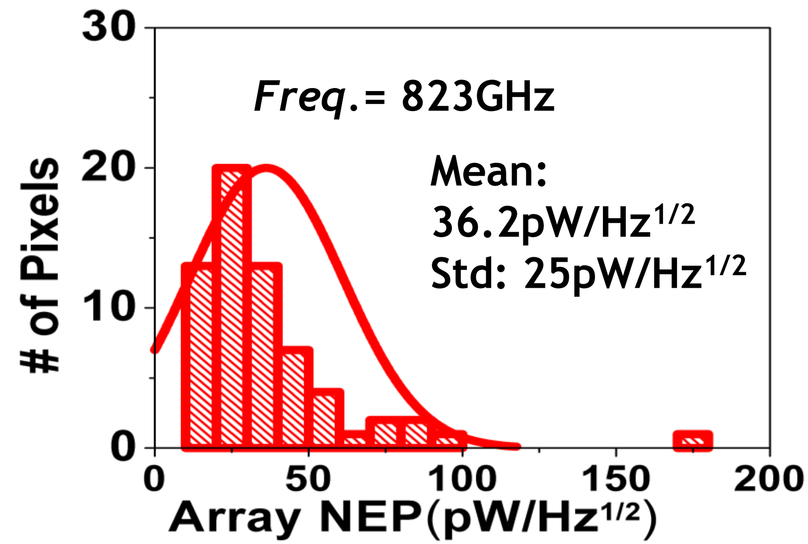
Lensless Imaging Set-up at UTD



- 820-GHz transmitted power is 0.1 to 0.5 mW with modulation frequency of 100kHz-1MHz.
- TI MSP430 board to interface between Labview and imager board.
- Spacings between source and object, and between object and detector are ~1 cm.

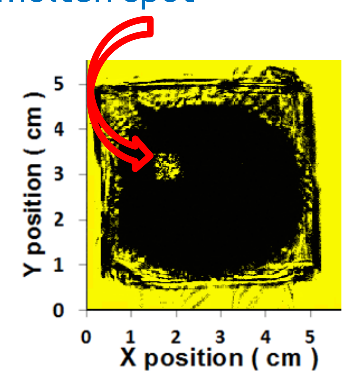
Measured Responsivity and NEP



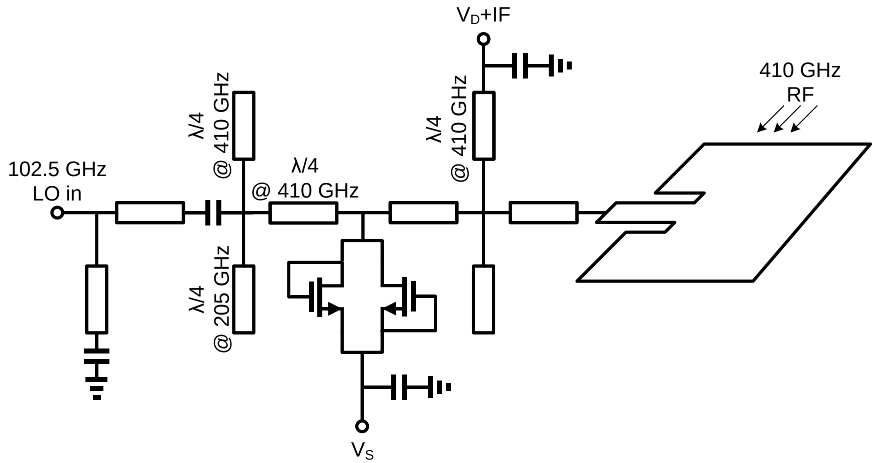


- **Measured responsivity and NEP distributions for 64 pixels on one array.**
  - Includes 13.5 dB on-chip amplifier gain.
- **Min NEP: 12.6pW/Hz$^{1/2}$, Select low NEP pixel post fabrication.**
- **36 pW/Hz$^{1/2}$ is the best performance among all NMOS based arrays and expected from Schottky array based on 840-GHz Schottky diode detector measurements.**

White spot correspond to molten spot

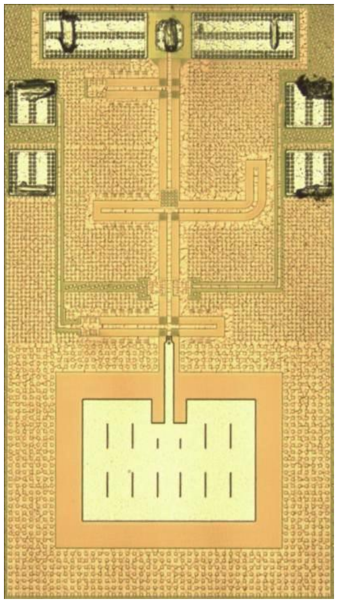


0.4 THz 4th Order Harmonic Mixer



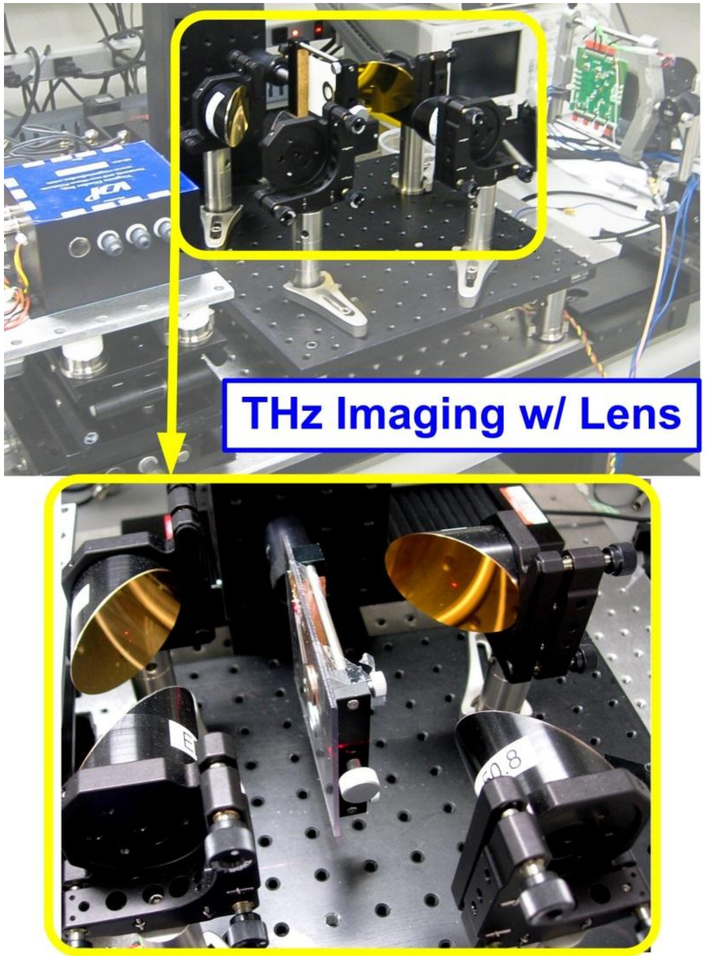
W. Choi et al., "410-GHz CMOS Imager Using a 4th Sub-Harmonic Mixer with Effective NEP of 0.3 fW/Hz$^{0.5}$ at 1-kHz Noise Bandwidth," 2015 IEEE VLSI Symposium on Circuits, pp. C302-C303, June 2015, Kyoto, Japan.

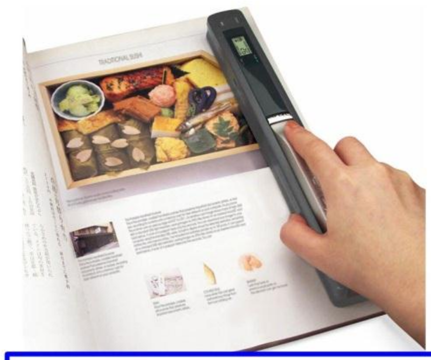
- **Harmonic isolation and rejection**
  - **Quarter-wavelength transmission lines at 2nd and 4th**
- **410GHz RF matching to 50Ω on-chip patch antenna**
- **102.5GHz LO matching to 50Ω signal generator.**
  - **Can be generated in 65-nm CMOS.**
- **More than 10 dB better sensitivity (BW=1kHz) compared to other CMOS mixers and comparable to SiGe mixers**
- **Effective NEP of -125dBm/Hz$^{0.5}$**

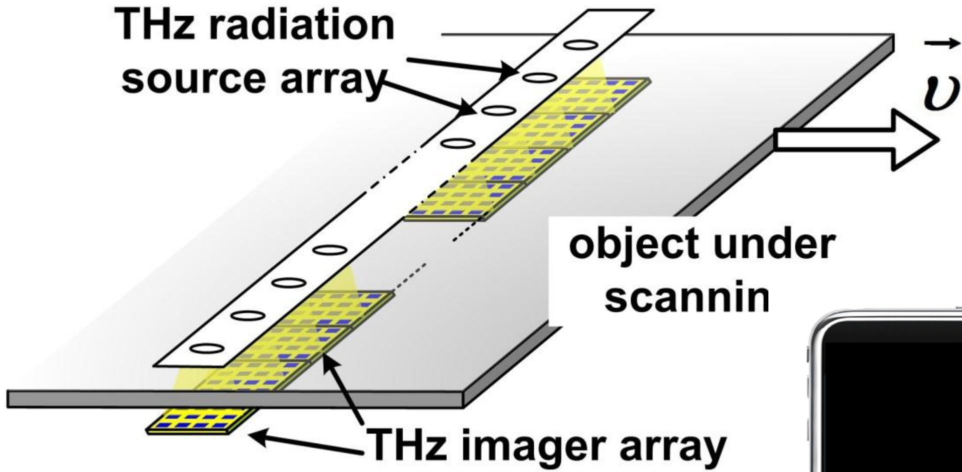


Freq. (GHz)	Process (nm)	Gc (dB)	NF (dB)	Sensitivity *w/ 1kHz BW** (dBm)	NEP (dBm/√Hz)	P_{LO} (dBm)	f_{LO} (GHz)	Topology
650	130 SiGe	-13	42	-101.8	-116.8**	6***	162.5	4th SHM
823	250 SiGe	-22	47	-96.8	-111.8**	0***	164.6	5th SHM
260	65 CMOS	-25		-81.4	-96.4**	-25	260	Mixer
820	130 CMOS			-60.5	-75.5			Detector
280	130 CMOS			-60.4	-75.4			Detector
349	65 CMOS			-78.9	-93.9**			SRR
410	65 CMOS	-16.5	33.8	-110.3	-125.3**	-1.6	102.5	4th SHM

Lensless Multi-Pixel Imaging



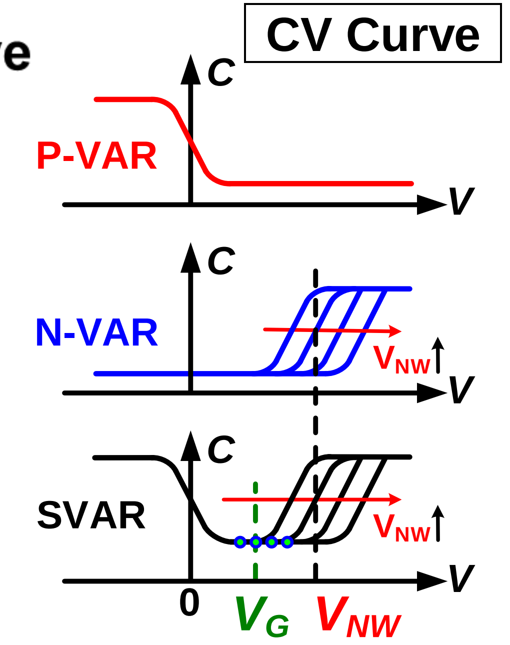


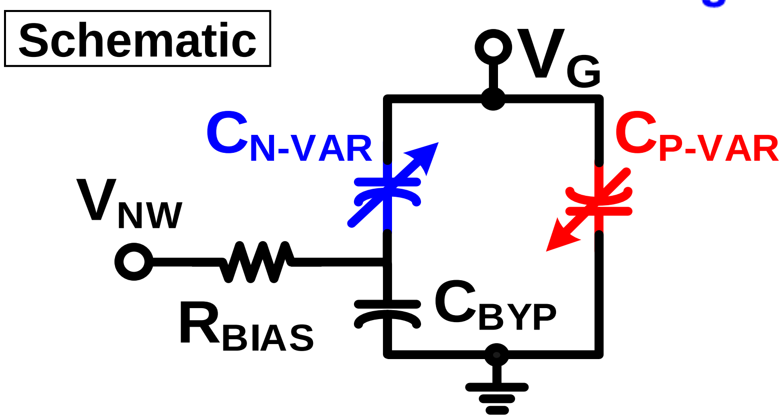


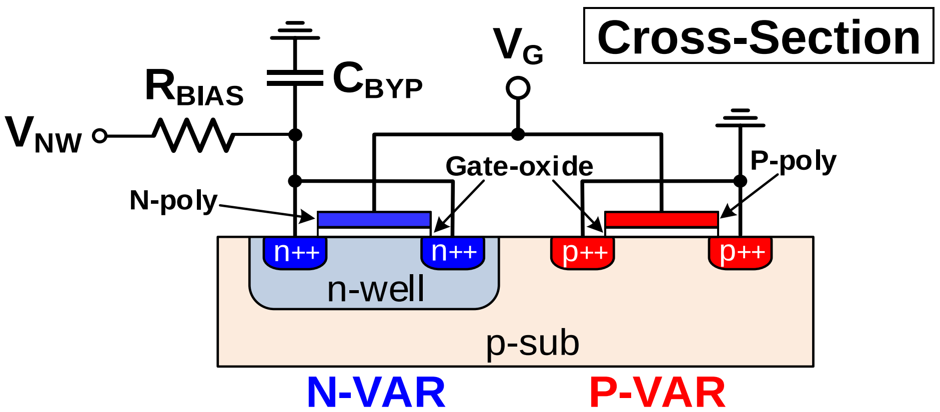
- Optical lens/mirrors are bulky and costly.
- Lensless proximity imaging in handheld devices

