Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: TI Kilby TeraHz Activity

Date Submitted: **5** March, 2010

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Re: IEEE 802.15-15-10-0154-01-0thz

Abstract: From a semiconductor vendor point of view, the interest in many appealing application areas in the Sub THz (100GHz-600GHz) range is outlined. Specific capabilities of nanometer CMOS silicon process today and in the next few years that enable cost effective implementations of transceiver systems will be discussed based on available research and existing Si process roadmap. Key transceiver architecture issues that make operating in this frequency range attractive will also be highlighted. For these new applications to happen including in the telecommunication area of interest to 802.15WG, support from spectrum regulatory authorities is needed.

Purpose: Information on development of future THz communication systems

TI Kilby Labs TeraHz Activity

Baher Haroun, IEEE Fellow, TI Fellow

Advanced Technology and Innovation
TI Wireless Business Unit and Kilby Labs

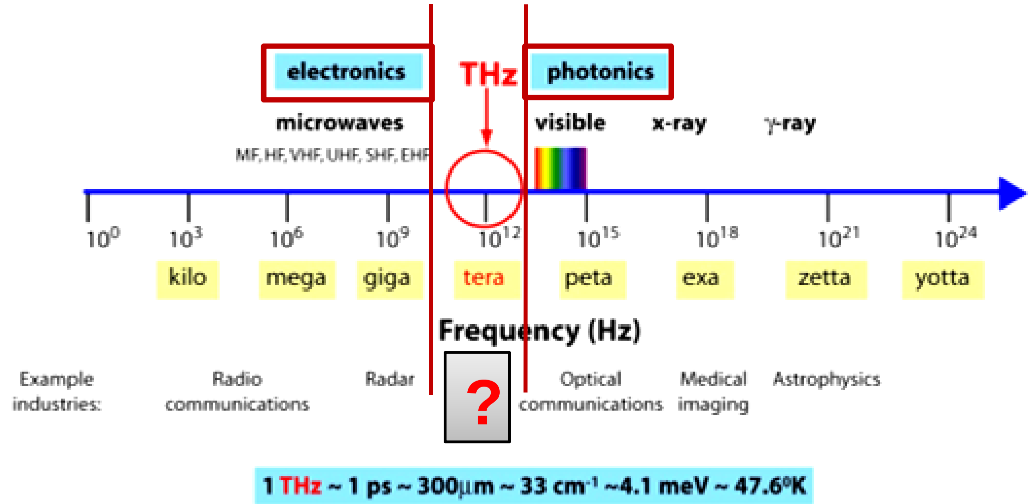
My Special Thanks to my colleagues at TI Kilby Labs;
Srinath Ramaswamy
Brian Ginsburg
Eunyoung Seok
Daquan Huang
Vijay Rentala
Swami Sankaran

Outline

- Why Sub THz now is interesting to a semiconductor company?
  - Synergy of multiple applications that can drive the cost down for sub-THz consumer applications (100GHz-600GHz) range
    - Docking links for Mobile/Notebooks at 20+ Gb/sec
    - Imaging (medical/security)
    - Material analysis/Spectroscopy (industrial, security and medical)
    - Telecommunication - wireless backhaul - 20+Gb/sec
- Wireless Links: why operating 300GHz+ is making sense for these high volume applications:
  - The argument for High Gain Antenna's on Chip at 300GHz
  - and Why Now?
    - Silicon CMOS as an enabling technology for Transmitters and Receivers
      - Key device capabilities and ITRS roadmap and how it plays in the sub-THz
    - The phase control possibilities in Advanced CMOS and arrays
    - What does it take to make a wireless link at 300GHz+
- Conclusions and Next steps

Properties at THz

Frequency Range
Terahertz region – 0.3-10THz
But loosely – 100GHz and upwards
Wavelengths
3 mm to 30 µm



Properties

- Behaves partly as light - Can be focused with a lens
- Behaves partly as Radio Frequency waves for propagation – we can use antennas and metal structures for radiation and guidance at these frequencies
- Thought to be Non-ionizing (health wise safer)

Material Properties

- Good penetration cloth, wood, concrete, plastics, paper
- Absorbed heavily by water in various frequency bands within the THz range
- Reflected by metals
- A lot of naturally occurring compounds have resonances and interactions in this regime

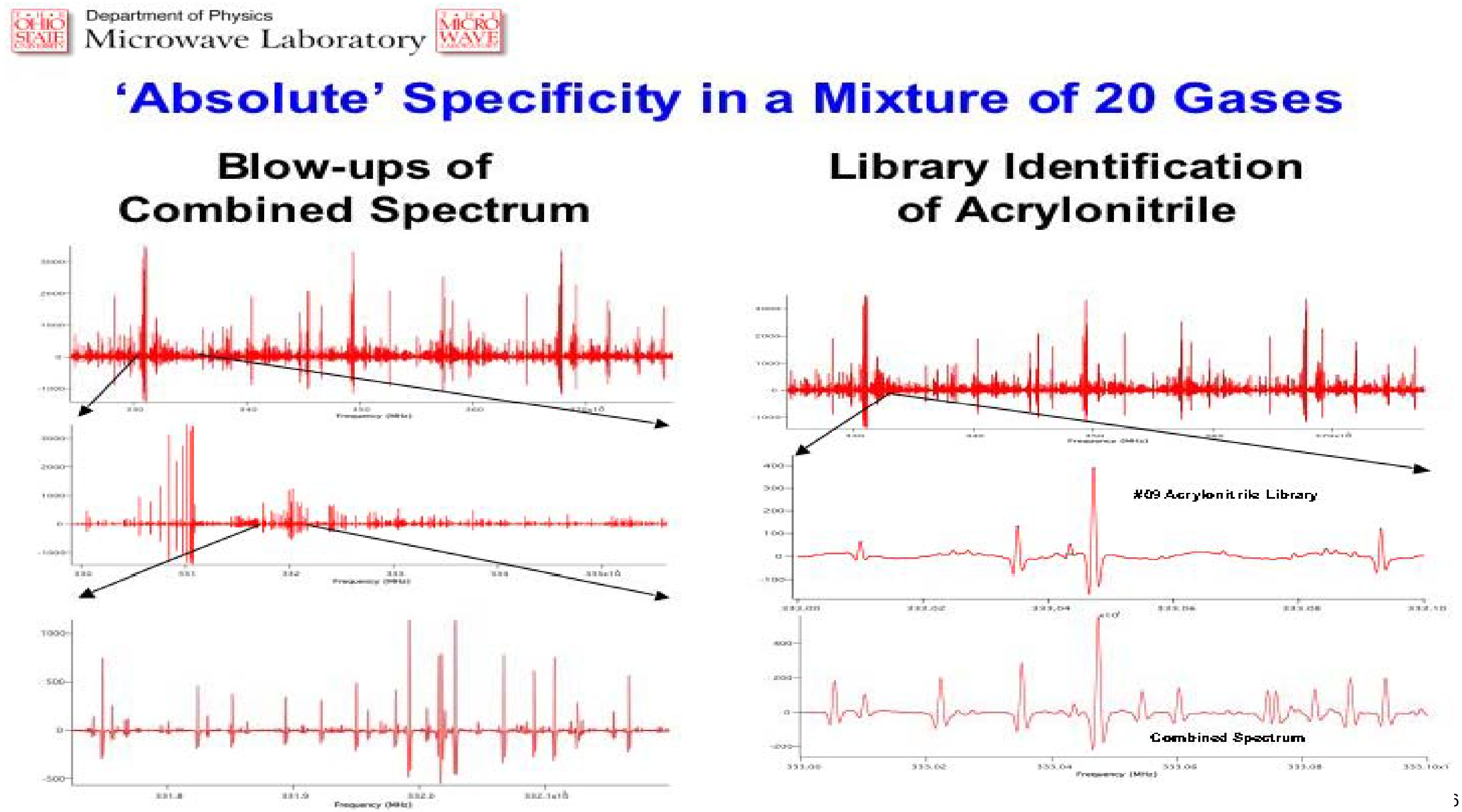
Application Space & Requirements

Application	Description	Signal Structure	Transceiver Requirement
Security	Sub-surface Imaging, Concealed explosives, weapons, drug inspection	Pulsed, FMCW, CW	Variable angle/Fixed angle
Medical	Imaging, monitoring, Early detection	Pulsed, FMCW, CW	Variable angle/Fixed angle
Non-destructive testing	Material Inspection, Structural integrity, Aviation and others	CW (Mostly)	Fixed angle/ Variable angle Amplitude detection
Spectroscopy	Chemical identification	CW, Stepped Frequency	Fixed angle, Amplitude Detection Wide tuning range
Communication	Mobile/Notebook docking (Terabit file transfers, HD stereo displays) Wireless Backhaul (20-40Gbpsec links)	CW – simple modulation	Very High Gain Rx and Tx antenna Electronic Beam Steering for simple link establishment

Spectroscopy Applications:

