LUND UNIVERSITY

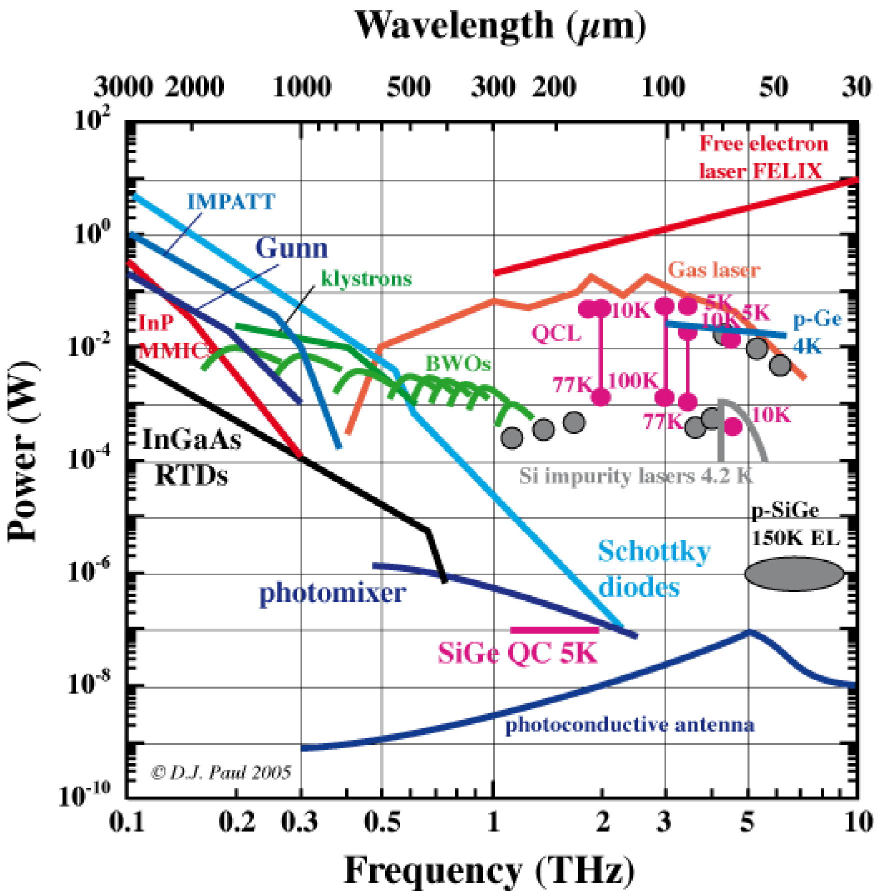
Pulse-Based THz Electronics

EITP05 – Nanoelectronics (vt 2020)

Outline

- Motivation
  - Wireless bandwidth
- Resonant Tunnelling Diode (RTD)
  - Signal generation
  - THz potential
  - High-rate wireless communications
- Integrated Antennas
  - Size matters
  - Substrate modes
  - Monolithic integration (wireless = no wires)
- Appliations
  - High-rate wireless communications
  - Radar
- Commercialisation
  - Acconeer AB (www.acconeer.com)

THz Signal Generation



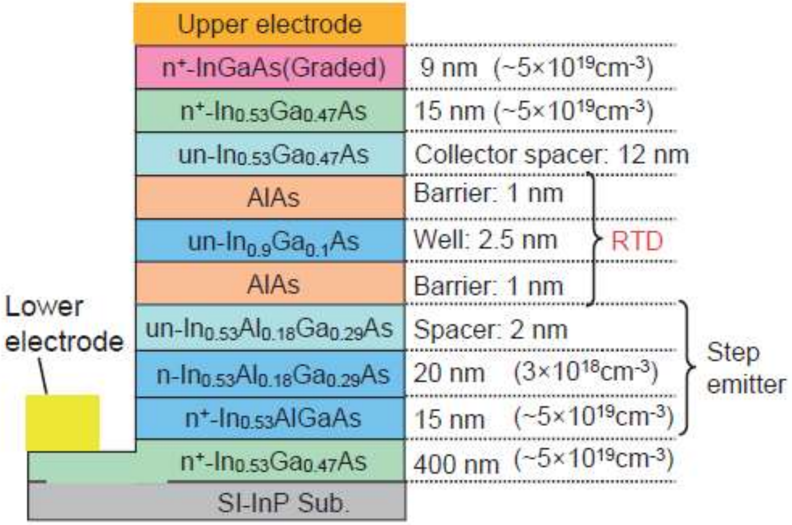
The THz Technology Gap

- Optical sources above 1 THz
- Direct generation below 1 THz
  - Transistor technology
  - Diode technology
- Multiplication from lower frequencies

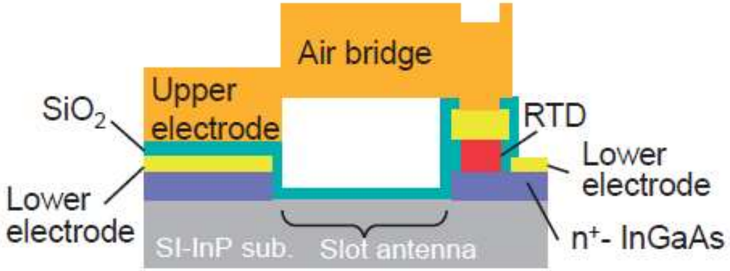
A combined approach with III-V Transistors and Tunnel Diodes

Resonant Tunnelling Diode (RTD)

- Double barrier structure in conduction band
- Zero bias
  - Bound state at energy above fermi level
  - No net current
- Small forward bias
  - Collector potential drops
  - Small net injection from emitter
- Forward bias ~ peak
  - Bound state aligned with emitter carriers
  - High current
- Forward bias > peak
  - Bound state drops below emitter
  - Scattering assisted conduction
- Forward bias >> peak
  - Thermionic emission through/over barriers



(b)



(c)

Resonant Tunnelling Diode (RTD)

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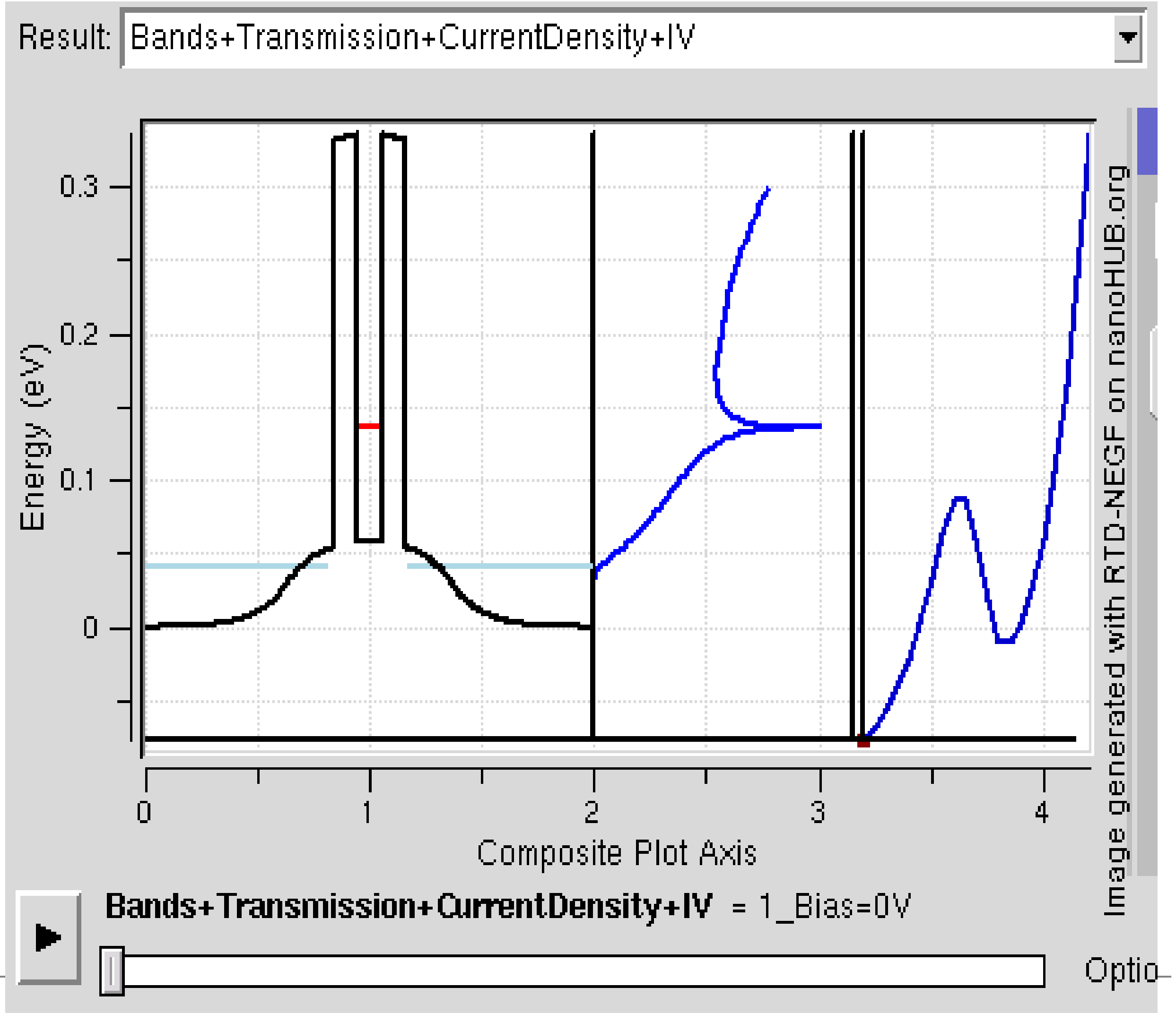
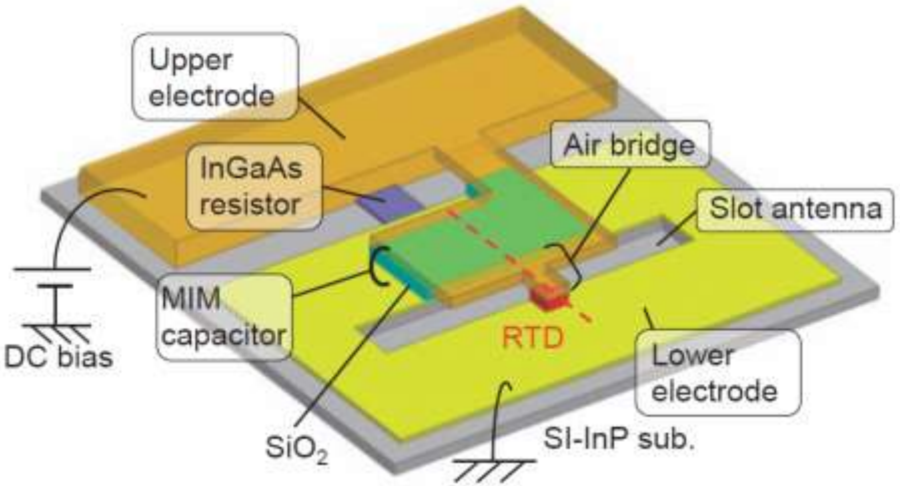


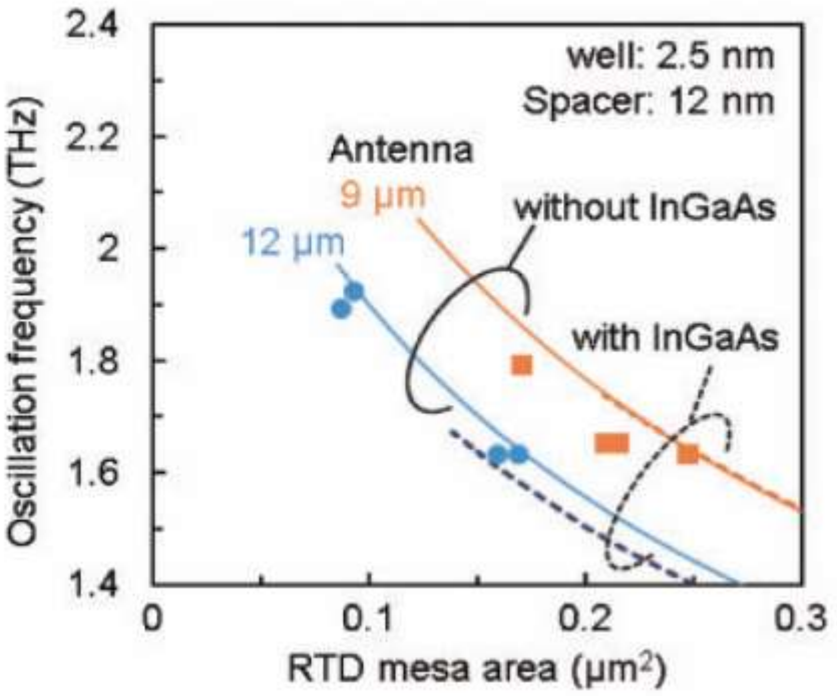
1.92 THz Signal Generation

Oscillation up to 1.92 THz in Resonant Tunneling Diode by Reduced Conduction Loss

T. Maekawa, H. Kanaya, S. Suzuki, and M. Asada

- Increased maximum frequency to 1.92 THz (0.4 μW) in RTD
- 12 μm integrated slot-antenna (lens aperture)
- Reduced conduction loss in antenna fabrication process





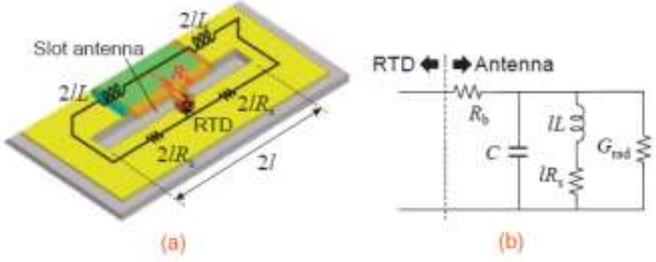
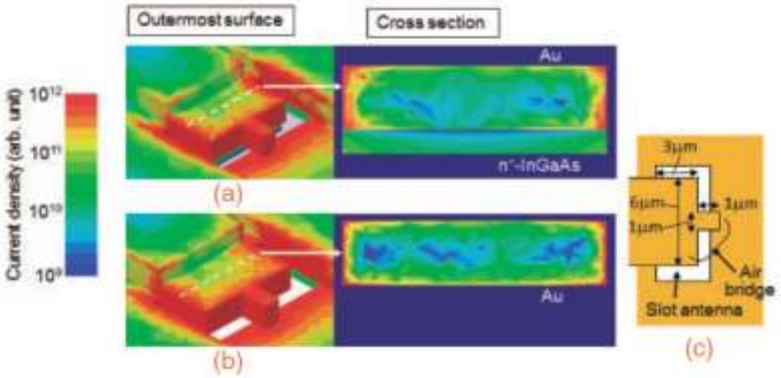
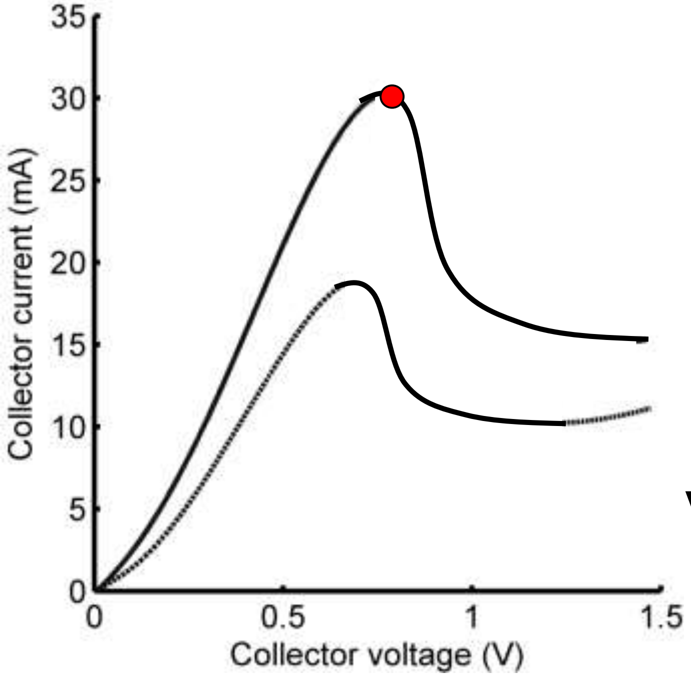


Fig. 2. Equivalent circuit of antenna. (a) Schematic illustration of equivalent-circuit elements around antenna electrode. (b) Entire equivalent circuit of antenna.

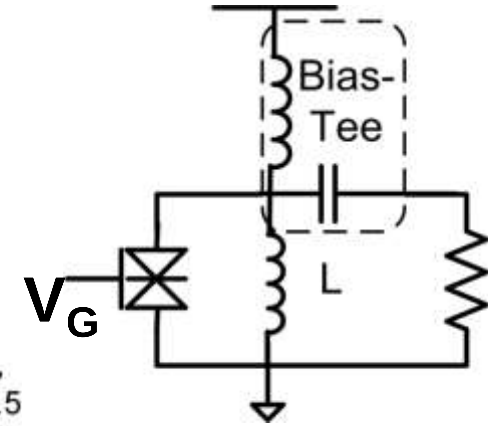


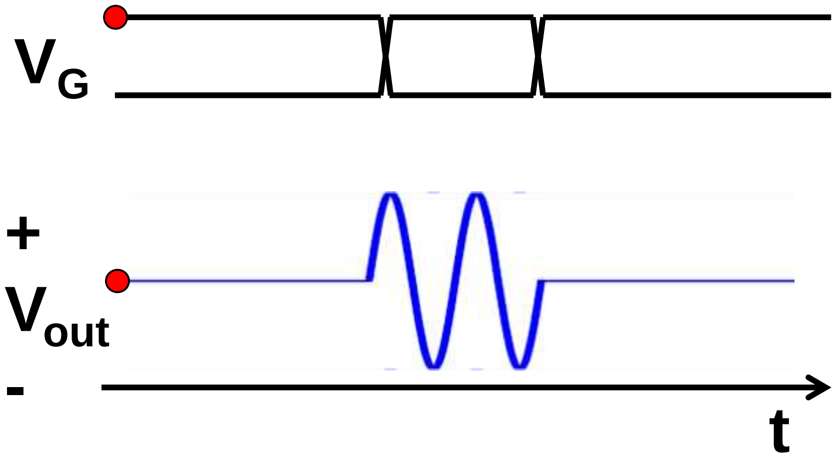
Wavelet Generator

Adding Functionality to the Diode



$v = L \cdot di/dt$





Startup

$$v(t) = \frac{2v_o}{\sqrt{1 + \left(\left(\frac{2v_0}{v(0)}\right)^2 - 1\right) e^{-\epsilon\omega_0 t}}} \cos(\omega_0 t + \varphi(0))$$

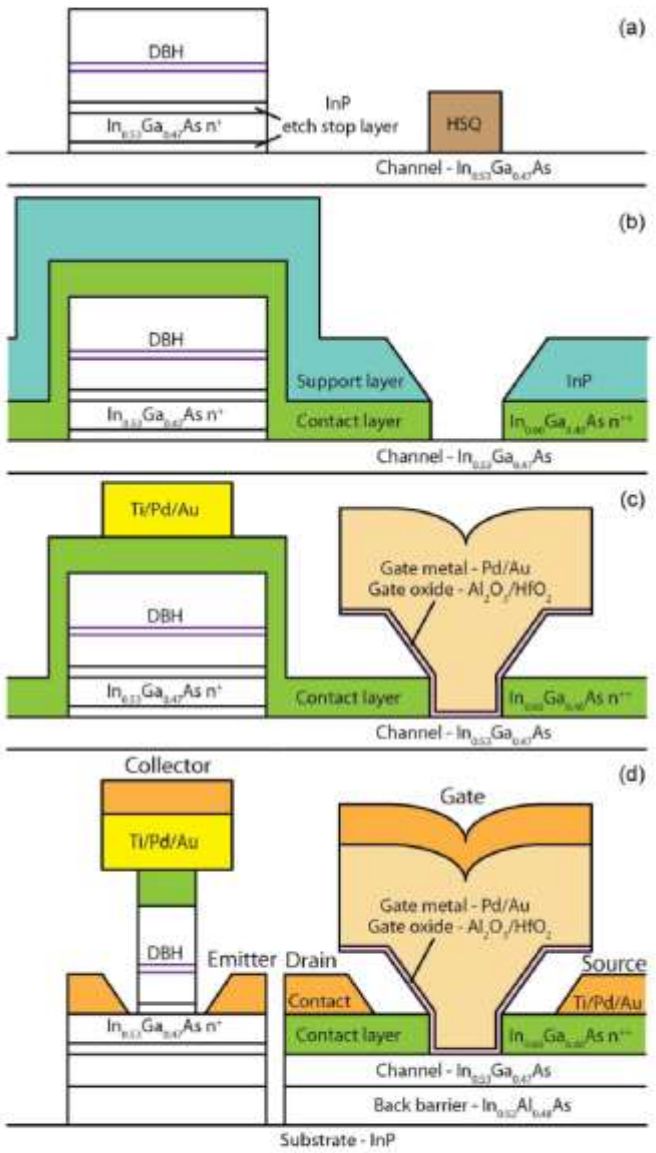
$$\epsilon = -\left(g_{oeq}(0)\sqrt{\frac{L_{eq}}{C_{eq}}} + \frac{1}{Q_{tank}}\right)$$

Decay

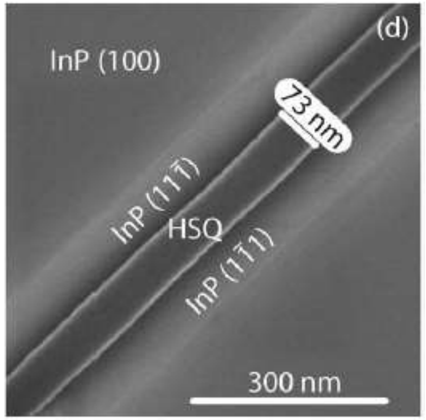
$$v(t) = V_{max} e^{\frac{-\omega_0}{2Q_{tankPDC}} t} \cos(\omega_0 t + \varphi(0))$$

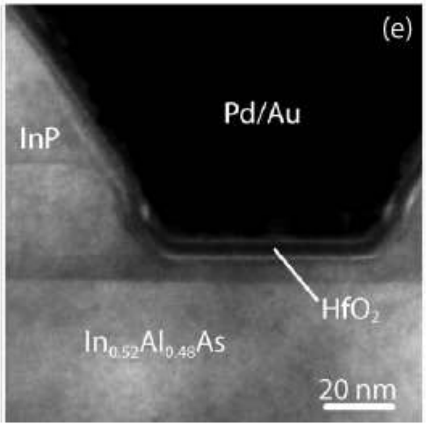
Egard et al IEEE MWCL2009

RTD/MOSFET Process Flow



- MBE grown wafers AlAs/InGaAs/InAs/InGaAs/AlAs RTD
- HSQ Dummy Gate
- InGaAs/InP MOVPE regrowth
- Gate formation
- Removal of InP
- Contact formation
- RTD etching
- Contact formation

