From 1 Tbs per Carrier to 1 THz

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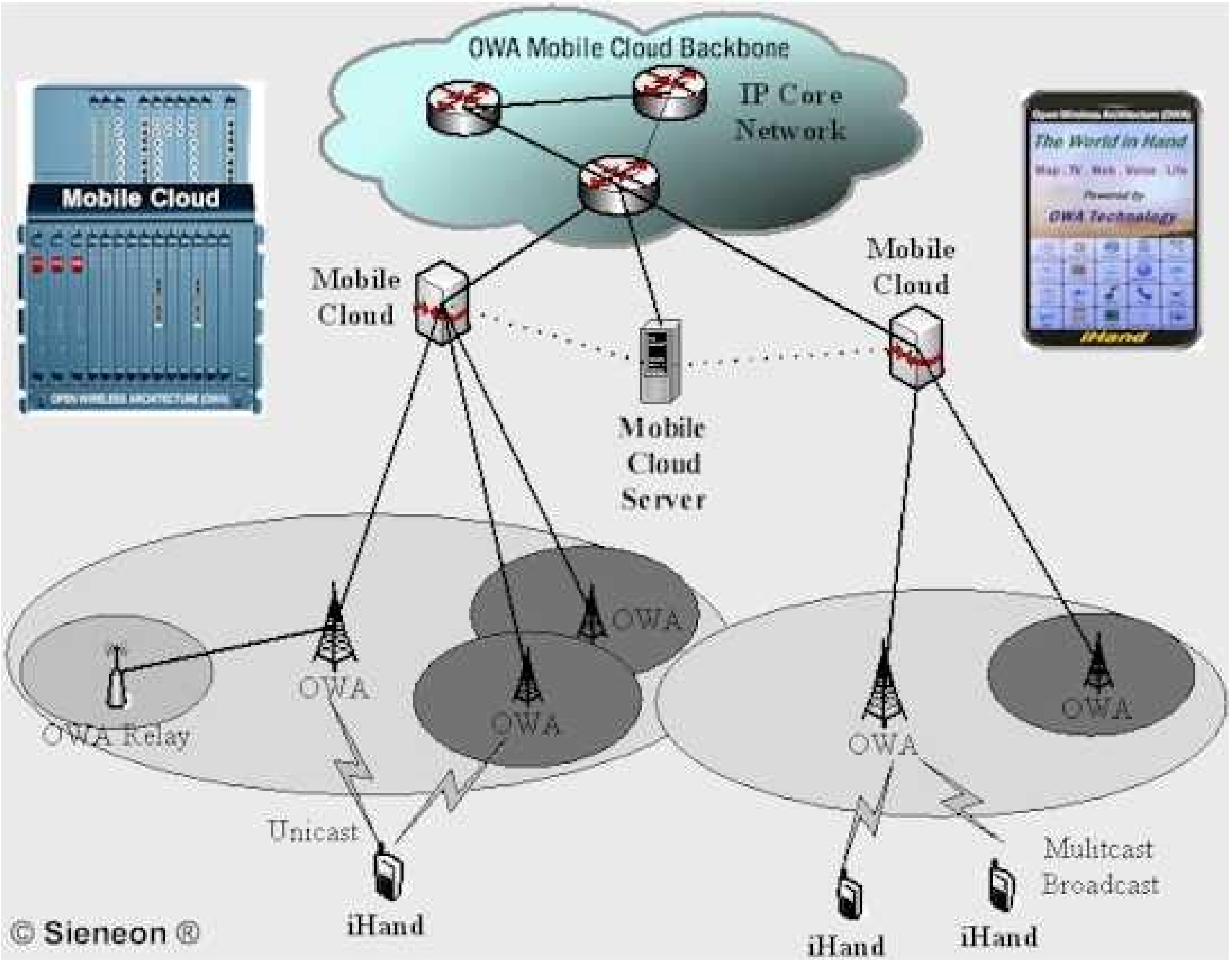
European Microwave Conference

Outline

- Introduction
- Examples of Tbs Wireless and Photonics Systems
- Segmented Power DAC Architectures
- Conclusions

We are addicted …

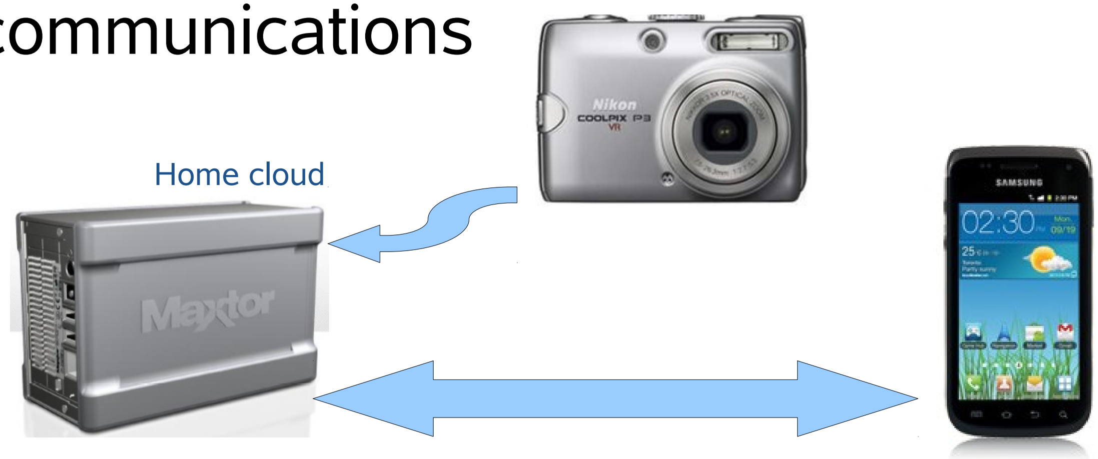
What's in a cloud?



- wireless links
- optical fiber links
- data centers

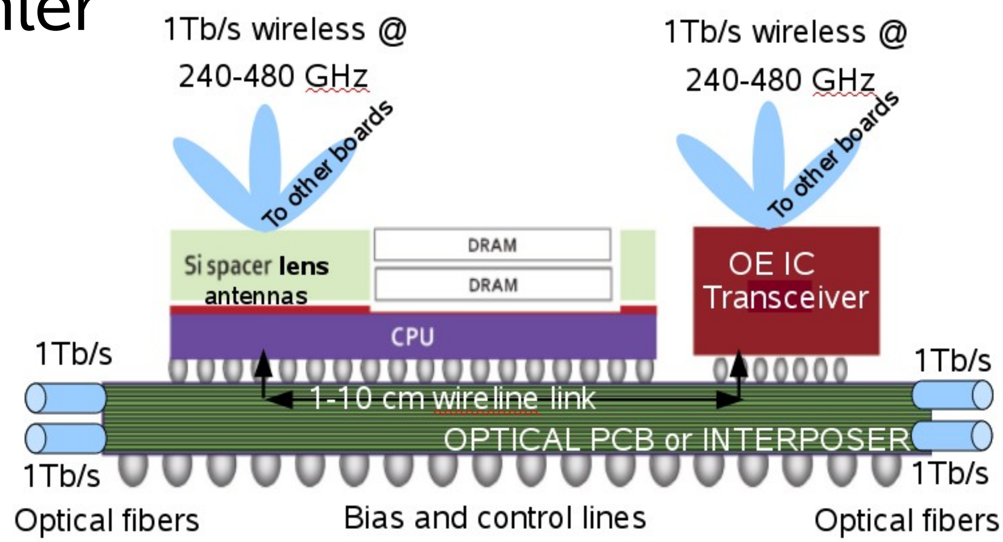
Why 100+Gb/s wireless?