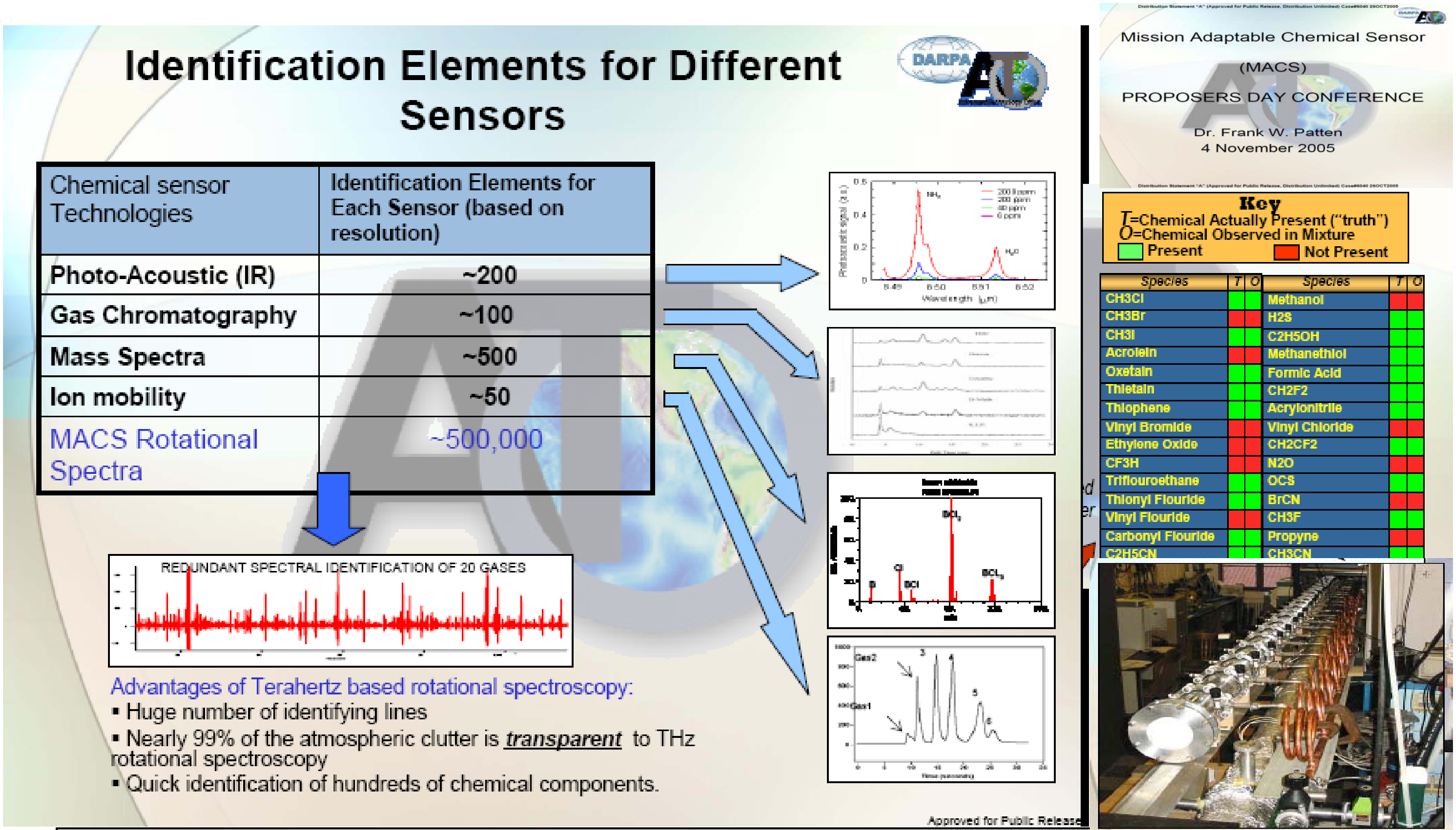
Accurate recognition to few part-per-trillion for many gases.
Abundant &unique “absorption” spectral lines in the 100-600GHz range.

Slide from: Prof. Frank C. De Lucia, Ohio State University, AMERDEC, 2006:
http://www.physics.ohio-state.edu/~uwave/2008site/Resources/talks%20without%20notes%20ppt%20files/HOE.HVL.1.19.06.ppt



Spectroscopy Demonstration: Expensive setup

From Dr. Frank W. Patten DARPA-ATO-2005 Public released Proposer Day Conf. 2005 presentation.
Or http://www.schafertmd.com/conference/PACT/downloads/Reiss-Smart-Transitions-PACT-Proposers-Day.pdf

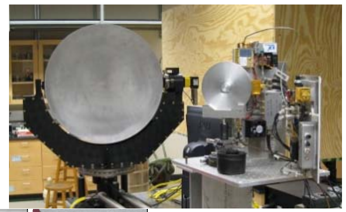


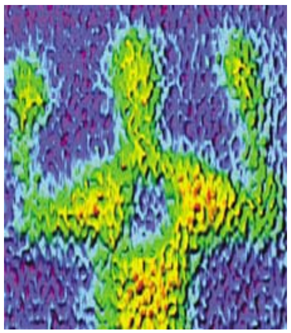
Imaging: Already Many applications Demonstrated.. Expensive Equipment.

Imaging uses the Reflection property of THz waves:
Applications in Medical and Security

Department of Physics
Microwave Laboratory

How do you look at THz images?

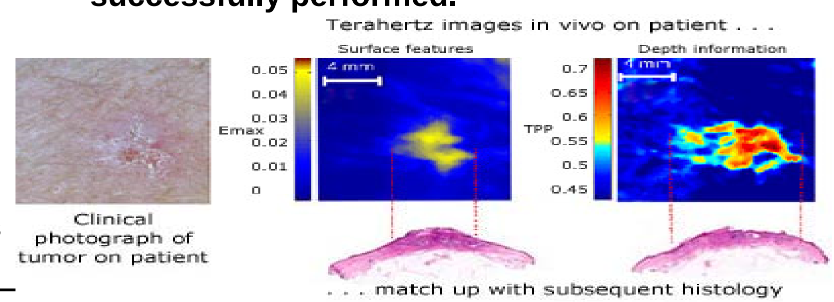




TeraView

http://teraview.com/terahertz/id/34

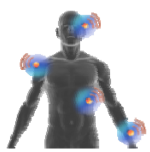
Terahertz in skin cancer
TeraView has worked with clinical collaborators to establish the ability of terahertz to distinguish between basal cell carcinoma and other forms of malignant, benign and healthy tissue associated with skin cancer and related diseases. Both extensive ex vivo measurements for tissue classification and histopathological use, and preliminary in vivo measurements directly on patients have been successfully performed.

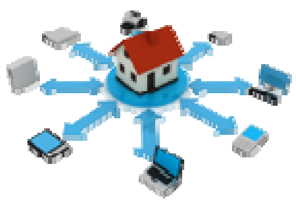


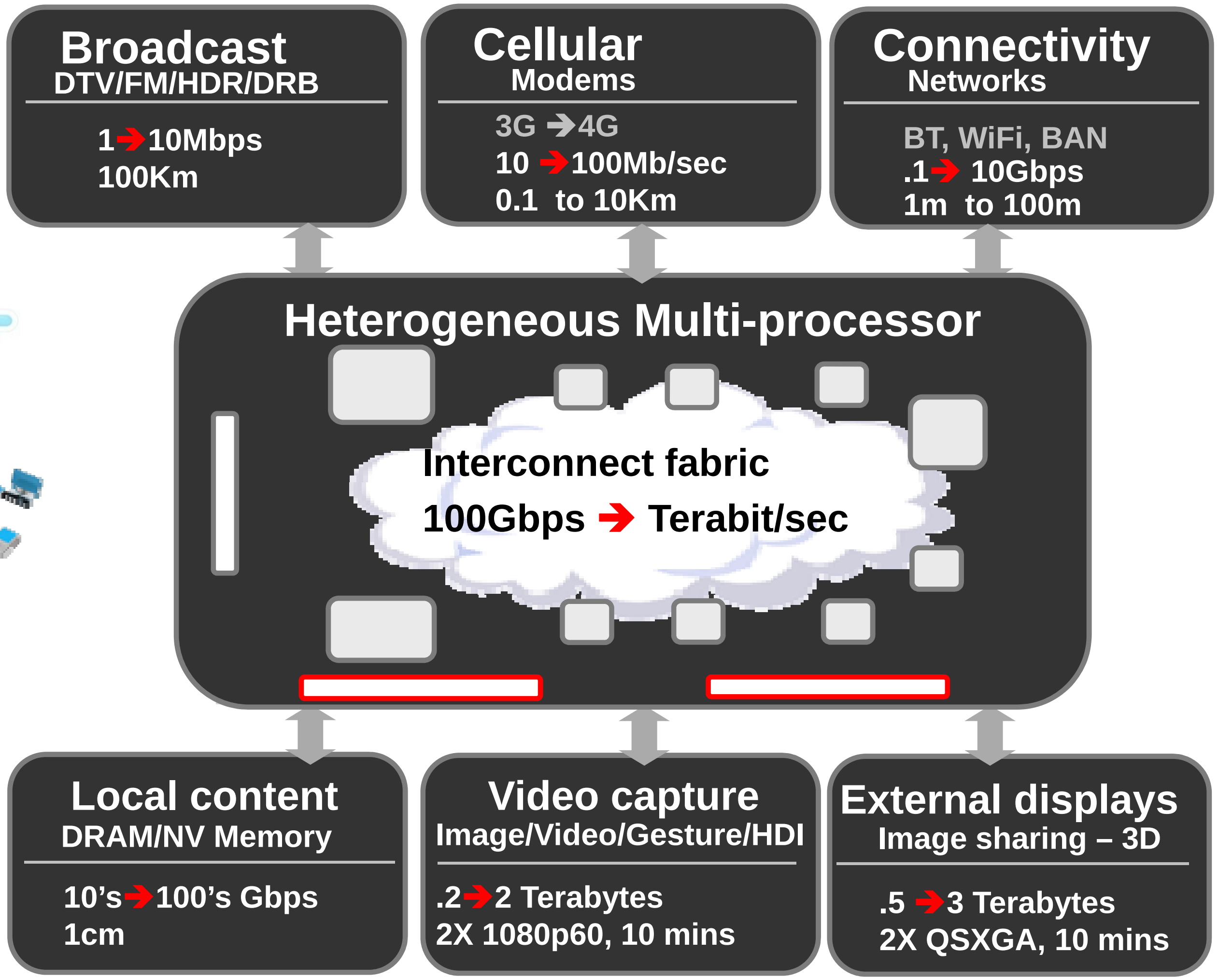
Slide from**: Prof. Frank C. De Lucia, Ohio State University, AMERDEC, 2006**: http://www.physics.ohio-state.edu/~uwave/2008site/Resources/talks%20without%20notes%20ppt%20files/HOE.HVL.1.19.06.ppt