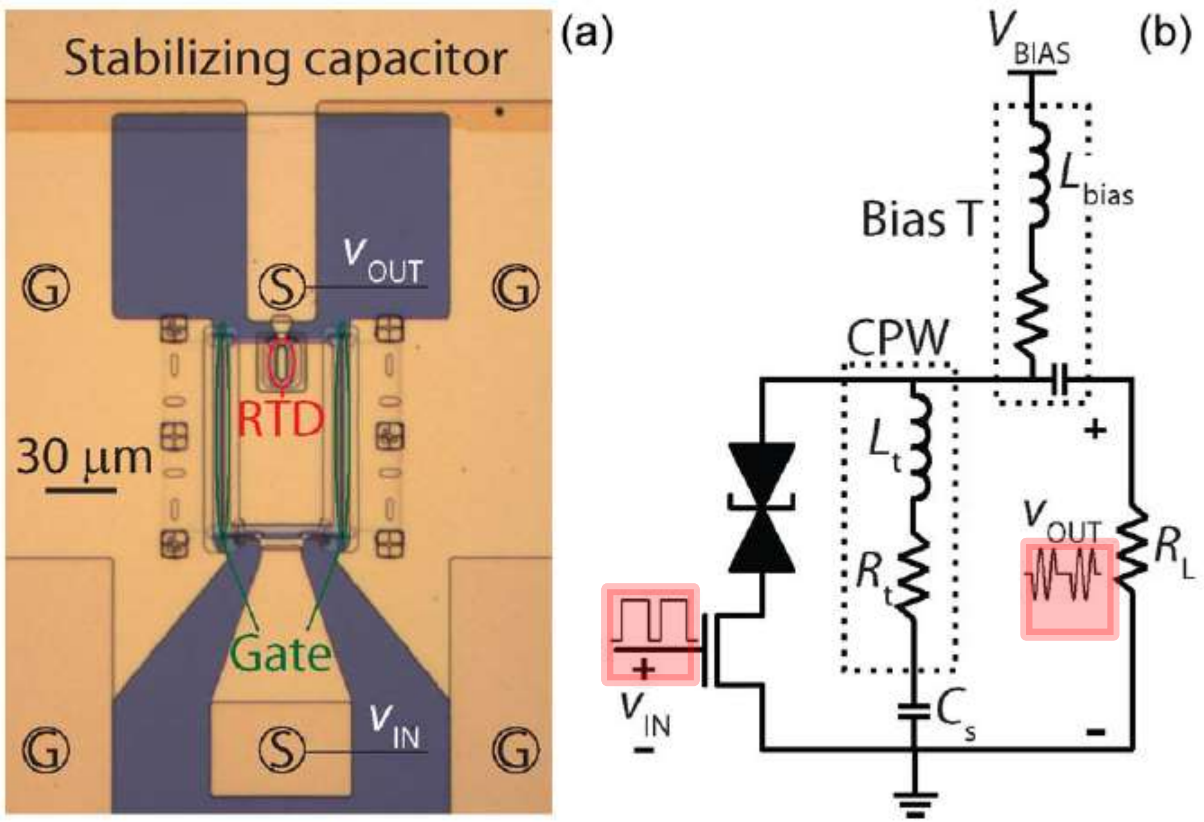




Wavelet Generator

The MOSFET is used to switch the oscillator current

The inductance is given by a coplanar waveguide (CPW) stub



L_t=22 pH

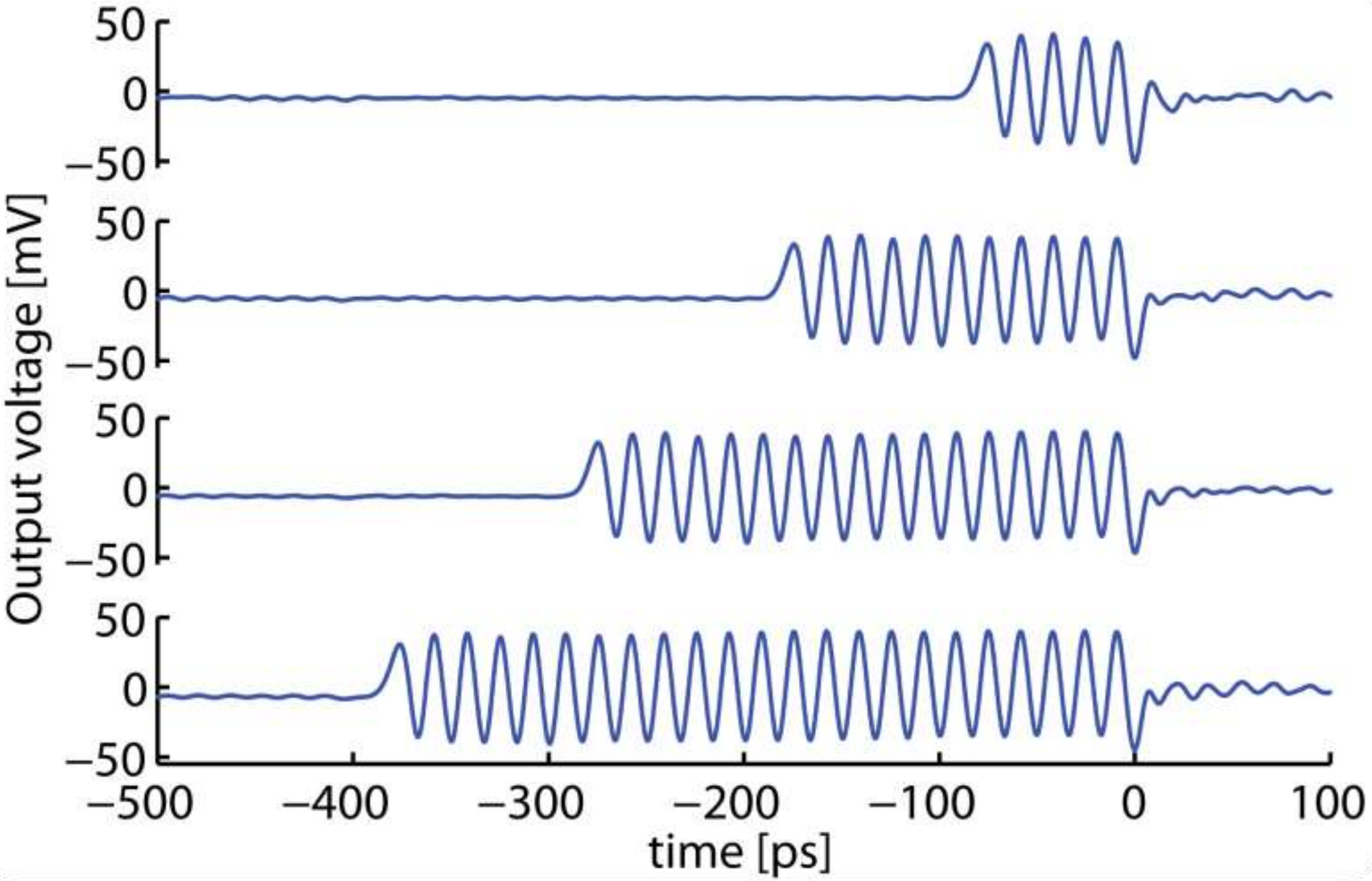
C=4.5 fF/µm^2

A=2.2x22 µm^2

g_{min}=-120 mS

60 GHz Wavelets: Control of Pulse Width and Position

170 mV_{pp} after de-embedding



Input pulse length

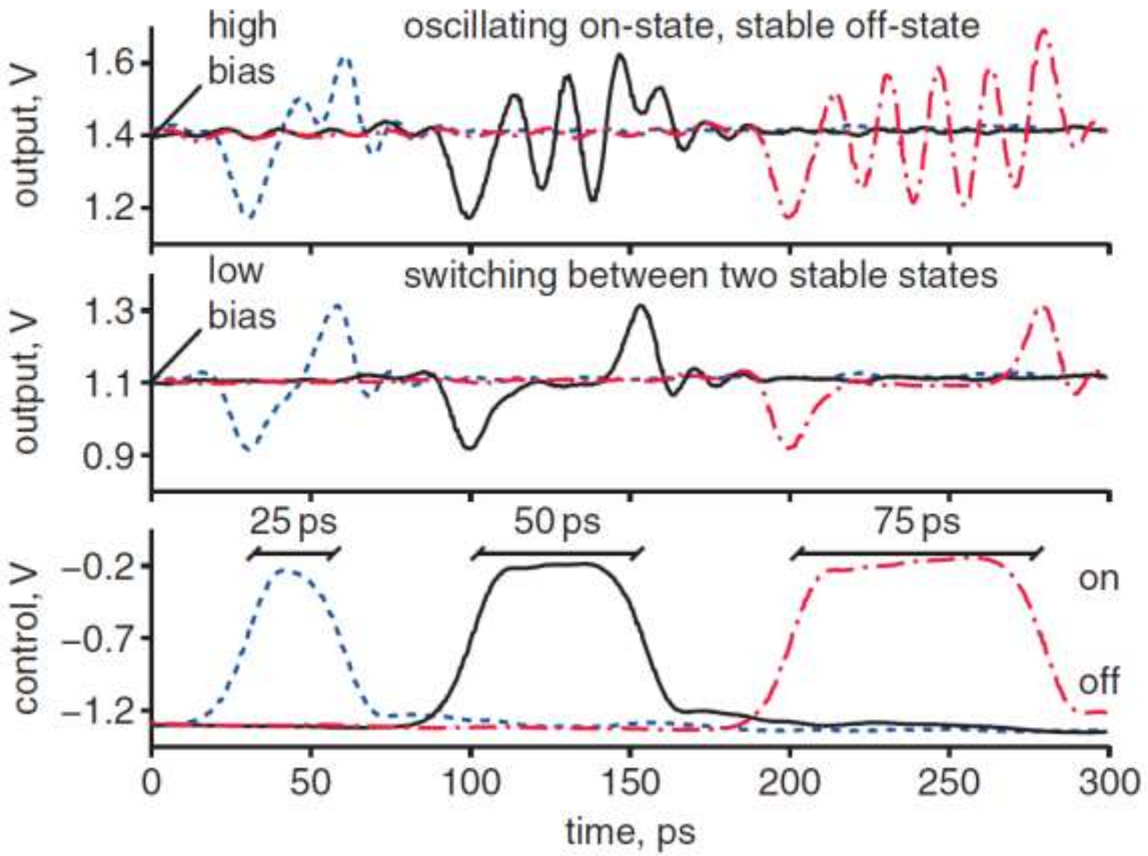
74 ps

181 ps

280 ps

383 ps

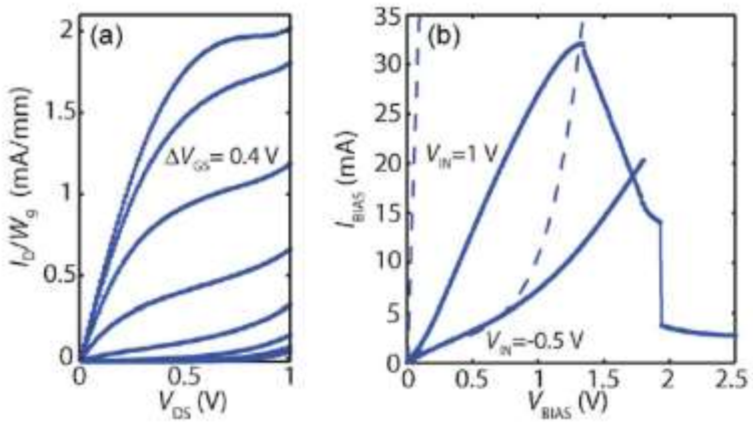
60 GHz Wavelets: 25 ps Control Pulses



L Ohlsson et al Electronics Letters 2015

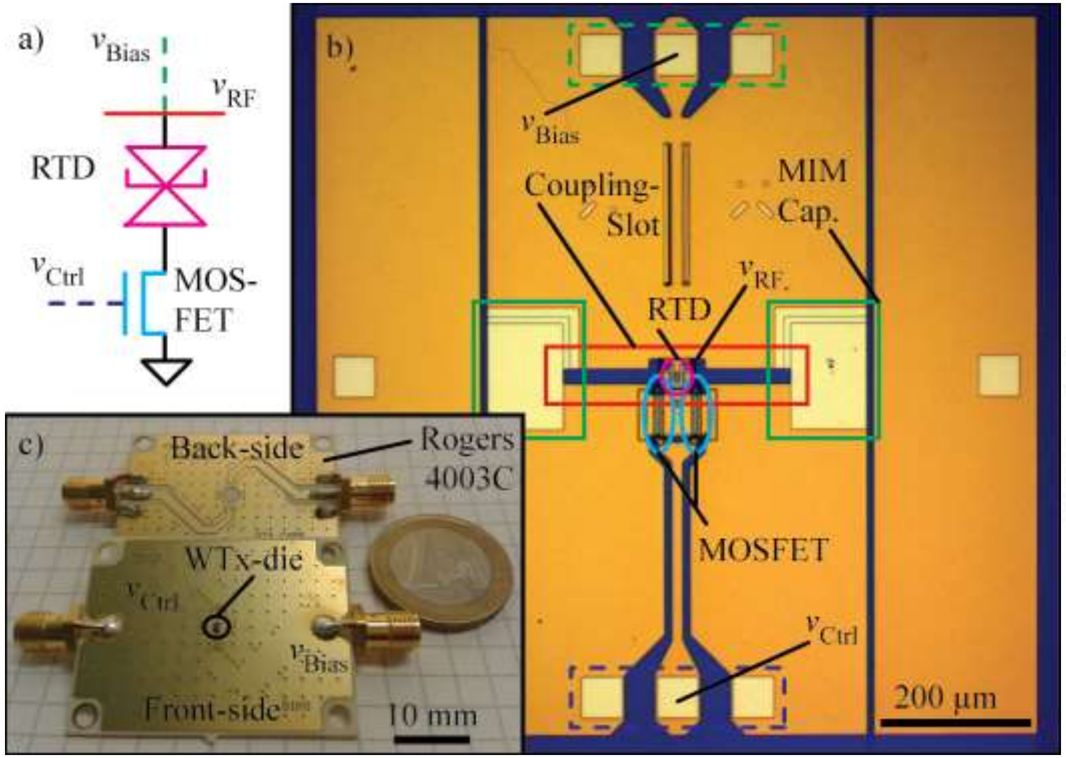
Wavelet generator triggered by 25 ps input pulse

Initial and final part controlled by capacitive load



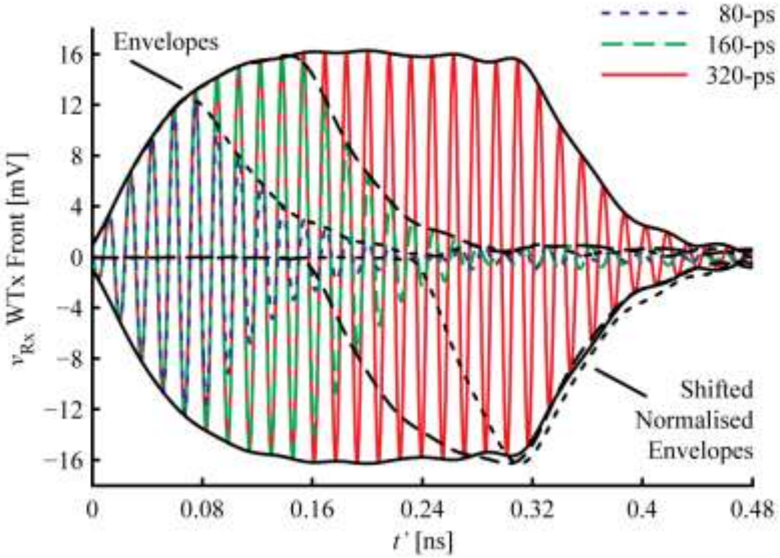
Emission from λ/4 antennas

III-V MOSFET Oscillators on Antennas



L Ohlsson et al IEEE MWCL 2014

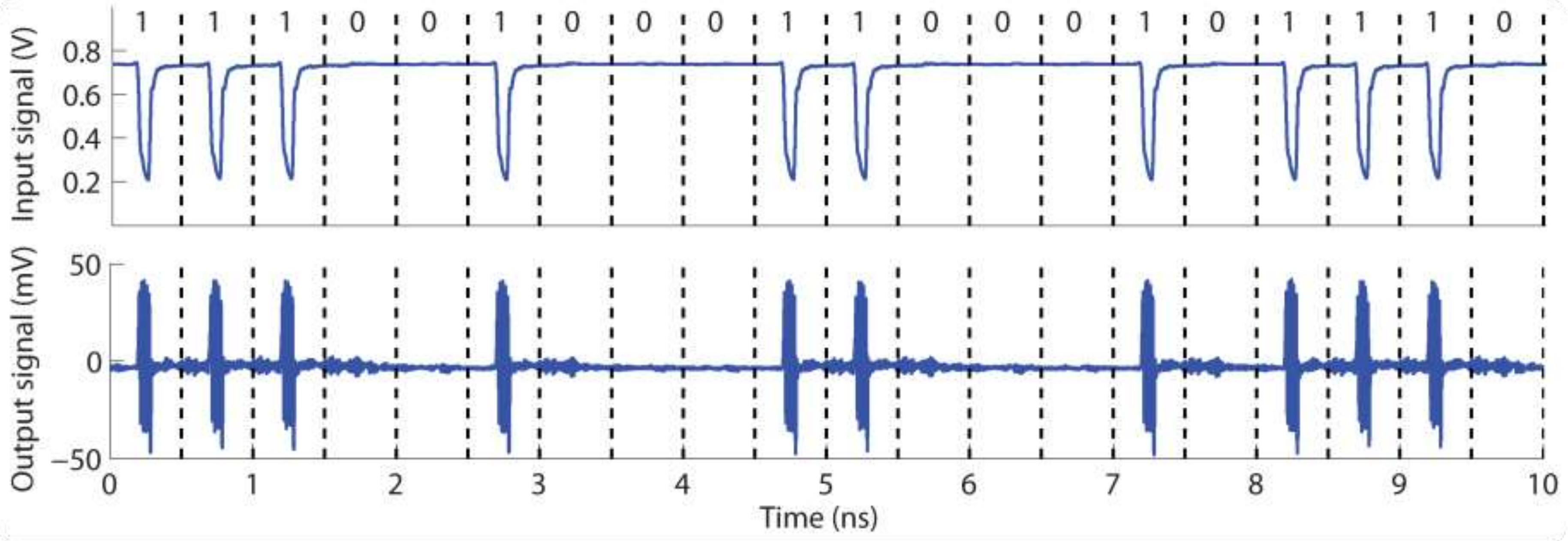
Emission of wavelets from physically small antenna



Antenna adds pulse distortion

60 GHz Communication

- 2 Gpulses/s on-off keying at 60 GHz



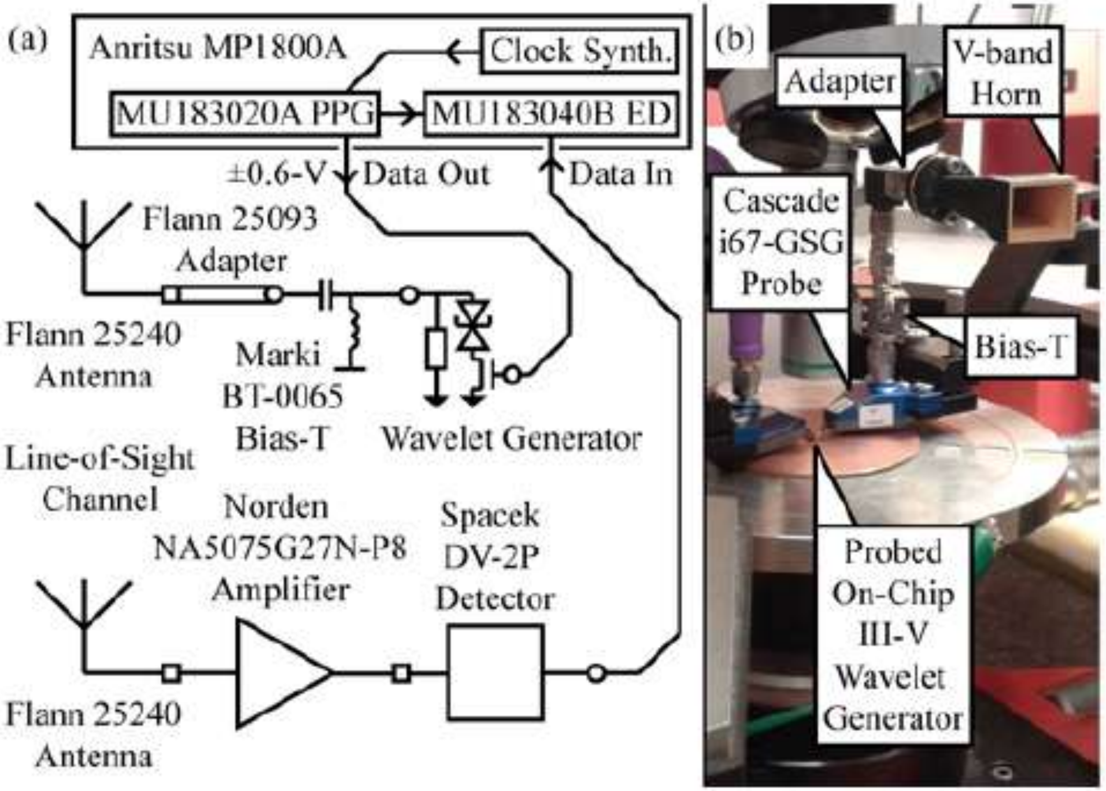
- 100 ps pulse length, 162 mV_{pp} with losses embedded