- Near field communications



- Short-range reconfigurable wireless data transmission in the data center

- Board-to-board



Need >10x improvement in efficiency, bandwidth

Need digital techniques at over 100 Gbaud

Need centre frequencies above 200 GHz

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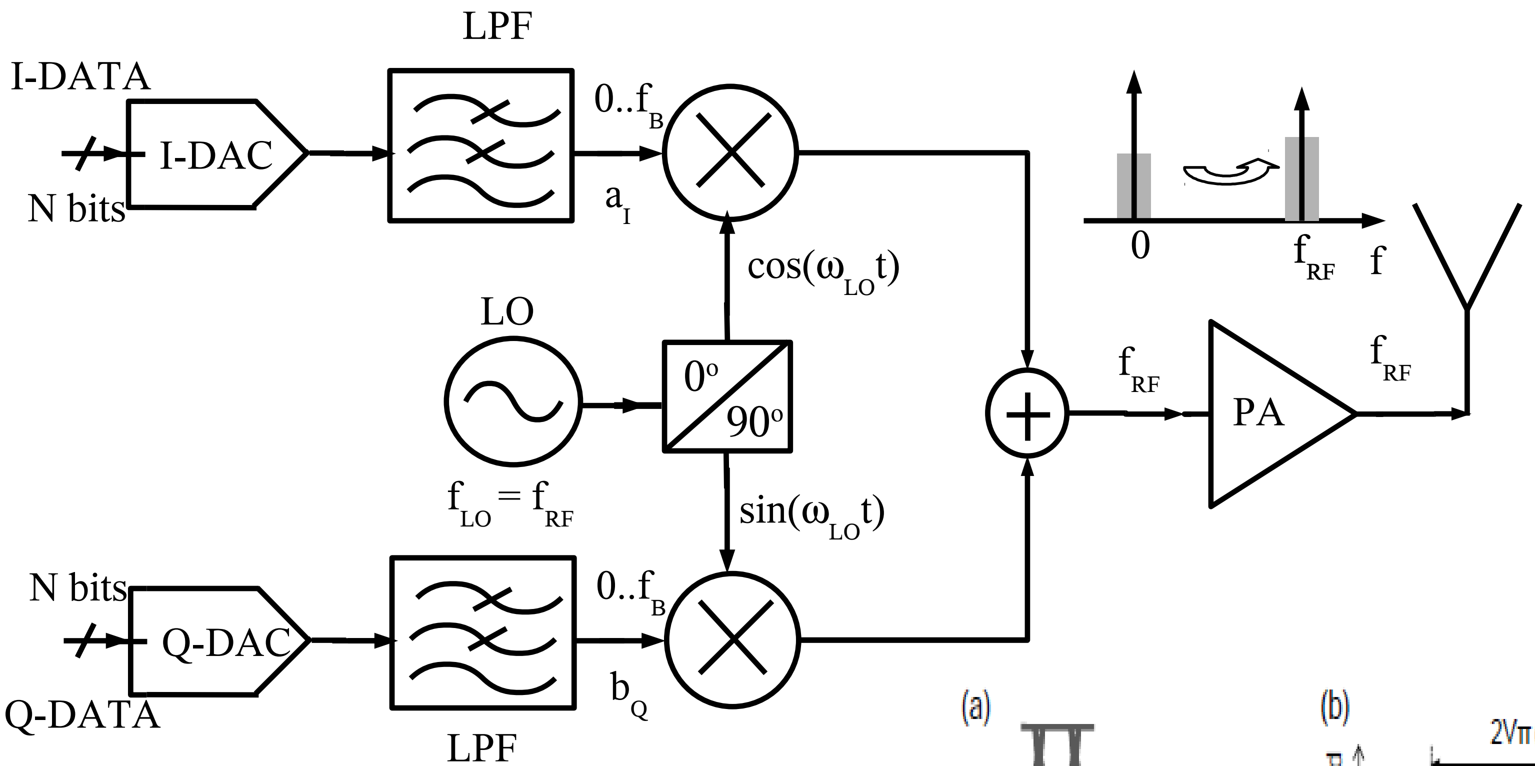
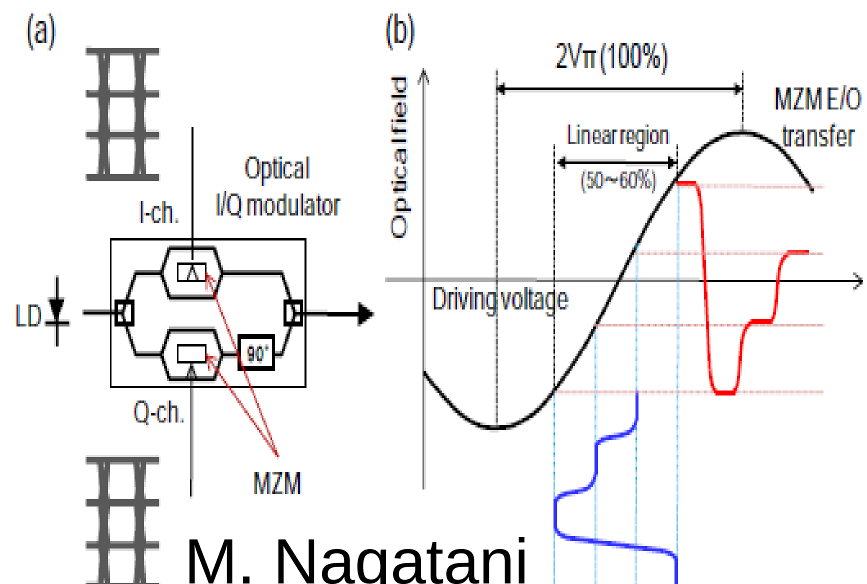
State-of-the-Art mm-Wave Radio/Fiberoptics TX

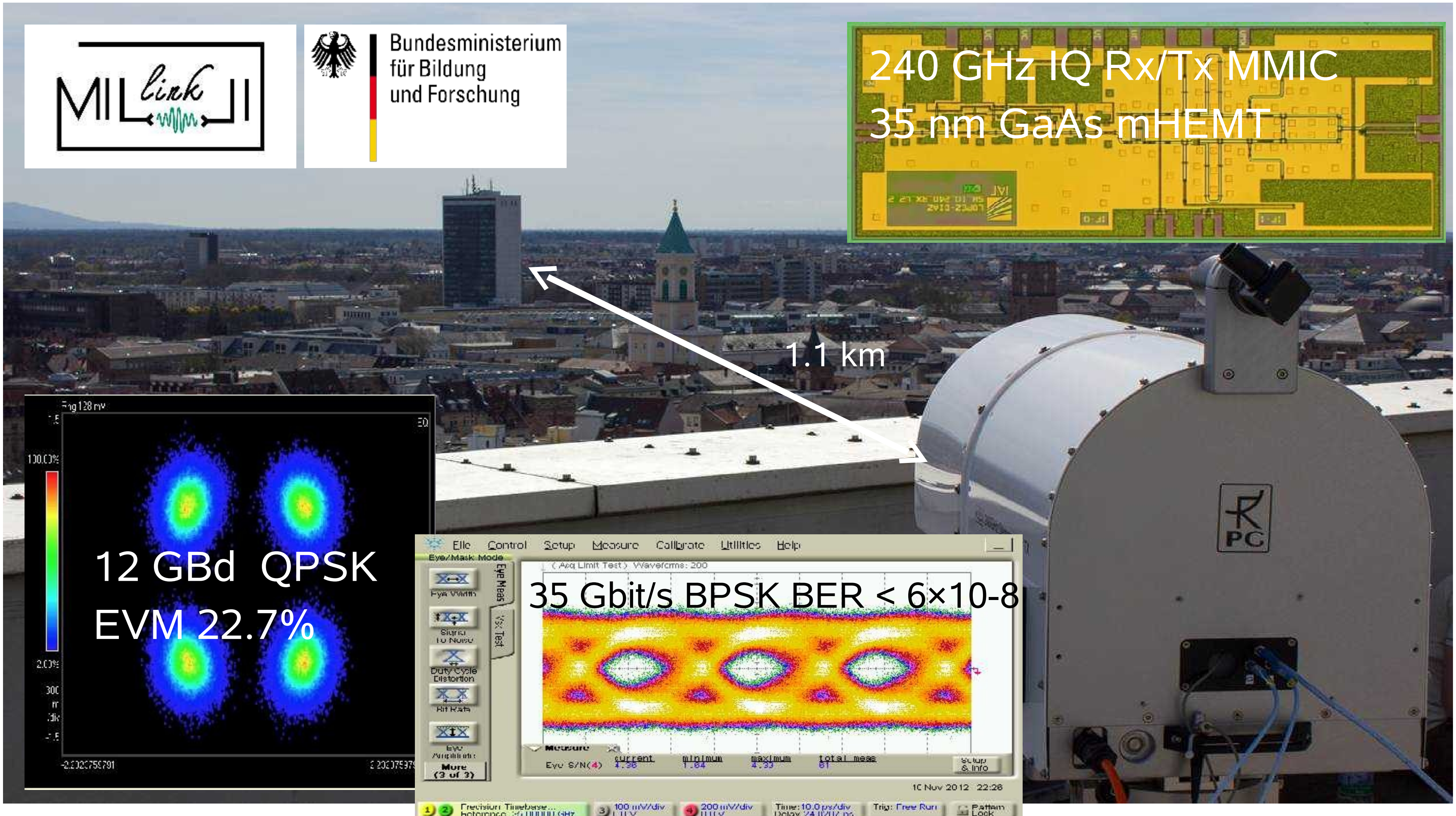


- Versatile
- Transparent to modulation scheme
- Linear
- Inefficient!