Mobile Application: 20+Gbpsec wireless “docking”!

Today:0.5Gbpsec ➔1-4years: 5Gbpsec➔ 5-10yrs: 20+Gbpsec
Stereo 4K Movie: 2(3D)*4096*2160* 60 Frames * 24bit =25.5Gbpsec!!





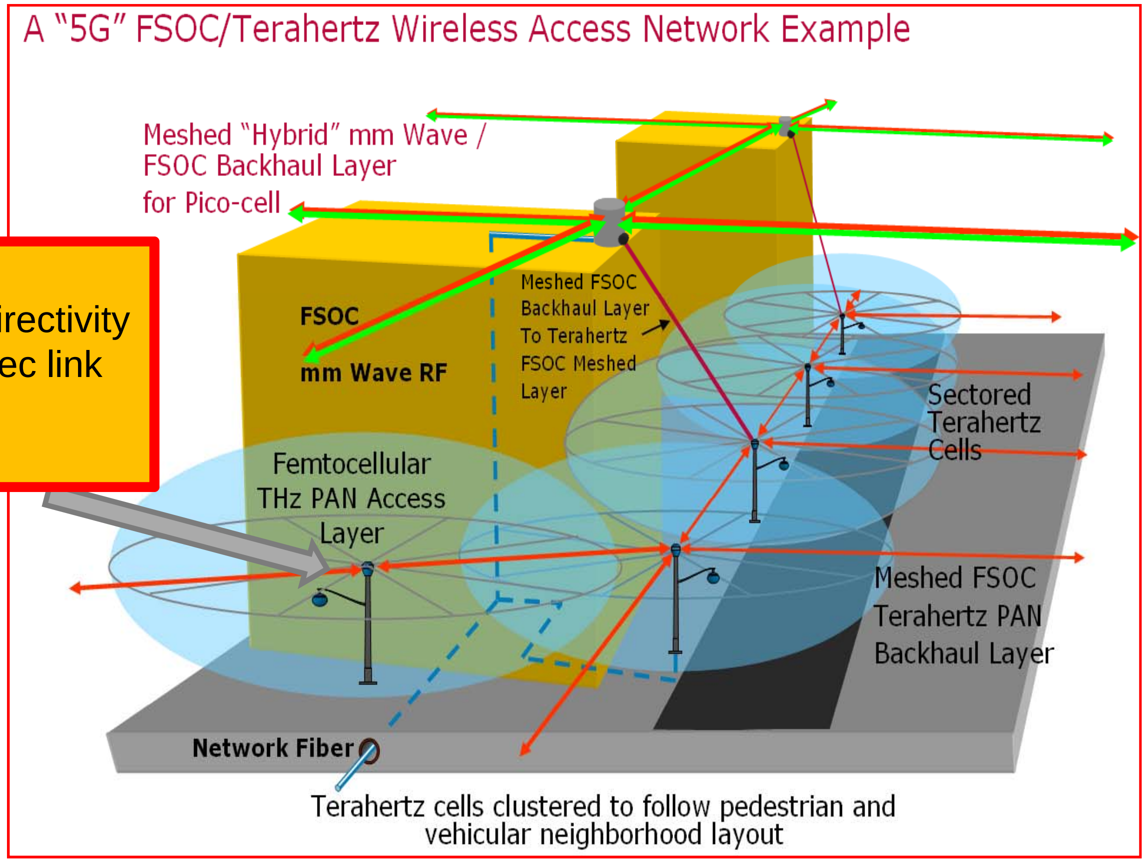


Bandwidth increases by 10~100X➔ Seamless adaptive connectivity?

From G. Delagi ISSCC-2010 Plenary Presentation — Texas Instruments

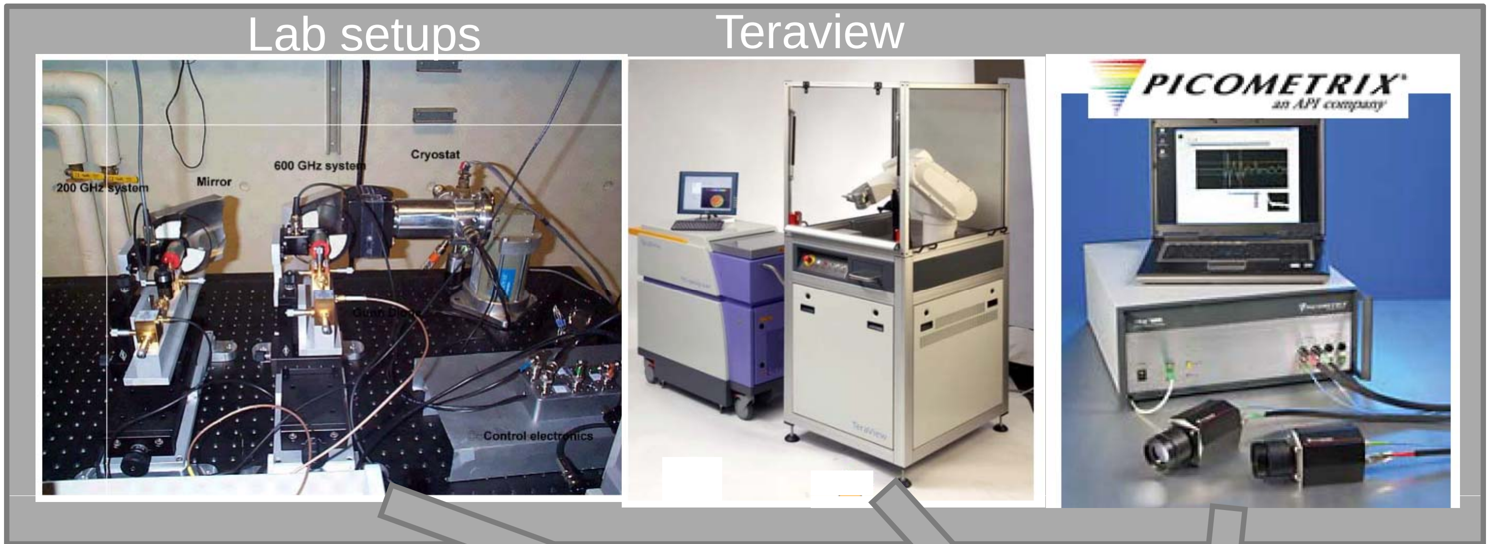
Telecommunication: Wireless THz links for Femtocell wireless back haul Network (Courtesy: David Britz AT&T , 2009)

Femtocell Needs:
1- High Antenna Gain/Directivity for Point to Point Gbpsec link
2- Low Cost
3- Power efficient



Courtesy: David Britz: dbritz@research.att.com
AT&T Labs Research – Shannon Laboratories

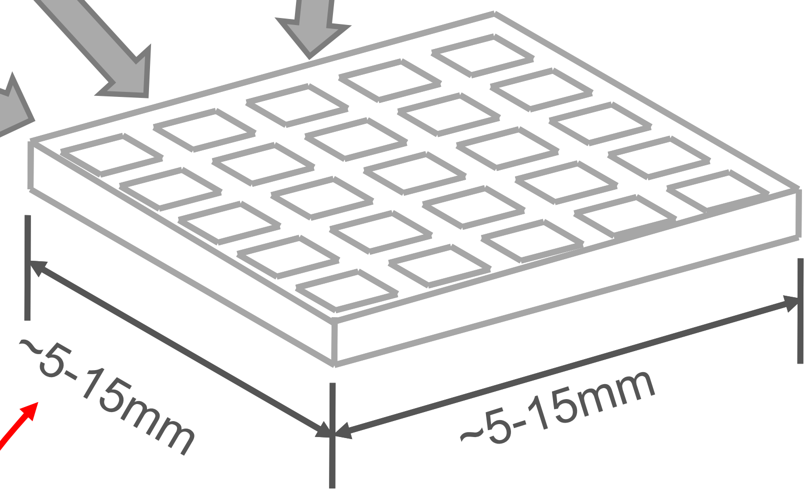
Big Picture – Goal for Semiconductor Manufacturer