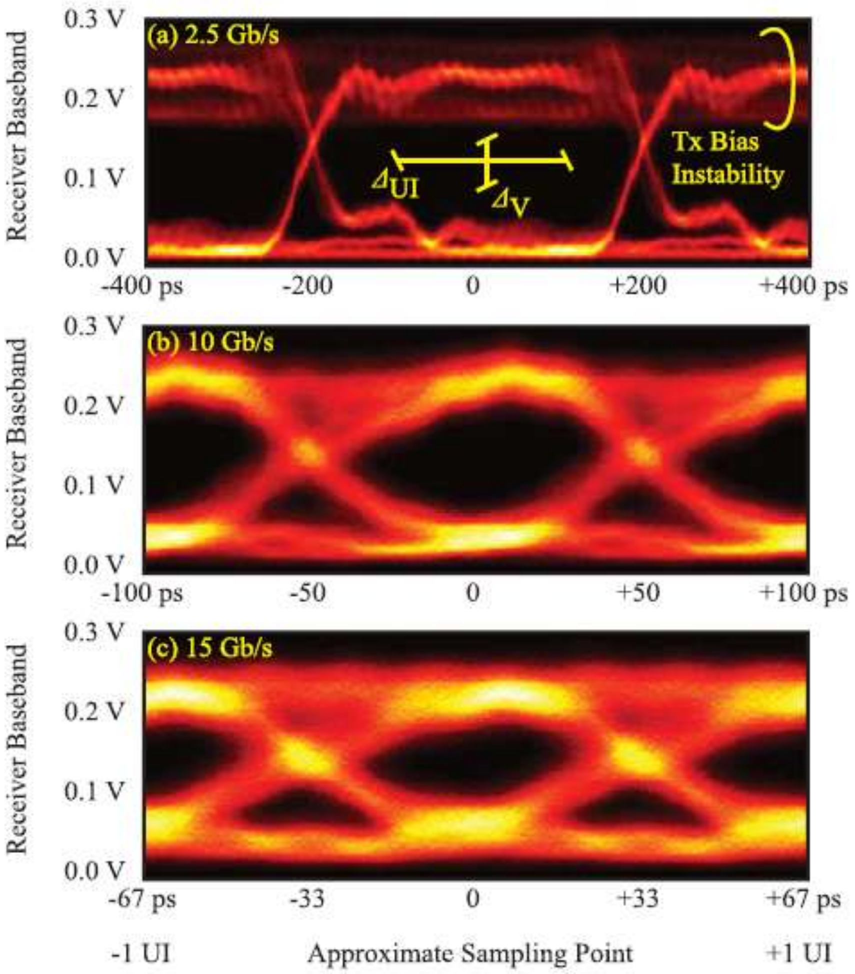
A 15-Gb/s Wireless On-Off Keying Link

BER < 10^{-5} @ 10 Gbps up to 1.5 m

BER < 10^{-3} @ 15 Gbps up to 1.5 m

2×10^{9} switches per datapoint



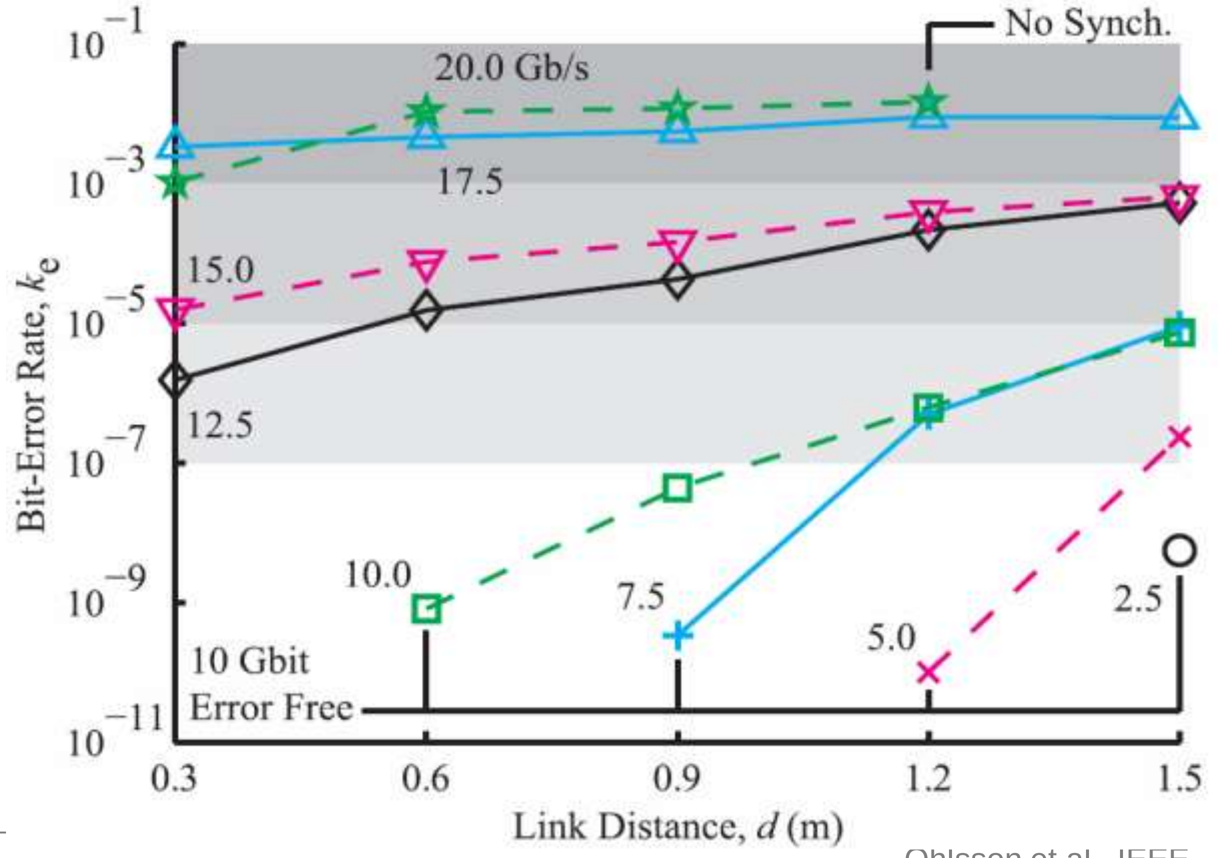


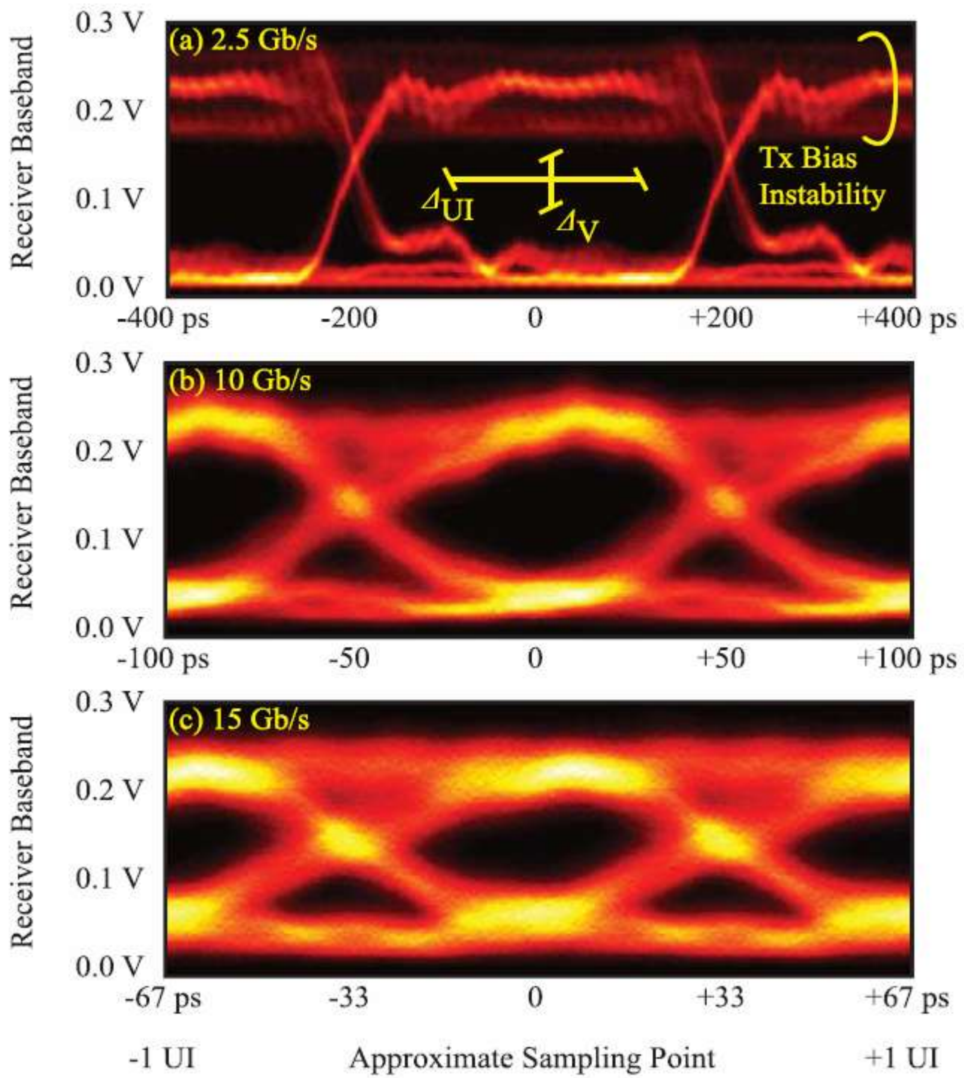
Ohlsson et al IEEE Access 2014

OOK Wireless Communications

A 15-Gb/s Wireless ON-OFF Keying Link

- Up to 20 Gb/s OOK at 1.5 m link distance

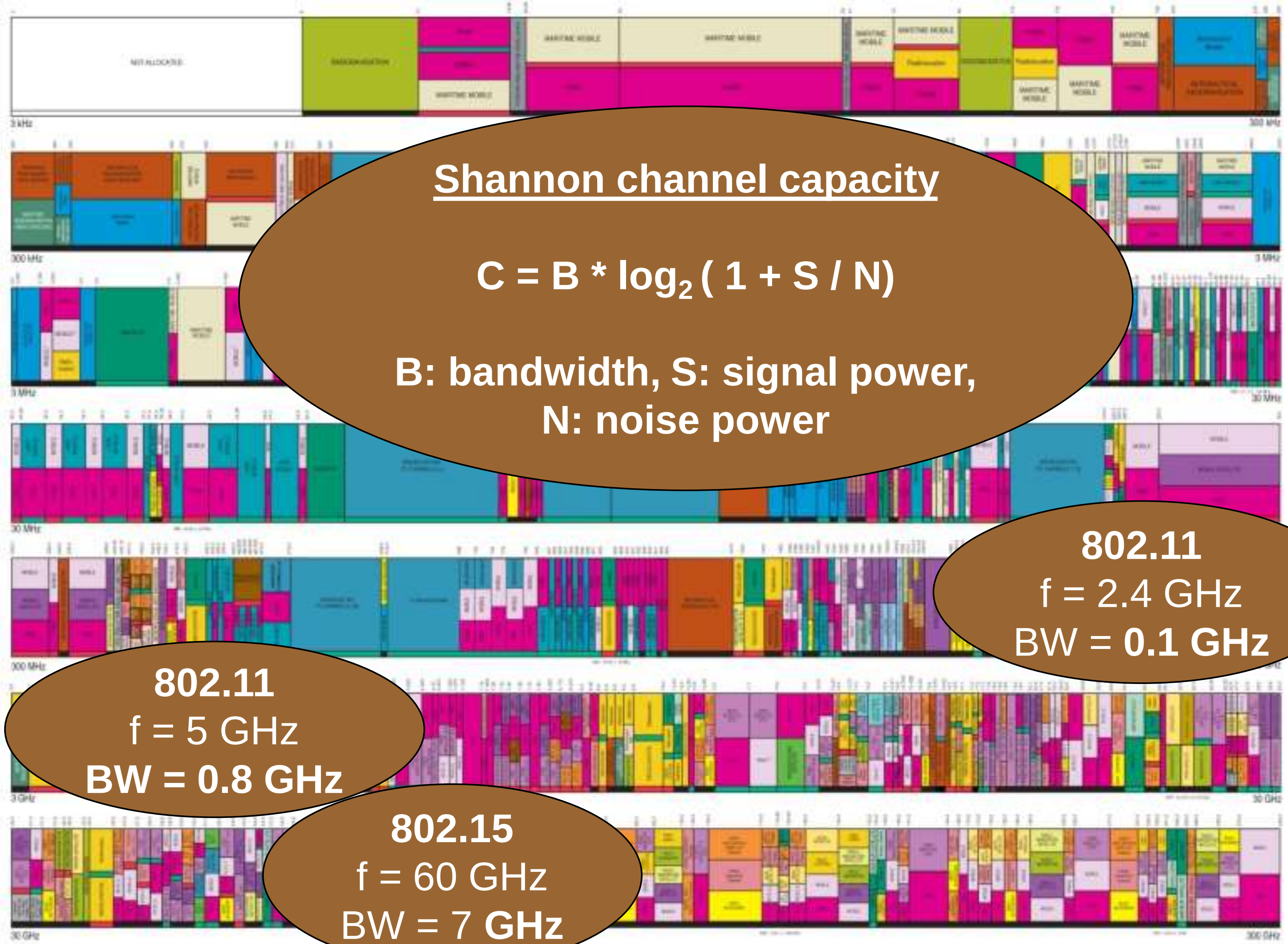




Ohlsson et al., IEEE Access, (2), 2014

Motivation

Federal Communications Commission (FCC) spectrum allocations for the US



Shannon channel capacity

$$C = B * \log_2 (1 + S / N)$$

B: bandwidth, S: signal power, N: noise power

802.11
f = 2.4 GHz
BW = **0.1 GHz**

802.11
f = 5 GHz
BW = 0.8 GHz

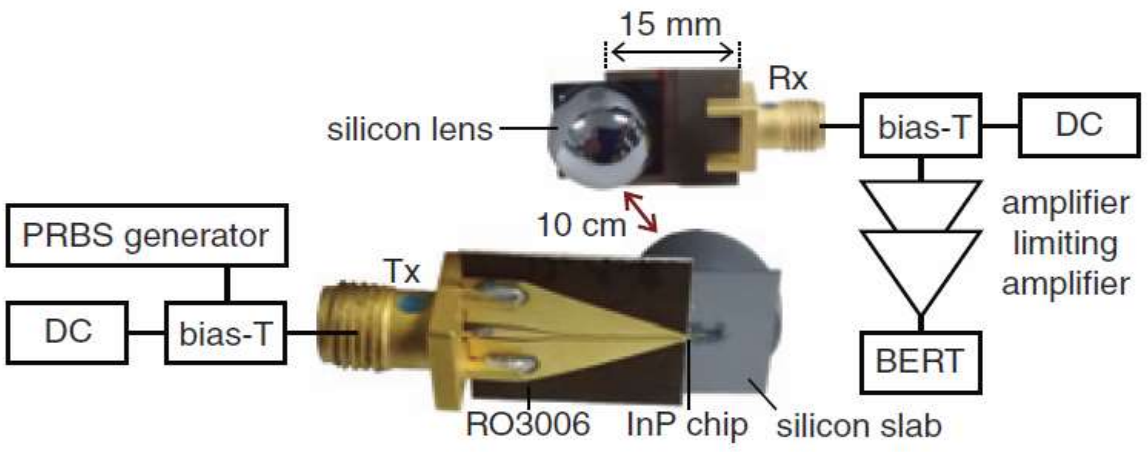
802.15
f = 60 GHz
BW = 7 **GHz**

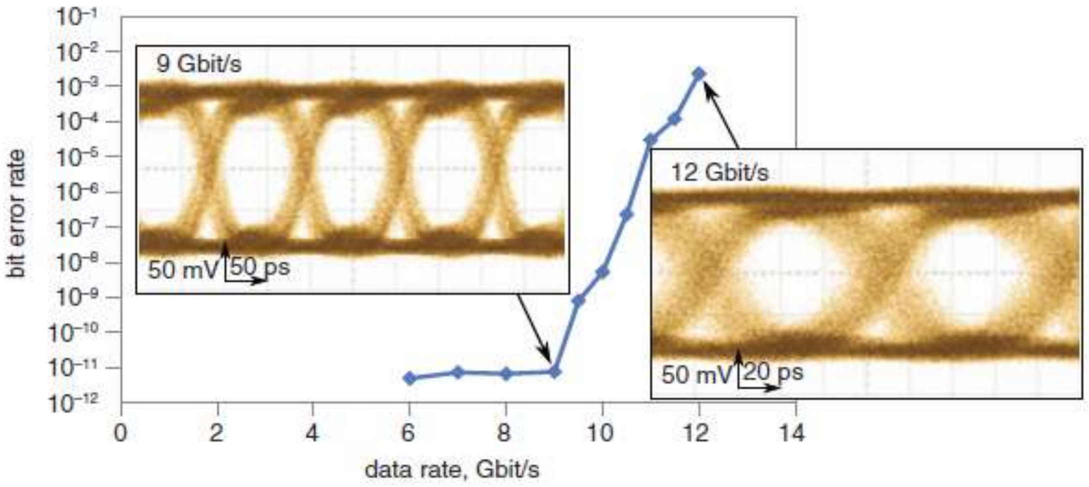
OOK Wireless Communications

High-Speed Error-Free Wireless Data Transmission Using a Terahertz Resonant Tunnelling Diode Transmitter and Receiver

S. Diebold, K. Nishio, Y. Nishida, J.-Y. Kim, K. Tsuruda, T. Mukai, M. Fujita, T. Nagashima

- On-off keying (OOK) wireless transmission (10 cm) of 4K video (6 Gbps) at terahertz frequencies
- RTD front-ends at transmitter and receiver with 6G-SDI interfaces
- 286 GHz signal generated by RTD biasing according to digital data
- Demodulation by using RTD as detector (non-linear characteristics)
- Error-free transmissions up to 9 Gbps and operation up to 12 Gbps

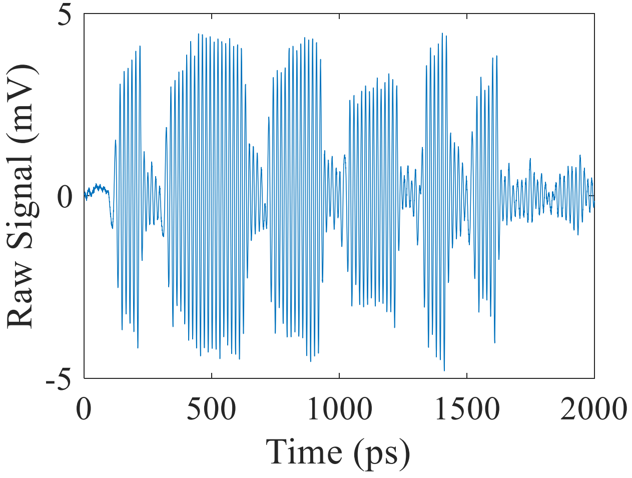


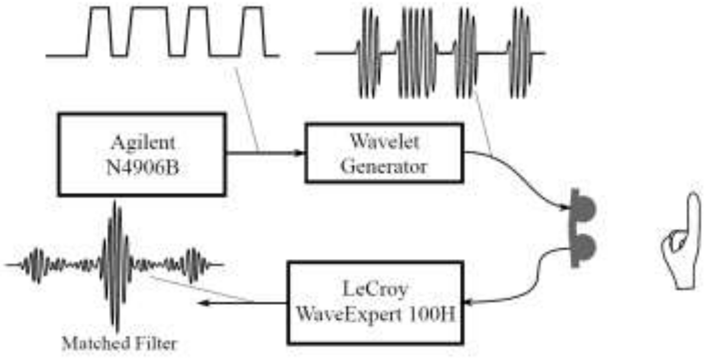


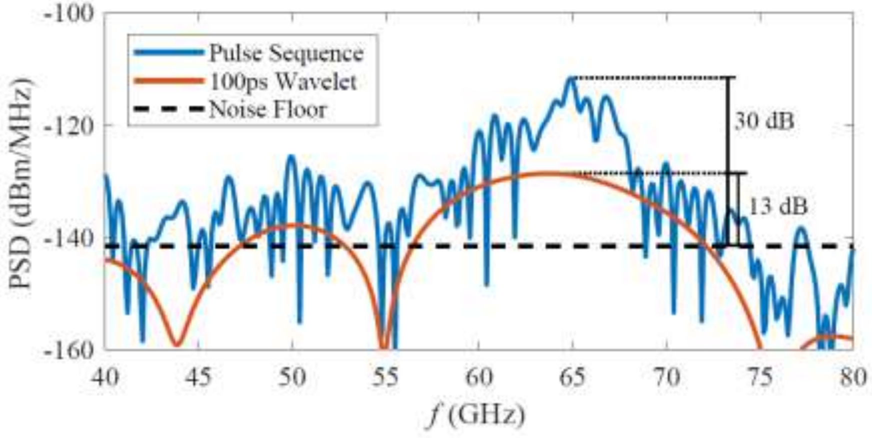
S. Diebold et al., El. Lett., (52), 2016

Radar: Human Hand Reflection Measurements

Use of pulse train “Coded Waveform”