M. Nagatani

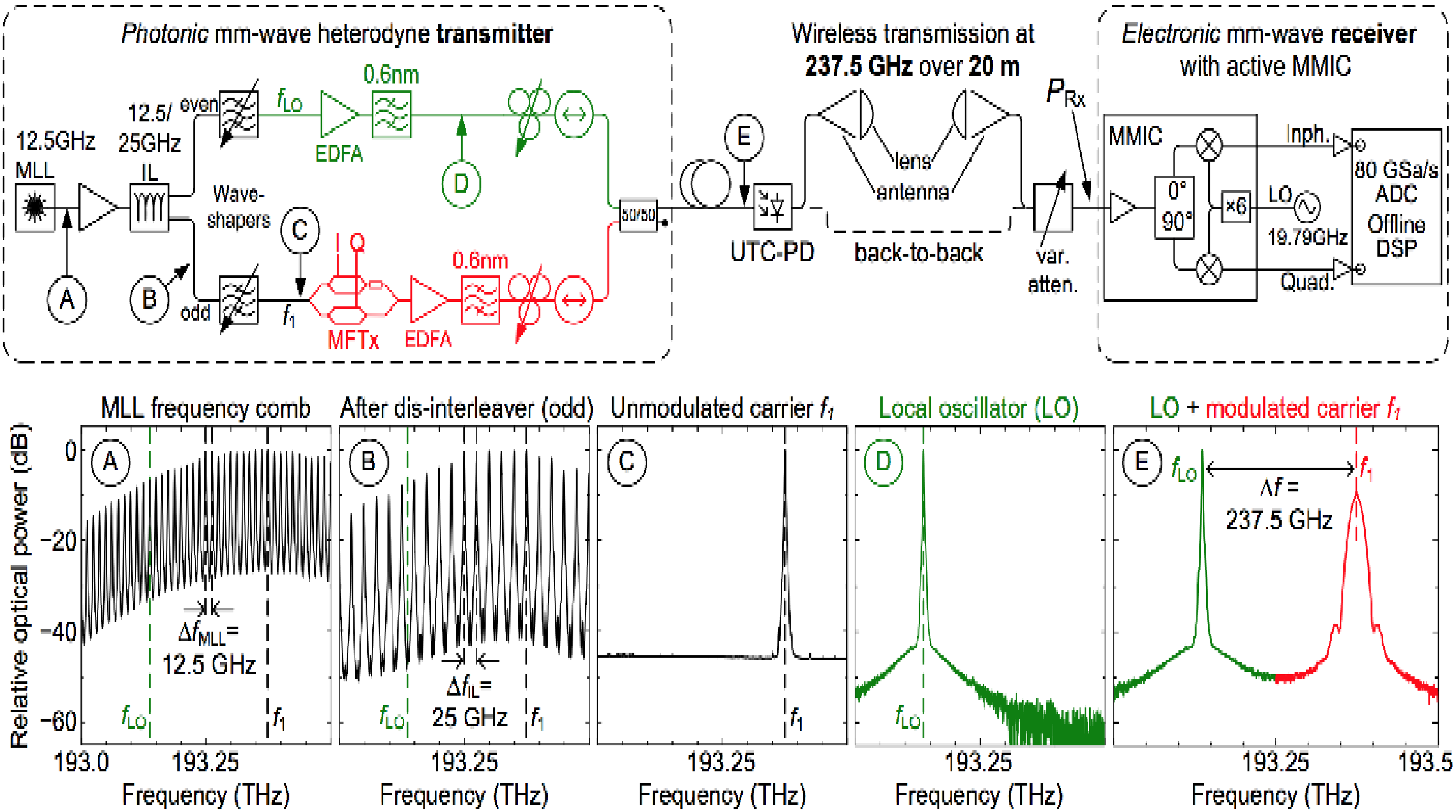
240-GHz, 1.1km Wireless Link



Fraunhofer IAF · KIT Karlsruhe Institute of Technology · Radiometer Physics GmbH · SIEMENS · KATHREIN

Courtesy of Ingmar Kalfass, Universität Stuttgart

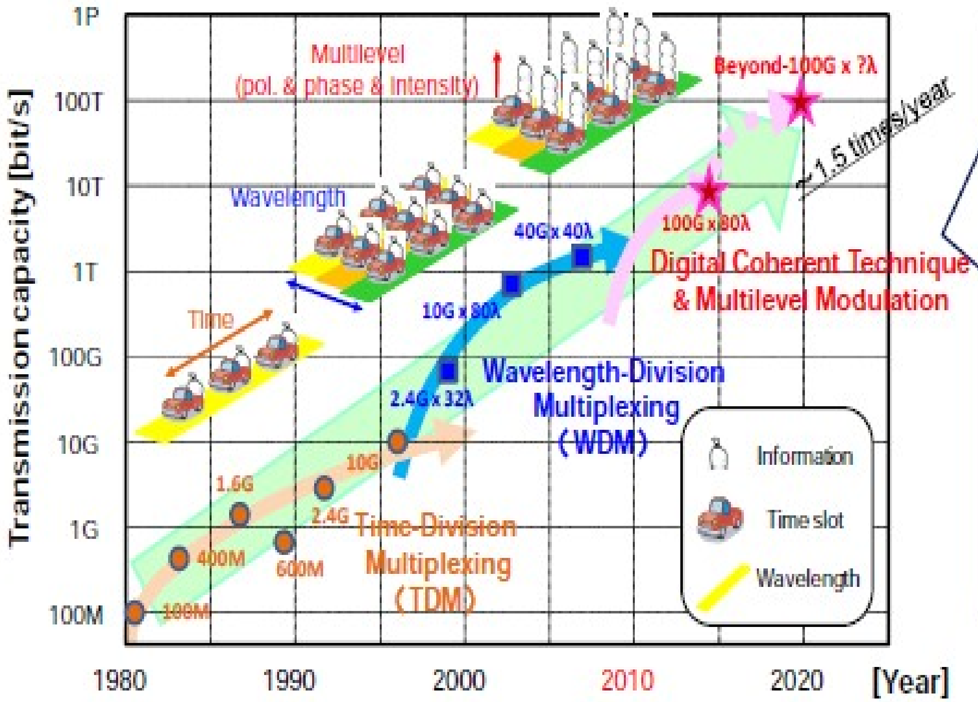
100 Gb/s with Optical Tx & Electronic Rx



König et.al. OFC2013

Courtesy of Ingmar Kalfass, Universität Stuttgart

Trends in Optical Communications

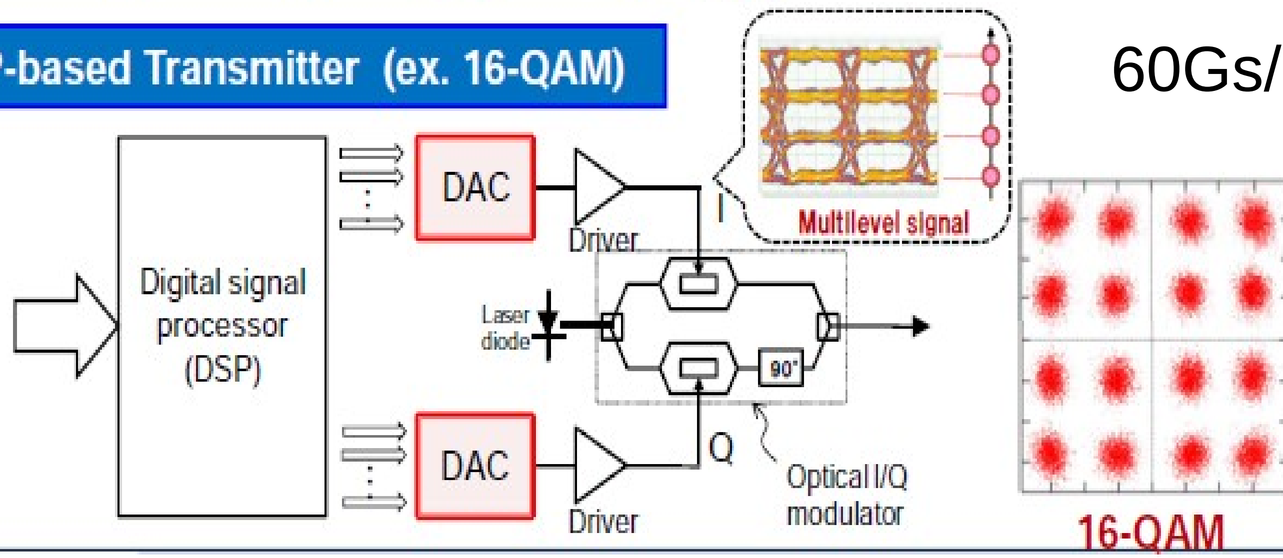


Key technologies for beyond-100Gb/s/wavelength

- Digital coherent technique (Coherent detection + DSP)
- High-order multilevel modulation (ex. m-QAM)

DSP-based Transmitter (ex. 16-QAM)

60Gs/sec InP DACs



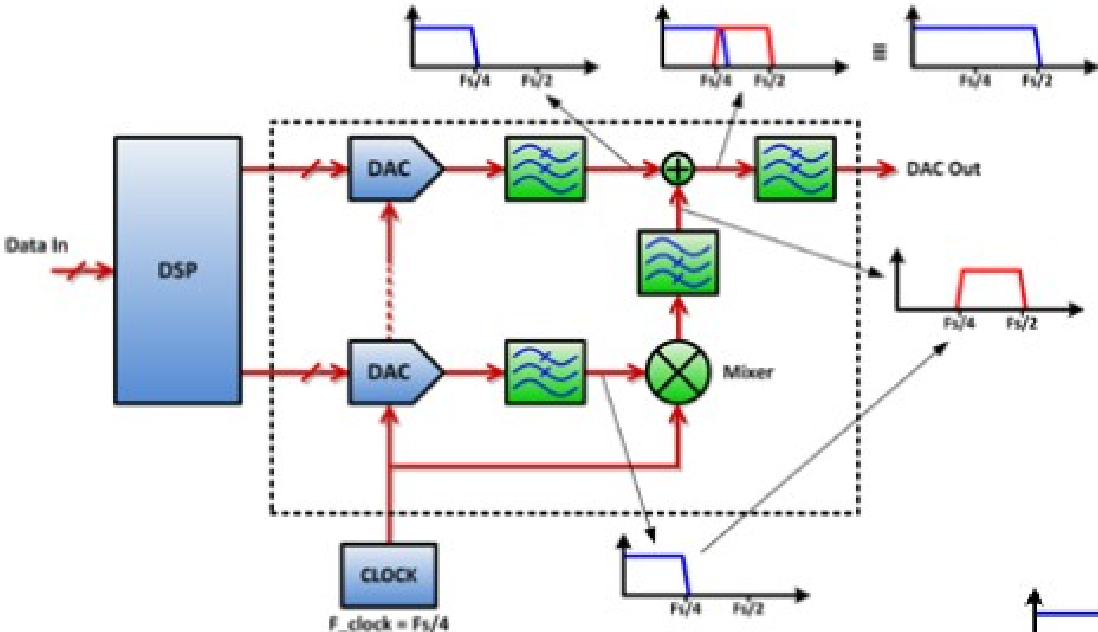
Courtesy of Koichi Murata, NTT

How Can We Get to 1 Tb/s per Carrier?