Current methods

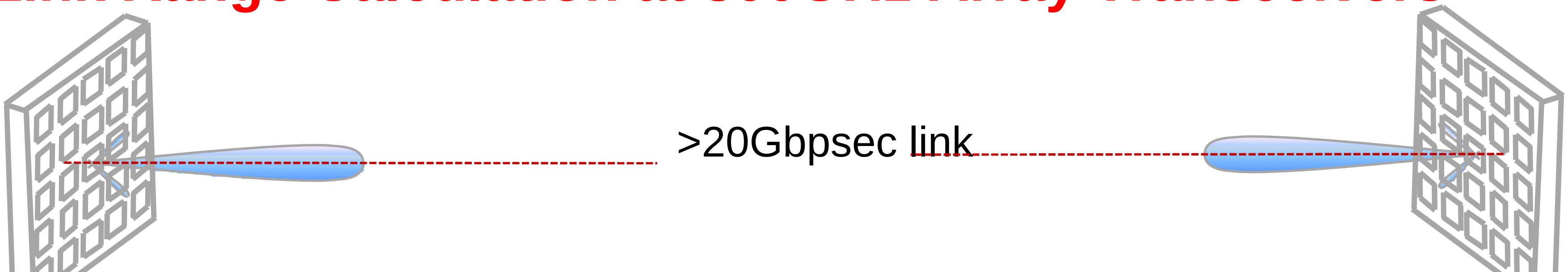
- Expensive
- Not end-user friendly
- Requires
  - Large space (big lasers, spectrometers, etc)
  - Or exotic/special meta-materials
- Need lots of power

- **Goal**
  - THz devices that are small and compact to fit in a typical 5x5mm2 → 15*15mm2 package for cost effective consumer apps
  - ➔ Few $ to 10's of $$ to enable high volume markets.
  - Since gain is hard to achieve at THz, we rely on
    - Antenna arrays to produce gain
    - Accurate modeling of the devices at these frequencies to extract the maximum possible power out of the process



- Coherent CW THz source
- On-chip Phased Antenna Array
- On-chip sub-mm integrated TX/RX

Link Range Calculation at 300GHz Array Transceivers



$$R_{max} = \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^3 kTB_n F L_d SNR}}$$

R_{max} = Maximum Reception Range (m)

P_t = Tot. Power Radiated from Antenna (W)

G_t = Transmit antenna gain (dBi)

G_r = Receive antenna gain (dBi)

λ = Carrier wavelength (m)

k = Boltzmann's constant ($J/{}^oK$)

T = Mean temperature (${}^oK$)

B_n = Signal Bandwidth (Hz)

F = Receiver Noise Figure

L_d = Atmospheric Attenuation ($Loss/km$)

SNR = SNR expected at the receive detector

Transmitted Power per antenna	1	mW
Transmit Antenna Element Gain (Patch antenna)	9	dBi
Transmit Antenna Array Power Gain **(Array=4 x 4 elements)**	12.0	dB
Receive Antenna Element Gain (Patch antenna)	9	dBi
Recieve Antenna Array Power Gain **(Array=4 x 4 elements)**	12.0	dB
Carrier Wavelength in Air (Carrier Frequency = 300GHz)	0.001	m
Incoming Noise Energy (kT @ 290K)	4.00E-21	J
Receiver Bandwidth	5	GHz
Receiver Noise Figure	10	dB
Atmospheric Attenuation (10dB/km @25mm/hr rain)	0.22	dB
SNR at receiver detector	9	dB
Maximum Range **"Mobile docking soln."**	**2.21**	m

~1W Rx or Tx, $

Chip Size: <10mm2

Transmitted Power per antenna	1	mW
Transmit Antenna Element Gain (Patch antenna)	9	dBi
Transmit Antenna Array Power Gain **(Array=32 x 32 elements)**	30.1	dB
Receive Antenna Element Gain (Patch antenna)	9	dBi
Recieve Antenna Array Power Gain (Array=32 x 32) elements)	30.1	dB
Carrier Wavelength in Air (Carrier Frequency = 300GHz)	0.001	m
Incoming Noise Energy (kT @ 290K)	4.00E-21	J
Receiver Bandwidth	5	GHz
Receiver Noise Figure	10	dB
Atmospheric Attenuation (10dB/km @25mm/hr rain)	1.25	dB
SNR at receiver detector	9	dB
Maximum Range **"Femto-cell wireless backhaul"**	**125.37**	m

~50W Rx or Tx, $$$

Chip Size: <280mm2

Texas Instruments

Why is directivity needed (Beyond Range)?

From: Siliconization of 60 GHz, Ali. M. Niknejad
IEEE microwave magazine   February 2010

High Directive Tx and Rx antennas result in:
➔Much Lower Delay spread for multi-path
  ➔Sub nsec (horn; G=25db) vs >10nsec
  ➔Much lower Freq. fading dips in freq over the wide band channel
➔No need for equalization (e.g DFE)
  ➔Hundreds of FIR taps needed
➔No need for OFDM modulation expensive for 5GHz+ BW
➔Lower Blocker level at Rx
  ➔Easier FE design/Linearity req.

➔ Arrays are a key for Sub-THz communication

➔Electronically Steerable beams allow Locking Rx to Tx antenna beams simplifying deployment.

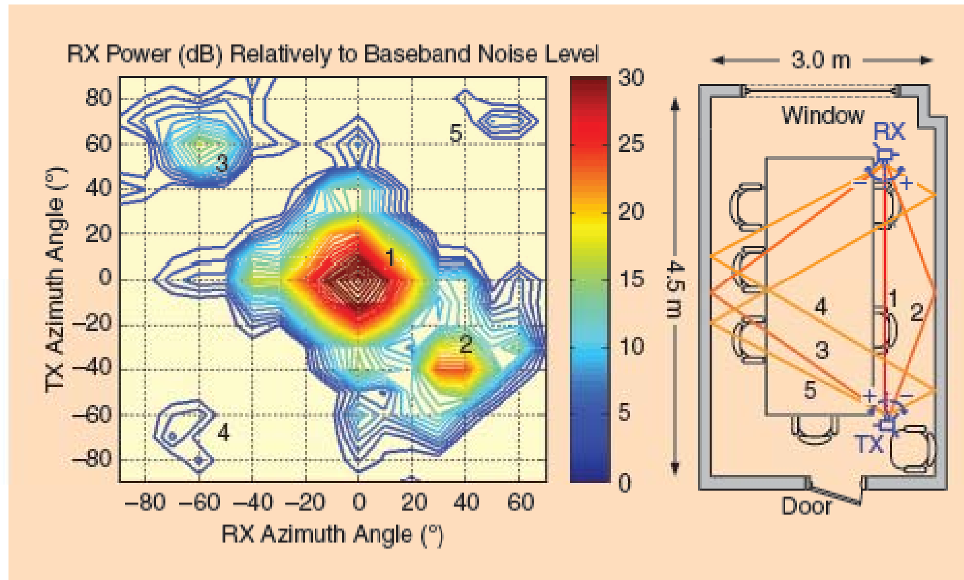
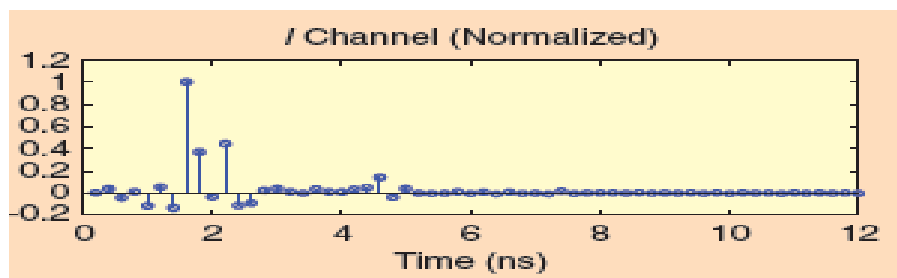
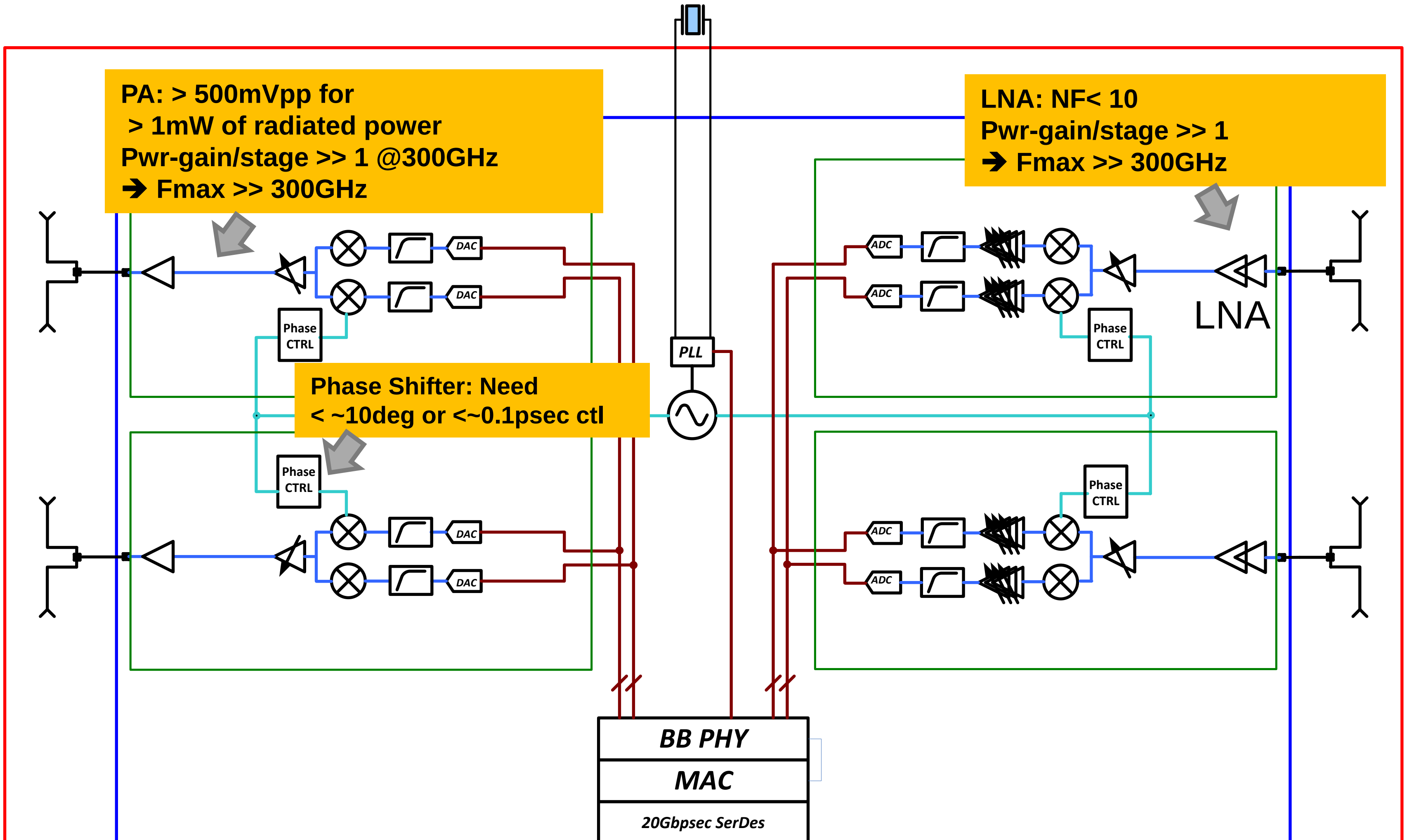