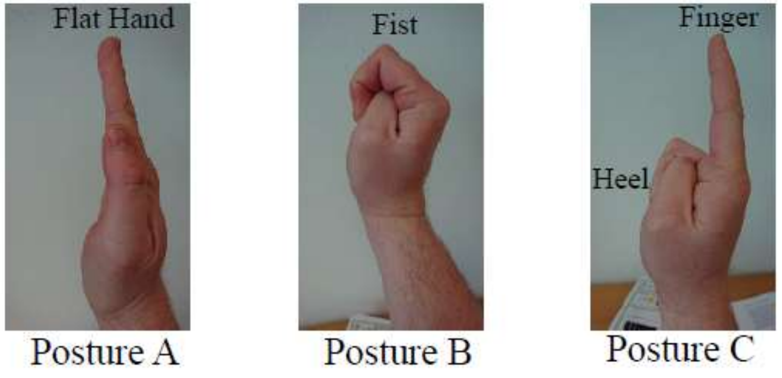


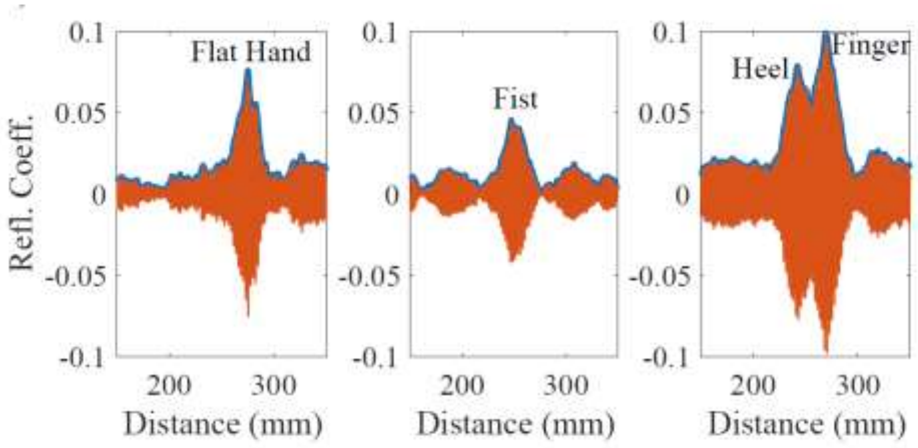


Radar cross-section

σ_{heel}=-29.5 dBsm

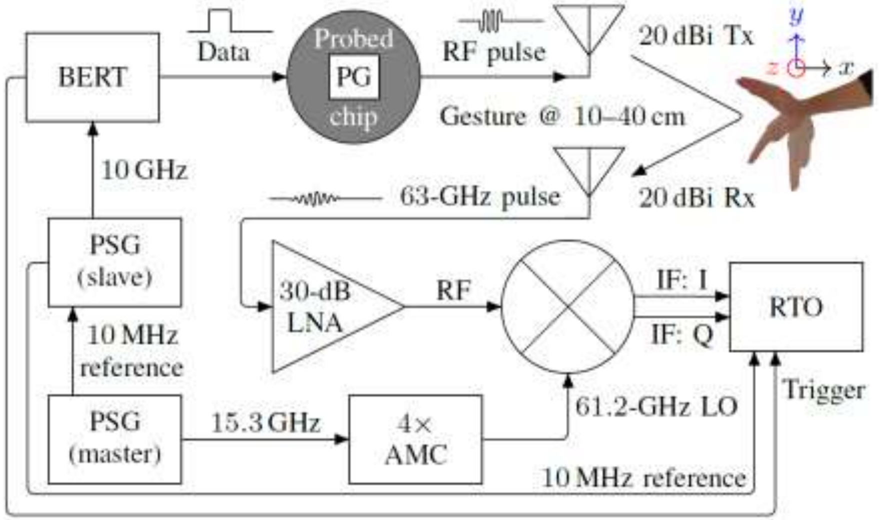
σ_{finger}=-30.6 dBsm

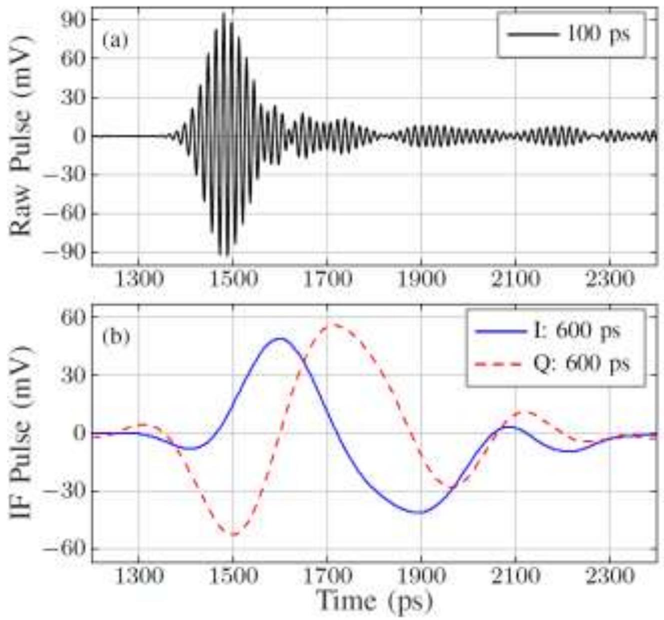




S. Heunisch et al IEEE AWPL 2019

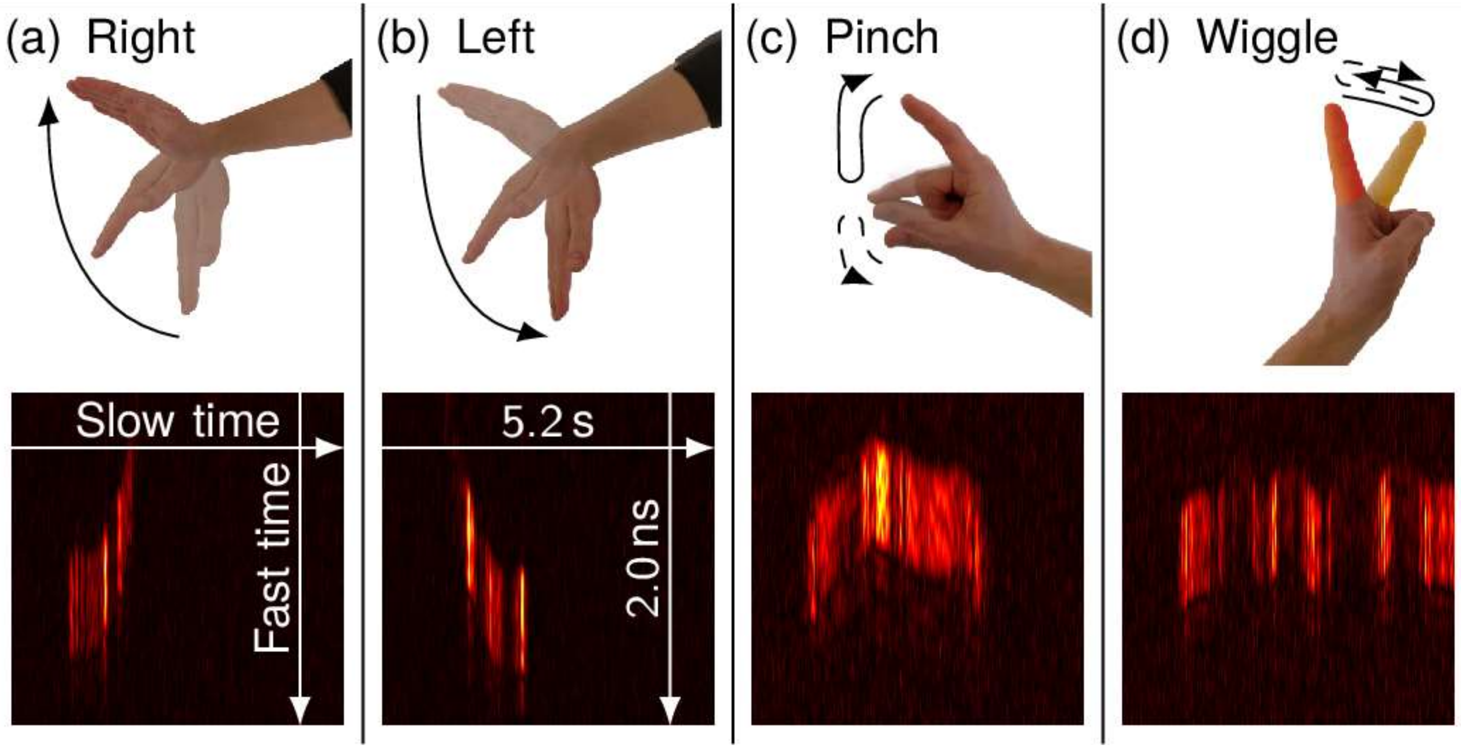
Human Hand Reflection Measurements





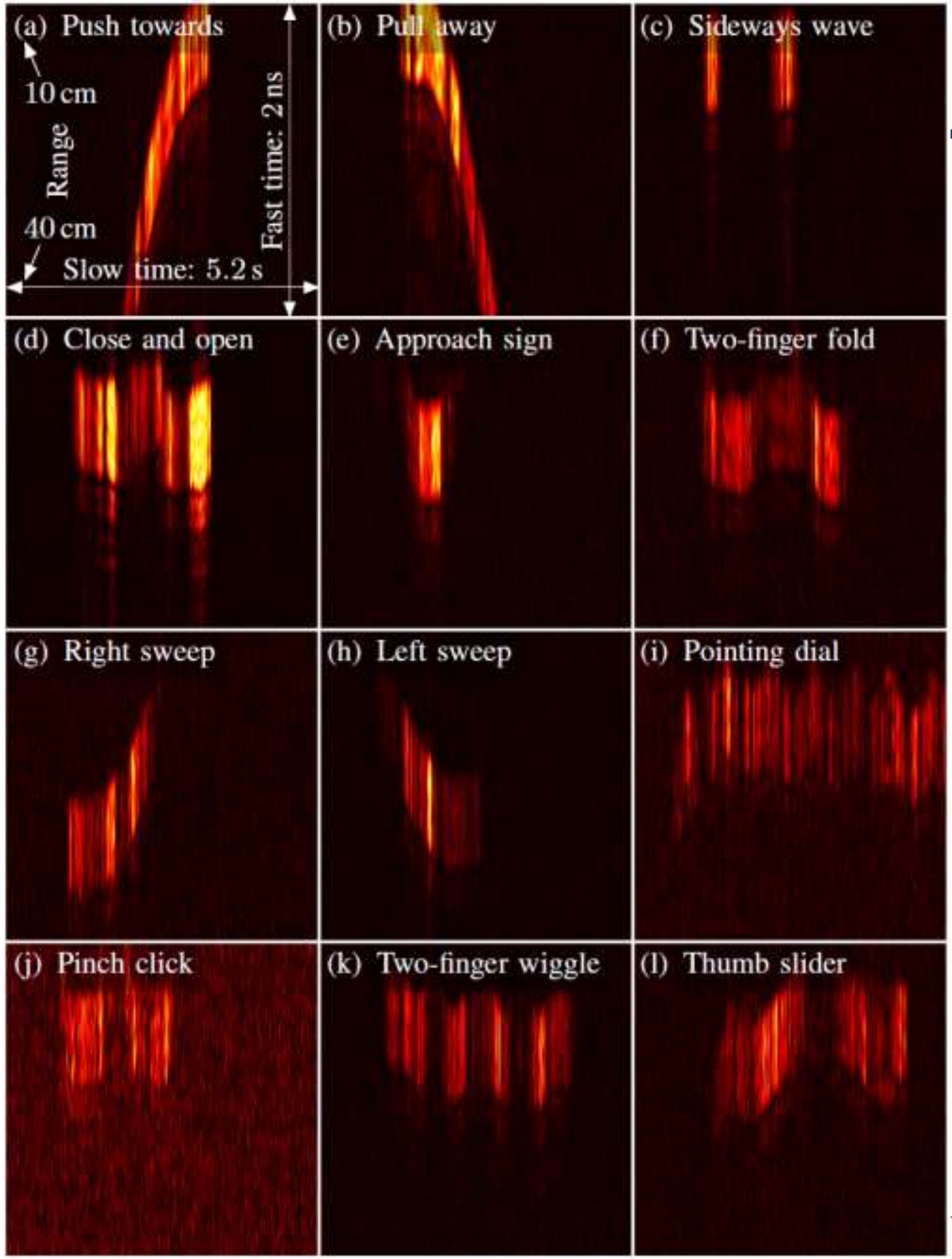
Real time tracking of hand and finger movements

Pulsed coherent radar => Low power consumption



L. Ohlsson Fagher et al IEEE Sensors Letters 2019

Signature Classification



2160 measurements from 2 persons

12 gestures, Convolutional Neural Network (ResNet50)

60/40% training/validation split => 99.5% accuracy

True class \ Predicted class	a	b	c	d	e	f	g	h	i	j	k	l
a	72											
b		72										
c			72									
d				72								
e					72							
f						72						
g							72					
h								72				
i									72			
j							1			71		
k									2		69	1
l												72

L. Ohlsson Fagher et al IEEE Sensors Letters 2019

From Research to Nasdaq

A phonecall from SSF …

One mail from a radar compay…

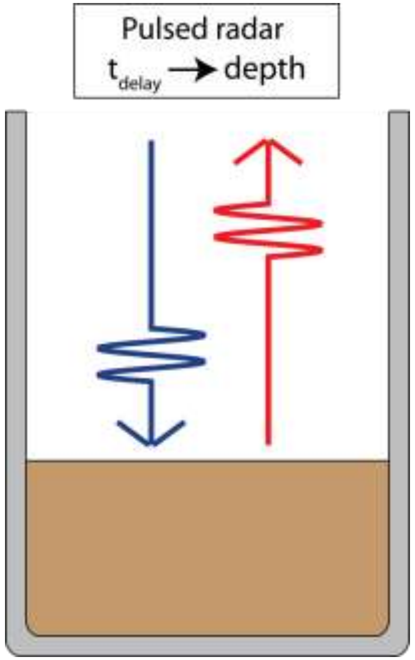
Success with SSF/VINNOVA competition

Collaboration with LU Innovation

Recruitment from industry (Mårten Öbrink)

Investment from Almi

Engagement of local network



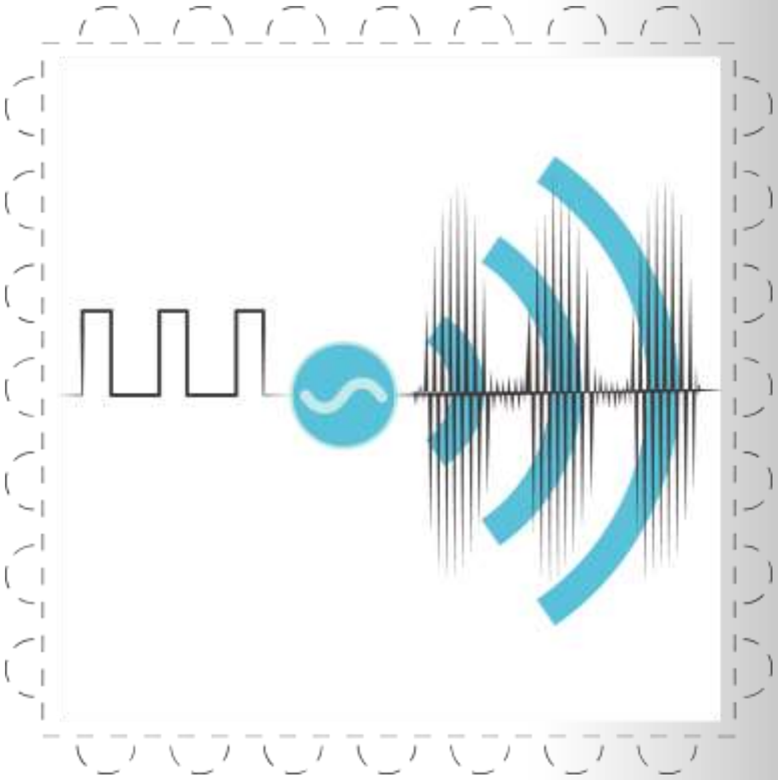
GRUNDEN TILL ACCONEER

En idé: Pulsade oscillatorer

Tvärvetenskap: Nanoteknik och IT

Drivande forskare: Entreprenörer

Industriellt nätverk: Telekom



acconeer

GRUNDEN TILL ACCONEER

En idé: Pulsade oscillatorer

Tvärvetenskap: Nanoteknik och IT

Drivande forskare: Entreprenörer

Industriellt nätverk: Telekom

acconeer

acconeer

PROPRIETARY AND CONFIDENTIAL

Road to commercialisation

2007

Research project in Nanoelectronics at LTH

LUNDS UNIVERSITET

2012

acconeer

Company founded with support from Lund University

2014

System level demonstrator successfully tested

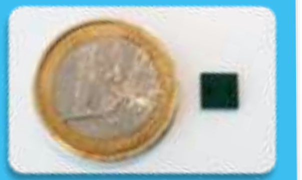
2016

First prototype

2017

Commercial product
Ready for production:

- ✓ First design wins
- ✓ First purchase orders received

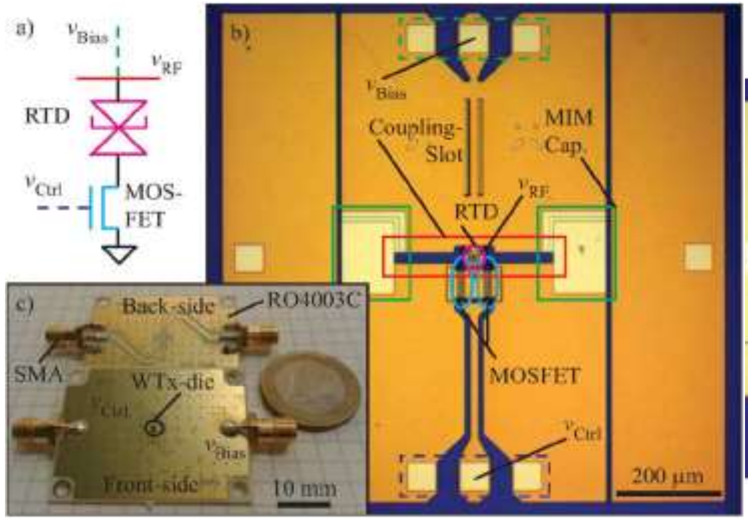


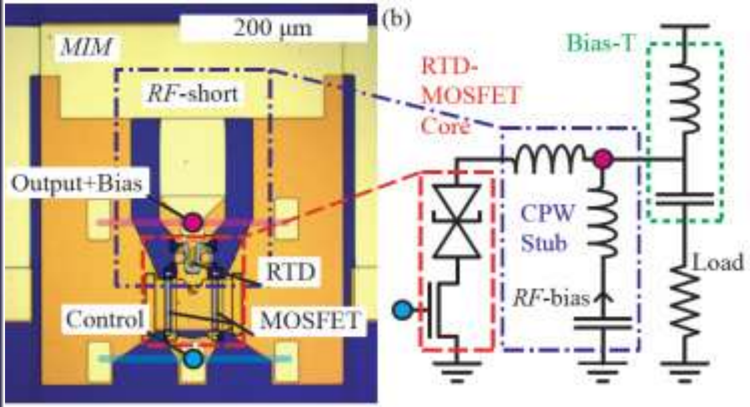
2018

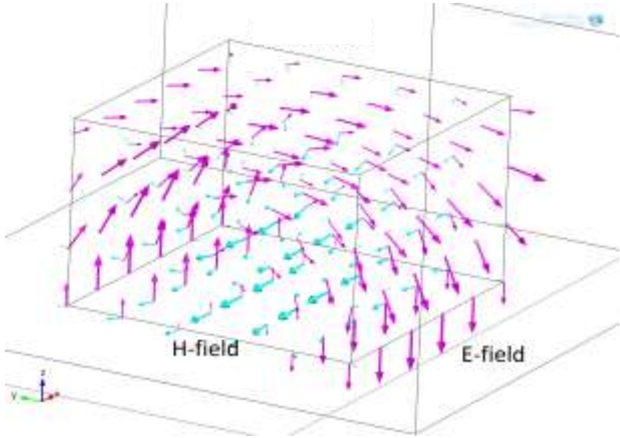
Commercial ramp up

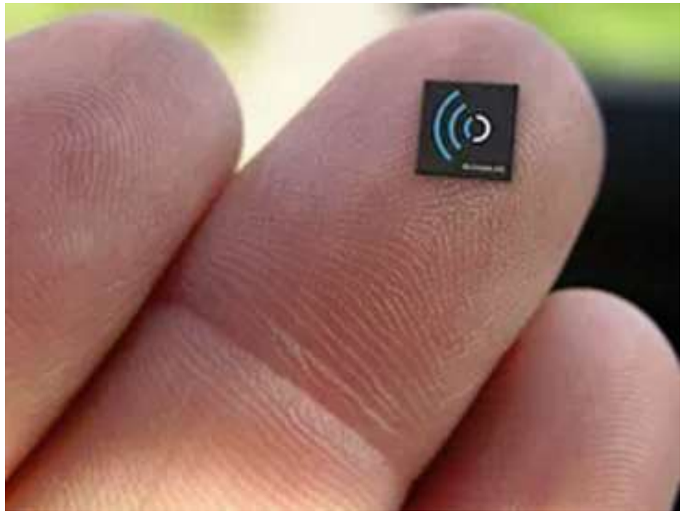
Summary

- Motivation
  - Wireless bandwidth
- Resonant Tunnelling Diode (RTD)
  - Signal generation
  - THz potential
- Integrated Antennas
  - Size matters
  - Substrate modes
  - Monolithic integration (wireless = no wires)
- Applications
  - High-rate wireless communications
  - Radar
- Commercialisation
  - Acconeer AB (www.acconeer.com)