- Fiber: Dual-polarization, 16-QAM at 125 Gbaud
  - 8 data lanes at 125 Gb/s
  - Need phase equalization in receiver
  - Need 8 bit 125-GS/sec DACs
  - Need OSNR> 20 dB, optical amplifiers

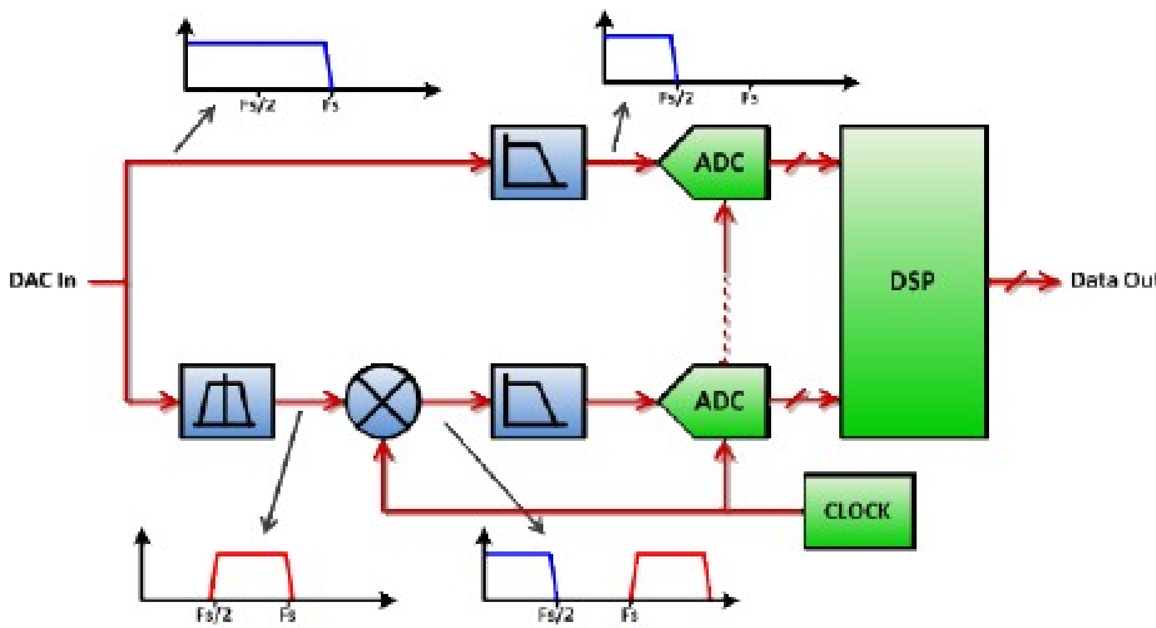
- Wireless: 256-QAM at 125 Gbaud
  - 8 data lanes at 125 Gb/s
  - Need amplitude and phase equalization in receiver
  - Need 12 bit 125-GS/sec DACs
  - Need SNR> 26 dB