Symmetric Accumulation Mode MOS Varactor

- Varactor mode frequency multiplier ideally can have conversion loss of 0 dB.
- Shunt N- & P-type A-MOS Varactors → SVAR
  - A-MOS equivalent of APDP
- Odd-order harmonic generation
- Even-order harmonic cancellation
- Adaptive C-V control
- Dynamic Cut-off Frequency, $f_{cd} = \frac{1}{2\pi R_s}\left[\frac{1}{C_{min}} - \frac{1}{C_{max}}\right]$
  - ~1.5 THz simulated using thin oxide varactors

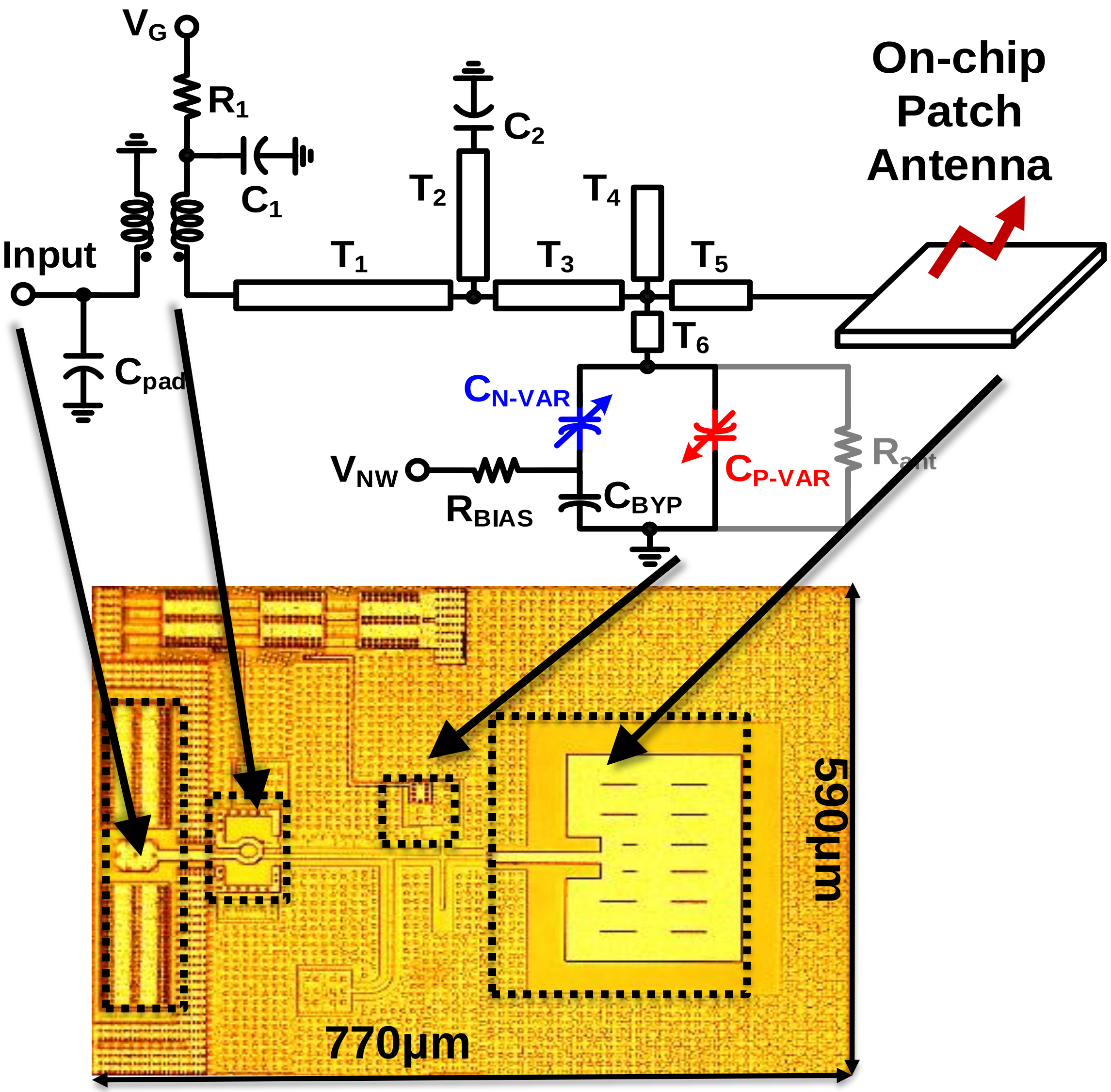




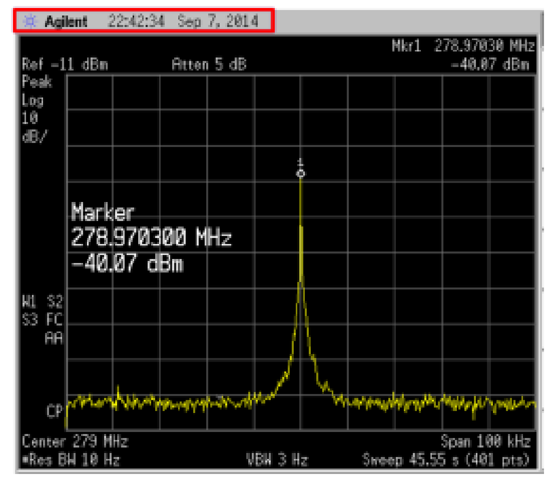


D. Shim and K. K. O, "Symmetric Varactor in 130-nm CMOS for Frequency Multiplier Applications," IEEE Electron Devices Letters, vol. 32, no. 4, pp. 470-472, April, 2011.

0.4 THz Signal Generation (X3)



- Generated ~0.5 mW at 447 GHz in 65-nm CMOS using a 149-GHz input signal with power of 16 mW.
- Third order is the dominant mode.
- Does not need an idler because even orders are suppressed.



Performance Comparison

	This Work	[3]	[4]	[6]	[8]
Type	SVAR x3	3-Push VCO	2-Push VCO	Active x4	A-MOS x2
Freq. (GHz)	447	482	390	400	480
EIRP (dBm)	-5	N/A	-26.6	N/A	N/A
P_{out} (dBm)	-3.2	-7.9	N/A	-8	-6.3
CL (dB)	15.2 (12dBm)	N/A	N/A	19.5	14.3
BW (GHz)	66† (15.4%)	0††	8.6†† (2.2%)	60 (15%)	70* (14.6%)
P_{DC} (mW)	0**	61	21	31	0**
Area (mm²)	0.4543†††	0.02	1.43***	0.4015	0.075
Technology	65nm CMOS	65nm CMOS	45nm CMOS	45nm SOI	65nm CMOS

† Limited by meas. setup

†† Oscillator tuning-range

††† Includes on-chip antenna/bond-pads

* Simulated 3-dB bandwidth

** Except for leakage in protection resistor

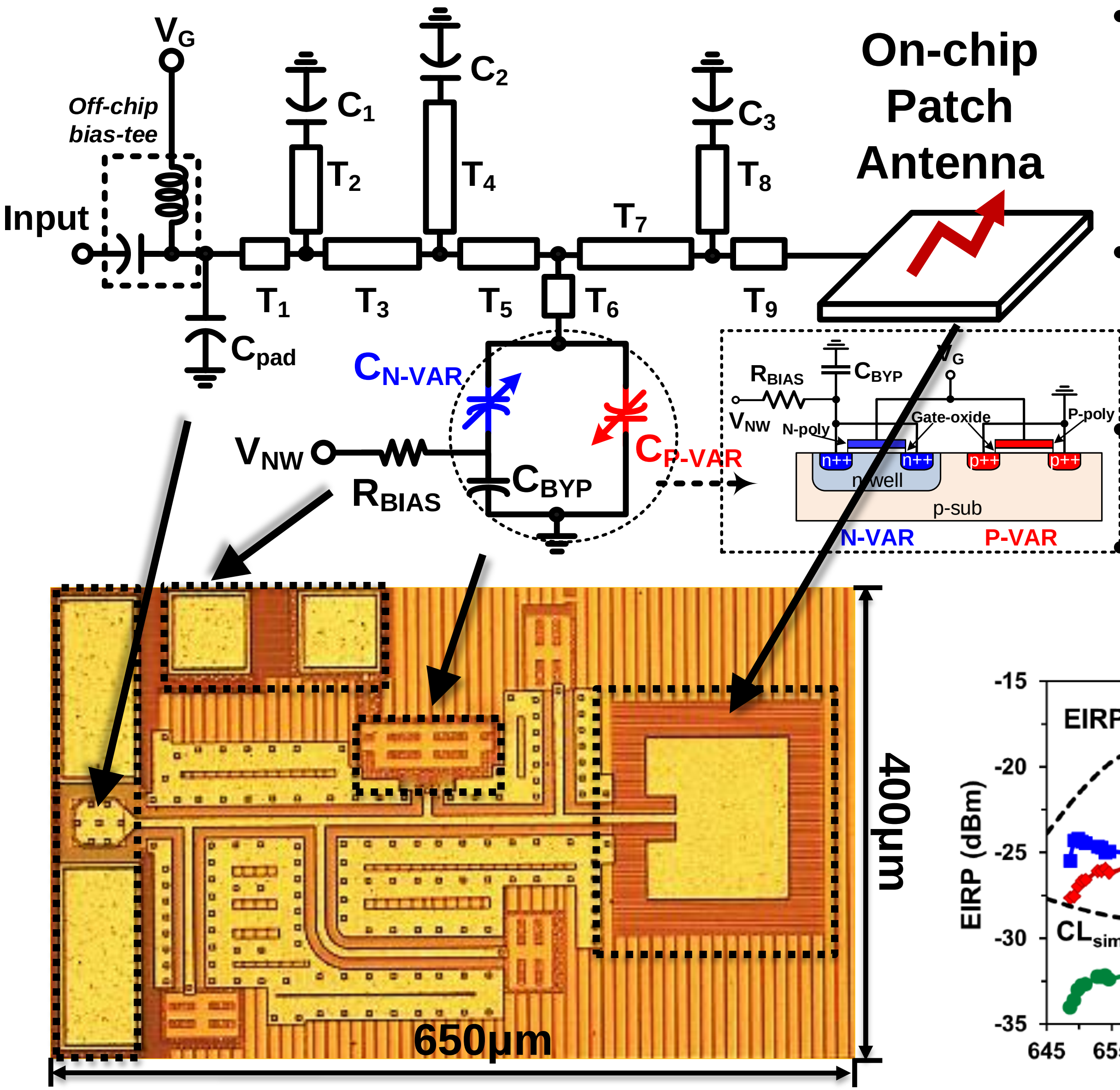
*** Includes other circuit blocks

[3] O. Momeni et al., JSSC 2011.
[4] D. Shim et al., VLSI Symp. 2012.
[6] F. Golcuk et al., IMS Symp. 2013.
[8] R. Han et al., MTT 2013.

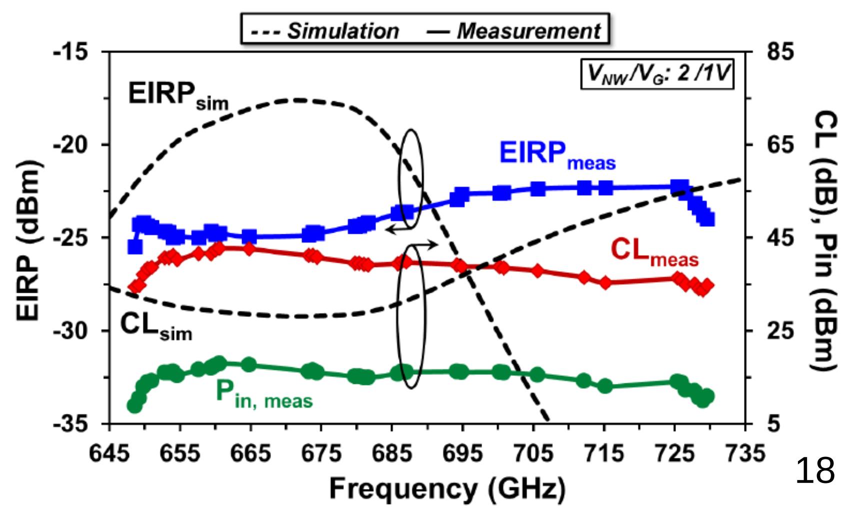
Z. Ahmad, I. Kim, and K. K. O, "0.39-0.45THz Symmetric MOS-Varactor Frequency Tripler in 65-nm CMOS," 2015 RFIC Symposium, May 2015, Phoenix, AZ.

- Highest power generated above 400 GHz in CMOS.
- Driver can be integrated in 65-nm CMOS.