Figure 3. *The measured 60 GHz channel in a conference room setting. The measurements clearly show evidence of quasi-optical propagation, e.g., simple to resolve multipath reflections. From [1].*



Typical Array Transceiver



For Power Efficiency of the Transceiver, you want the Mixer (freq. translation) right after least # gain stages from 1st LNA
➔ MOS passive Mixer Noise Figure is also very critical and also improves with higher Fmax, and lower Cgs

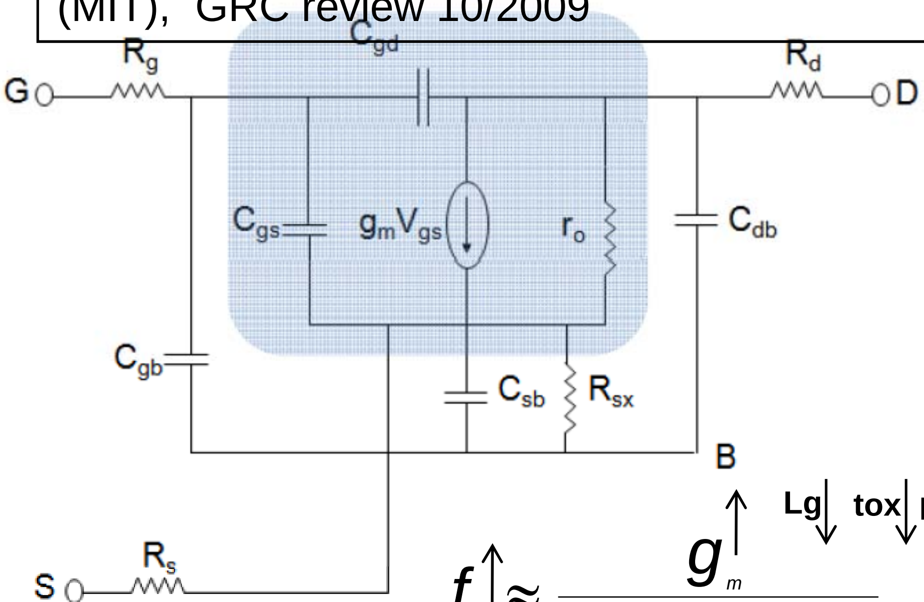
Can nm CMOS provide the power gain @ 300GHz?

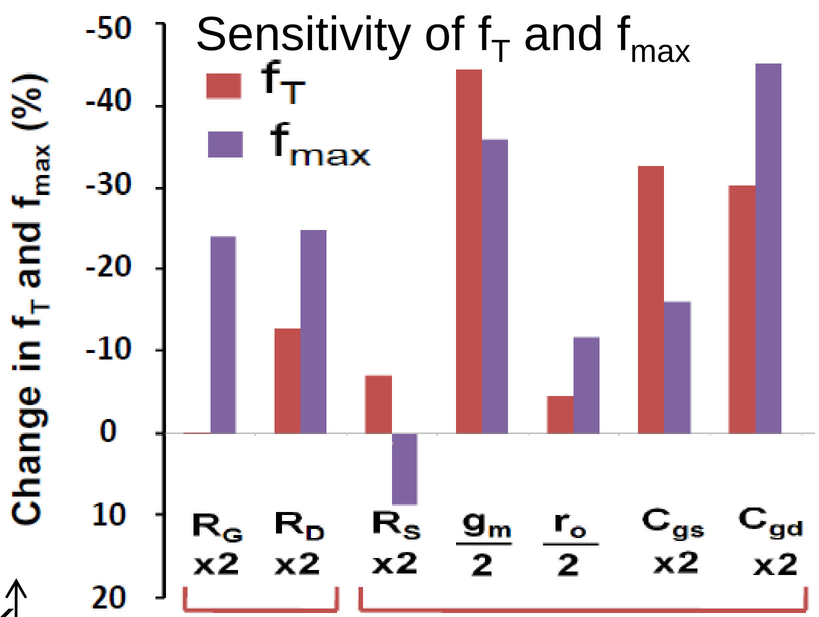
Fmax is the frequency beyond which it is not possible to have power gain above unity using a single MOS device for a given process. It is also the maximum freq. of oscillation using a single device and is a figure of Merit that is most relevant to Tx and Rx chain design.
We need “Power Gain” > 1 to transmit, or to Receive in a lossy channel.

F_{max} is Sensitivity to process parameters: as gm, 1/Cgd, 1/Cgs, 1/Rg

➔ all improve with Process node shrink: effective Lg and Cgd, Cds reduce with lithography, Idrive(channel mobility using stress techniques) go up hence gm goes up, use of HiK dielectrics make effective Tox go down hence gm goes up and metal gate makes Rg go down

Adapted from U. Gogineni, J. del Alamo, et al., (MIT), GRC review 10/2009





Highly layout dependent; do not scale well

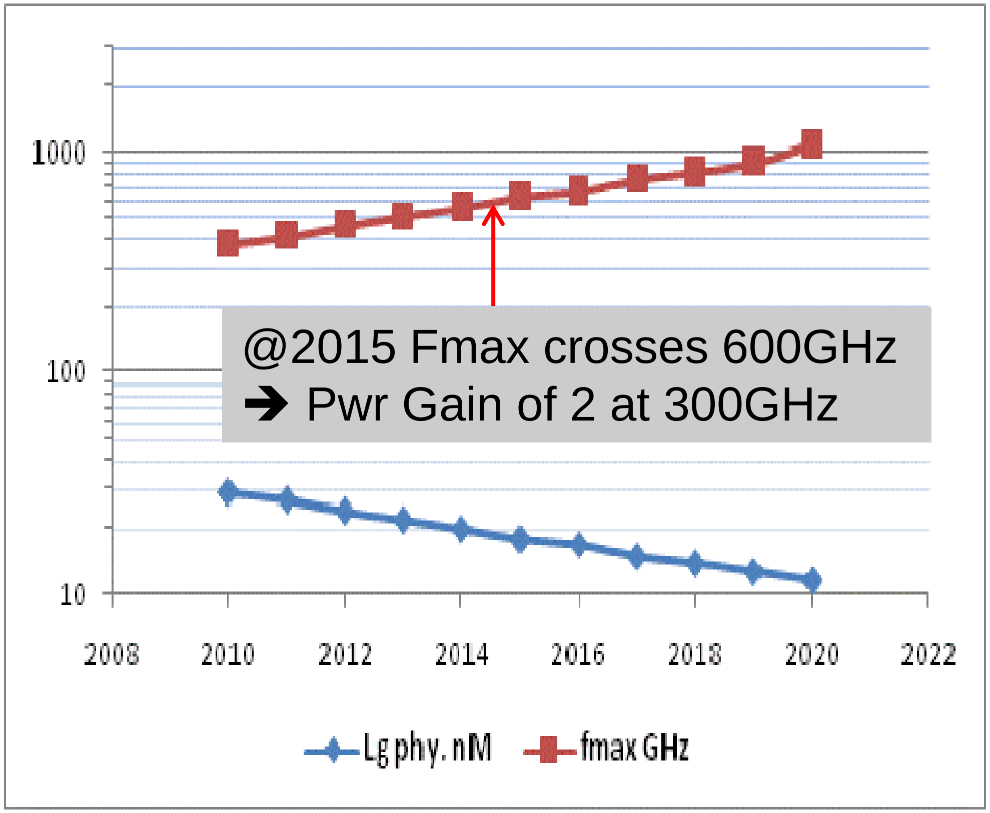
$$f_T \uparrow \approx \frac{g_m \uparrow}{2\pi(C_{gs}\downarrow + C_{gd})}$$