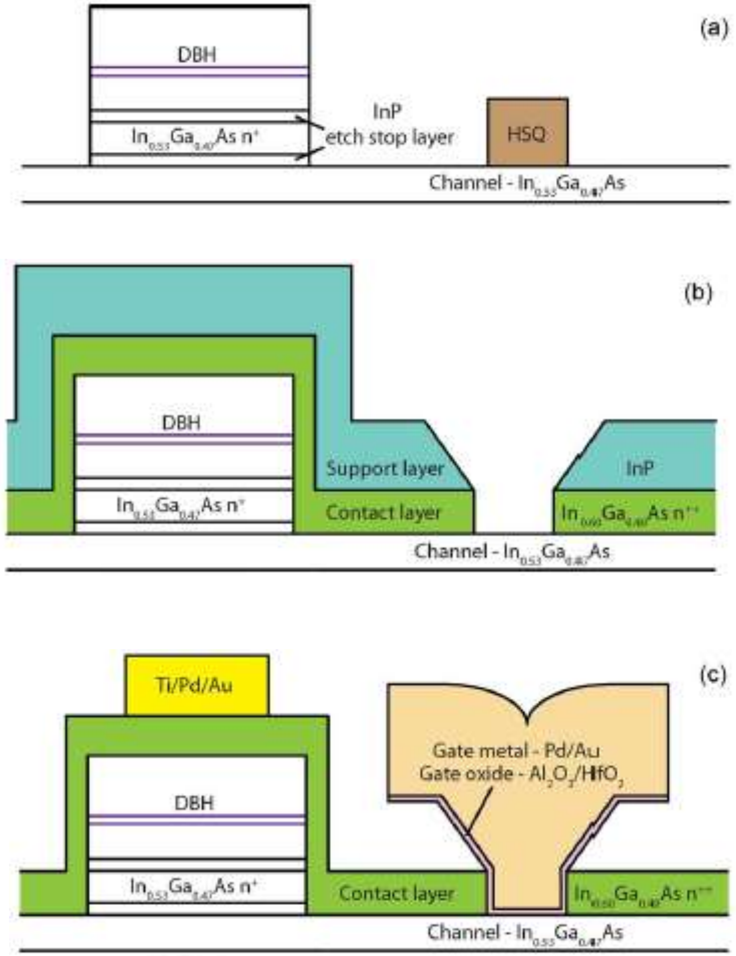


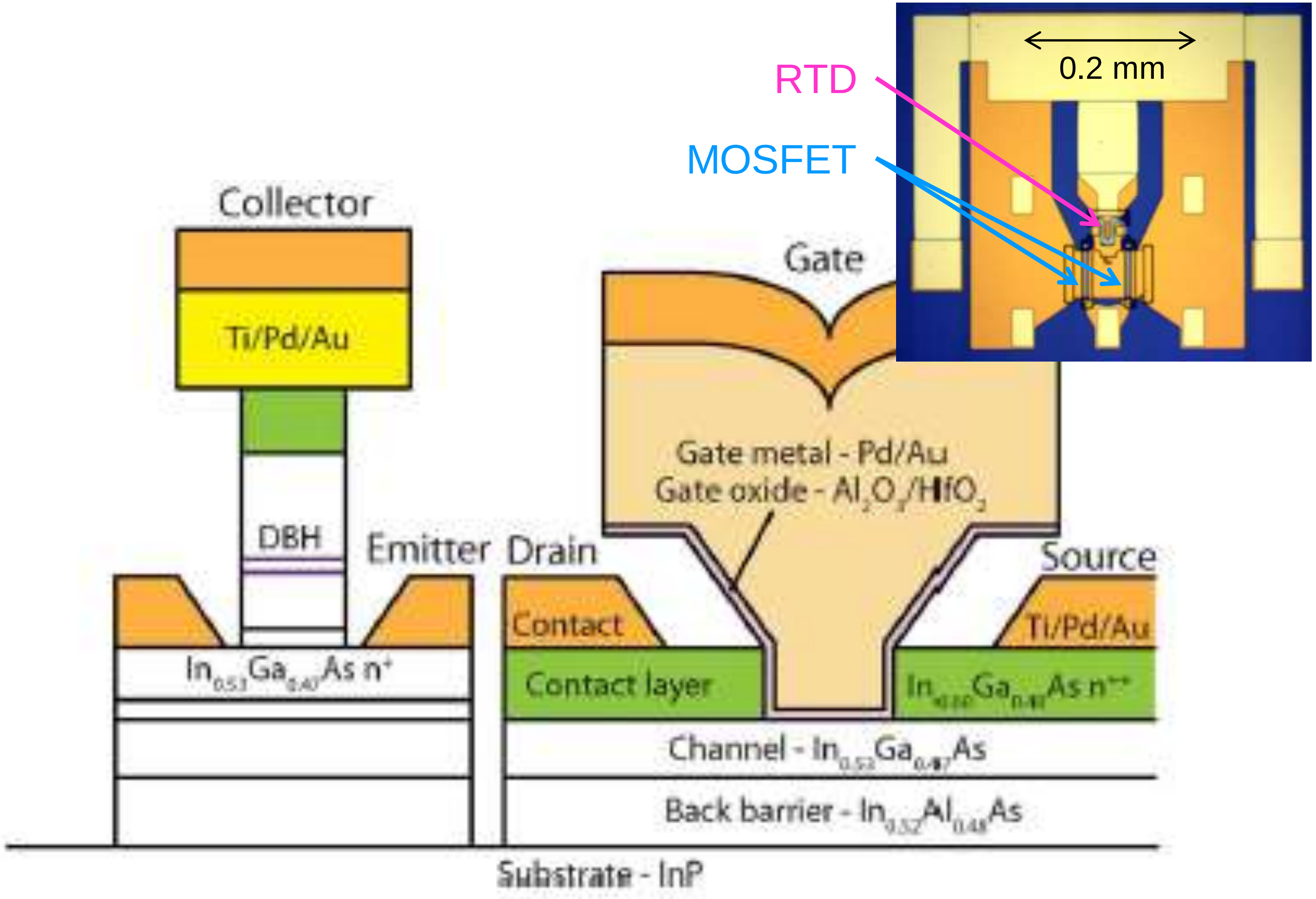






Mm-Wave (30-300 GHz) RTD-MOSFET

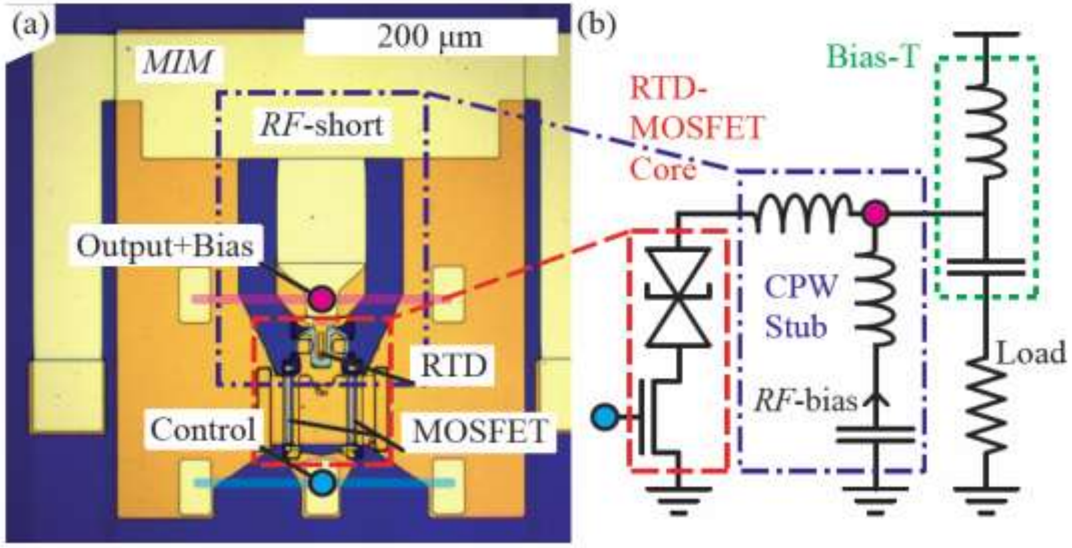


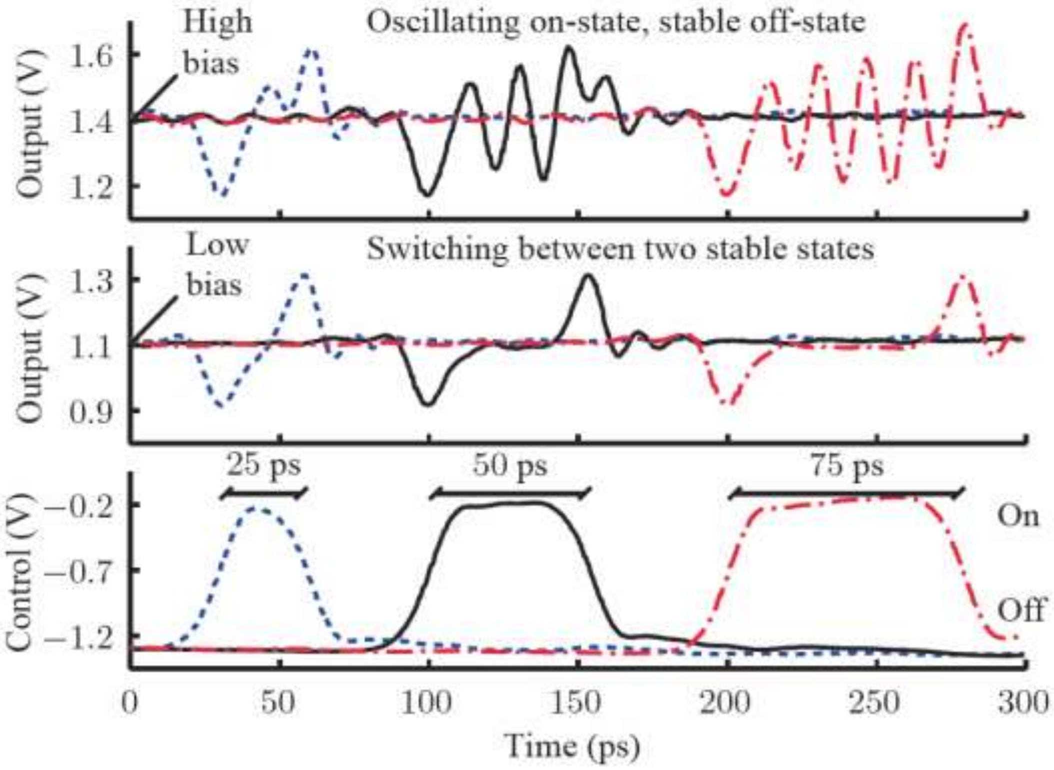


Egard et al., *IEEE EDL*, 2012

RTD-MOSFET Pulse Generation Dynamics

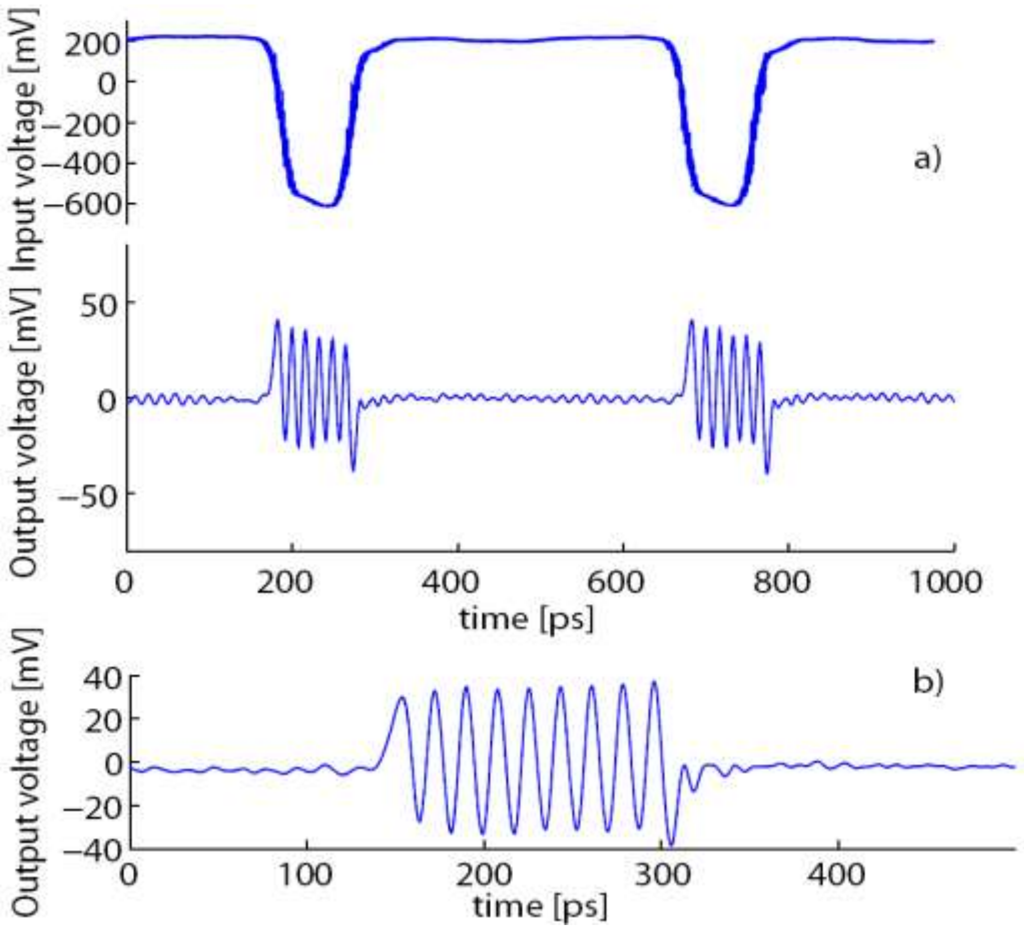
- MOSFET used to switch in/ disconnect RTD
- Low bias
  - RTD switched up towards peak, G > 0
  - Only bias transients in inductor, v = L di/dt
- Higher bias
  - RTD switched into NDR region, G < 0
  - Oscillation starts





Ohlsson, Fey, Wernersson, *Electronics Letters*, 2015

The GTD Pulse Generator



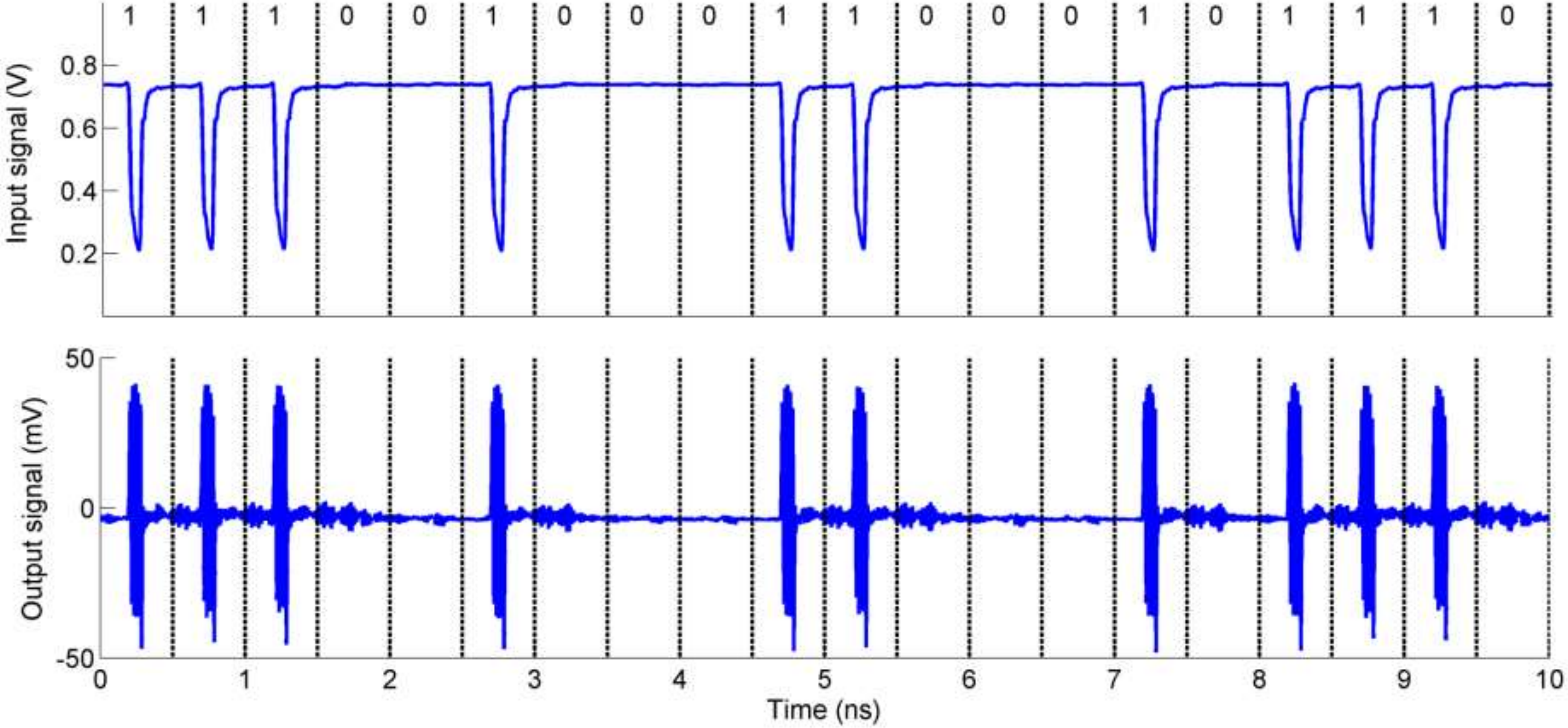
Digital control signal

62 GHz, 100 ps long

56 GHz, 160 ps long

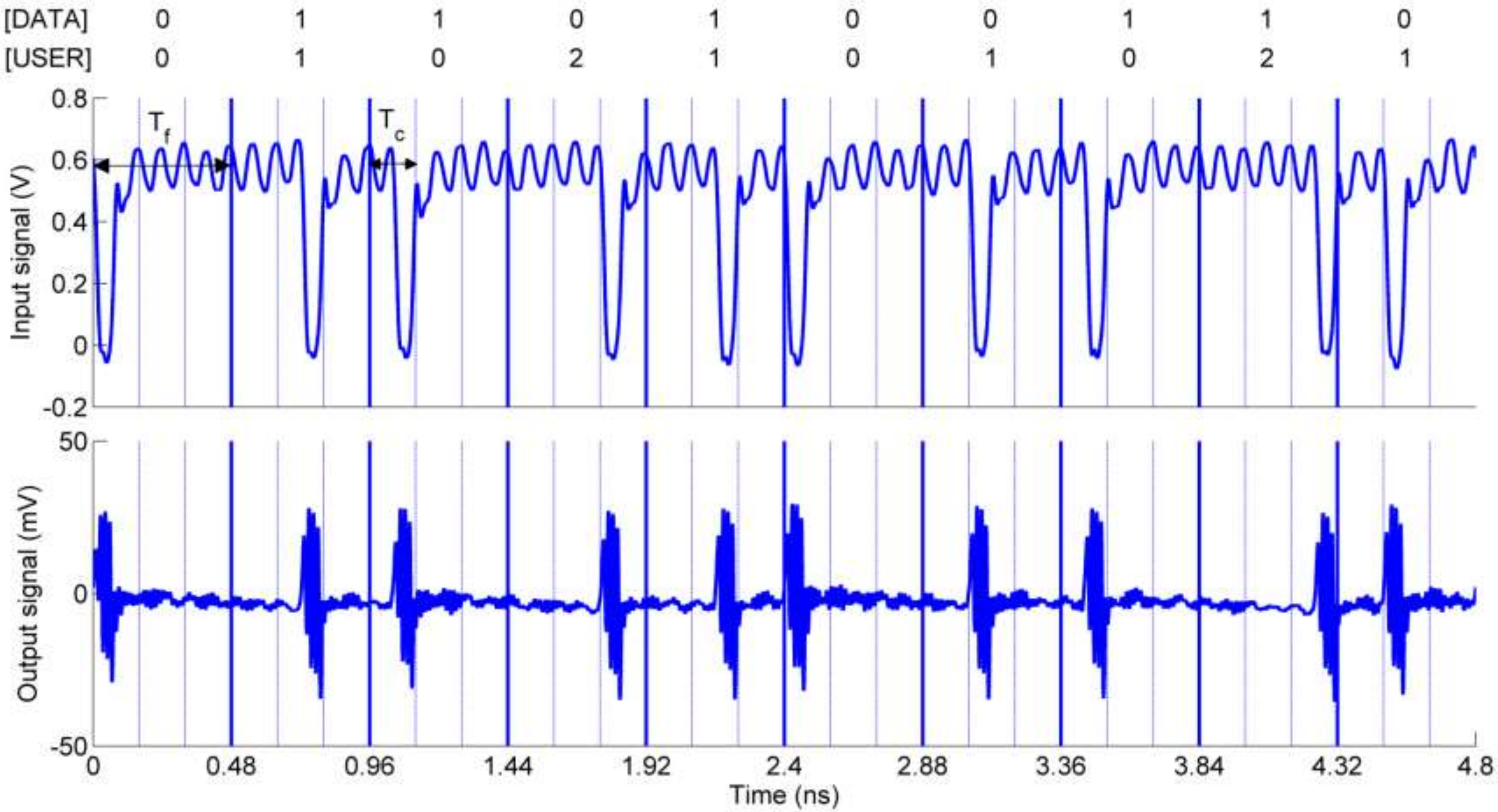
2 Gpulses/s OOK @ 60 GHz

- 100 ps pulse length
- 162 mVpp
- 59 GHz centre frequency



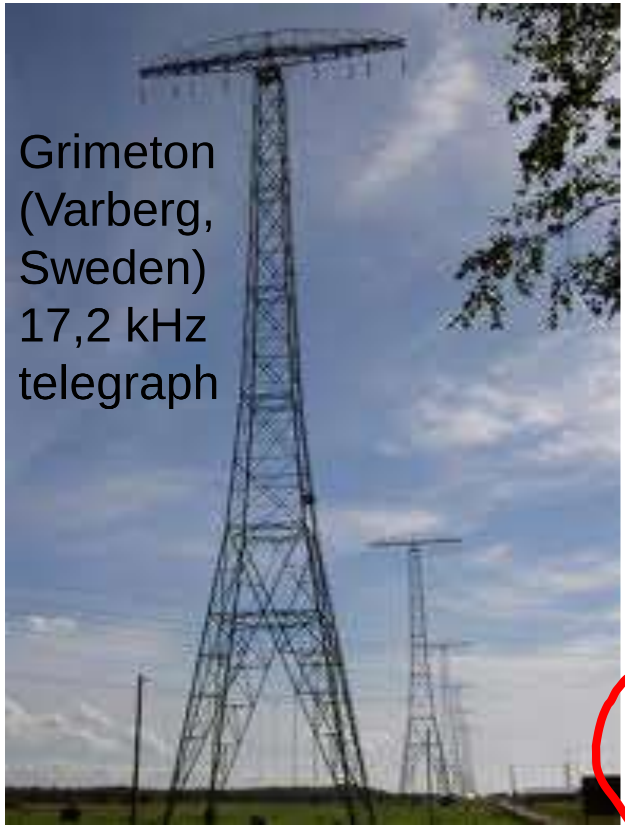
2.08 Gpulses/s TH-PPM @ 60 GHz

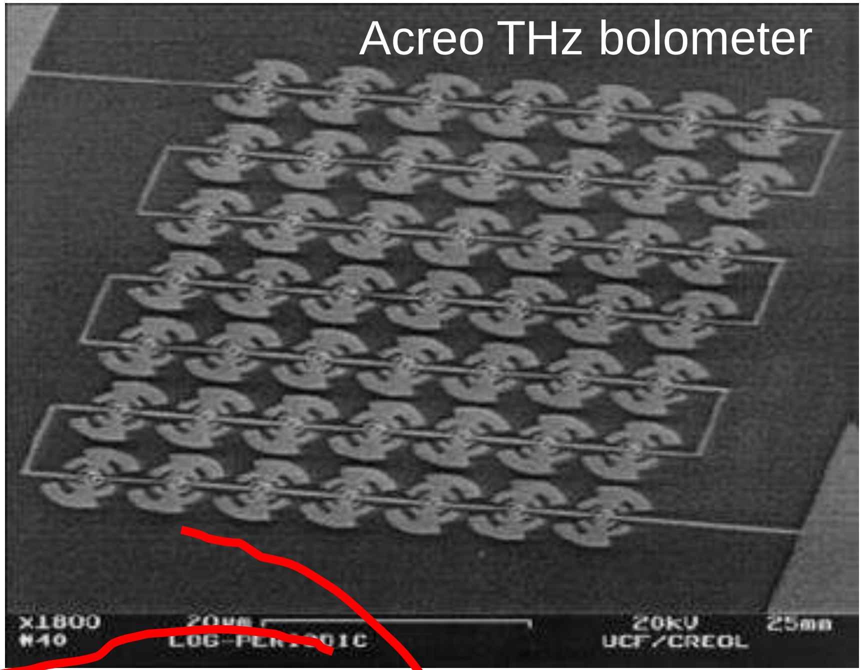
- 46 ps pulse length
- 148 mVpp
- 62 GHz centre frequency



Different Bands = Different Antennas

- Longwave to THz (size matters)



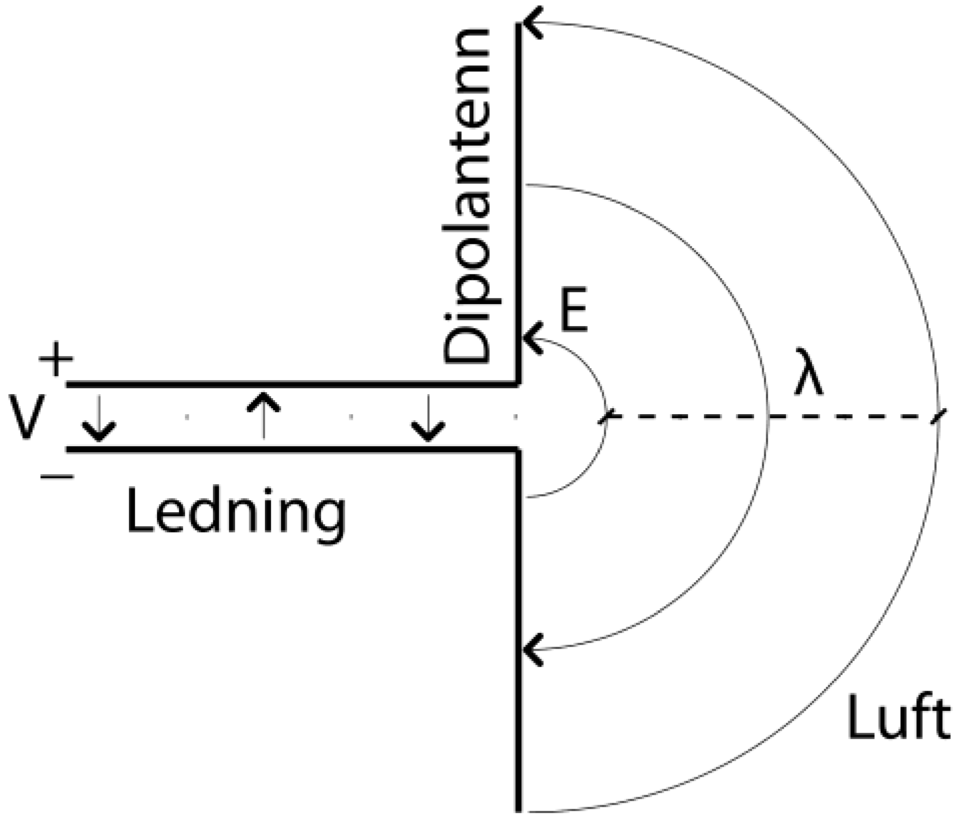


In between:

mm-Wave (30-300 GHz)

What Radiates, and Why?