0.7 THz Signal Generation (X5)

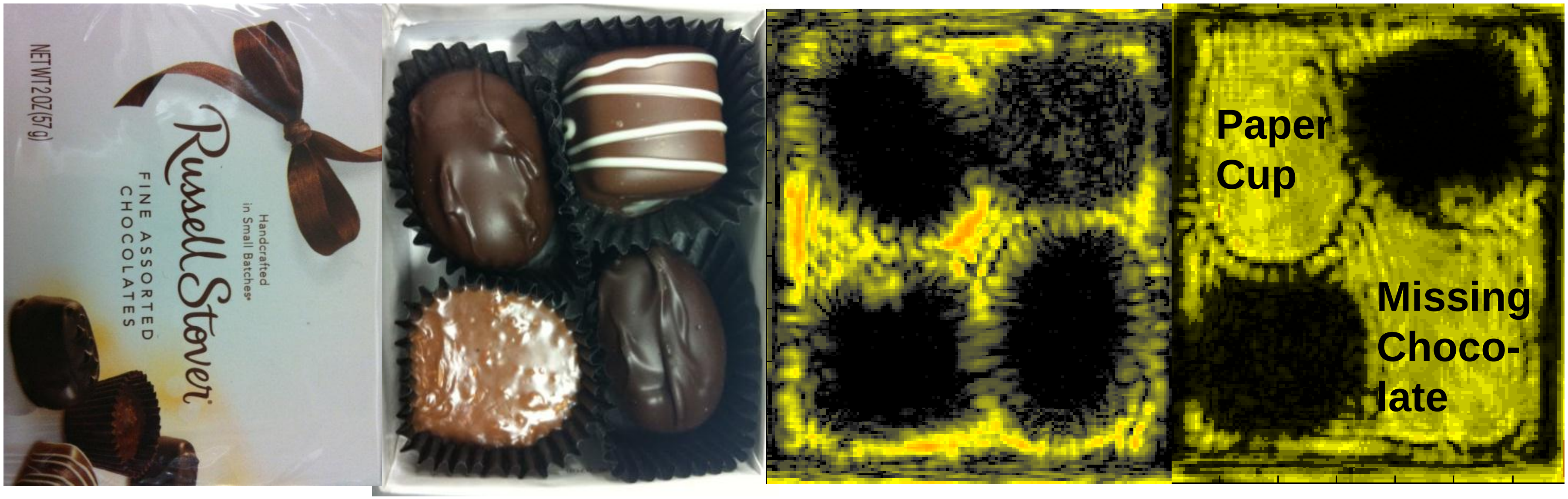


- Generated ~10μW at 726 GHz with input signal at 145.2 GHz with power of 10 mW in 65-nm CMOS.
- Used a VDI detector for measurements. Cutoff frequency is ~ 500 GHz.
- Incorporates an idler for the third order harmonic.
- Driver can be realized in 65-nm CMOS.

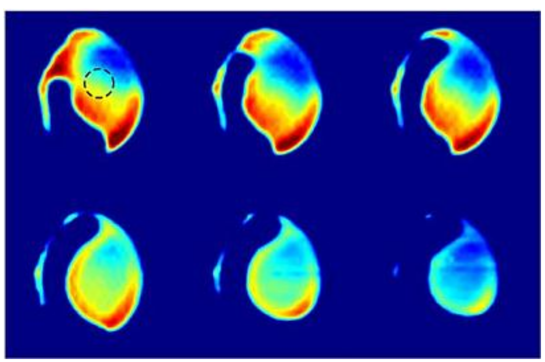


Potential Applications

"Life was like a box of chocolates. You never know what you're gonna get."



You never know what you're gonna get with life, but you may have more ideas about what you're gonna get in a box of chocolate.

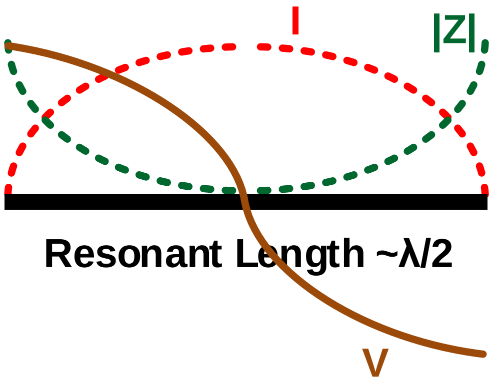


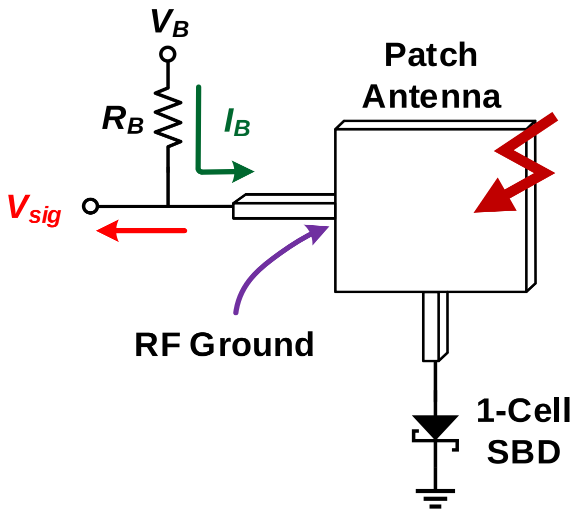
Corneal hydration
Z. Taylor *et al*, T-TST2015

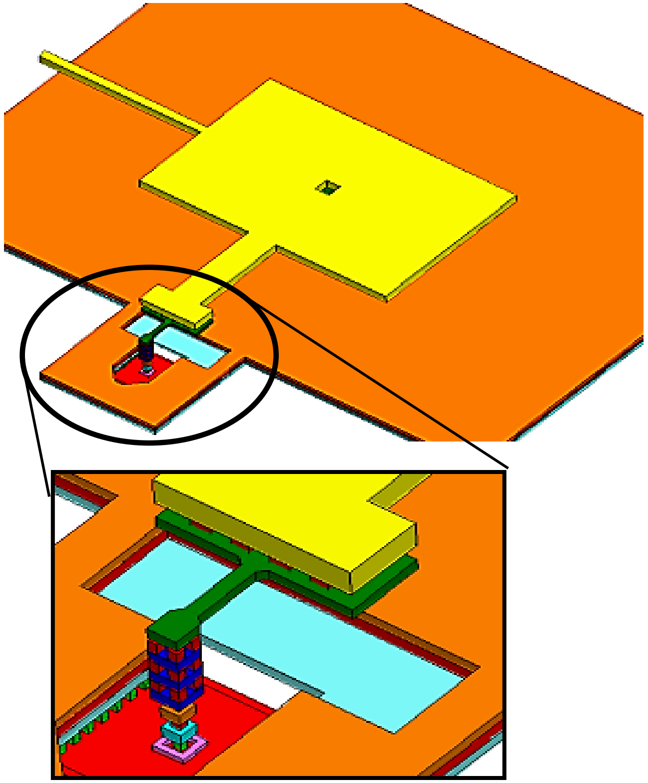
- **Package inspection**
- **See through dry walls for detection of studs, electrical wiring, and pipes.**
- **Authentication**
- **Medical imaging**

- **For a range of ~5 cm, -10 dBm TX and 20-dB NF receiver acceptable.**

Far-IR Detection in CMOS up to 9.74THz



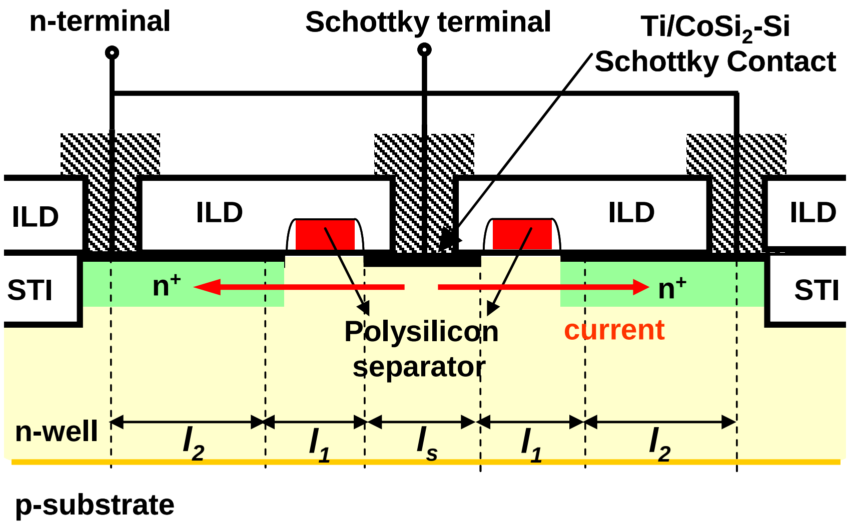


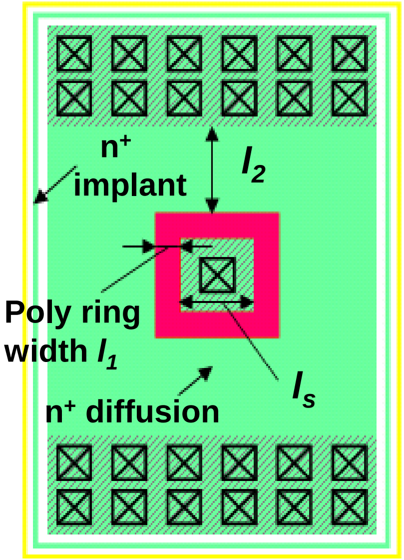


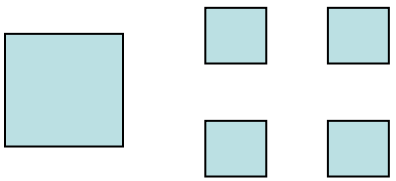
Freq. (THz)	L x W (μm^2)	H (μm)	Directivity (dBi)	η_{rad} (%)
5	12 x 18	3.3	7.4	86
10	6.6 x 11	2.4	8.6	88

- **Single cell 0.4 x 0.4 μm^2 Schottky diode**
- **Bypass capacitors are too inductive**
- **Biasing and signal extraction through the virtual ground at the mid point of patch antenna.**
- **Direct connection without matching. Matching network has too much loss (conduction and radiation).**
- **130-nm UMC CMOS**

Polysilicon Gate Separated (PGS) Schottky Diodes





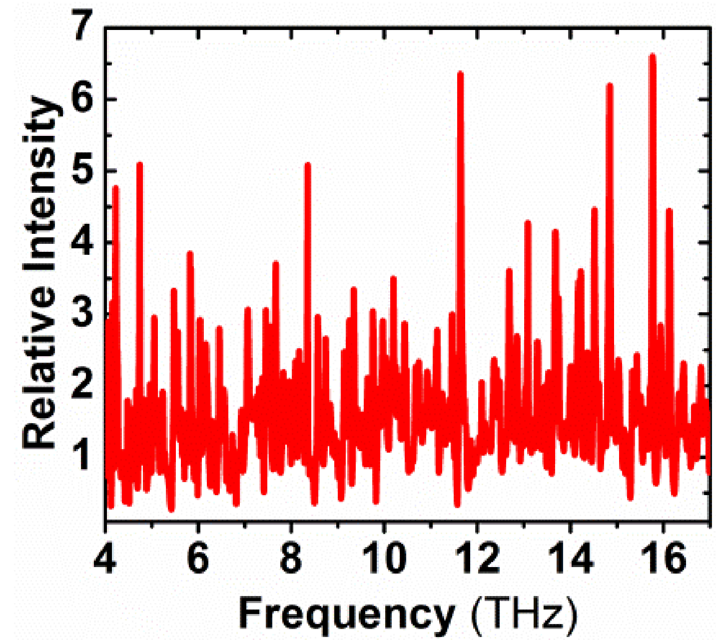


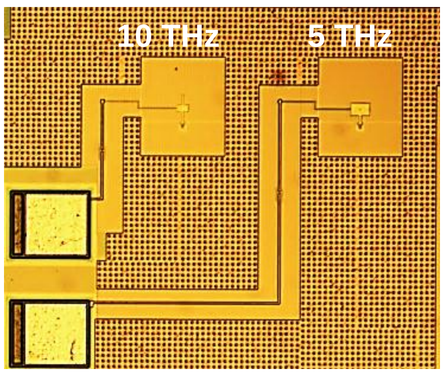
$$f_{cutoff} = \frac{1}{2 \cdot \pi \cdot R_{total} \cdot C_0}$$

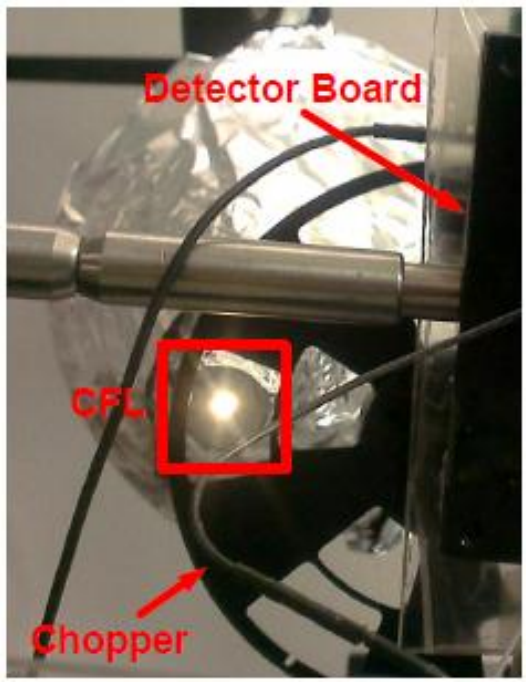
- Diffusion region without implant forms a Silicide-Si junction.
- Ohmic contacts on n-well form the n-terminal.
- Schottky diode area is separated from ohmic contact by polysilicon gate on gate oxide layer.
- Single cell diode area is 0.4 x 0.4 μm^2 in 130-nm CMOS.
- Requires no process modifications.
- $f_{cut\text{-}off}$ over 2 THz in 130-nm CMOS.