Lg↓ tox↓ Hi K↑

μ↑ Channel stress↑

$$f_{max} \approx \sqrt{\frac{f_T}{8\pi R_g C_{gd}}}$$

ITRS 2009 Roadmap for Fmax vs Process



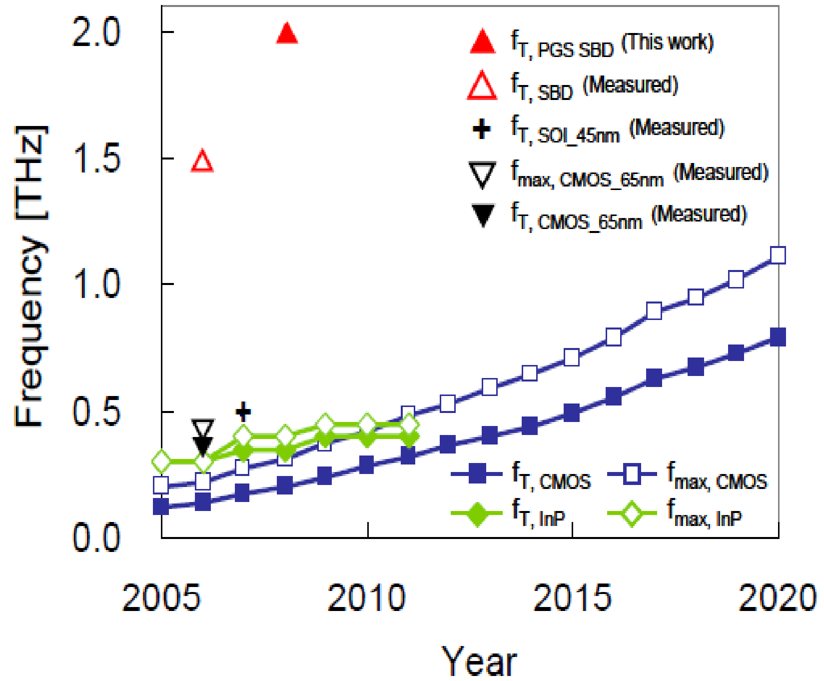
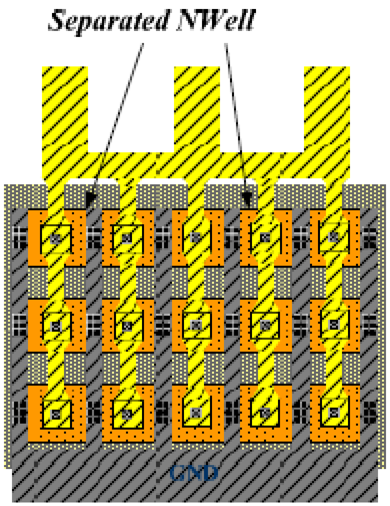


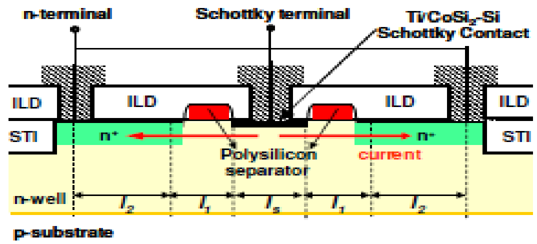
Figure 11.4.2: High frequency capabilities of NMOS transistors and PGS SBD's.

S. Sankaran et. al. ISSCC 2009, paper 11.4

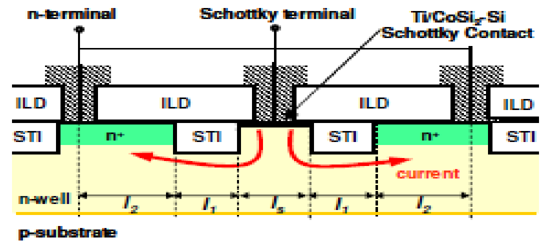
Towards Terahertz Operation of CMOS

Schottky diodes on CMOS-New component – No mask adder





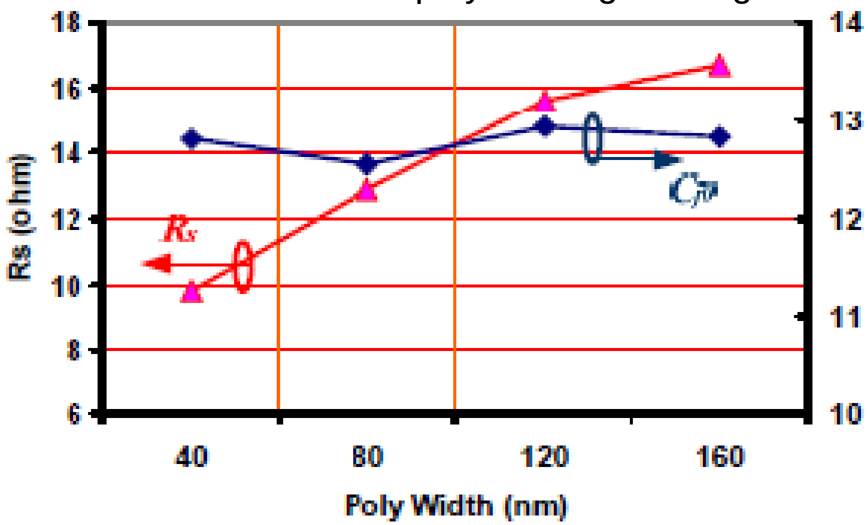
Polysilicon gate separated Schottky barrier diode.

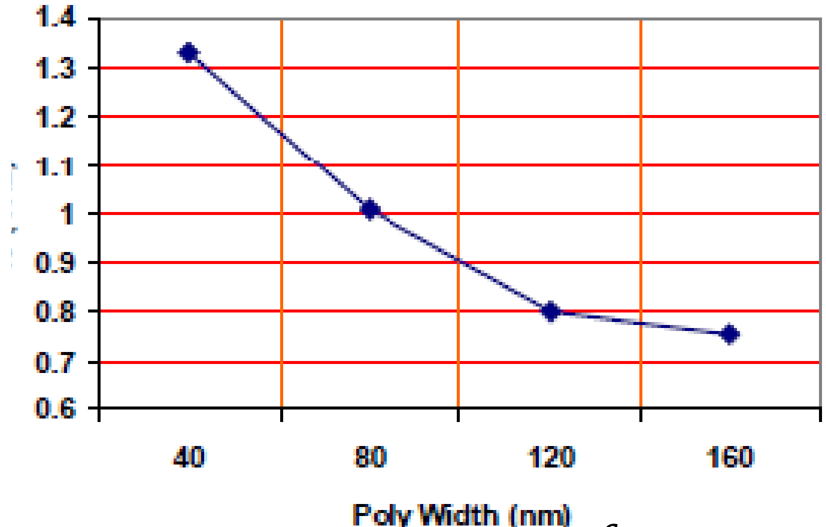


Shallow trench separated Schottky barrier diode.

Schottky diode area is separated by polysilicon gate on gate oxide layer.

The resistance of silicon region surrounded by STI becomes dominant.