Doubling DAC, ADC sampling rate by mixing

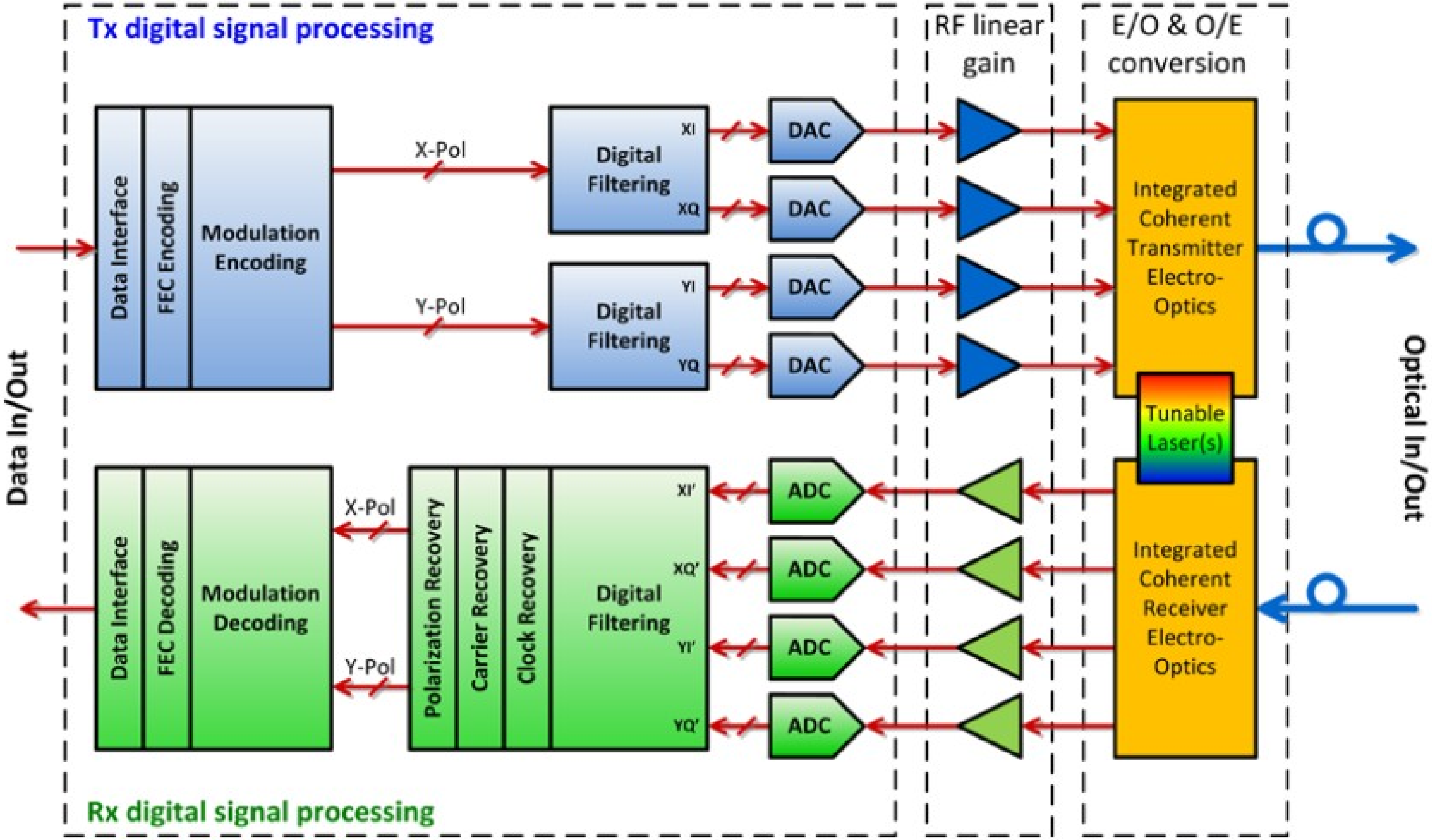


Ciena, CSICS 2013

2x64 GS/sec = 128 GS/sec



Flexible Coherent Fiberoptic Transceiver



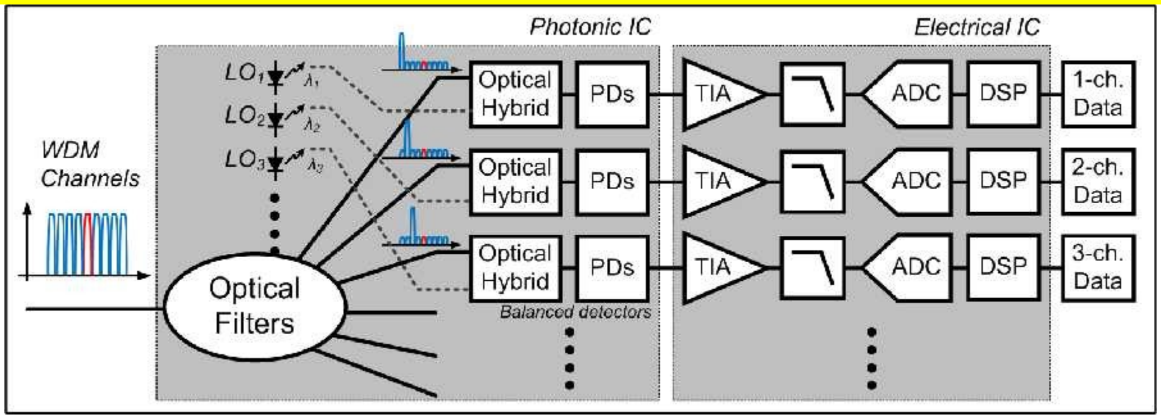
Ciena, CSICS 2013

16-QAM 4x128 Gbaud = 1.024 Tb/s

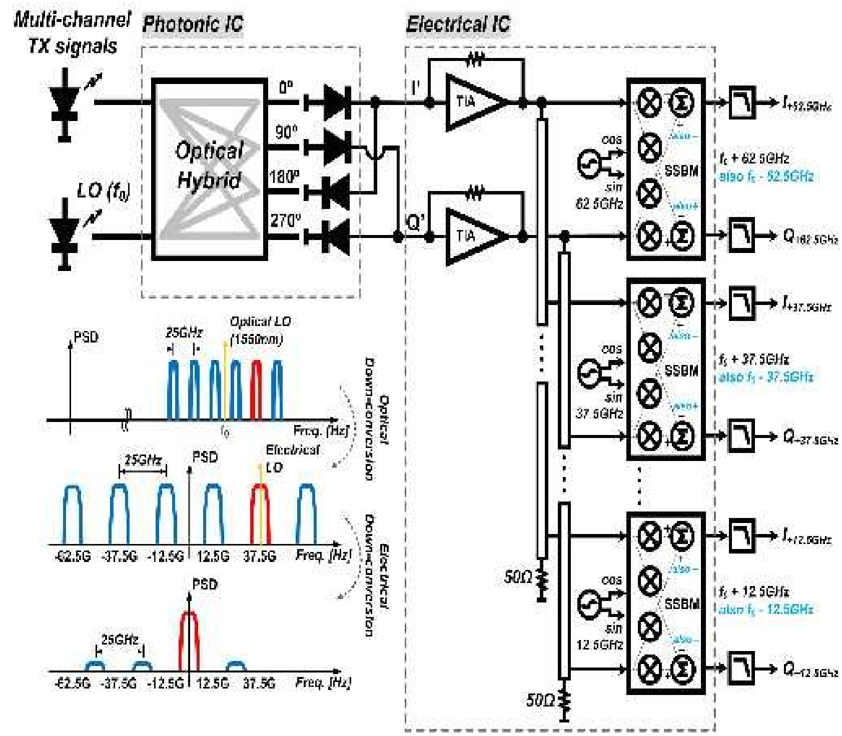
THz ICs for Optical WDM Recovery in the Electrical Domain

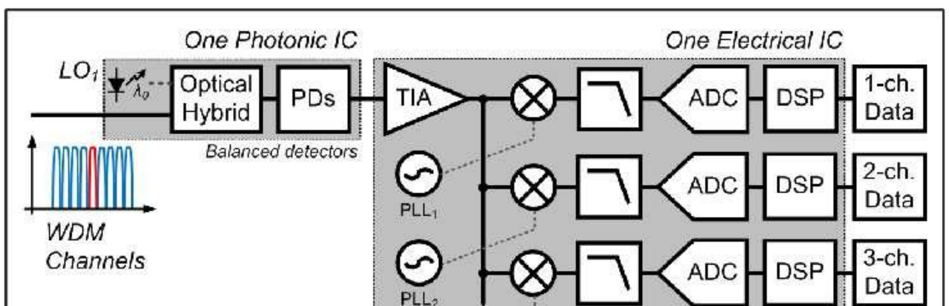
Bandwidth of optical fiber: ~5 THz ***Bandwidth of modern ICs: ~800GHz***

With THz transistors, and with optical single-sideband mixing, one electrical IC can receive 1.6 THz of optical spectrum: 64 WDM channels

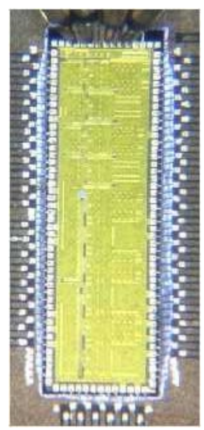


WDM receiver using THz ICs: after optical mixing, optical WDM channels become DC-800 GHz subcarriers





H-C Park *et al* (UCSB), ECOC 2013, Sept. 23-27



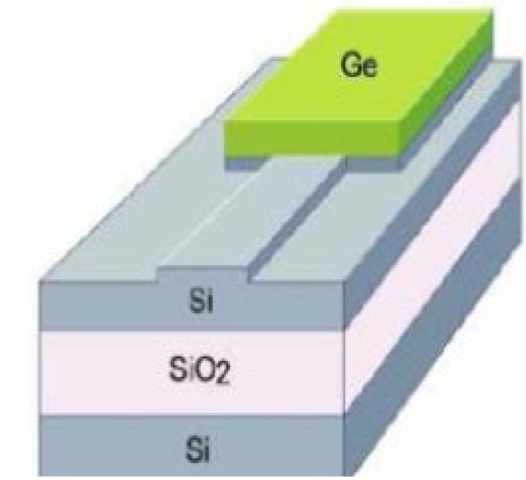
Courtesy of Mark Rodwell, UCSB

Silicon active components

- III-V Laser
- Ge photodiodes > 100 GHz bandwidth

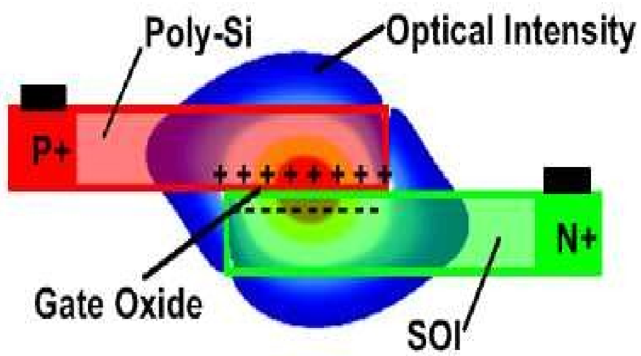
  Vertical structure

LETI



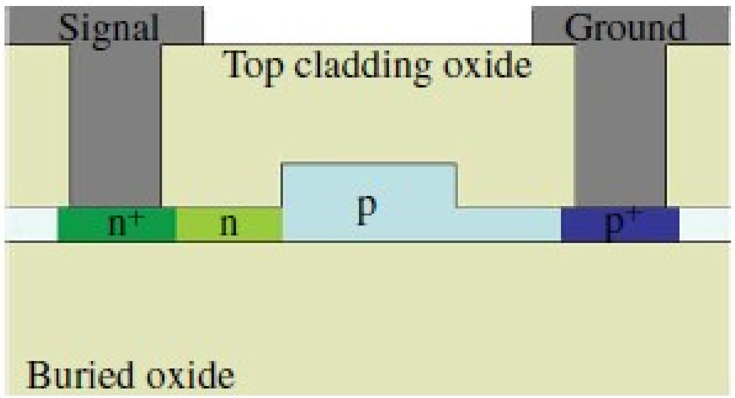
- Modulators <80 Gb/s

  Lateral structure



$$V_\pi \cdot L = 0.13 V \cdot cm$$

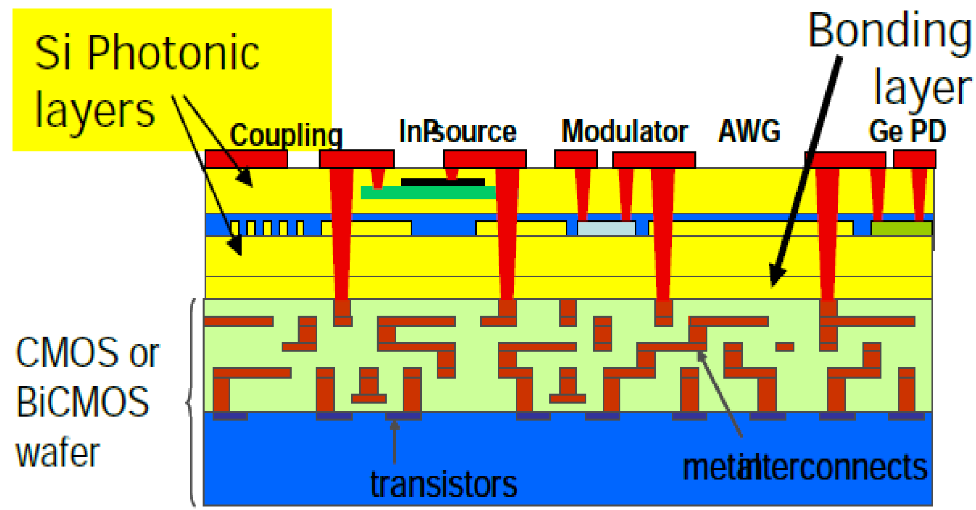
[X. Wu et al., ISSCC 2013]



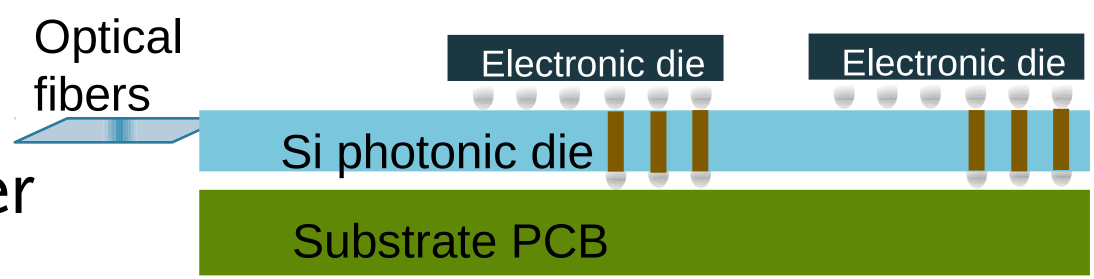
[D. Thompson et al. IEEE Ph.Letts, 2012]