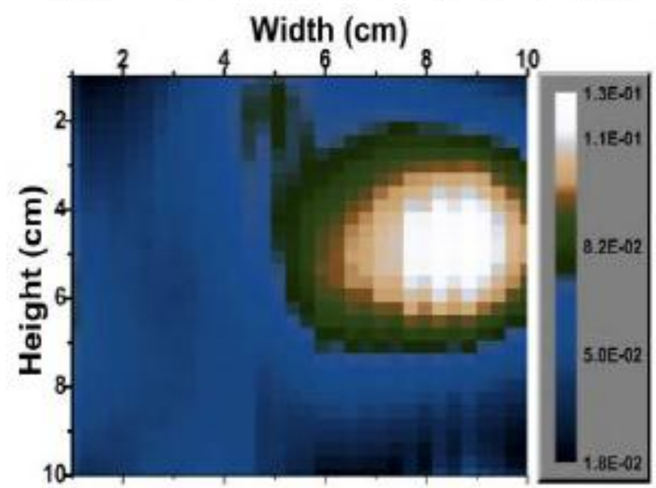
S. Sankaran et al., “Towards Terahertz Operation of CMOS,” *2009 ISSCC* Feb. 2009.

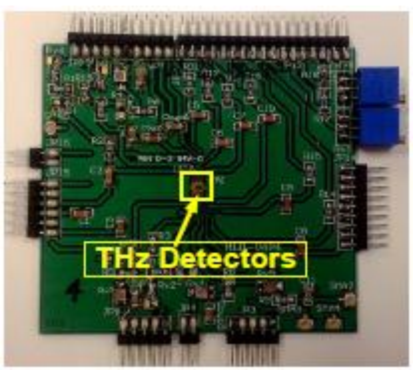
Far-IR Detection in CMOS up to 9.74THz











Performance Comparison of Far-Infrared Detectors

	Thermopile [1]	NMOS [2]	This Work – CMOS SBD's	
Frequency	500 ^{o}K (~45 THz)	4.25 THz	4.92 THz	9.74 THz
Responsivity (V/W)	4.1 (10 Hz)	230 (30 Hz)	383 (300 Hz)	14 (80 Hz)
Noise density (nV/Hz$^{0.5}$)	11	27.5*	123 (Shot)	28 (shot)
NEP pW/Hz$^{0.5}$	2680	110*	433 (Shot)	2000 (Shot)
Area	4 x 10^{6} μm^2	210 μm^2	216 μm^2	72.6 μm^2
Technology	Thin film Bi-Sb	65nm CMOS	130nm CMOS	

CMOS Electronic Detectors:

- **Smaller**
- **Easier to fabricate (No modifications to existing process. No thermal isolation)**

- **Small pixel size makes it better suited for high resolution imaging**
- **Can be faster because of electronic detection (??)**

[1] N. Neumann et al., AMA Conf. 2013.
[2] A. Lisauskas, et al., J. of Infrared, Millimeter, and Terahertz Waves, Jan. 14, 2014.

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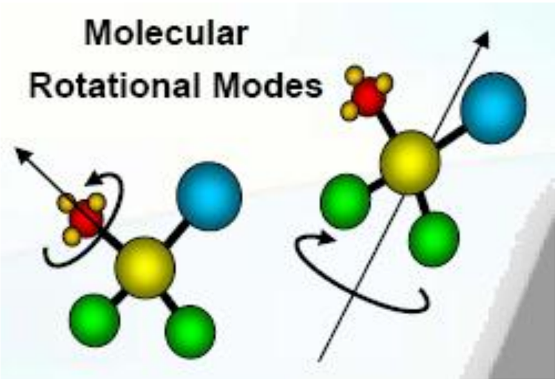
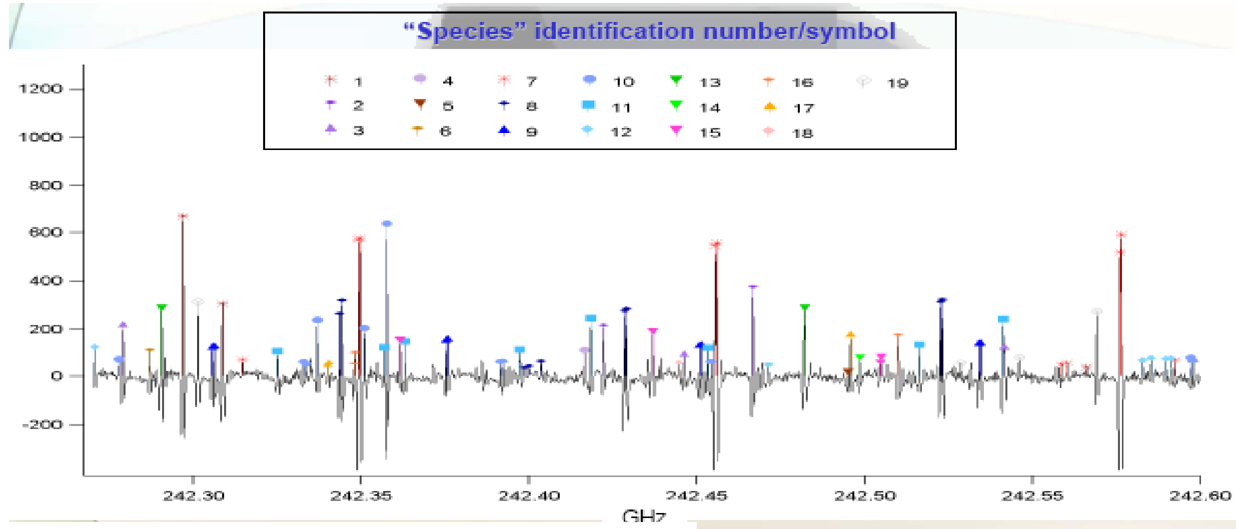
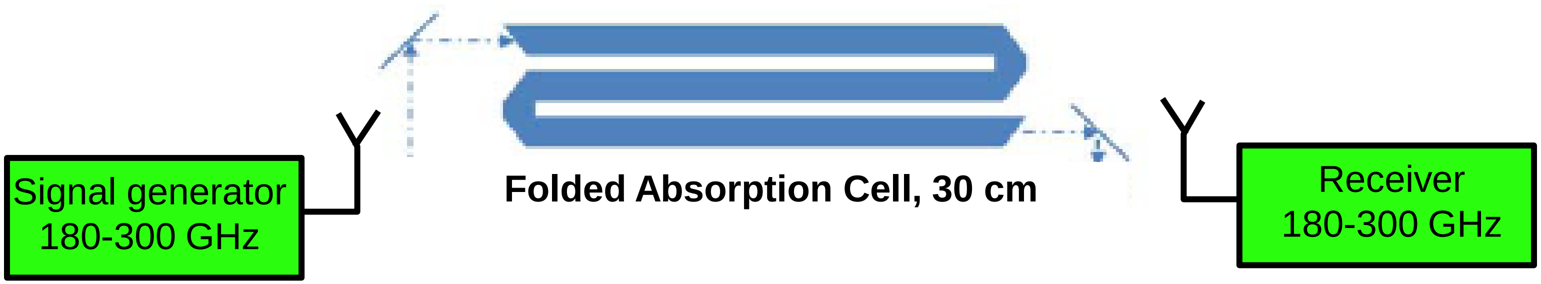
180-300 GHz Spectrometer



F. Patten, MACS Proposer Day Conf., Darpa, Nov. 2005





- **Rotational spectroscopy.**
- **Does not need calibration for identification of molecules. Only depends on spectra signature and independent of temperature.**
- **Specificity in the presence a large number type of molecules in a mixture.**
- **Detect down to PPT for some gases.**

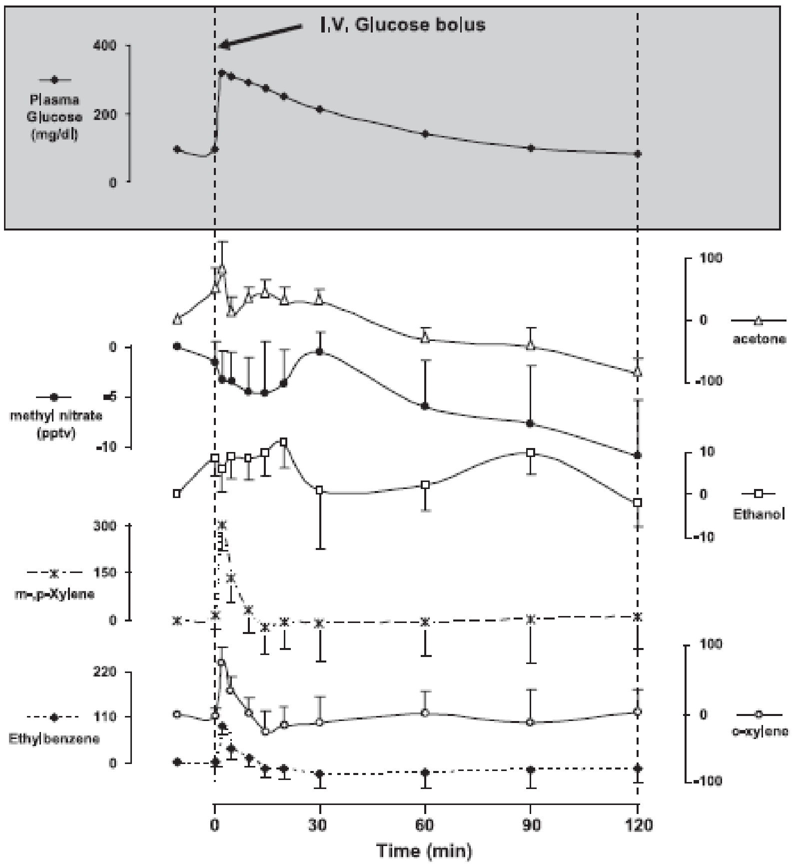
Partial EPA list of Harmful Molecules

Gas	Frequency (MHz)	Fatality Limit	Gas	Frequency (MHz)	Fatality Limit
Hydrogen Cyanide (HCN)	265887.1094	15-50 ppm/hr	Methyl Bromide (CH_3Br)	267801.2188	
Cyanogen Chloride (ClCN)	267199.53125		Ethylene Oxide (C_2H_4O)	263292.5156	200 ppm/hr
Cyanogen Bromide (BrCN)	263578.3438		Acrolein (C_3H_4O)	267279.3594	1.4 ppm/hr
Acetonitrile (CH_3CN)	239096.6719		Propionitrile (C_2H_5CN)	268829.0625	
Carbonyl Sulfide (OCS)	267530.4219		Vinyl Chloride (C_2H_3Cl)	266151.2969	
Methyl Chloride (CH_3Cl)	265785.4219		Methyl mercaptan (CH_3SH)	227564.6719	23 ppm/hr
Acrylonitrile (C_2H_3CN)	265935.2031		Methyl isocyanate (CH_3NCO)	269788.6094	5 ppm/hr
Dichloromethane (CH_2Cl_2)	259215.3906		Methanol (CH_3OH)	250507.1563	
Methyl Iodide (CH_3I)	269864.9063		Formaldehyde	211211	100 ppb

Blood Glucose Estimation from Breath

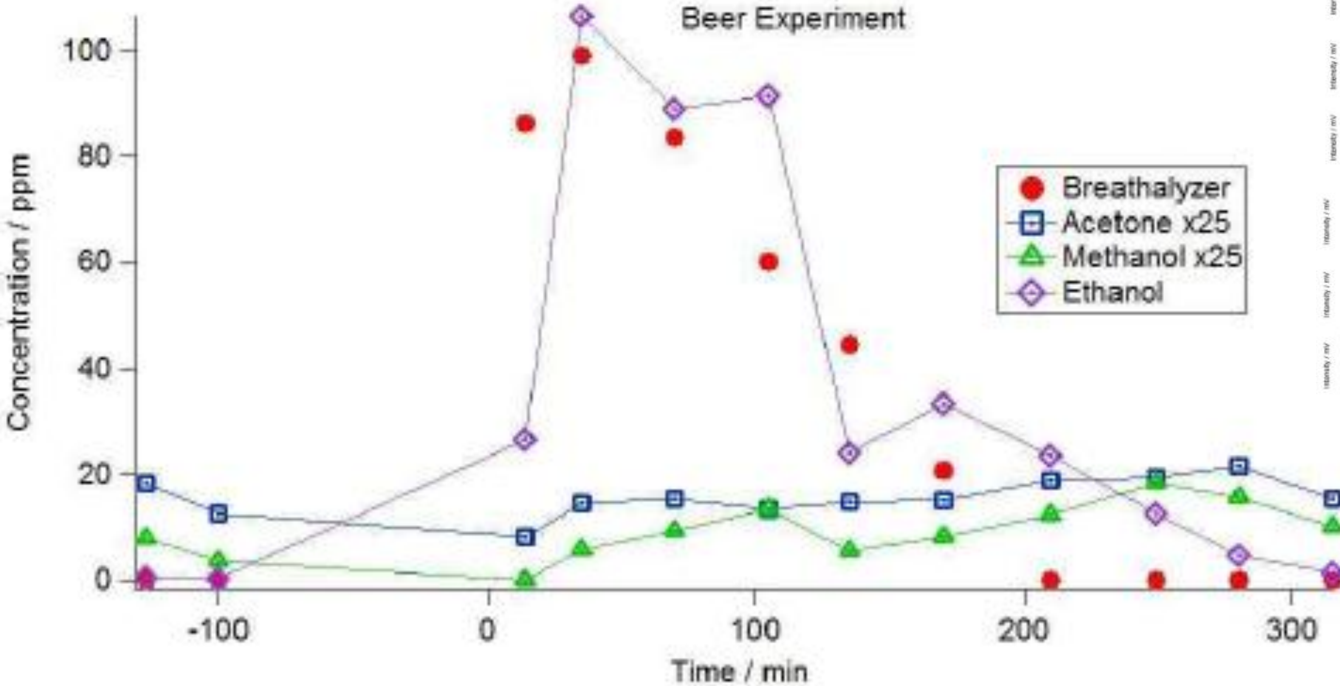
J Appl Physiol 107: 155–160, 2009.
First published May 7, 2009; doi:10.1152/japplphysiol.91657.2008.