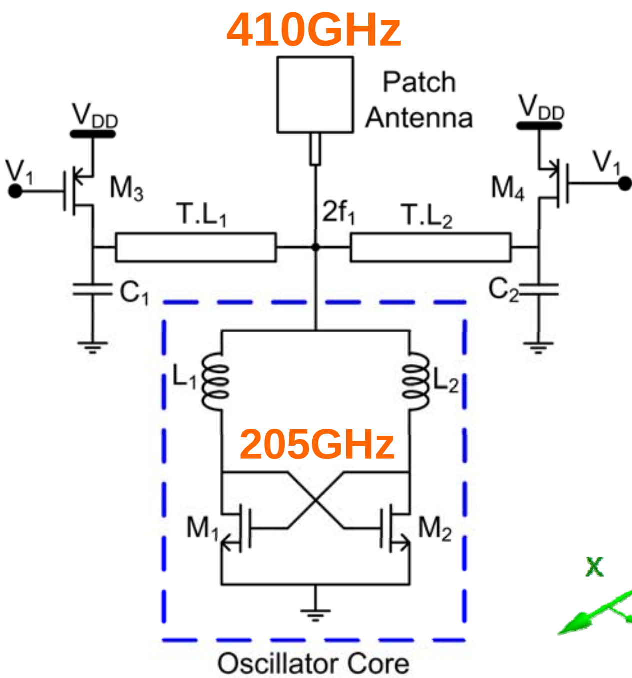


$$f_{cutoff} = \frac{1}{2\pi RC_0}$$

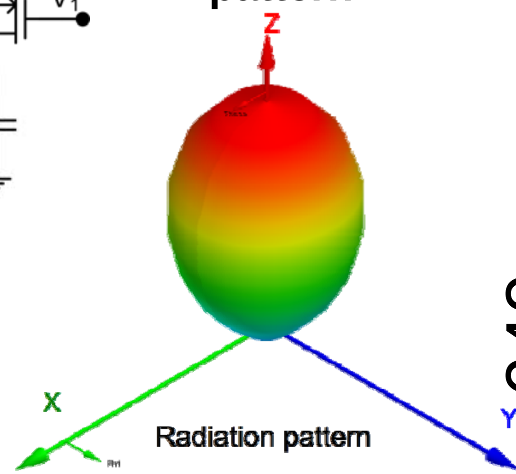
- S. Sankaran et. al. ISSCC 2009 & Kenneth. K. O, UTD , private communication

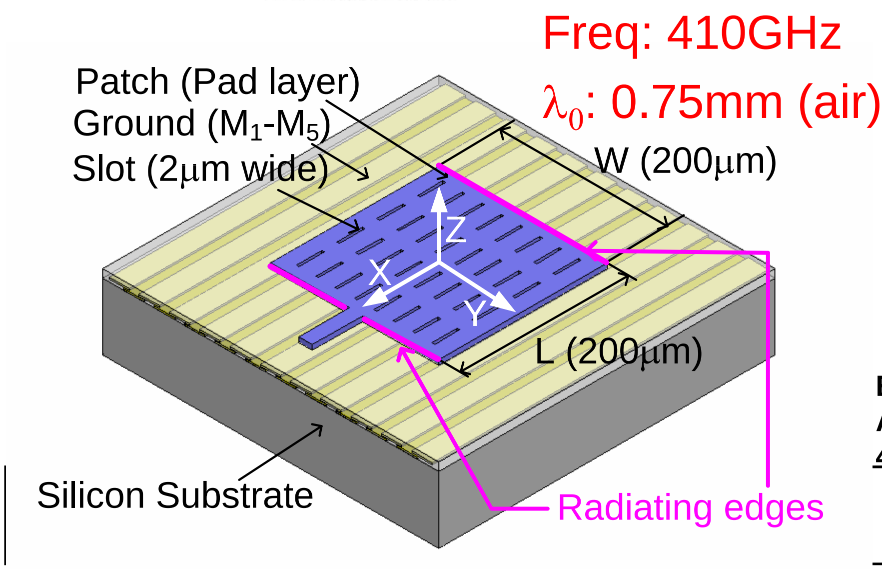
Cutoff frequency : 1~ 2THz

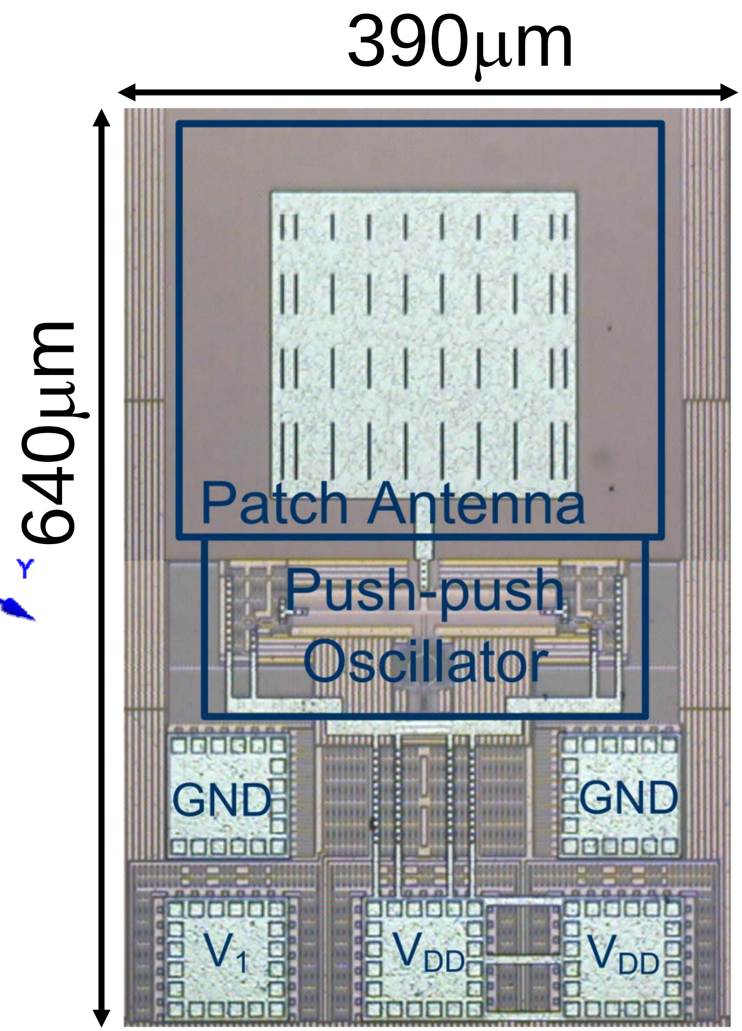
45nm TI CMOS process THz Signal Source



Ant radiation pattern





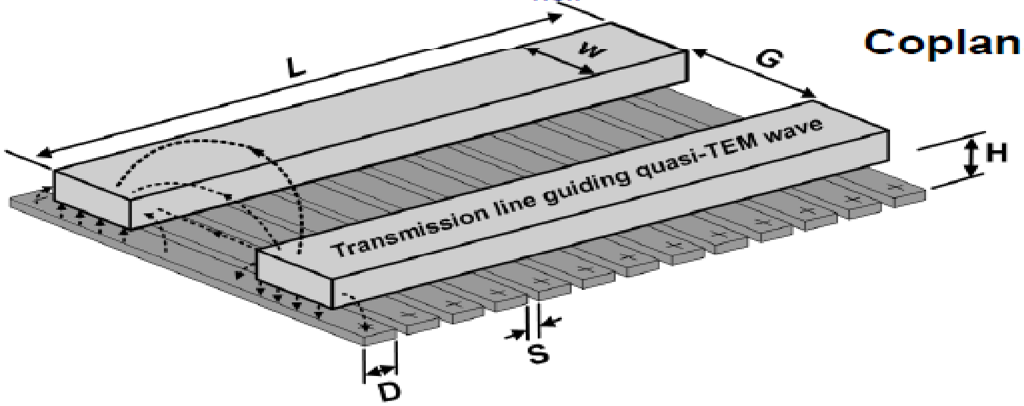


E. Y. Seok et al., "410-GHz CMOS Push-push Oscillator with a Patch Antenna," 2008 International Solid-State Circuits Conference, pp. 472-473, Feb. 2008, San Francisco, CA.

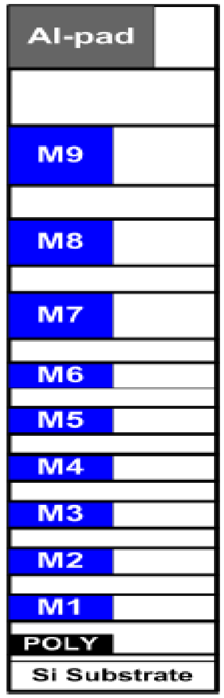
Can we tightly control phase on CMOS?
➔ Digital Controlled Artificial Dielectrics

Differential AD Transmission Line in CMOS

- ***Floating metal strips*** inserted underneath RF t-lines
  - Originally for shielding of conductive substrate
  - Recently utilized for increasing effective diel. constant
- CMOS is a multiple (n>7) metal interconnect process
  - Take advantage of process
  - Minimize H to maximize $\varepsilon_{r,eff}$



Coplanar Strip



Cross Section

– D. Huang, et al, Digest of Tech. Papers, pp. 1218-1227, ISSCC 2006
– D. Huang, et al, Tunable Artificial Dielectrics, US Patent App. 20080204170