- The Antenna Function
  - Couple energy
  - IV to EM-wave (Transmitter)
- Example: Dipole Antenna
  - V projected to E-field
  - Electrically large
  - Charge imbalance
- ”Half-wave” is enough
  - L=1,3,5... x λ/2



Antenna (de-)Evolution

- Where did the antenna go?

80's

f~1 GHz
λ~30 cm

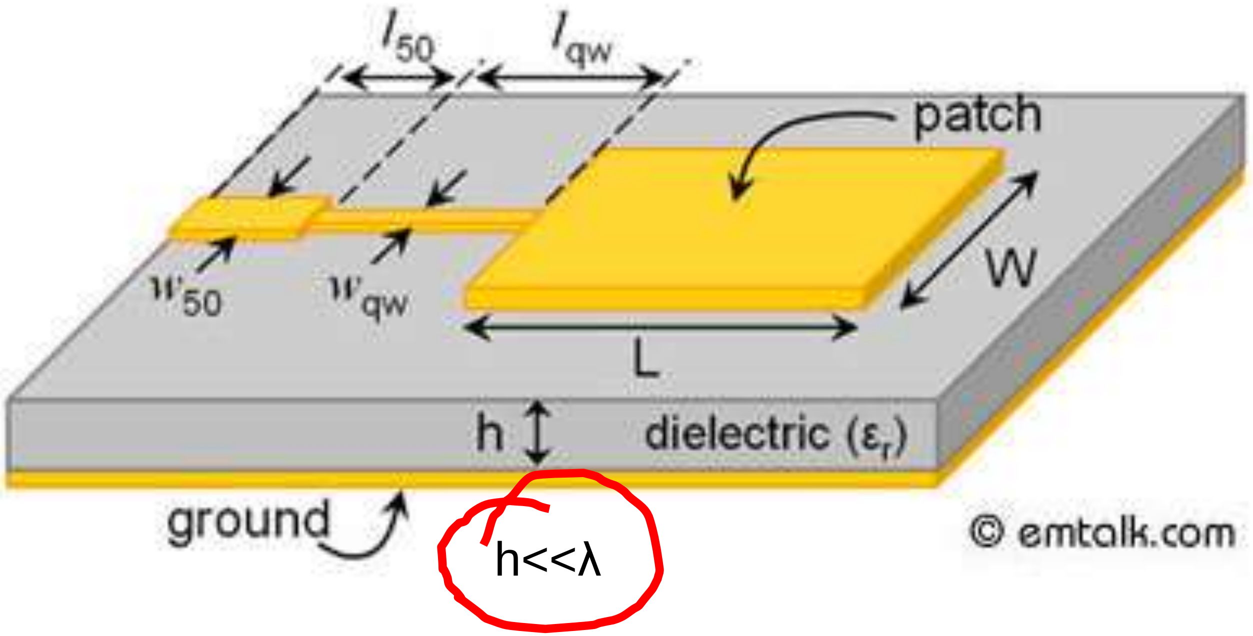
00's

WWII
"Walkie-talkie"

Smaller, Inefficient Antennas
(+ screen, processing, etc.)
= Power Drained Quickly

Patch Antenna

- Compact
  - Easy to integrate
- Easy to Fabricate
  - Milling or lithography
- Thin Substrate
  - h<<λ
  - Not possible at high frequency!



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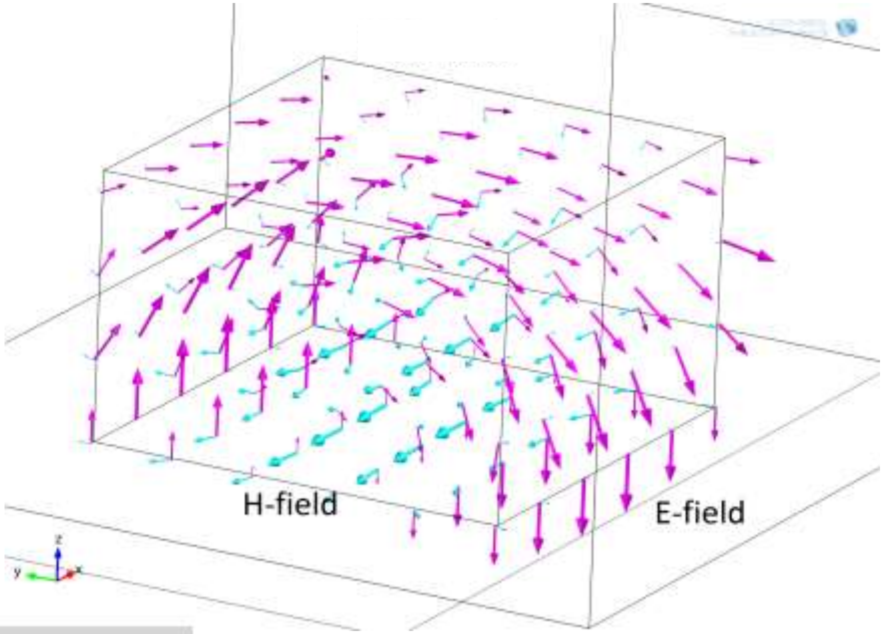
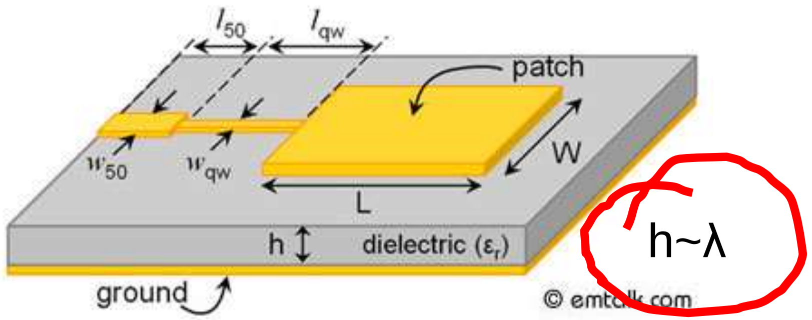
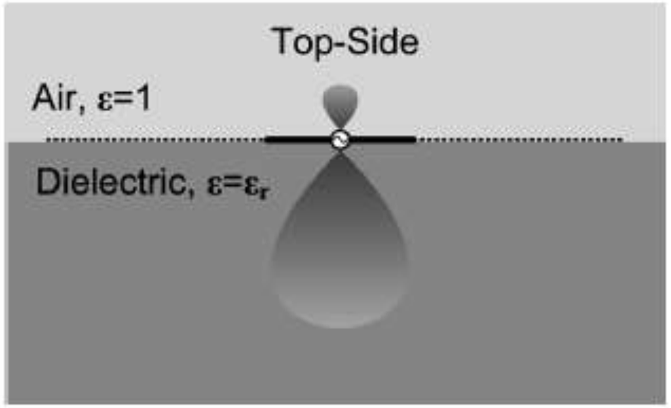
Modes in the Substrate

- Electrically Large Substrate
  - h~λ
- Mode = Resonant Pattern
  - e.g. EM waveform
- Substrate Absorbs Energy
  - May dominate over free-space radiation
- Unpredictable Scaling
  - New radiation mechanisms



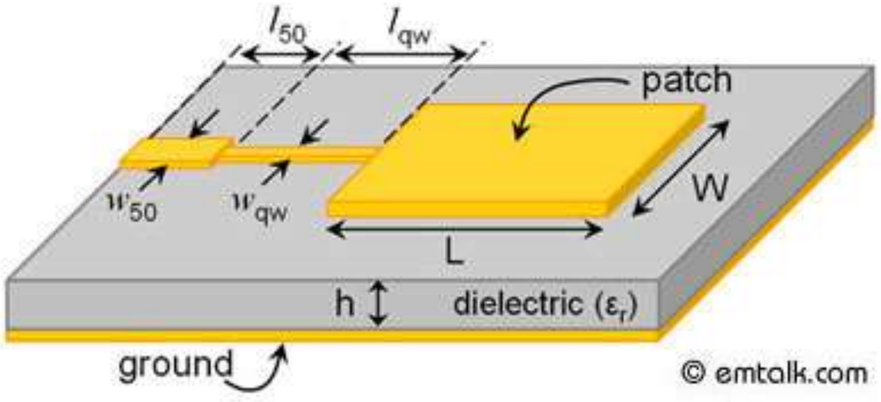




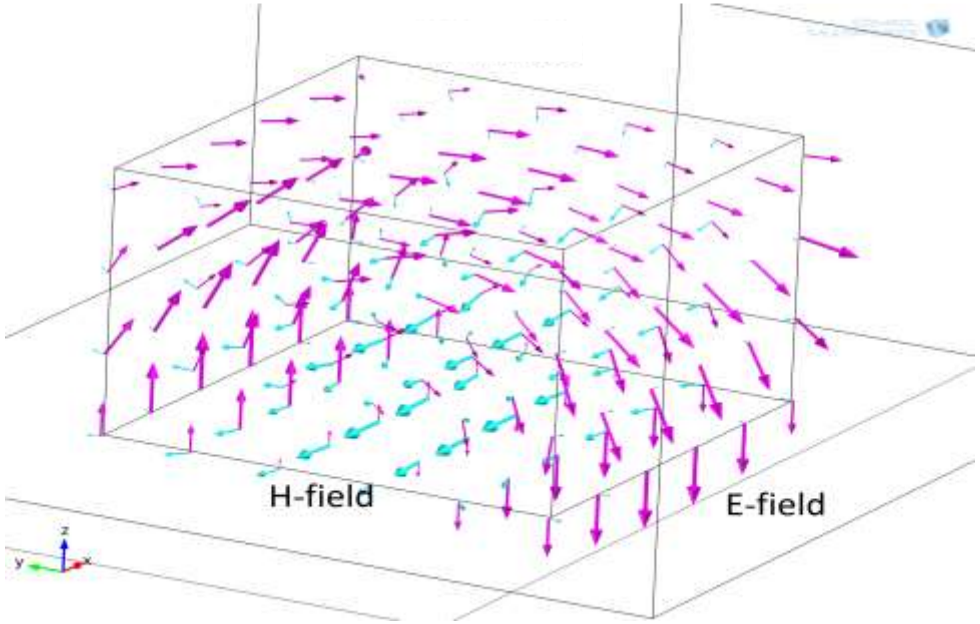
Babakhani et al.

Efficient Millimeter-Wave Antenna?

- Conventional Antenns are Inefficient and Hard to Fabricate
  - Substrate is significantly thick
  - Scaling don’t allow milled antenna
  - On-chip antenna ”radiates” into substrate
- Solution
  - Design a resonant mode for radiation



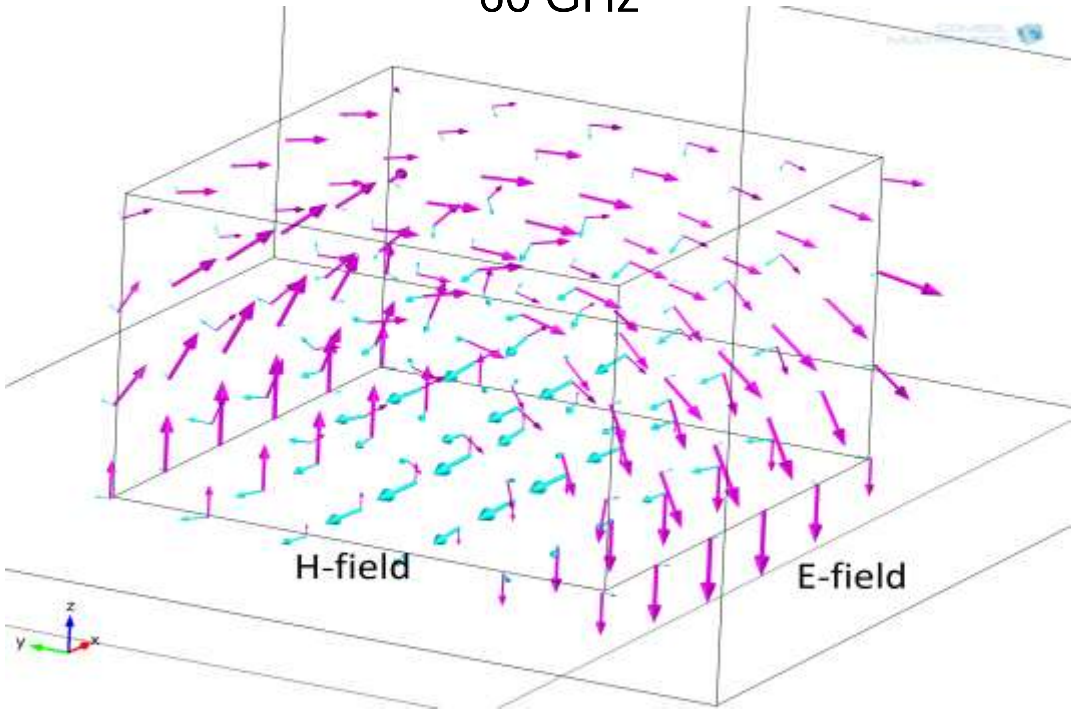
Don’t struggle against the physics, let it do the job for you instead!

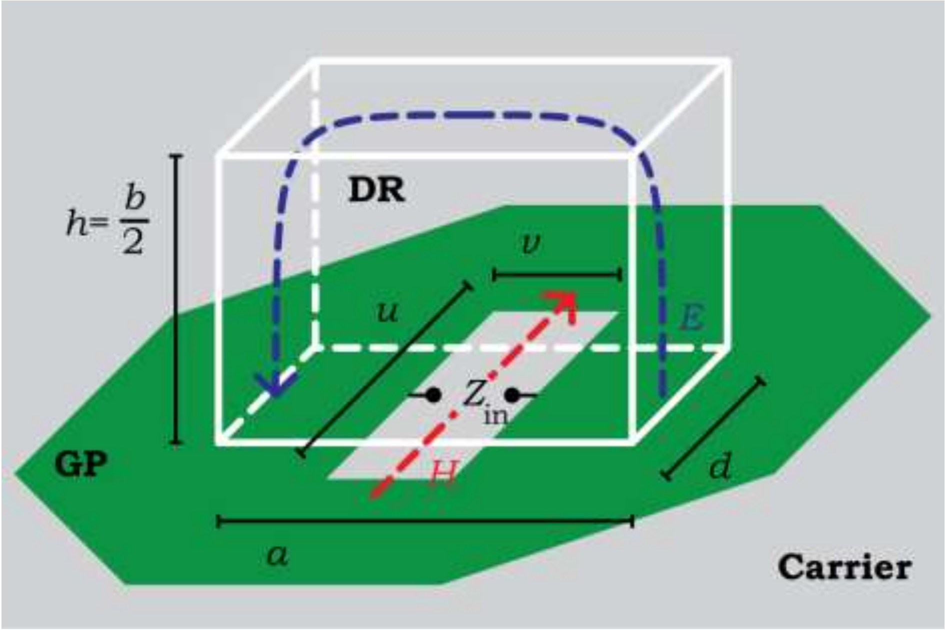


Dielectric Resonator Antenna (DRA)

- Utilise an electromagnetic mode for radiation
- 50 Ω chip antenna on carrier substrate
  - 98% radiation efficiency at 60 GHz

60 GHz

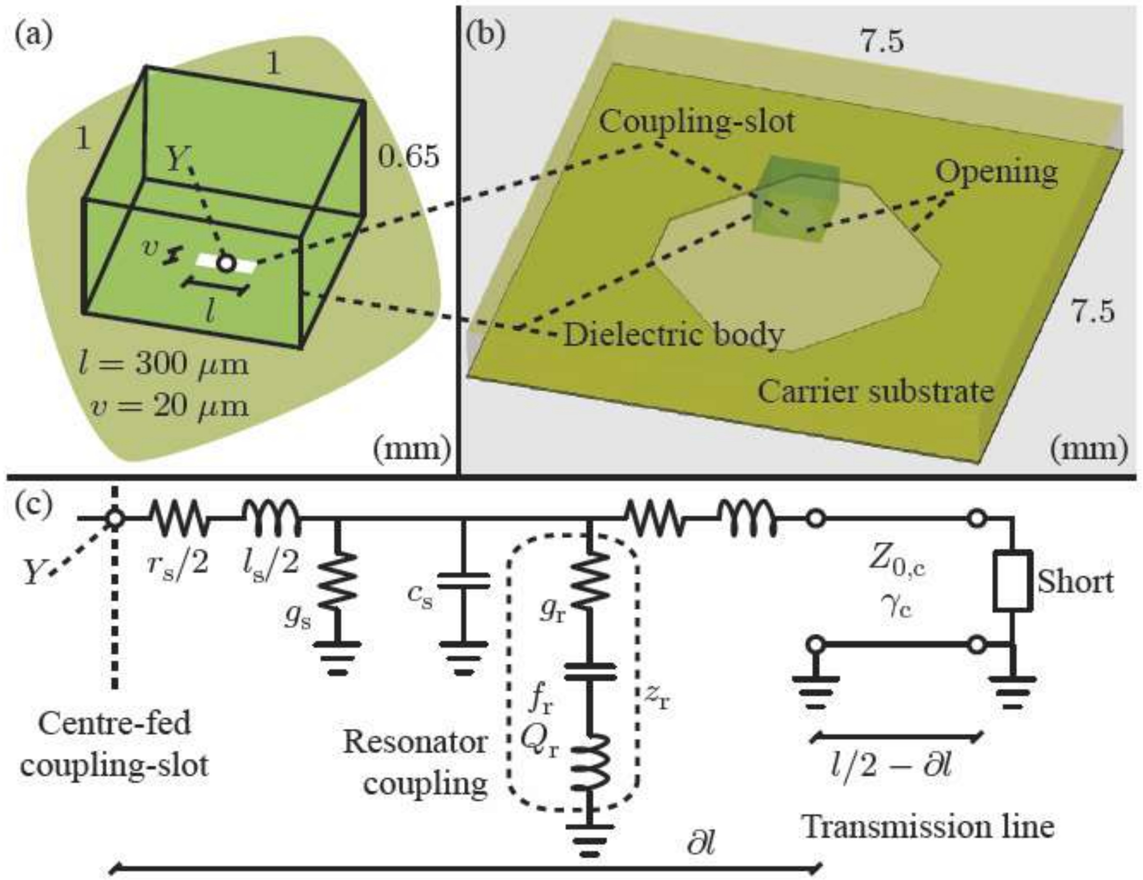


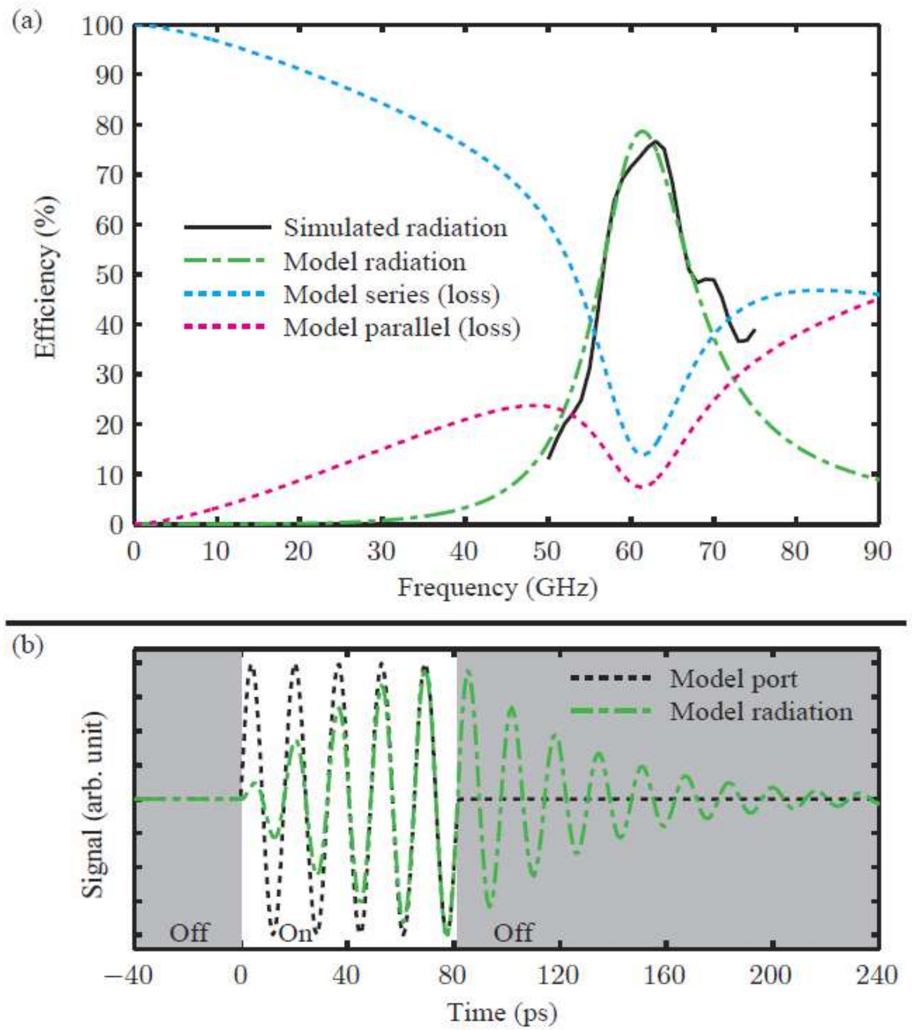


Slot-fed DRA

DRA Equivalent Circuit Model

- Transmission line with resonator coupling

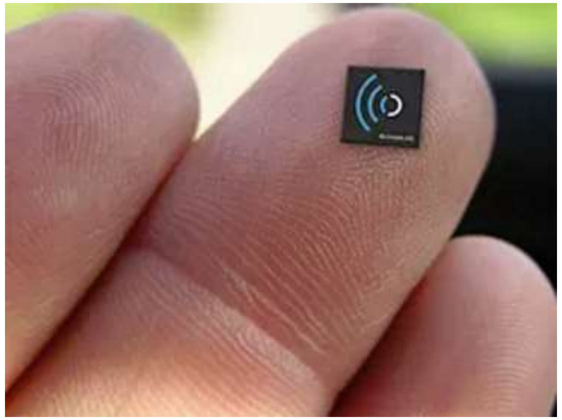


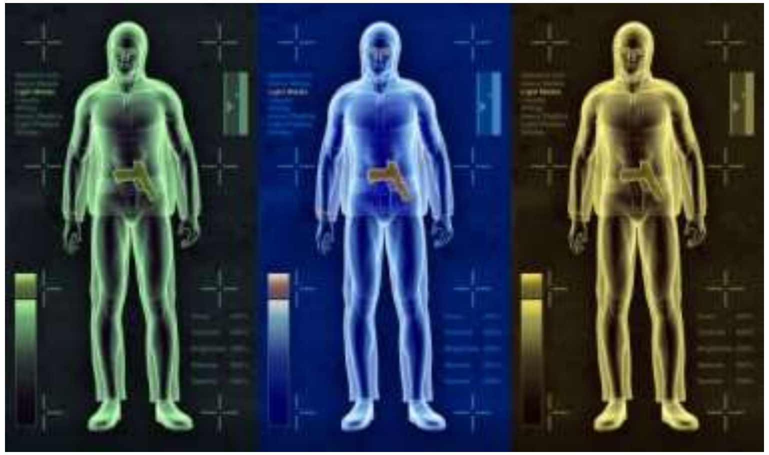


From Research to Enterprise

- Lund University
  - High-speed communication
  - Spectroscopy
  - Pulse scattering, etc.
- Acconeer AB (founded winter 2011/12)
  - Security screening, material qualification
  - Domestic robots
  - Portable devices

www.acconeer.com





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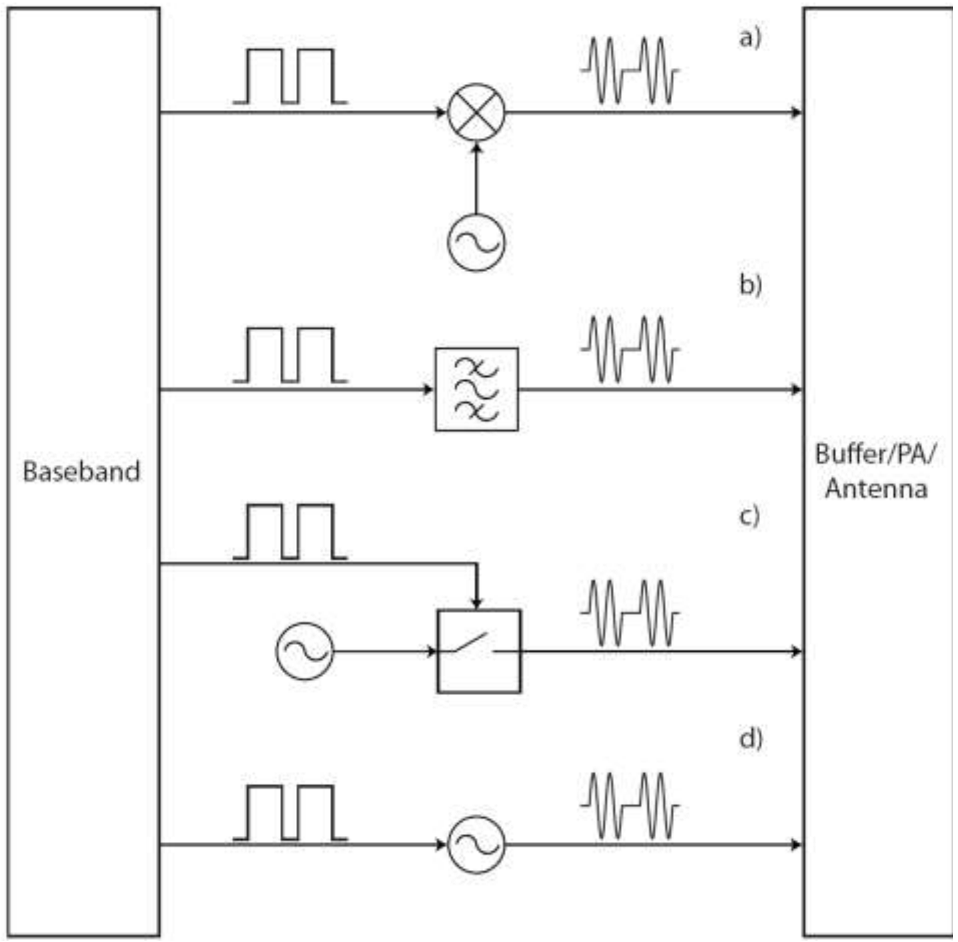
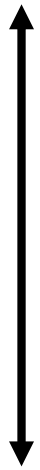
Different Pulse Generator Topologies