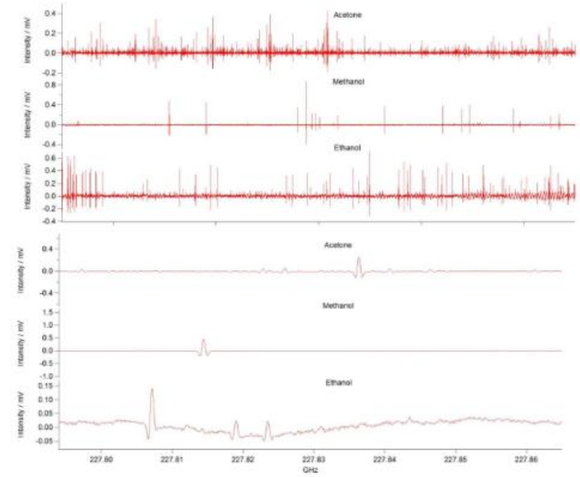
Improved predictive models for plasma glucose estimation from multi-linear regression analysis of exhaled volatile organic compounds



- Some 3000 different molecules have been detected.
- Breath analyses analyze blood, digestive system and environment.
- Spectrometer for blood sugar level detection for diabetic (Type I) patients (ethanol, acetone, methyl nitrate, ethyl benzene).
- Lung cancer detection.
- Current technique: gas chromatography mass spectrometry.

Breath Analyses Using Rotational Spectrometer

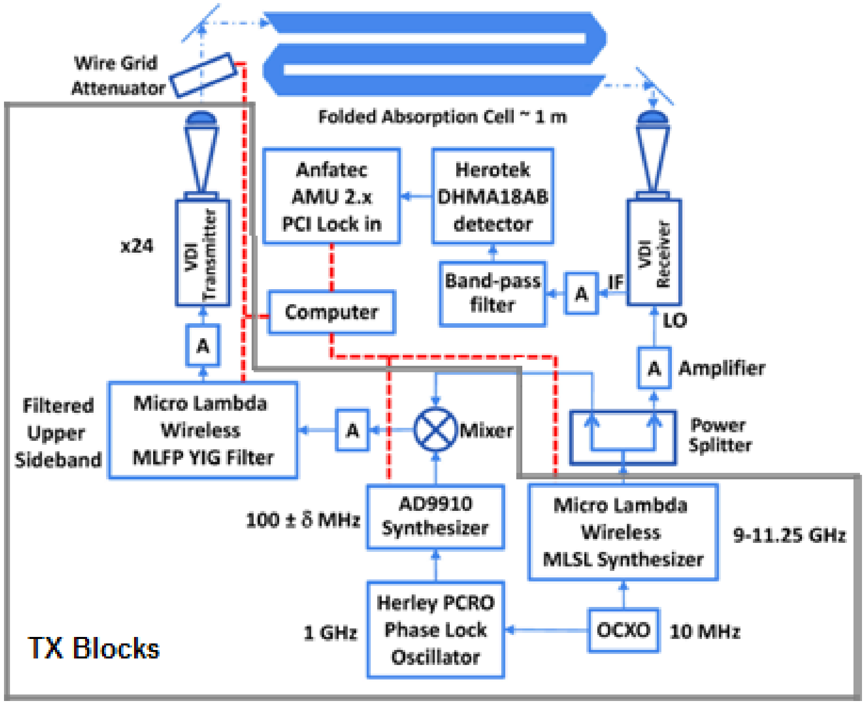


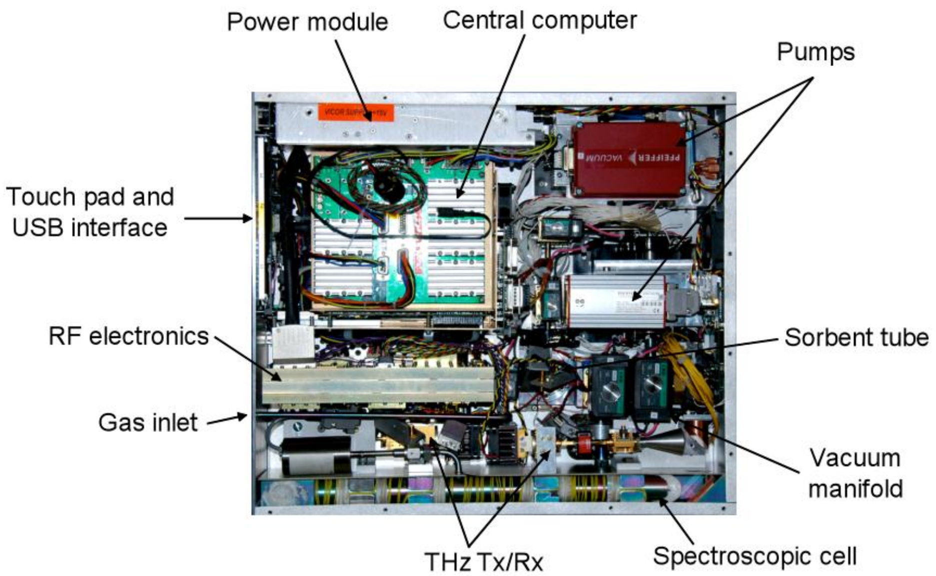


- **Breathlyzer is confused by acetone. Diabetic patients have acetone in their breath.**
- **Rotational spectrometer can distinguish acetone and ethanol.**
- **Acetone level has been correlated with the blood sugar level**.

Ivan Medvedev, Wright State University.

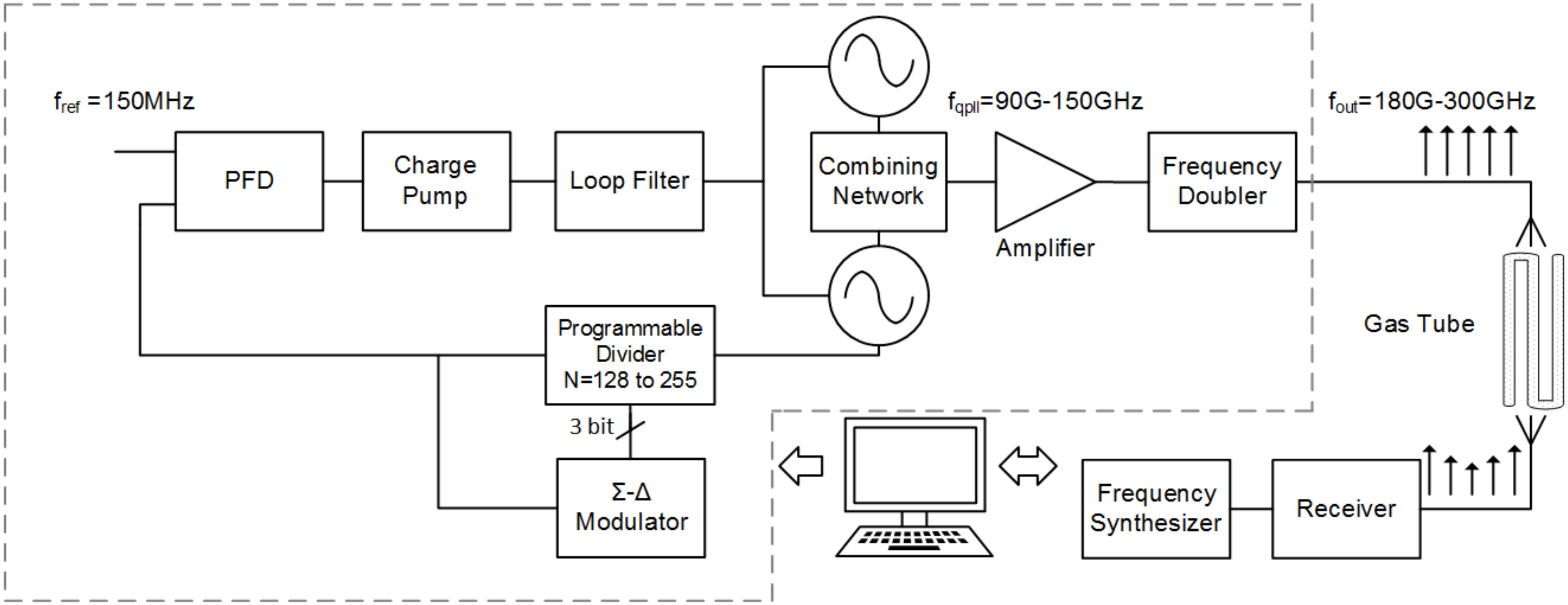
Rotational Spectrometer for Breath Analyses





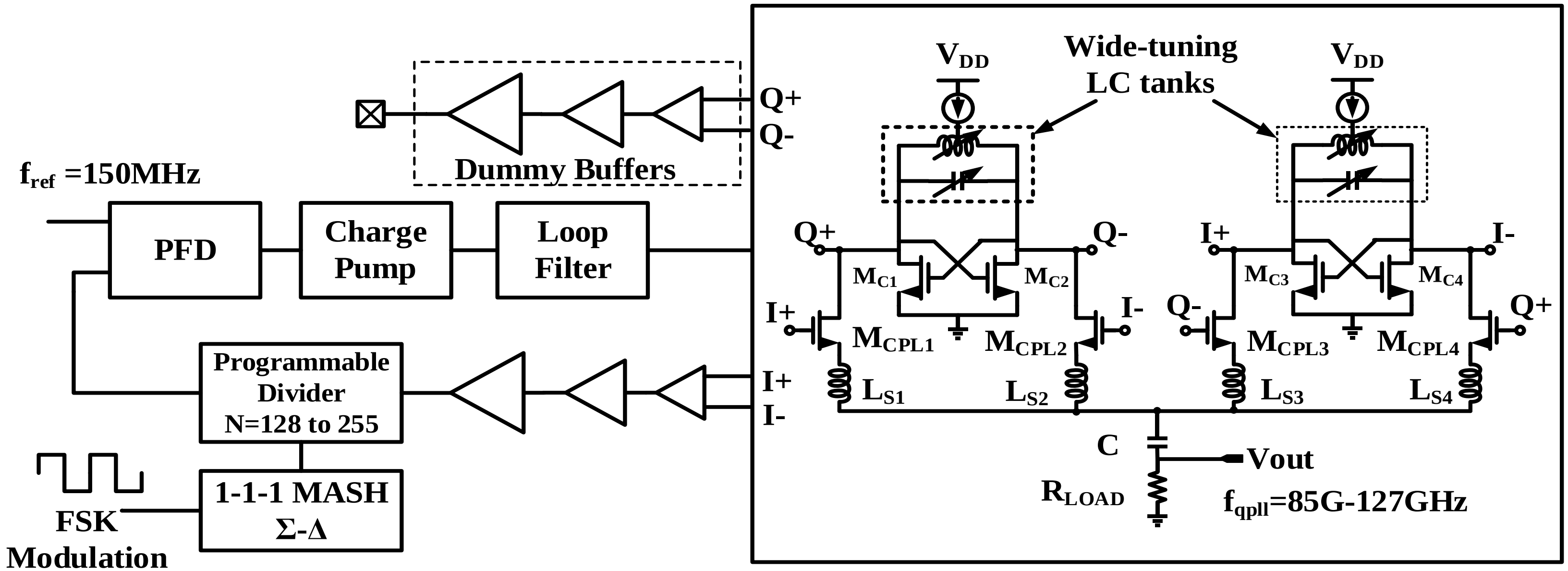
- **Size of a desktop computer**
- **Costs ~ $100k in parts. ~$90k is for electronics**
- **Vacuum cell (10 mT)**
- **Needs a pre-concentration system to take out N_2, O_2, water ..**

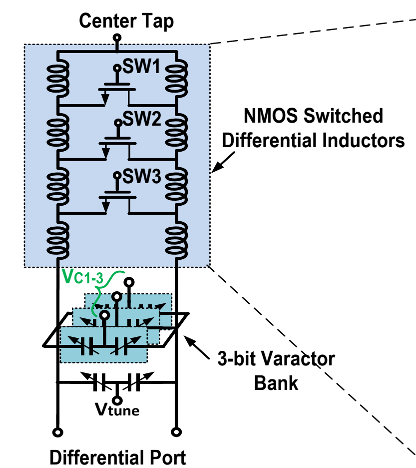
Transmitter Architecture



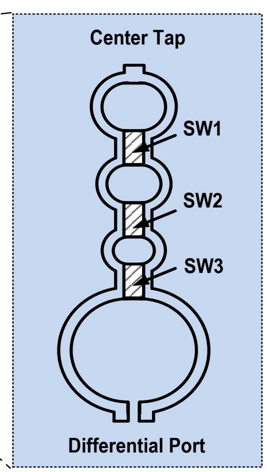
- **Uses a fractional-N PLL with quadrature coupled oscillators to generate 4 phases for X4 frequency to generate signals at 90-150 GHz.**
- **Amplification and frequency X2 to reach 180GHz to 300GHz**
- **Enables use of a single VCO to cover the entire frequency range.**
- **Output power of 1-20μW**
- **FSK modulation**