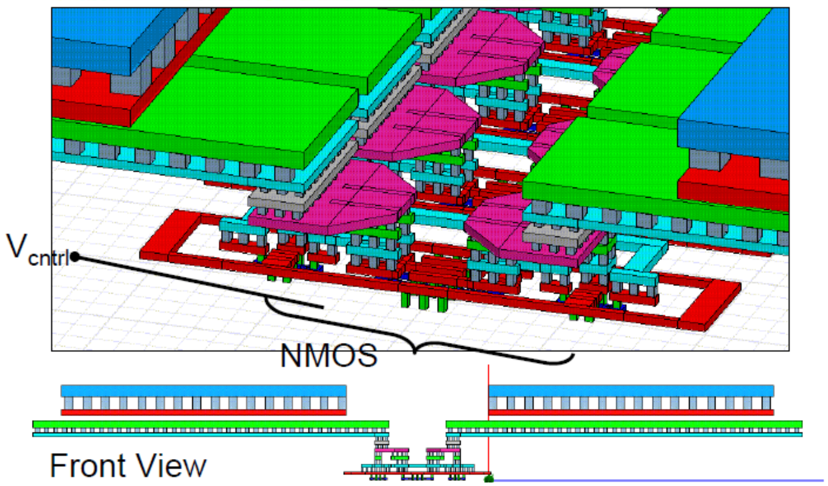
Work Done at UCLA D. Huang (now at TI)

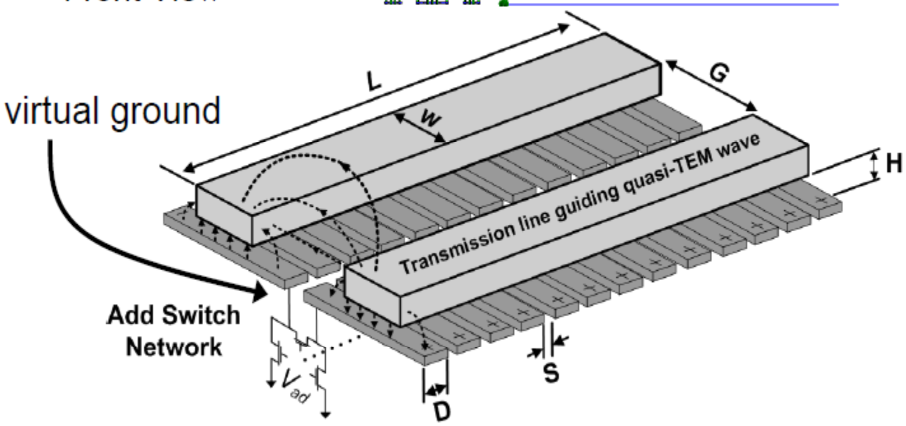
Steps of 5deg at 60GHz = 0.23psec
➔ Fine control of array delay possible

Physical CMOS Layout

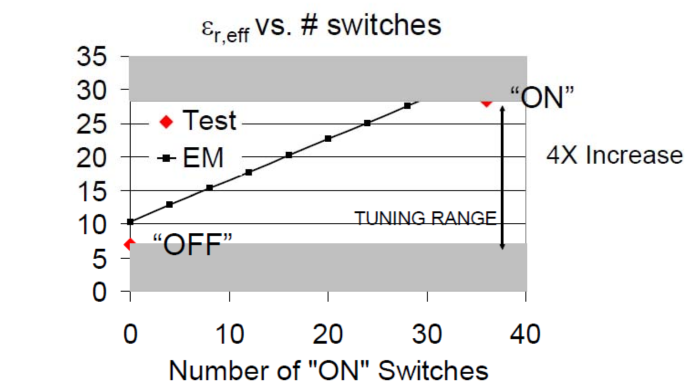
❑DiCAD transmission line

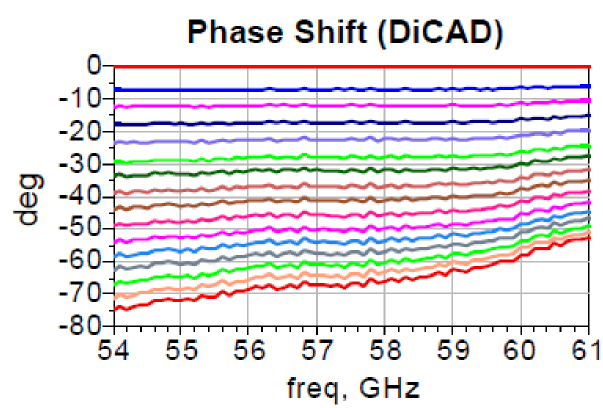
– (NMOS via connected to floating strips)





❑Effective dielectric constant increases from 7 to 28

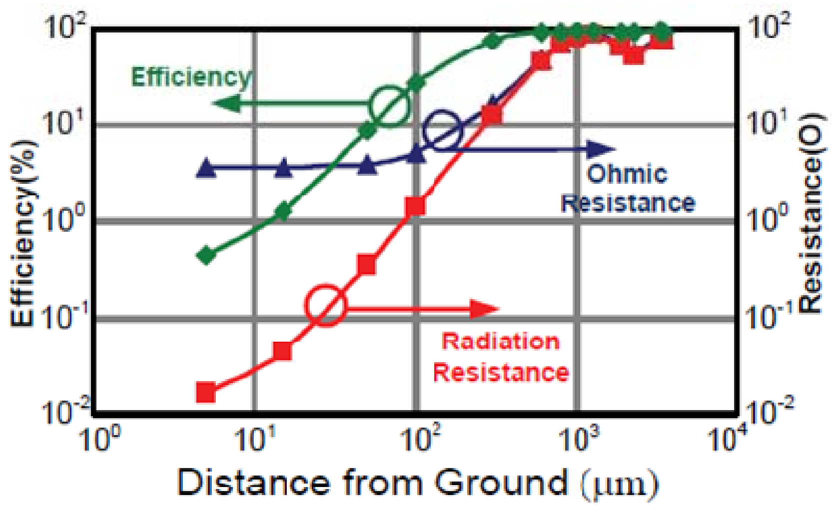


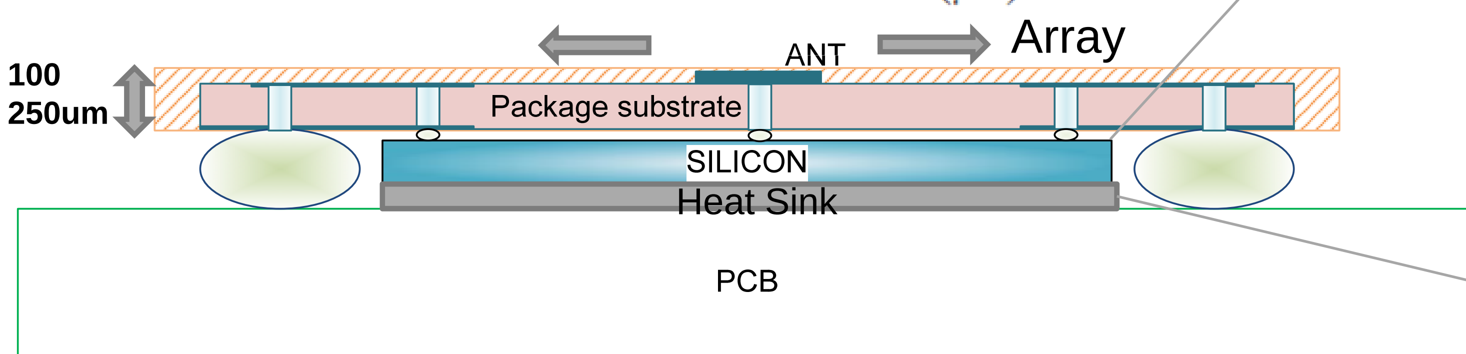


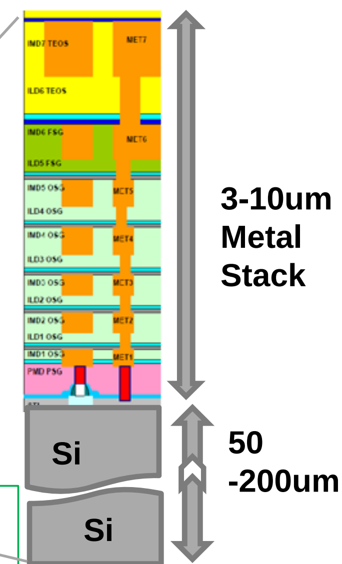
How do we get radiation efficiency from Silicon?

Combine Silicon with Package technology for a complete solution.
Advanced Package technology allows < 100um pitches for routing
Enabling working on 1mm Wavelength traces.
Moves Radiating element farther out from ground plane improving Radiation efficiency ➔ > 80% of power radiated possible.

Ali Hajimiri,
mm-Wave Silicon ICs: Challenges and Opportunities,
CICC 2007







Conclusions and Next Steps

- Sub THz transmit and receive using CMOS is enabling an appealing mix of high volume applications: in mobiles, telecom, medical and security.
- They can only be achieved on advanced CMOS 65nm and below, likely in the 28nm and 22nm time frame.
  - Expense of the manufacturing can only be justified by systems on chip that address multiple markets or very high value applications.
- CMOS process roadmap is showing that within the next few years capability to build systems operating above 300GHz is viable.
- All the elements to build transceivers, LNAs, Mixers, Power amps, oscillators, phase shifters, and other Baseband have been demonstrated with different blocks working in the 100-400GHz 65/45nm CMOS so far.
- Many ongoing R&D at Semiconductor companies and academia are pursuing this activity funded by SRC and Industry.
- It is not clear that regulatory environment is working to enable these critical new applications in telecom, medical and security by enabling band in the low sub-THz (300-400GHz) in the next few years. This needs cooperation of multiple industries to sensitize the regulatory authorities to allocate these bands for the different uses outlined in this presentation.