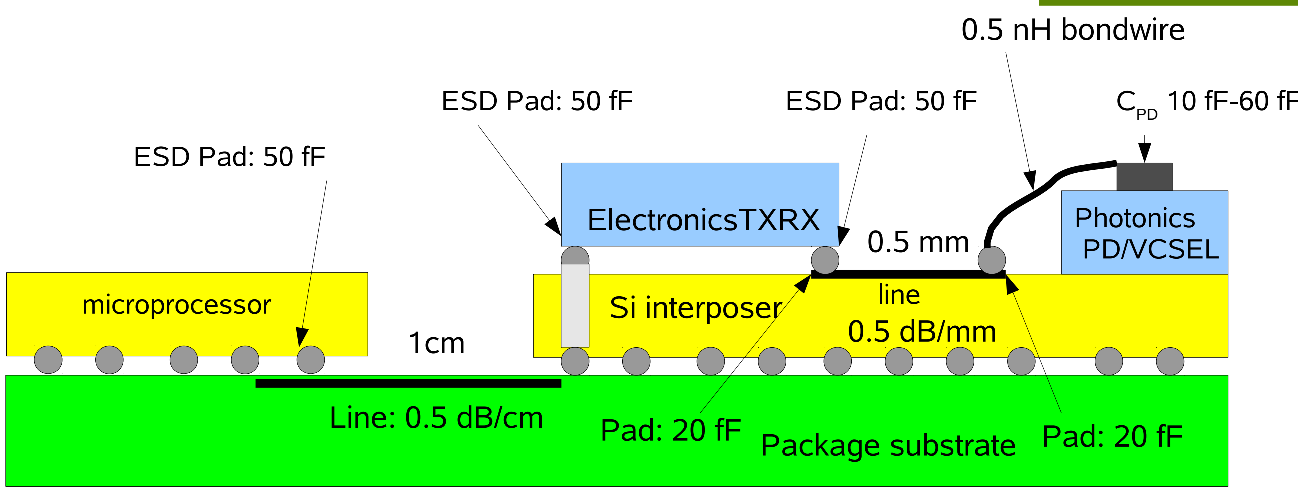
Electronics-photonics Integration

- Monolithic
  - Back-end of bulk CMOS
  - SOI CMOS
  - SiGe SOI-BiCMOS
- Heterogeneous
- Photonic/electric interposer



Heterogeneus integration (Leti)





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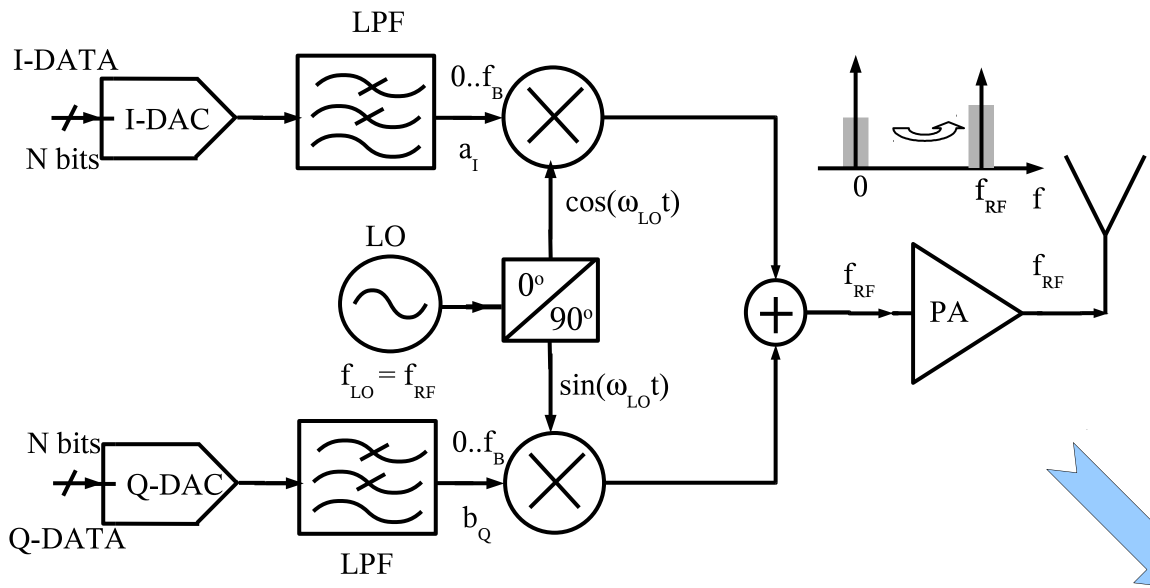
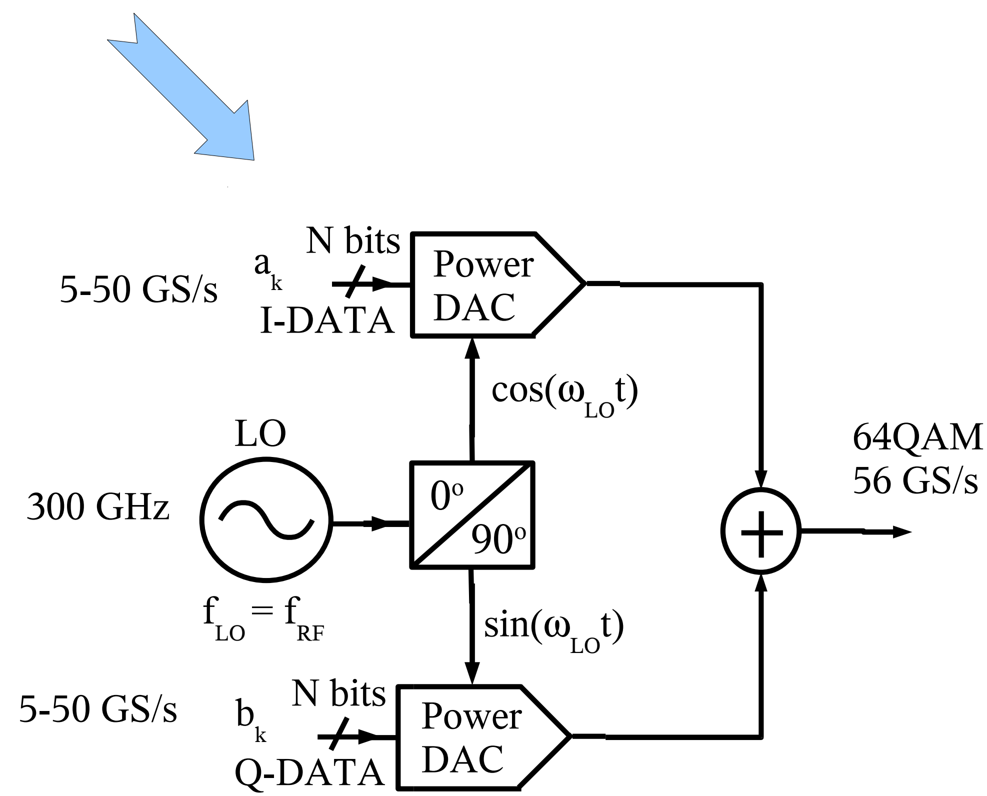
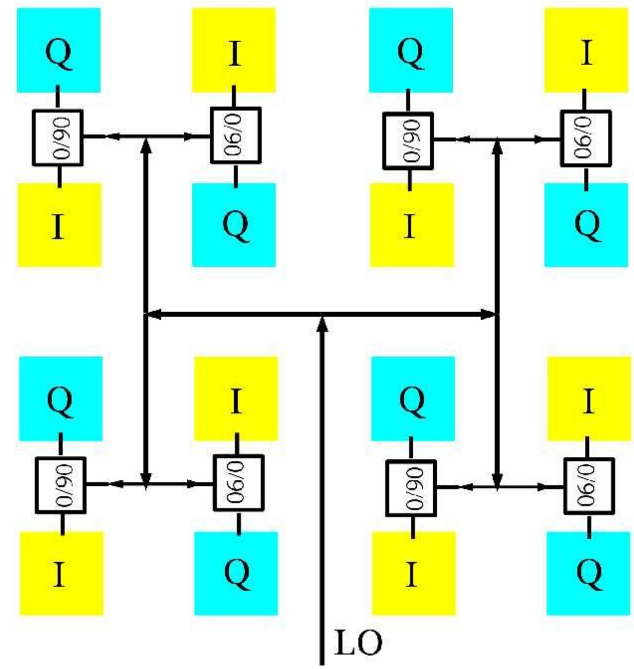
Direct Digital Modulation Transmitters



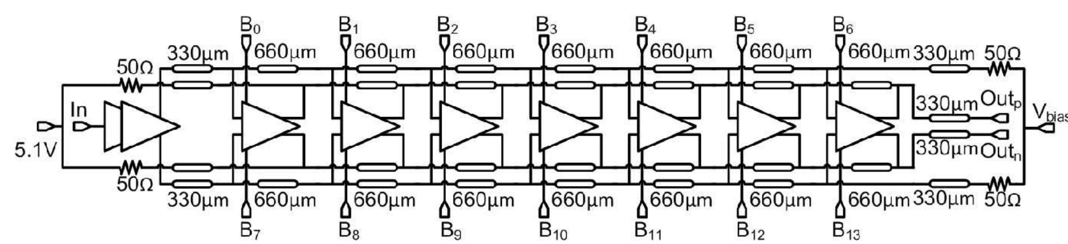


Segmented Power DAC Architectures

- Tuned (<100GHz BW) mm-wave wireless
  - Coarse segmentation at antenna level
  - Fine bits in each antenna element
  - Free-space power combining
  - 50 Gbaud