85-127 GHz Transmitter Prototype Design





Schematic of the wide-tuning L-C tank

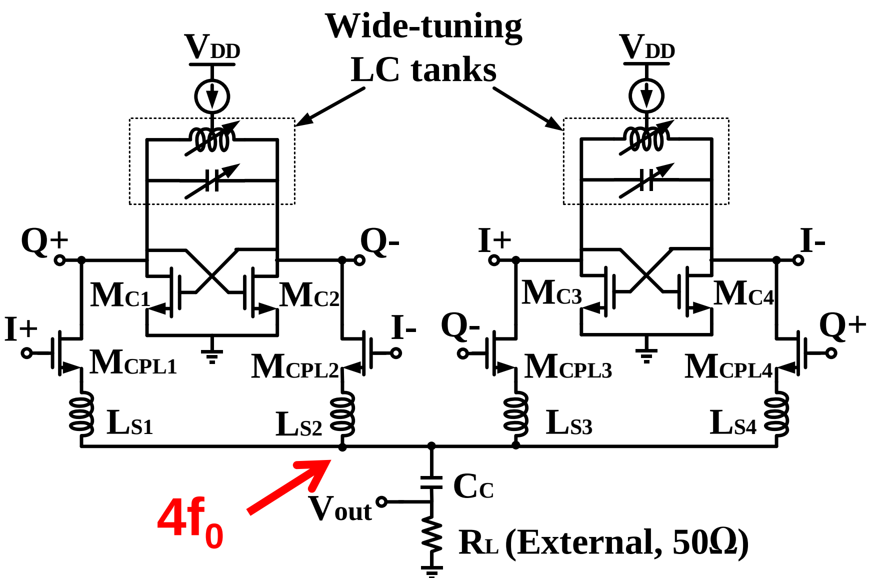


Layout of the NMOS switched differential inductors

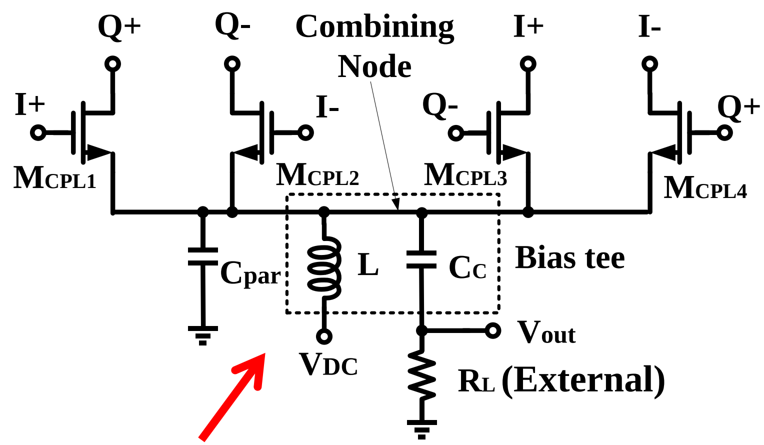
- Switched inductors and varactors for coarse frequency tuning.
- Varactors for fine frequency tuning.
- FSK using Σ-Δ modulator of fractional PLL
- Quadrature coupling to generate 4 switching events per oscillation period at the output node.

Quadrature Oscillator

- Quadrature phase generation by passive coupling.
- No DC power consumption for the combining network.
- Improves phase noise.
- Eliminates the need for a broad band bias tee.



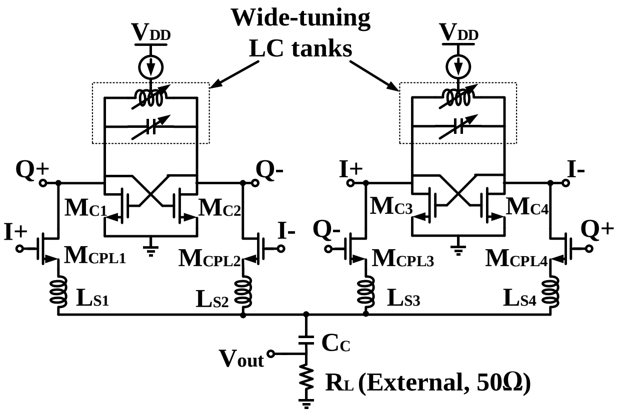
Wide-tuning LC VCO's coupled with a passive quadrature coupling and phase combining network.

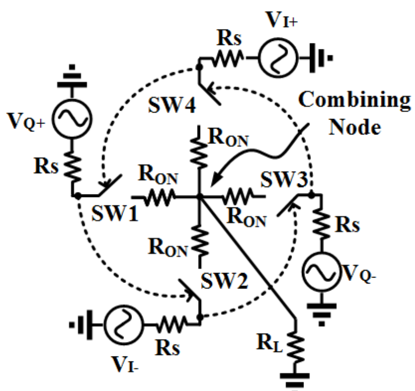


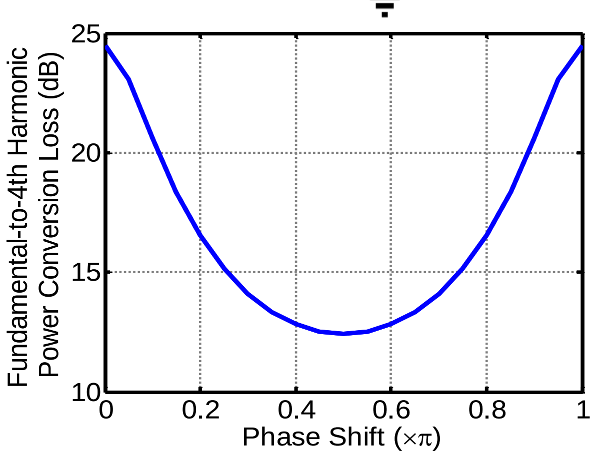
Difficult to implement.

J. Zhang, N. Sharma, W. Choi, D. Shim, Q. Zhong, and K. K. O, "85-to-127-GHz CMOS Signal Generation using a Quadrature VCO with Passive Coupling and Broadband Harmonic Combining for Rotational Spectroscopy," IEEE J. of Solid State Circuits. Vol. 50, no. 6, pp. 1361-1371, June, 2015.

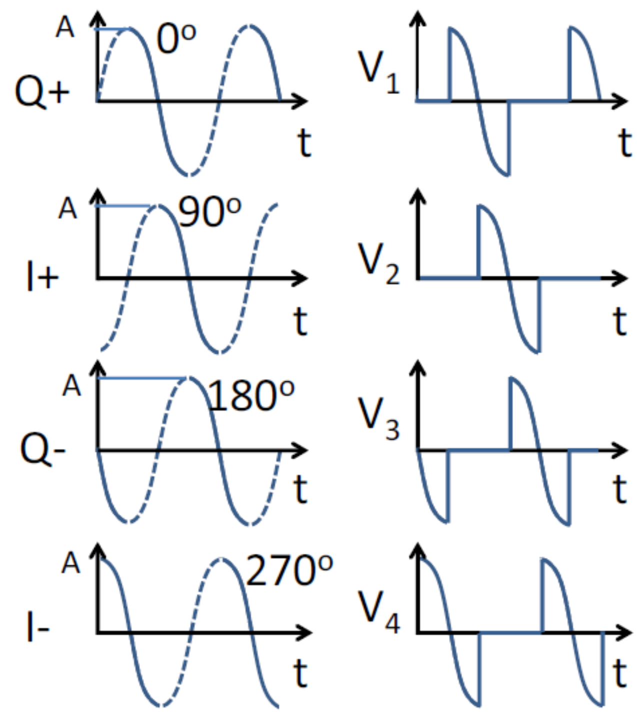
Quadrature Mixing for Harmonic Generation



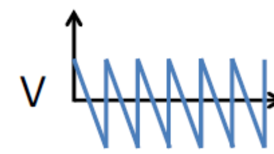




Phase Shifting → Quadrature Mixing → Phase Combining



$$V = \frac{-32R_L A}{(2R_L + R_S)} \sum_{n=1}^{\infty} \frac{n \cdot \cos\left(4n\omega t + \frac{\pi}{2}\right)}{(4n-1)(4n+1)\pi}$$

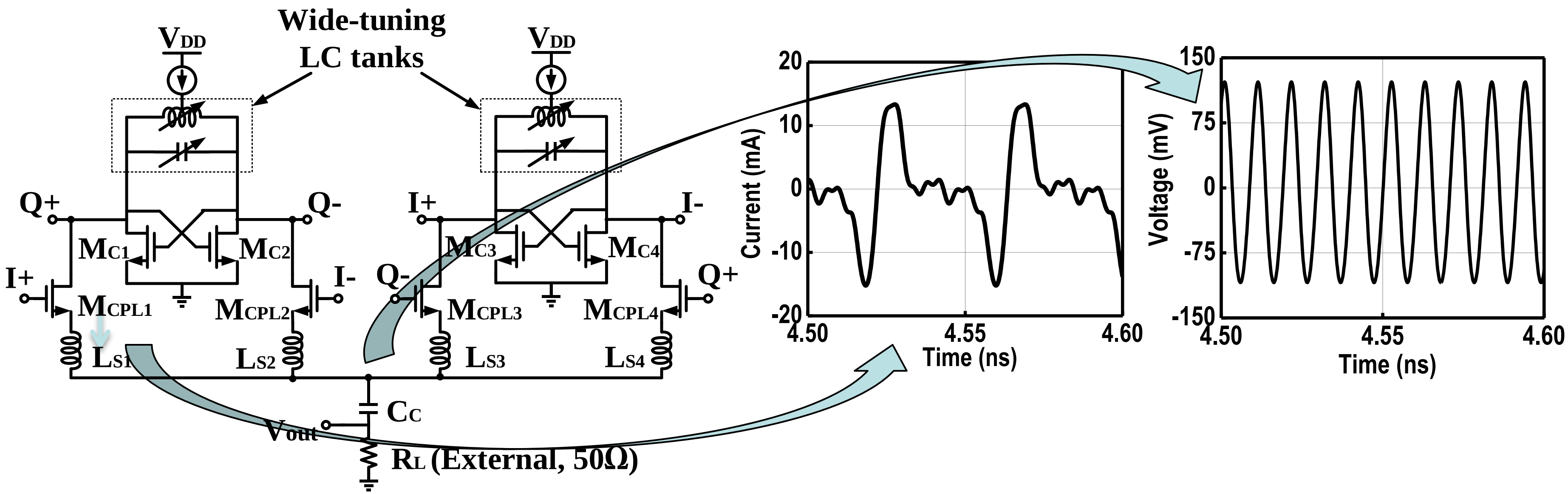


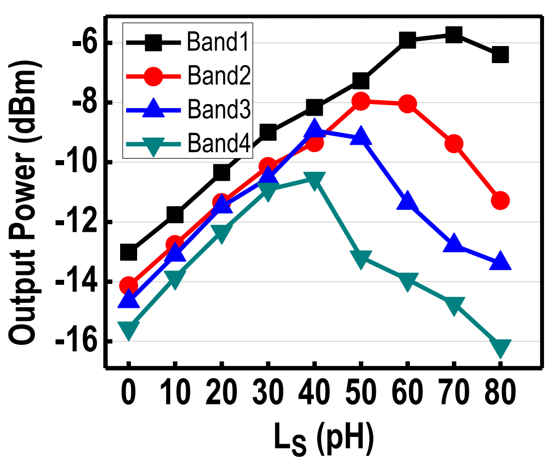
Minimum Fundamental-to-4th Power Conversion Loss