Established Approaches



Lund Approach

Opportunity for Low-Power Operation

Motivation

HDMI 2.0
Up to 18 Gbps

USB 3.0
5 Gbps

Wired vs. Wireless

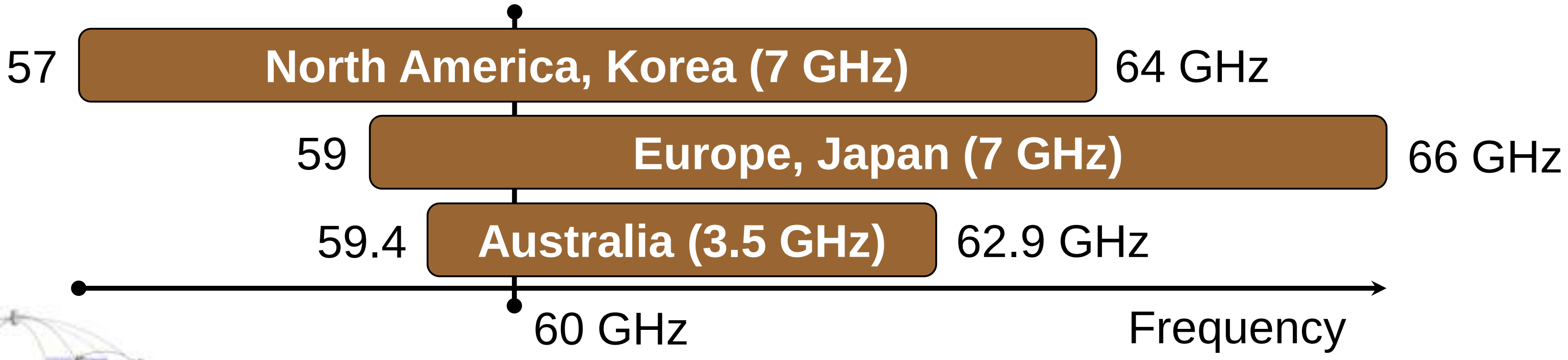
WiFi 802.11n
Up to 600 Mbps

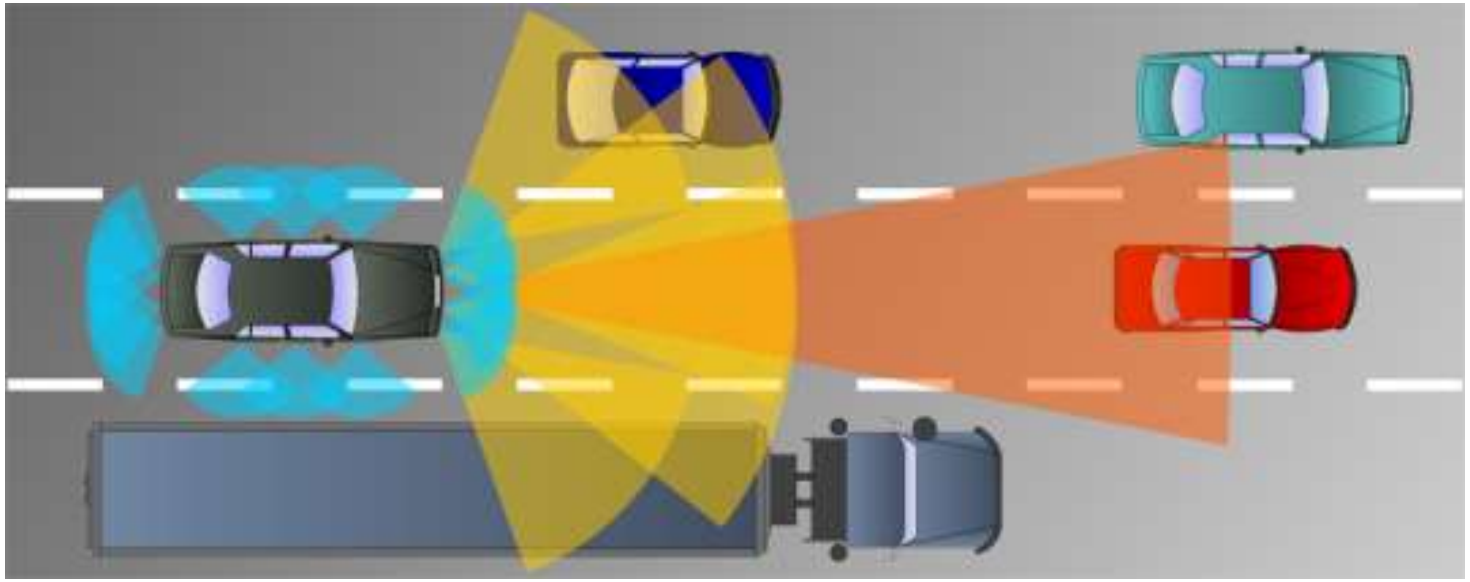
WiFi Direct
250 Mbps

Bluetooth 3.0
25 Mbps

Applications at 60 GHz and Above

- Applications
  - Wireless HDMI
  - Synchronization
  - Radar
  - Imaging
  - Localisation



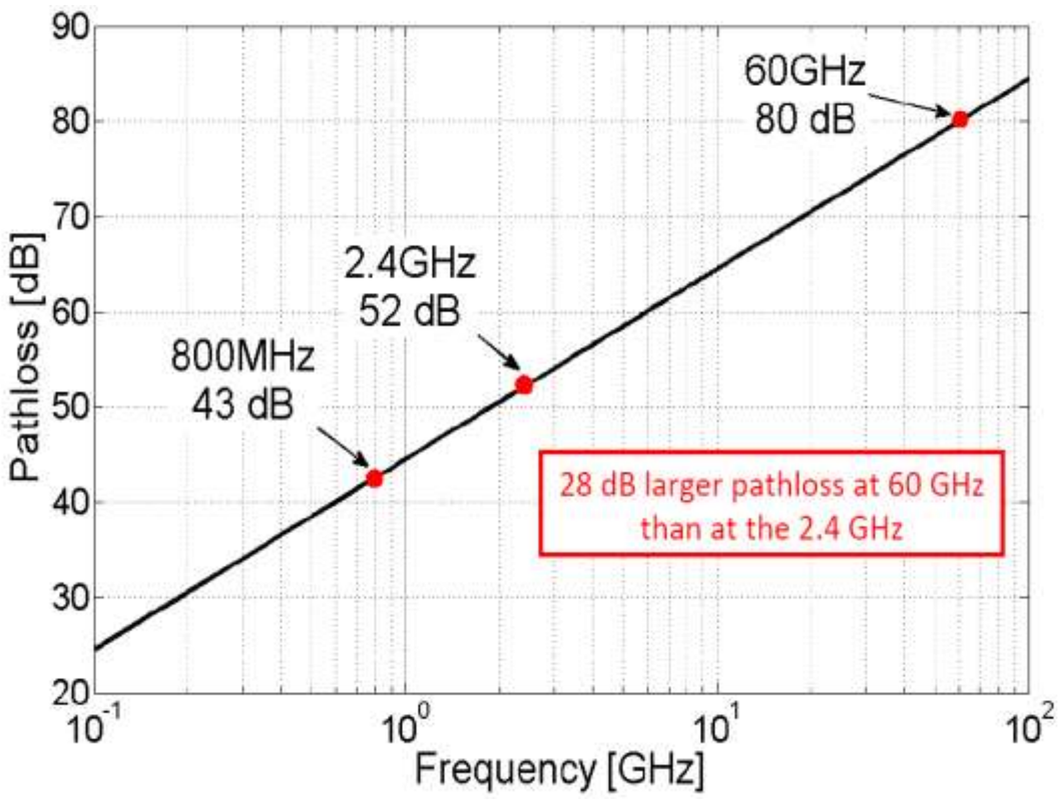


Benefits of Nanotechnology

- Potential to improve system performance using III-V technology
  - Faster devices, higher gain, lower energy consumption, better power handling, etc.
- Other approaches for signal generation and detection
  - Quantum diodes, TFETs, etc.

Impulse Radio at 60 GHz

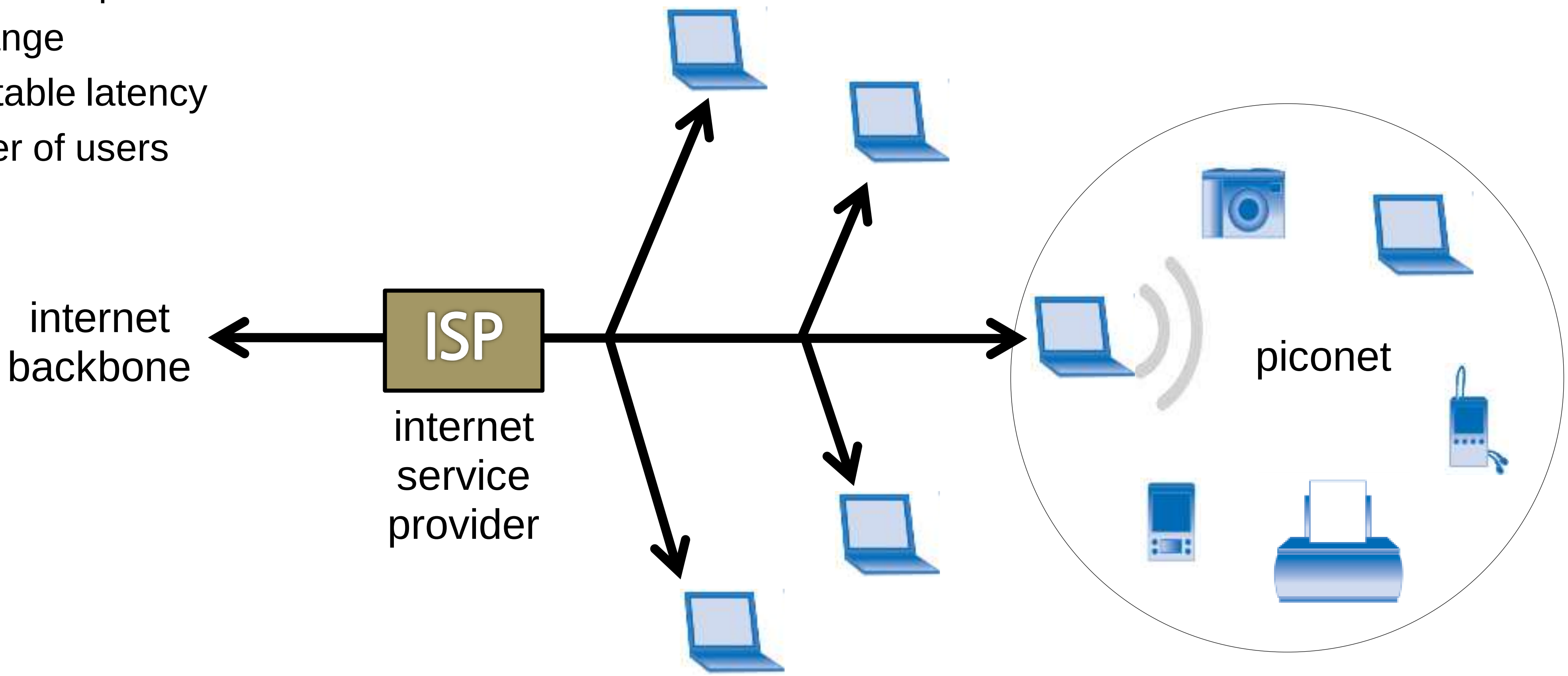
- 60 GHz band is unlicensed (but not unregulated)
- Robust – Simple modulation
  - OOK, on-off keying
  - PPM, pulse position modulation
- High bit rate – Utilises alot of bandwidth
  - 7 GHz bandwidth available
- Limited range – Allows reusage of spectrum
  - Pathloss, proportional to propagated wavelengths
  - 80 dB pathloss @ 60 GHz (4 meters) as compared to 52 dB pathloss @ 2.4 GHz
- Small form factor - Wavelength is 5 mm @ 60 GHz
  - Antennas, typically ~½ wavelength
  - Inductors, typically << wavelength



Free space path loss at 4 m

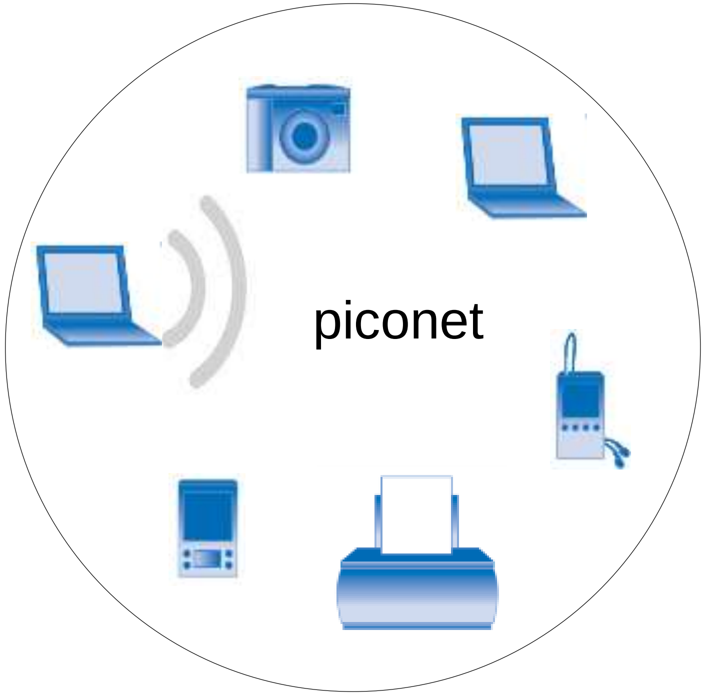
High-Speed Wireless Communication

- Application Trade-Offs
  - Size of data packets
  - Link range
  - Acceptable latency
  - Number of users



Multiplexing – Coexisting Networks

- Multiple Access Coding - Multiplexing
  - Coexisting networks on a spectral bandwidth
  - Hopping provides better security and averages fidelity
- Frequency Division Multiple Access (FDMA)
  - The band is divided into sub-bands
- Time Division Multiple Access (TDMA)
  - The band is used in different time-slots
- Code Division Multiple Access (CDMA)
  - A code-sequence with both time and frequency multiplexing is used for each channel



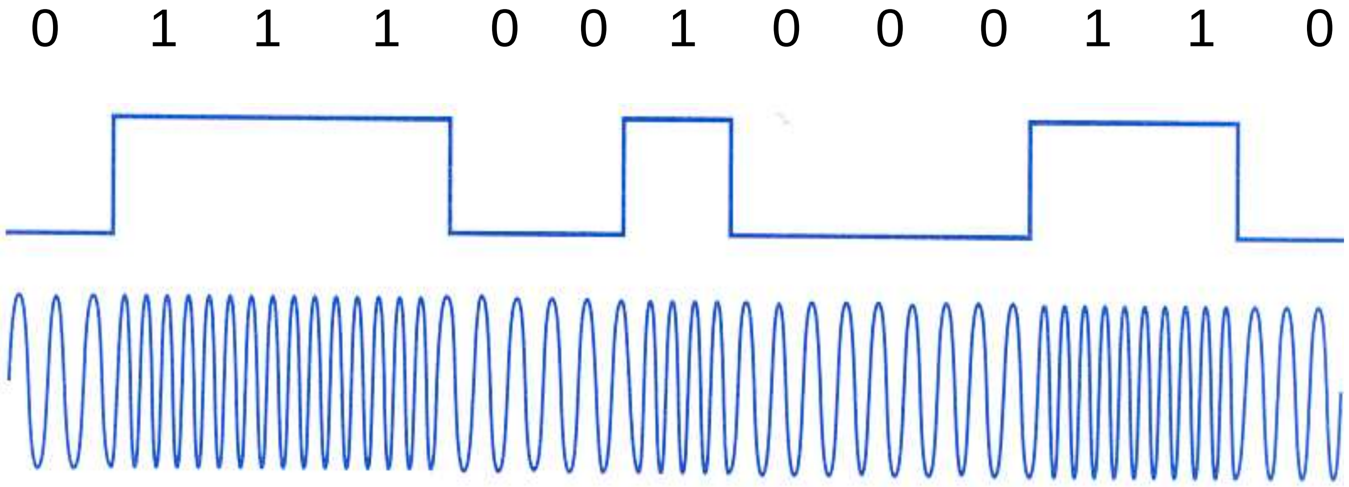
Example: Bluetooth

- Bluetooth
  - Bit rate: up to 18 Mbps
  - Carrier frequency: 2.45 GHz
  - Range: approx. 10 m
  - Maximum number of piconets: ~10

Binary data

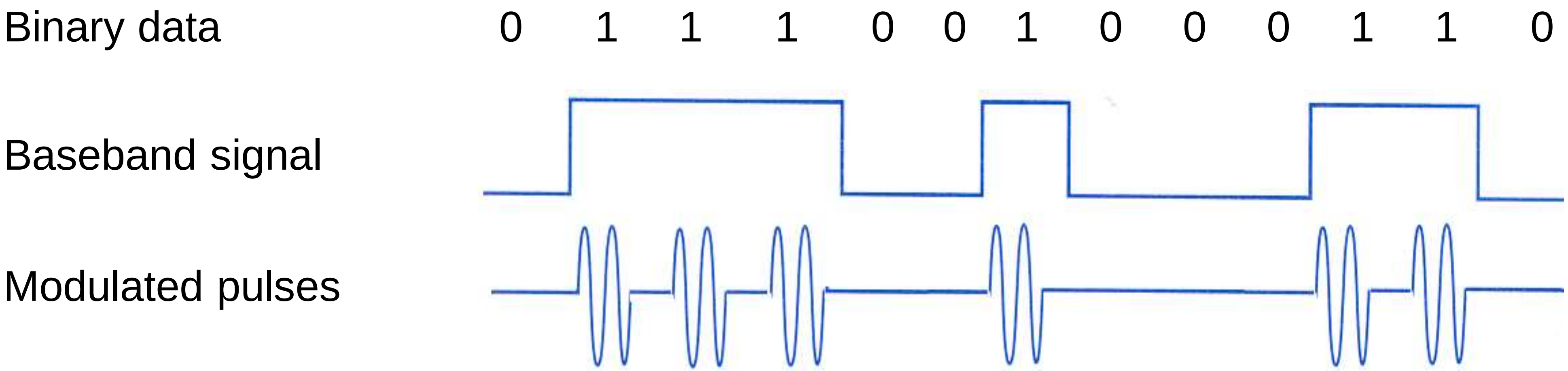
Baseband signal

Modulated carrier
(CDMA multiplexing)



Impulse Radio Communications

- Signal lacks continuous carrier
- Information is transmitted “digitally”