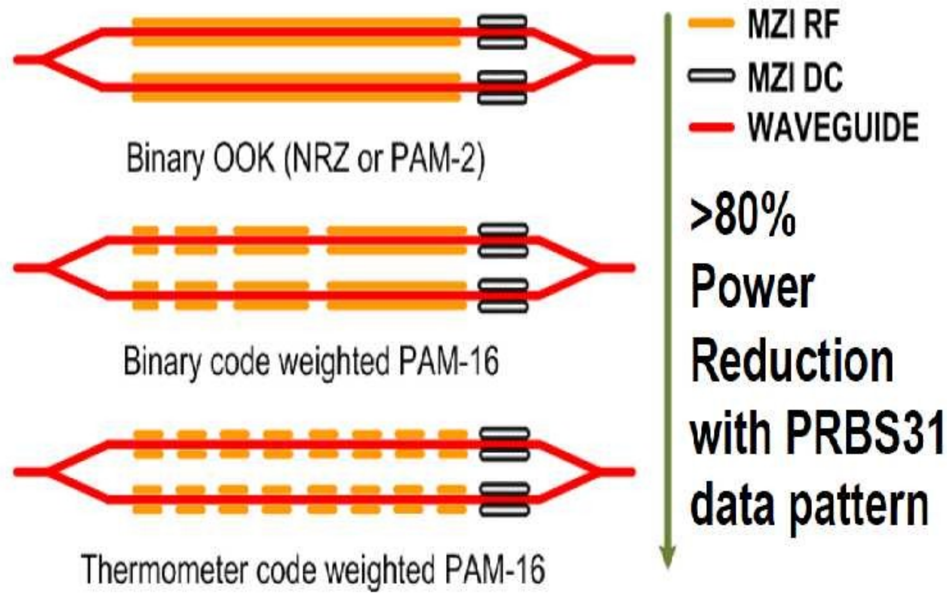


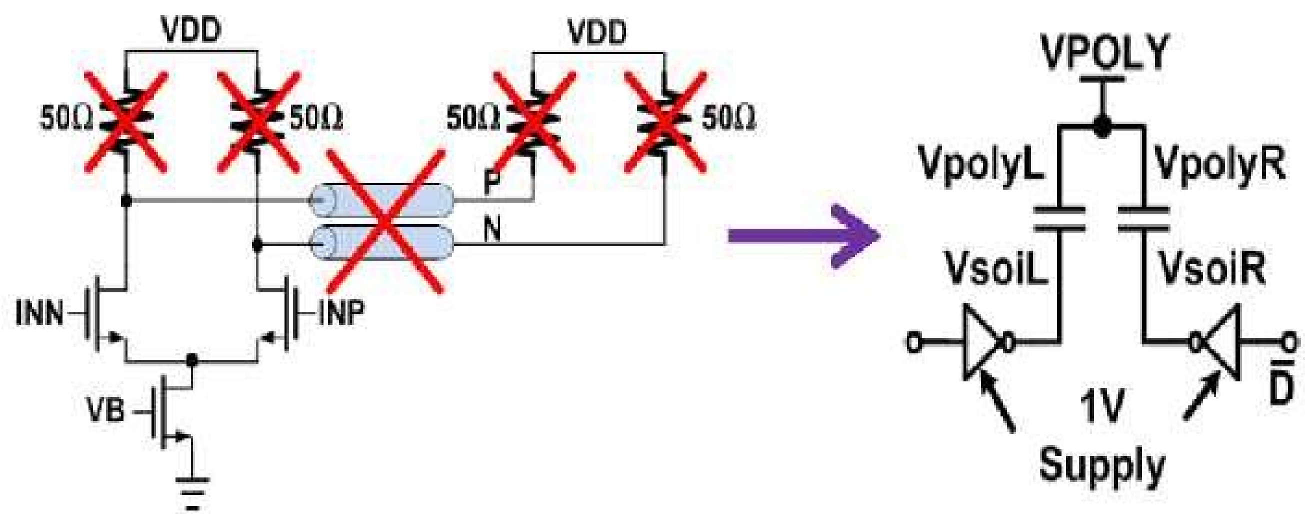
- Broadband (DC to >100 GHz) fiber
  - Course segmentation at DA cell
  - Fine segmentation in DA cell
  - T-line power combiner
  - 50-110 Gbaud



Segmented Power DAC Architectures (ii)

- Optical
  - Coarse segmentation at modulator electrode level
  - Fine bits in driver element
  - Optical waveguide power combining
  - 5-50 Gbaud

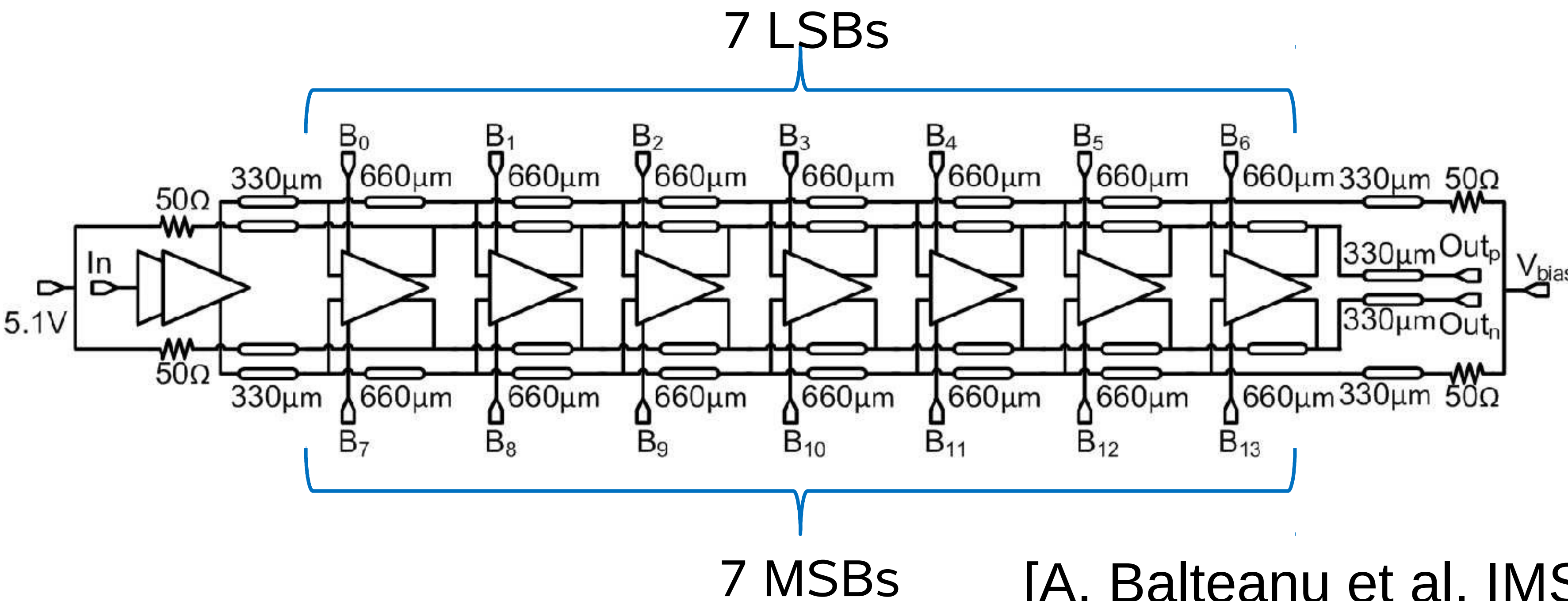




[X. Wu et al., ISSCC 2013]

Broadband Power DAC

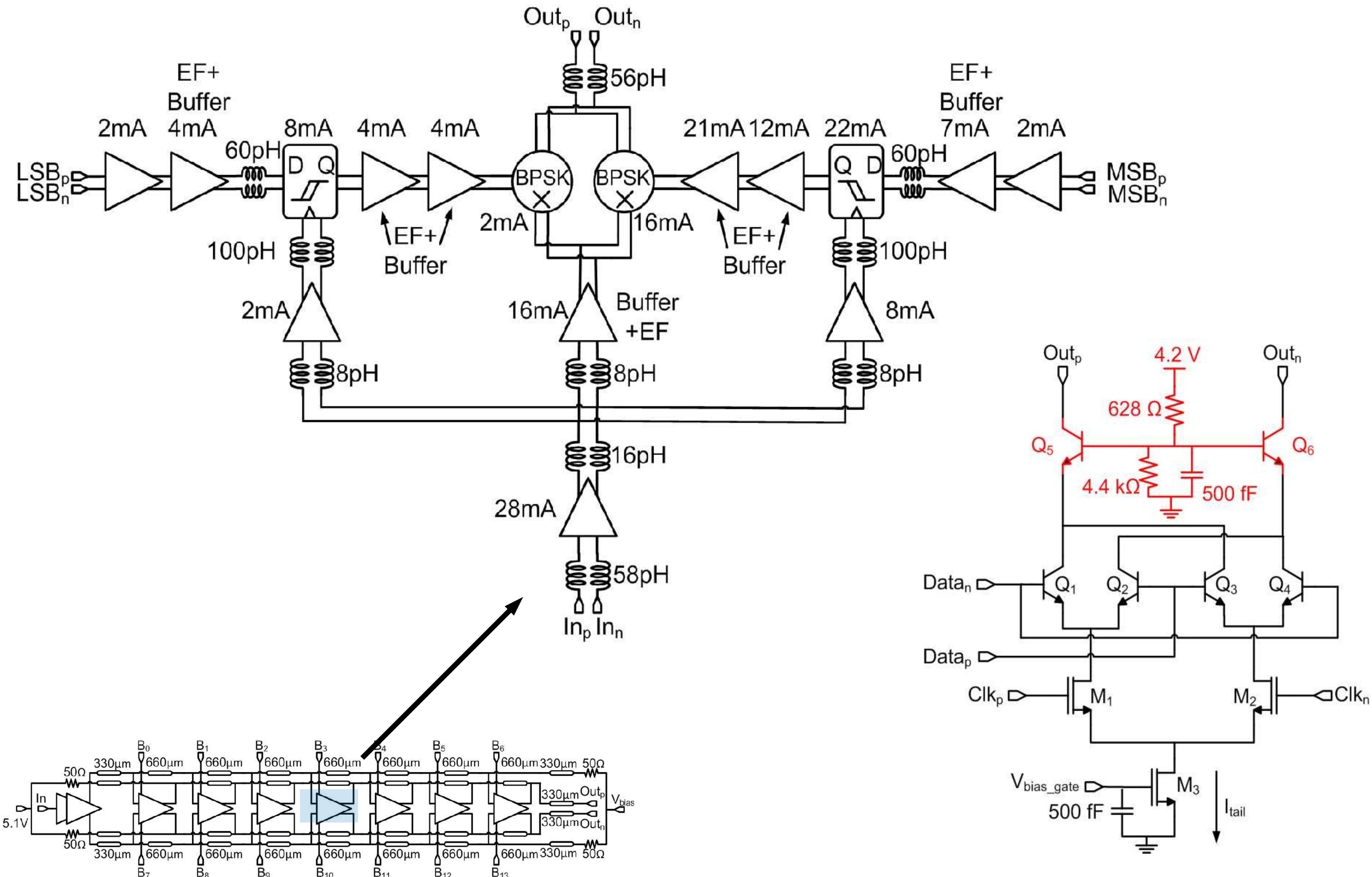
Distributed Segmentation: 7 MSBs and 7 LSBs in 8:1 size ratio