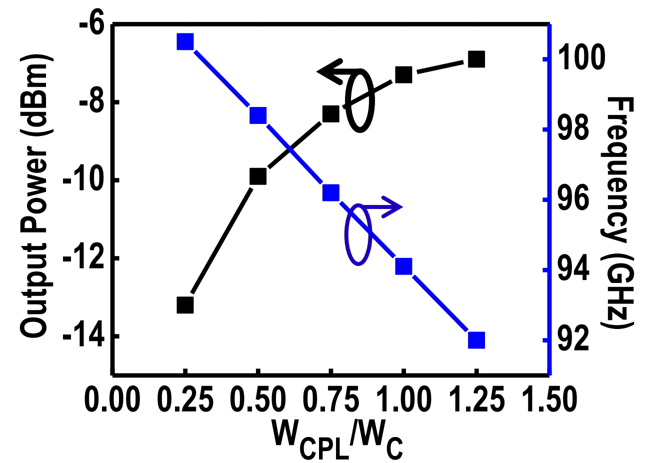
Conversion loss $\approx 12.4\ dB$

Fundamental-to-4th harmonic conversion

Coupling and Phase Combining Network

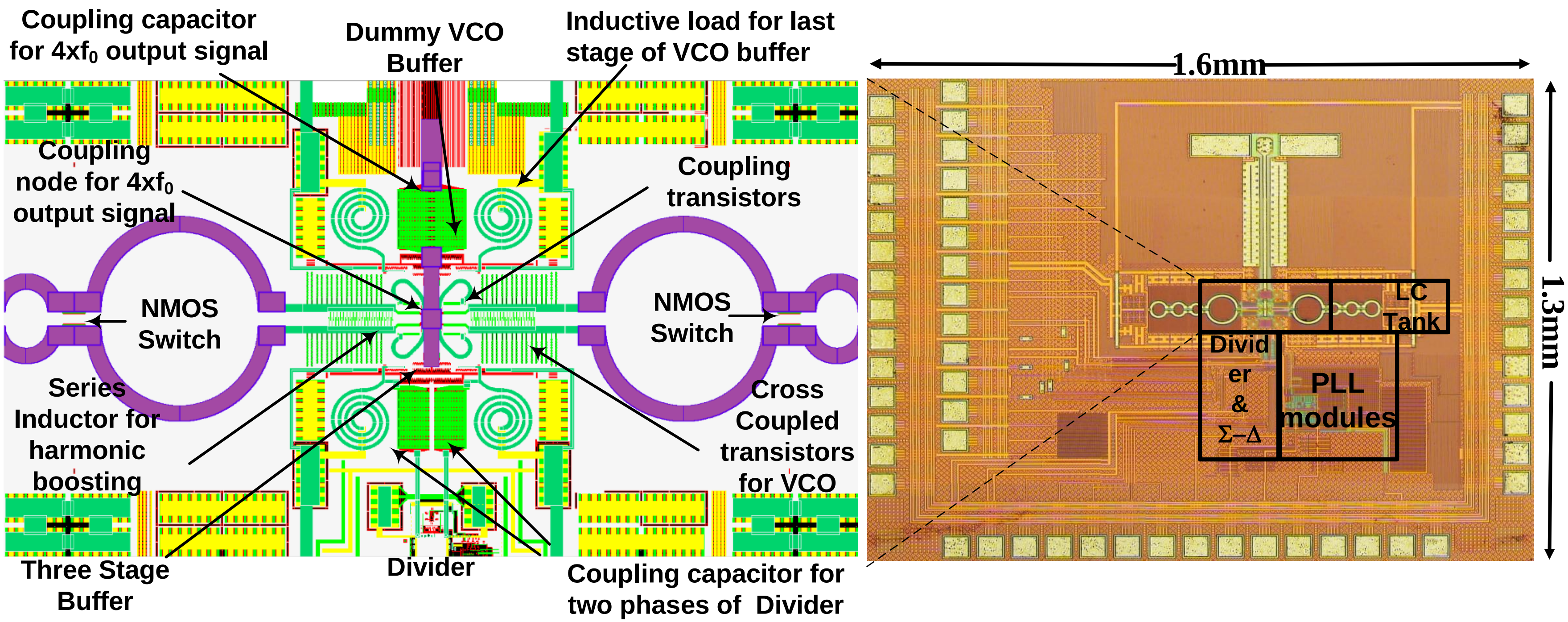






- **Degeneration inductors, L_{S1}-L_{S4} for better power matching and enhanced generation of 4th order harmonic.**

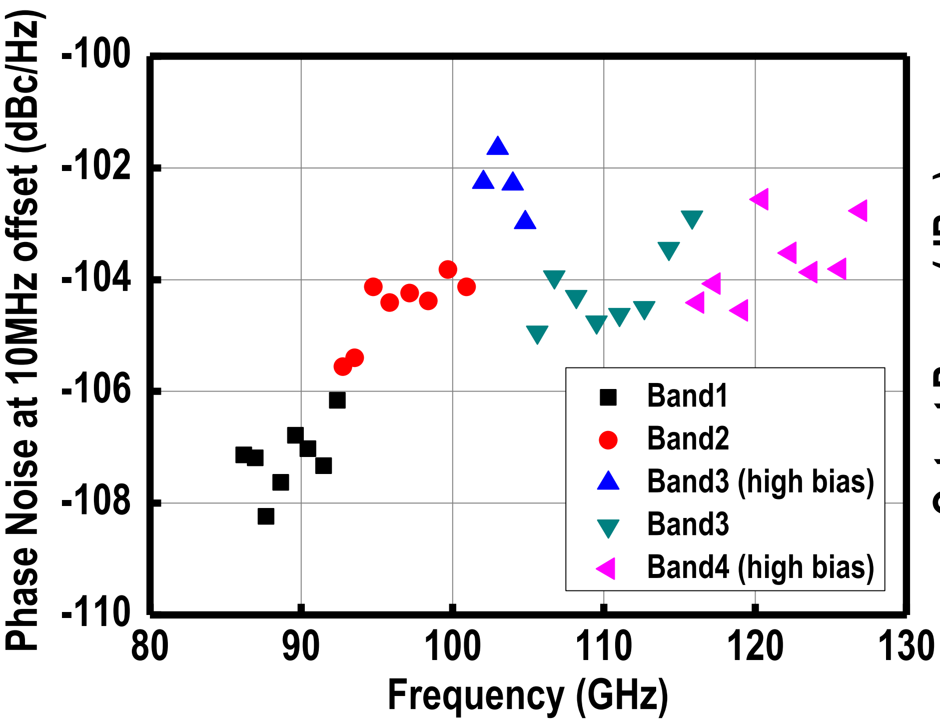
Layout and Die Photograph



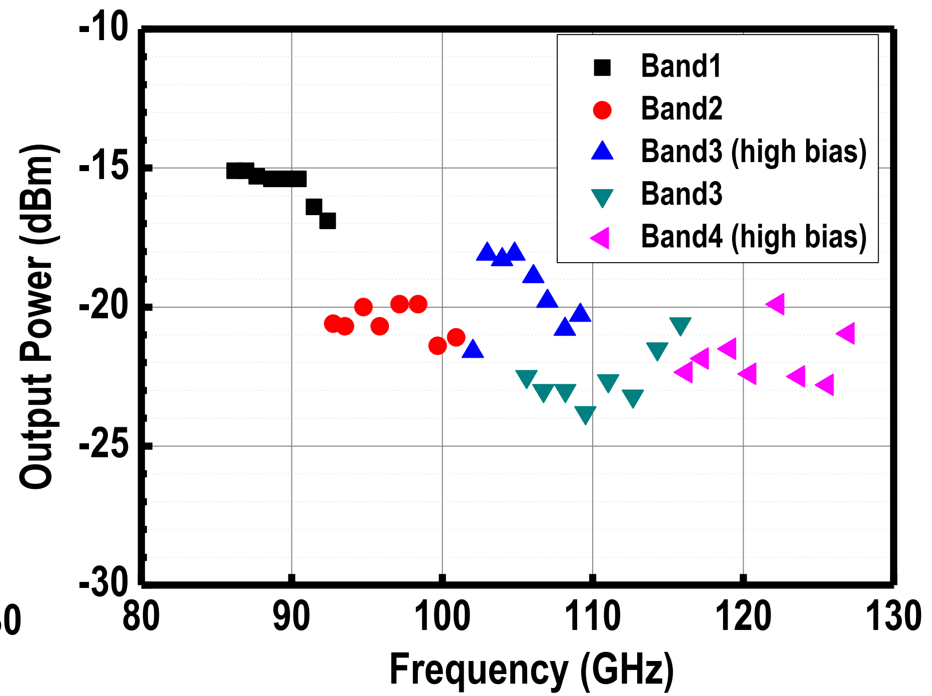
- **Layout of 300 μm by 200 μm section around VCO.**
- **Harmonic combining transistors, inductors and other elements arranged in a compact layout.**
- **Symmetry maintained around VCO using dummy buffers.**
- **Coupling node feeds the fourth harmonic signal to the output transmission line.**
- **Fabricated in TI 65-nm CMOS.**

Phase Noise and Output Power

Phase Noise across frequency

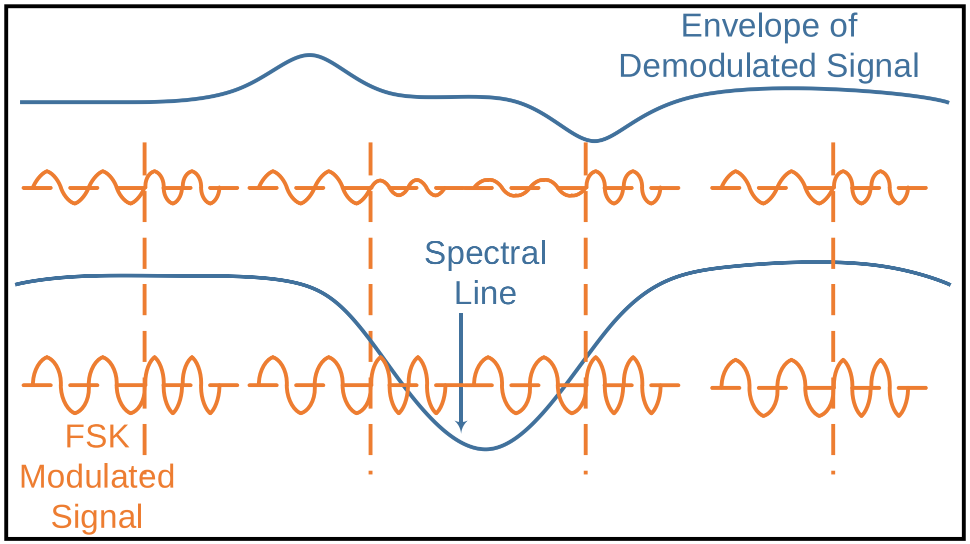


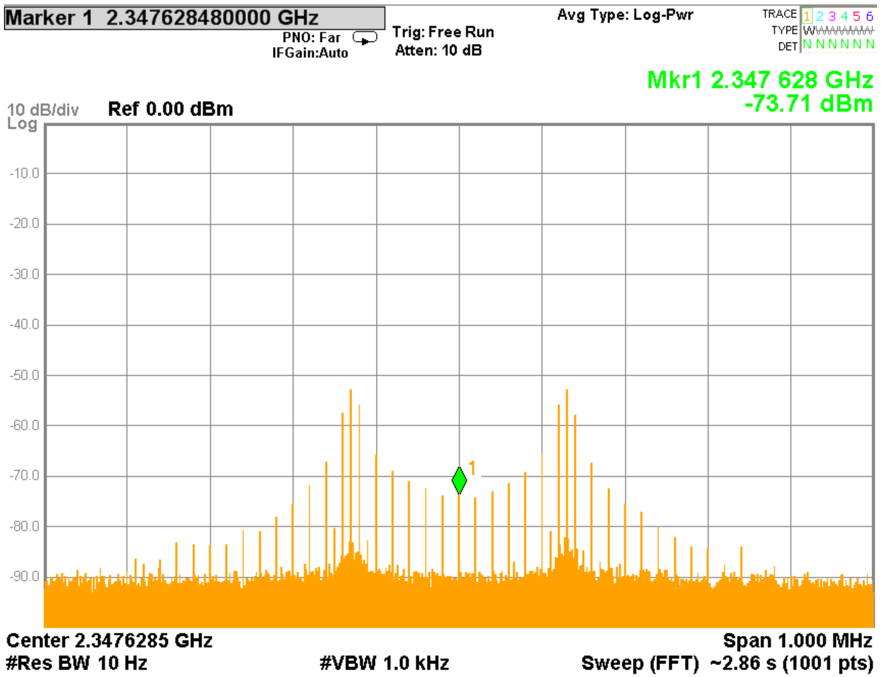
Power output across frequency



- **Phase noise meets the spectrometer requirement across the frequency range (< -88 dBc/Hz at 10MHz offset @ 150 GHz).**
- **Output power is higher than -23 dBm across the whole range.**

FSK Modulated Transmitter Output



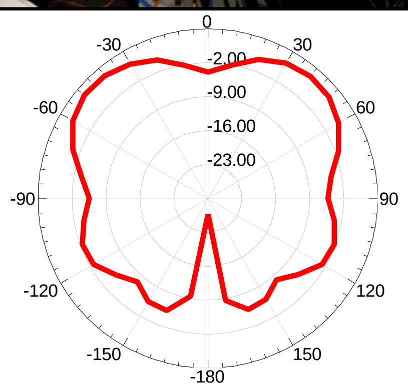


- **Bandwidth around 1-2 MHz**
- **Settling time of about 6μs.**
- **Minimum frequency step of about 570 Hz.**
- **Frequency deviation < line width.**
- **Receiver lock-in amplifier detects the change in amplitude at frequency of modulation.**

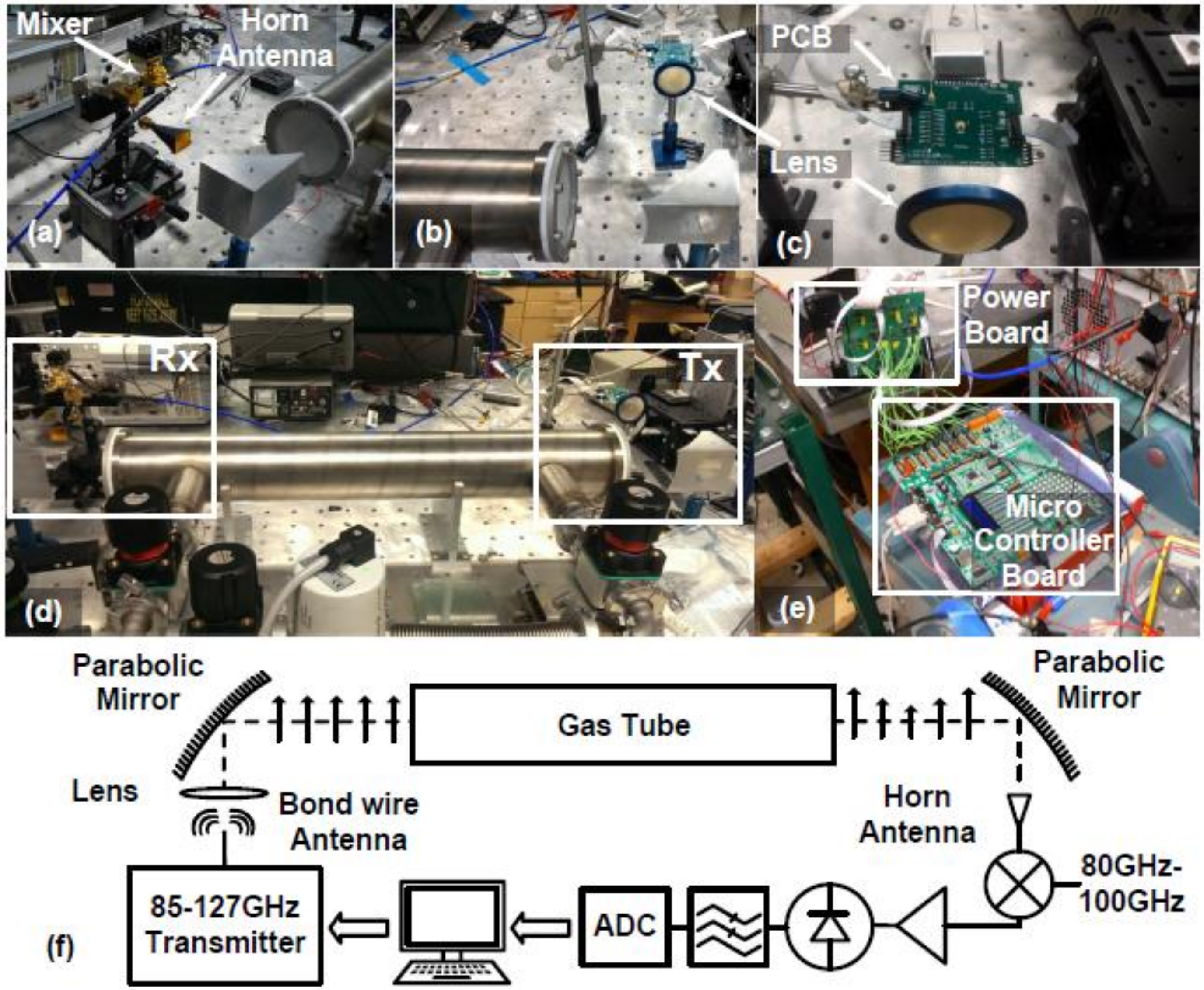
Center Frequency =129GHz
Modulation Frequency = 10 kHz
Frequency Deviation = 270 kHz