Ultra Wideband (UWB) Communications

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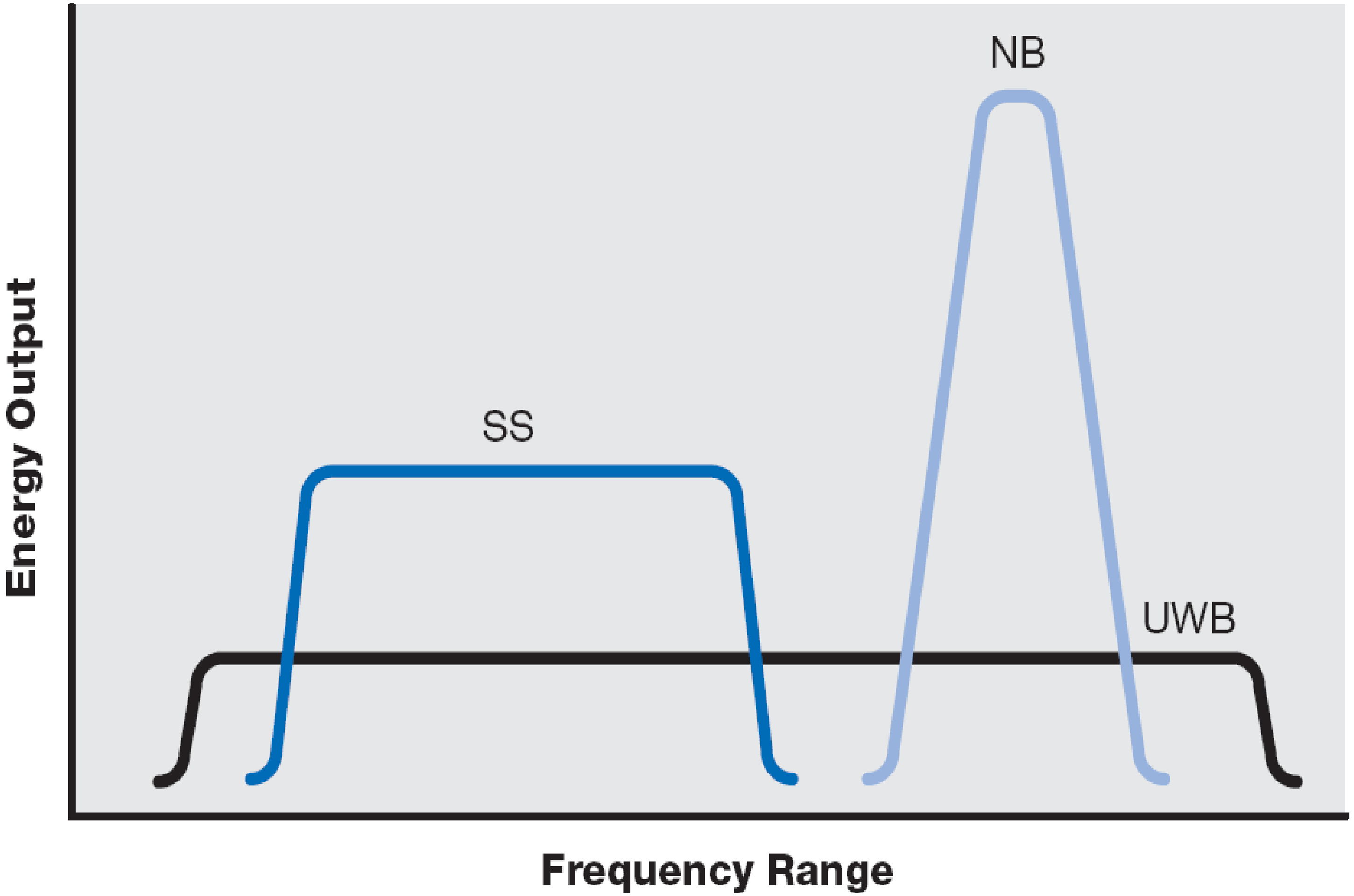
- UWB System
  - Bit rate: 480 Mbps
  - Carrier frequency: 3-10 GHz
  - Link range: 3 m
  - Maximum number of piconets: ~3
- Benefits
  - The power is “distributed” over a wide frequency band
  - Coexists with other systems without degrading their performance (ideally)
  - Multipath fading can never occur over the whole band



Pulse Generation Techniques

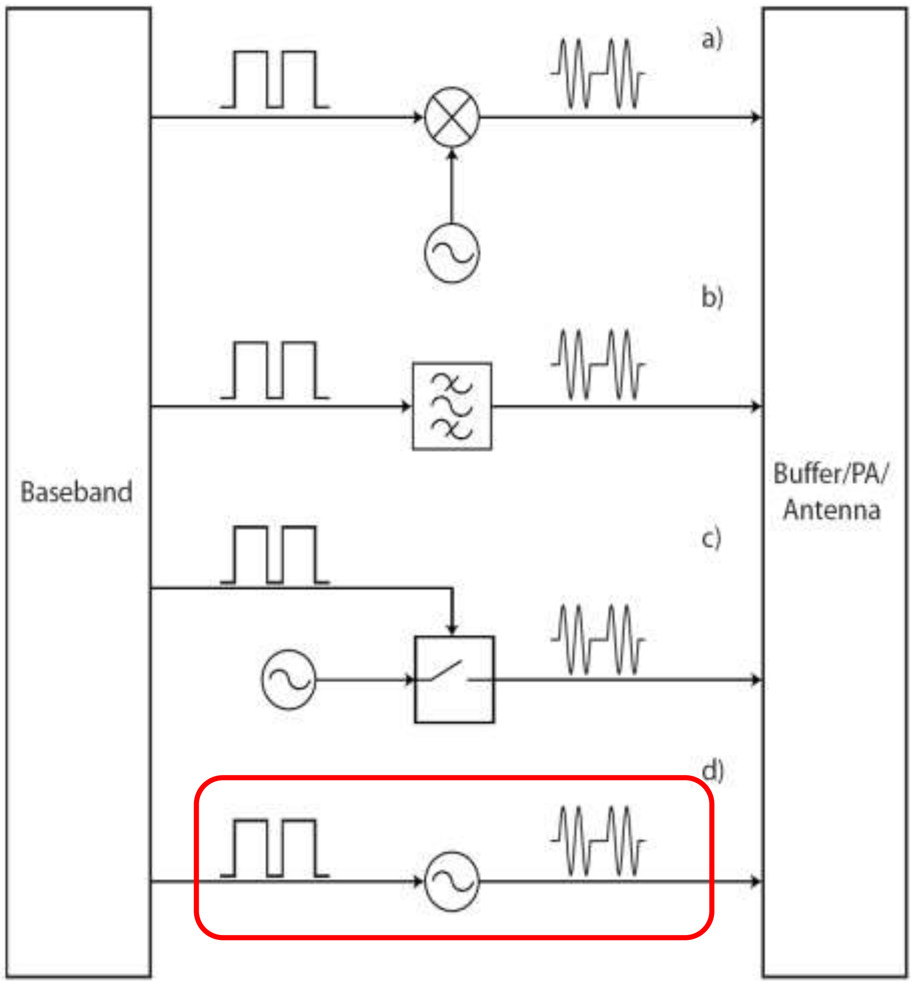
- Need short baseband pulses
- Energy efficiency?

<u>Mixer</u>
LO always on
Mixer conversion loss

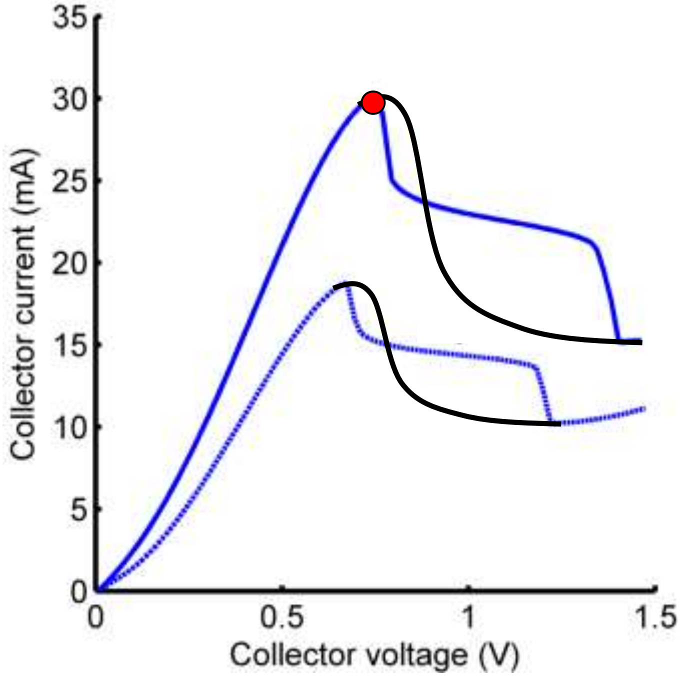
<u>Filter</u>
Little energy at target band
Filter loss

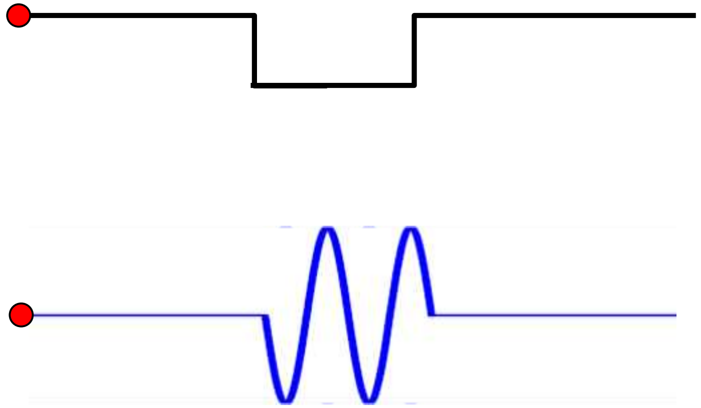
<u>RF switch</u>
LO always on
Switch loss

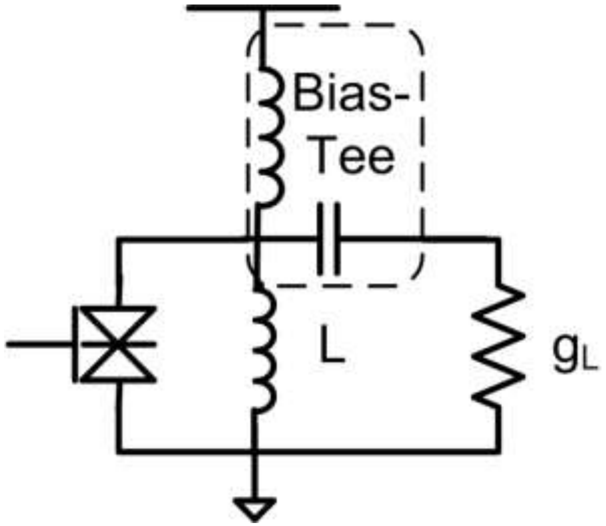
<u>Switched oscillator</u>
LO only on when needed
Switch loss



Nanotechnology from Lund







Signal startup:

$$v(t) = \frac{2v_o}{\sqrt{1+\left(\left(\frac{2v_0}{v(0)}\right)^2-1\right)e^{-\epsilon\omega_0 t}}}\cos(\omega_0 t+\varphi(0))$$

$$\epsilon = -\left(g_{oeq}(0)\sqrt{\frac{L_{eq}}{C_{eq}}}+\frac{1}{Q_{tank}}\right)$$

Signal quench:

$$v(t) = V_{max}e^{\frac{-\omega_0}{2Q_{tank}PDC}t}\cos(\omega_0 t+\varphi(0))$$

III-V MOSFET/RTD Integration

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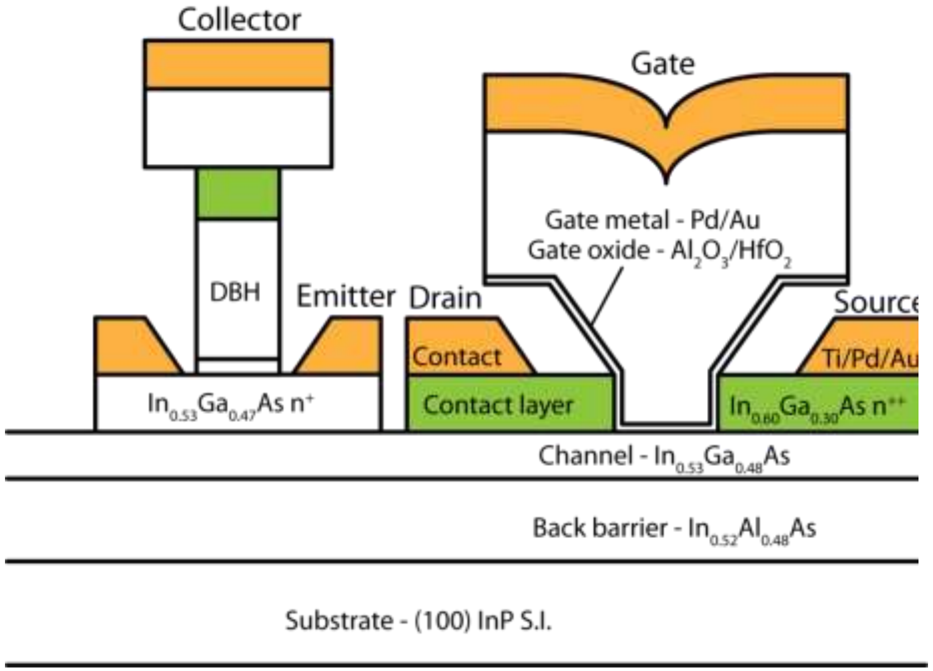
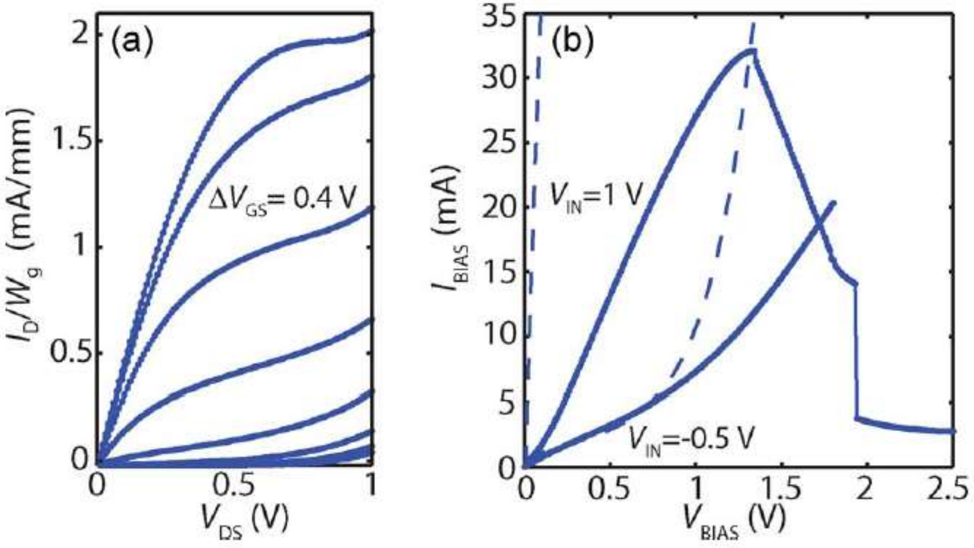
Co-integration of InP/InGaAs MOSFET and RTD on SI InP Substrate



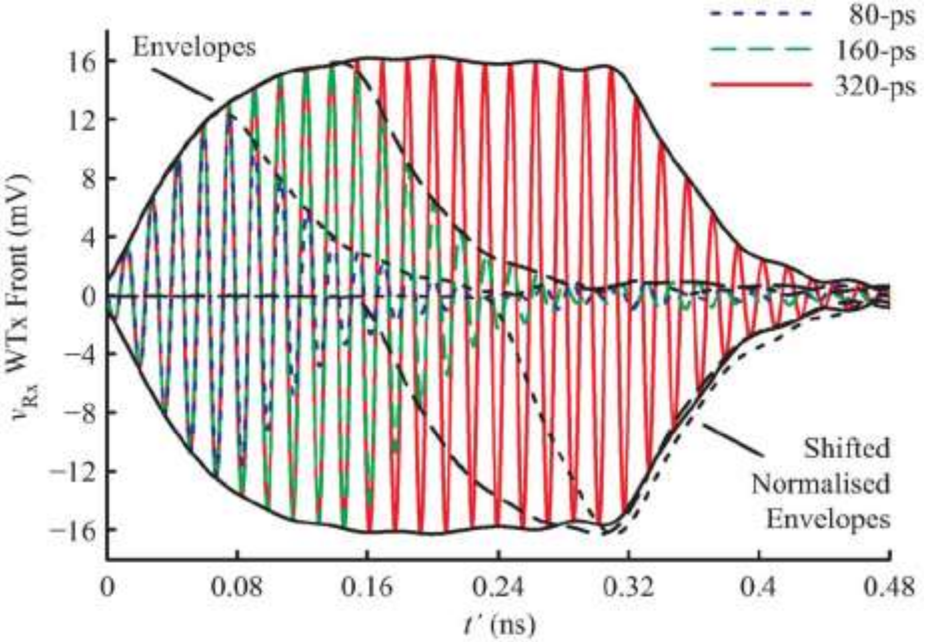


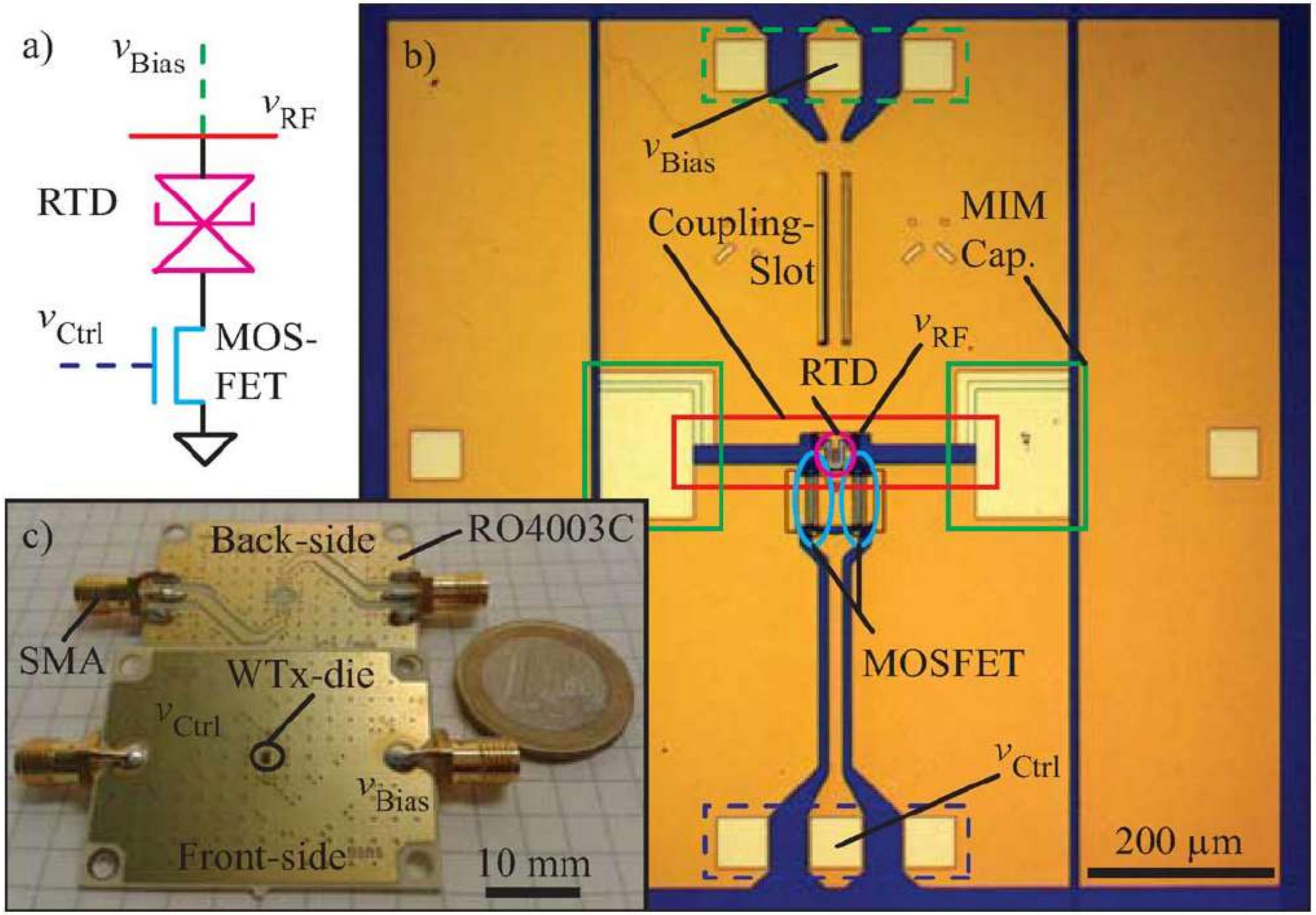
Egard et al IEEE EDL 2012

Low R_{on}=199Ωµm
High I_{on}=2.0mA/µm
High g_m=1.9mS/µm

Antenna Integrated with Pulse Generator

- Pulse Generator on DRA
- Transmitter
  - 60 GHz
  - Pulse length < 100 ps
  - 5 dBm pulse power
  - 9% dc-RF (37 mW, only when on)

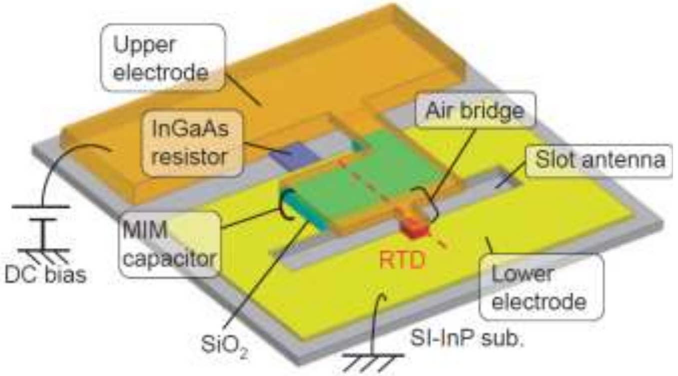


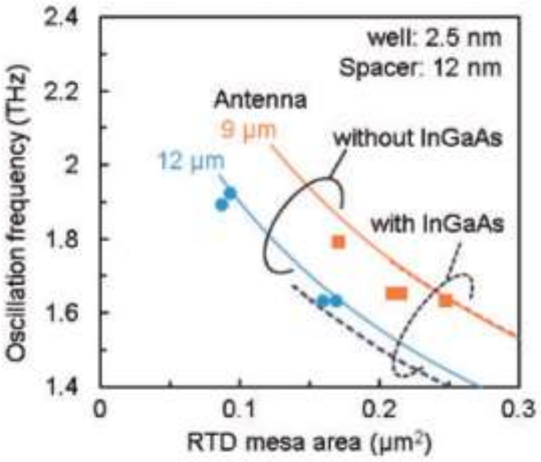


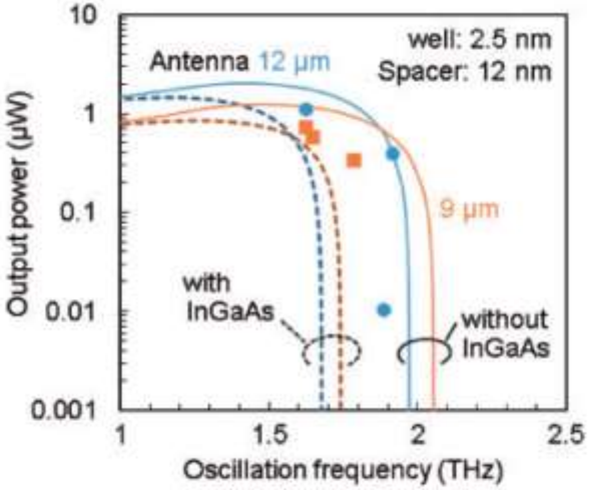
1.92 THz RTD Signal Generation

Oscillation up to 1.92 THz in Resonant Tunneling Diode by Reduced Conduction Loss

- **Increased maximum frequency to 1.92 THz (0.4 μW) in RTD**
- **12 μm integrated slot-antenna (lens aperture)**
- **Reduced conduction loss in antenna fabrication process**







Maekawa, et al., Appl. Phys. Express, (9), 2016