N. Sharma, J. Zhang, Q. Zhong, W.-Y. Choi, J. P. McMillan, C. F. Neese, F. C. De Lucia[2], K. K. O, “85-to-127 GHz CMOS Transmitter for Rotational Spectroscopy,” 2014 IEEE Custom Integrated Circuits Conference, Sept. 2014, San Jose, CA.

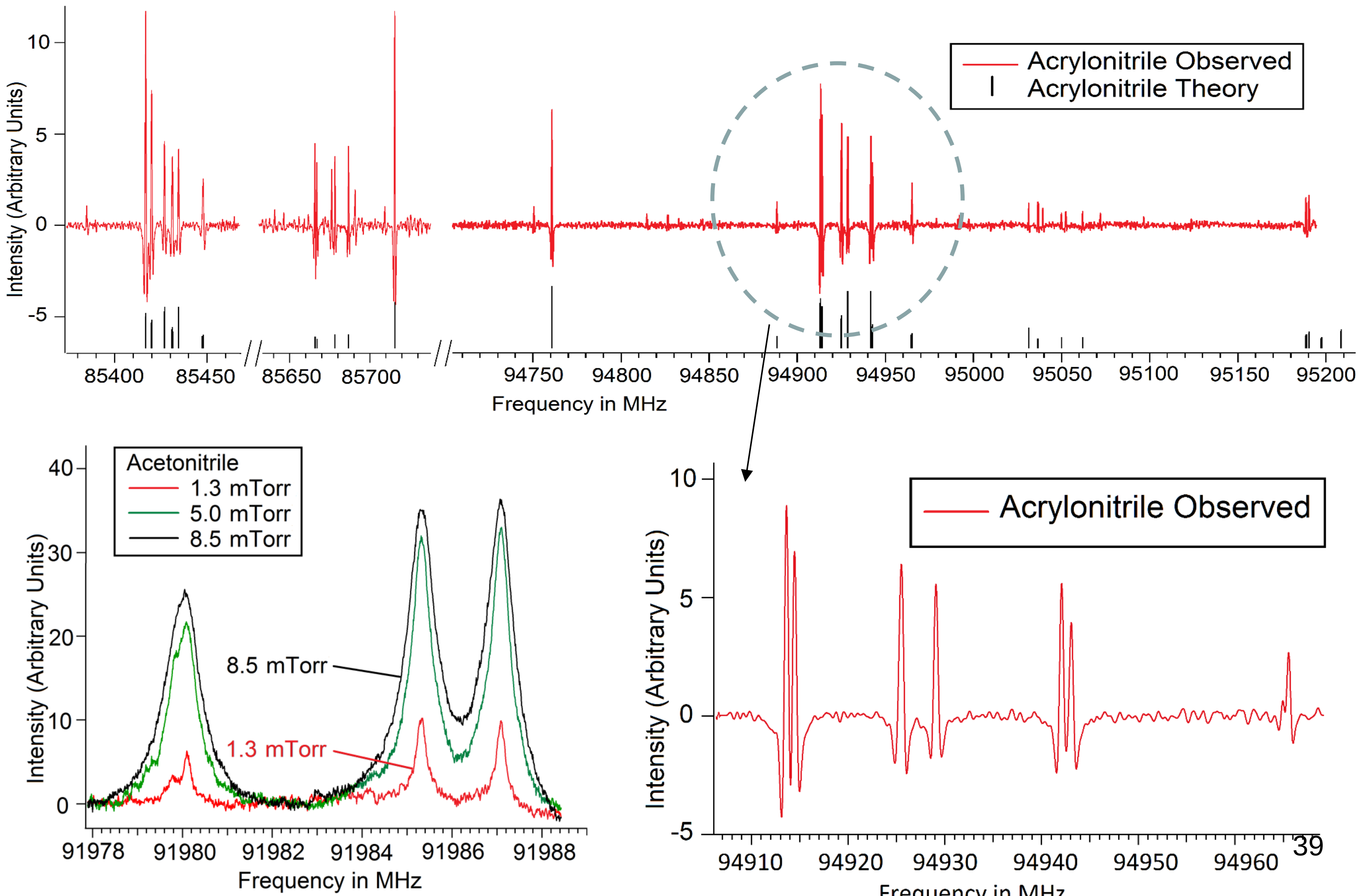
Spectrometer Demonstration



Simulated Radiation Pattern
(Phi=90 degree @85GHz)



Measured Gas Spectra



Comparison Table

	[6]	[7]	[8]	[9]	This Work
Architecture	ADPLL	FN	Int. PLL	PLL+ILVCO	FN + Mult.
Process Tech.	65nm	90nm	65nm	65nm	65nm
f_{center} (GHz)	60.5	40.4	74	61.7	106.7
Tuning Range	11.6%	6.2%	10.8%	11.9%	39.4%
Freq/Div Step	/32	3kHz	/8	2.16GHz	~570Hz
PN @ 10MHz	-110	-114	-103	-113	-102 /-107
F_{ref} Spur	-74	-54	-49	-67/-58	-55/-70
Power (mW)	48	64	65	80	65/80
FOM_T	-170	-164	-162.9	-173.6	-178

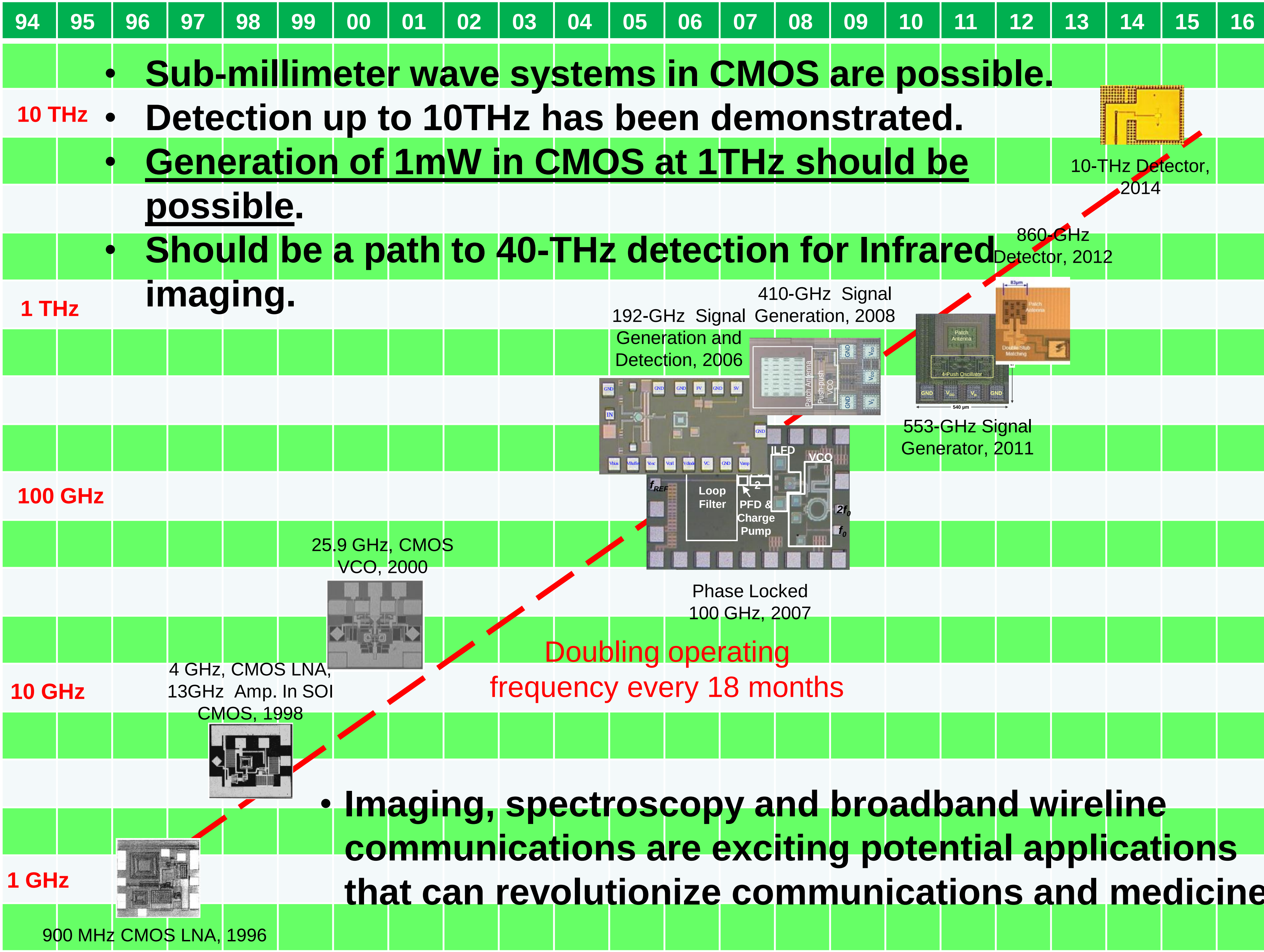
- **Tuning range is ~4X higher than all other millimeter wave PLLs while the operating frequency is 30-60 GHz higher.**
- **Phase noise performance acceptable for rotational spectroscopy.**
- **Broadband amplifiers and frequency doubler are being implemented to support 200-300 GHz operation.**

Dielectric Waveguide Communication

Frequency (THz)	0.18 to 0.36	Received power (dBm)	-17.5
Channel Bandwidth (GHz)	45	Thermal noise density (dBm/Hz)	-174
Range (m)	1	Noise figure of receiver (dB)	28
TX power to transition (dBm)	-8	Bandwidth (bits/s (dB-Hz)) 30Gbps	105
Propagation loss	2.5	E_b/N_o (BER of $1x10^{-18}$) (dB)	~16
RX transition loss (dB)	3.5	Sensitivity (dBm)	-25.0
TX transition loss (dB)	3.5	Link margin (dB)	~7.5

Noise Figure of Receiver: 20-dB Noise Figure for the 300-GHz 2nd harmonic mixer and 8-dB Noise Figure for the 30-GHz bandwidth amplifier

- **Channelizing ~200GHz bandwidth using frequency and polarization division multiple access, perhaps enable ~300 Gbps communication.**
- **Given ~-3 dBm at 447 GHz, TX power can be increased to improve the link margin.**
- **No photonic components needed. Maybe able to compete with photonics on the chip-to-chip and board-to-board communications.**


94
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13
14
15
16
10 THz
1 THz
100 GHz
10 GHz
1 GHz
• Sub-millimeter wave systems in CMOS are possible.
• Detection up to 10THz has been demonstrated.
• Generation of 1mW in CMOS at 1THz should be possible.
• Should be a path to 40-THz detection for Infrared imaging.
10-THz Detector, 2014
860-GHz Detector, 2012
410-GHz Signal Generation, 2008
192-GHz Signal Generation and Detection, 2006
553-GHz Signal Generator, 2011
Phase Locked 100 GHz, 2007
Loop Filter
PFD & Charge Pump
ILFD
VCO
25.9 GHz, CMOS VCO, 2000
Doubling operating frequency every 18 months
4 GHz, CMOS LNA, 13GHz Amp. In SOI CMOS, 1998
900 MHz CMOS LNA, 1996
• Imaging, spectroscopy and broadband wireline communications are exciting potential applications that can revolutionize communications and medicine.

Acknowledgement

- **The efforts were supported by**
  - **DARPA (N66001-03-1-8901)**
  - **NASA (NAG10-316)**
  - **SRC (Task ID: 1327, 1386).**
  - **SRC TxACE (Task ID: 109, 152)**
  - **C2S2 (Task ID: 2047.004.004, 2047.004.011)**
  - **Samsung Electronics (GRO)**

- **The authors also thank TI for fabrication support.**