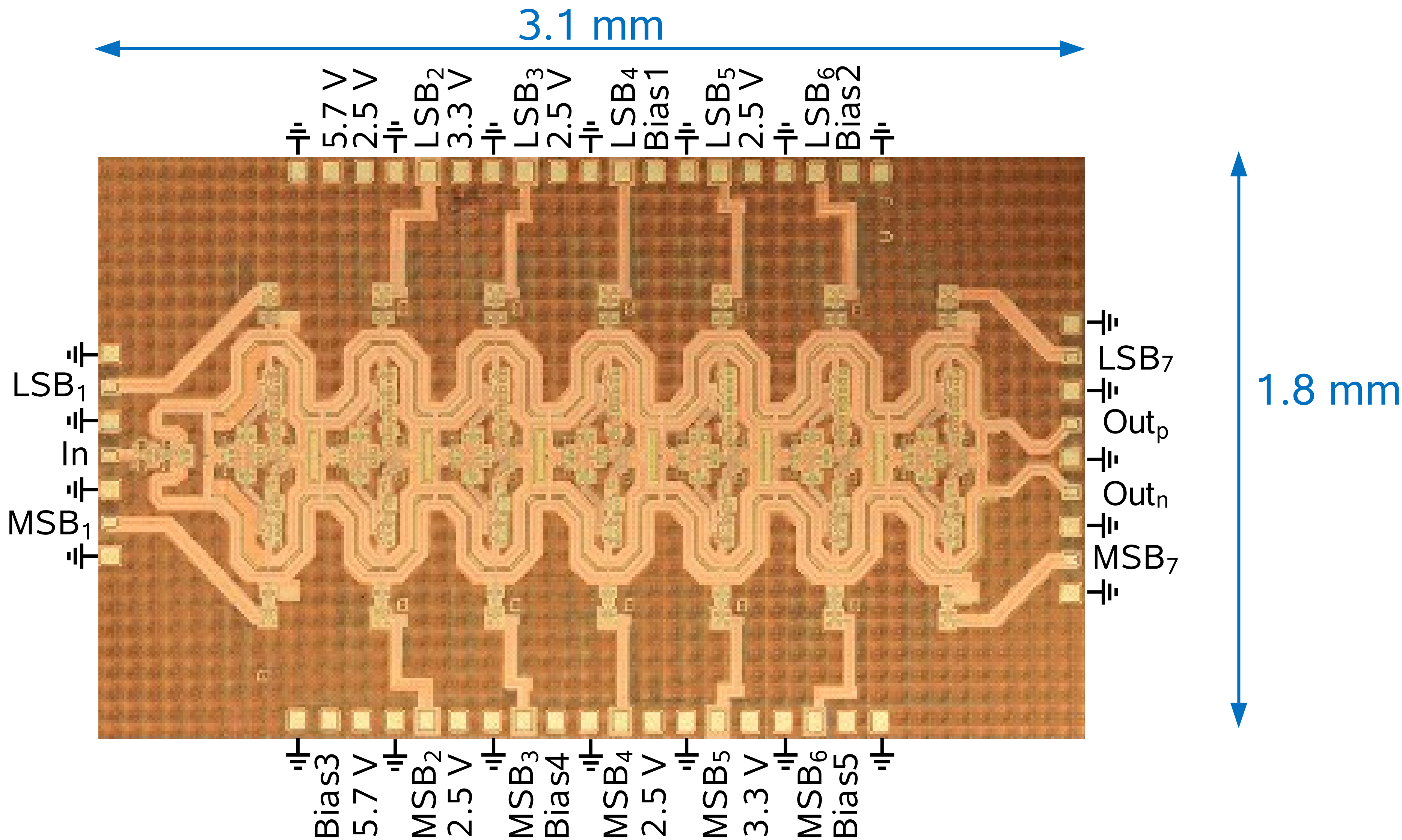
[A. Balteanu et al. IMS 2012]

- Applications as m-PAM optical modulator driver
- Gb/s radio testing (DC to 60 GHz)

Distributed DAC Cell

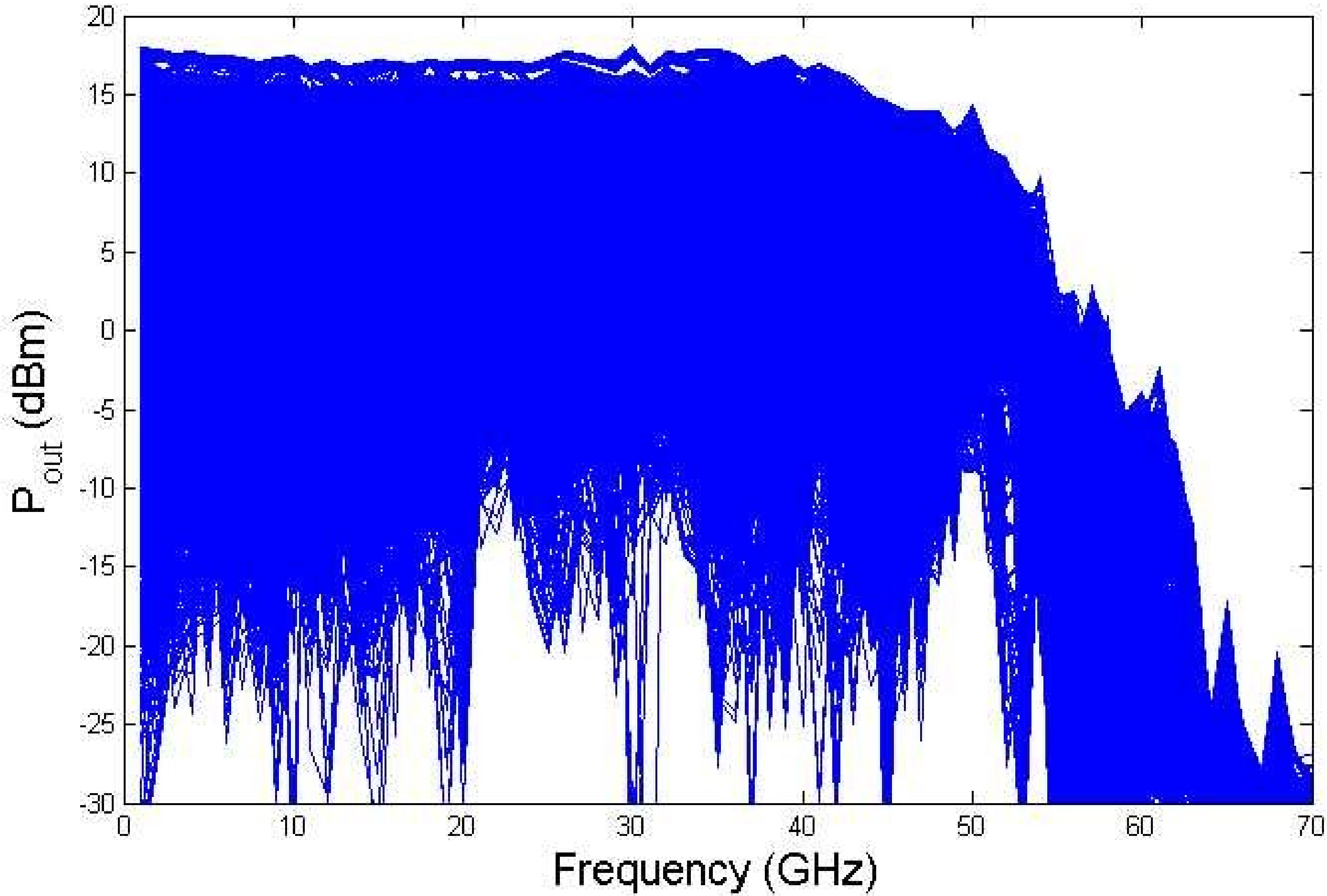


Die Photo and Technology

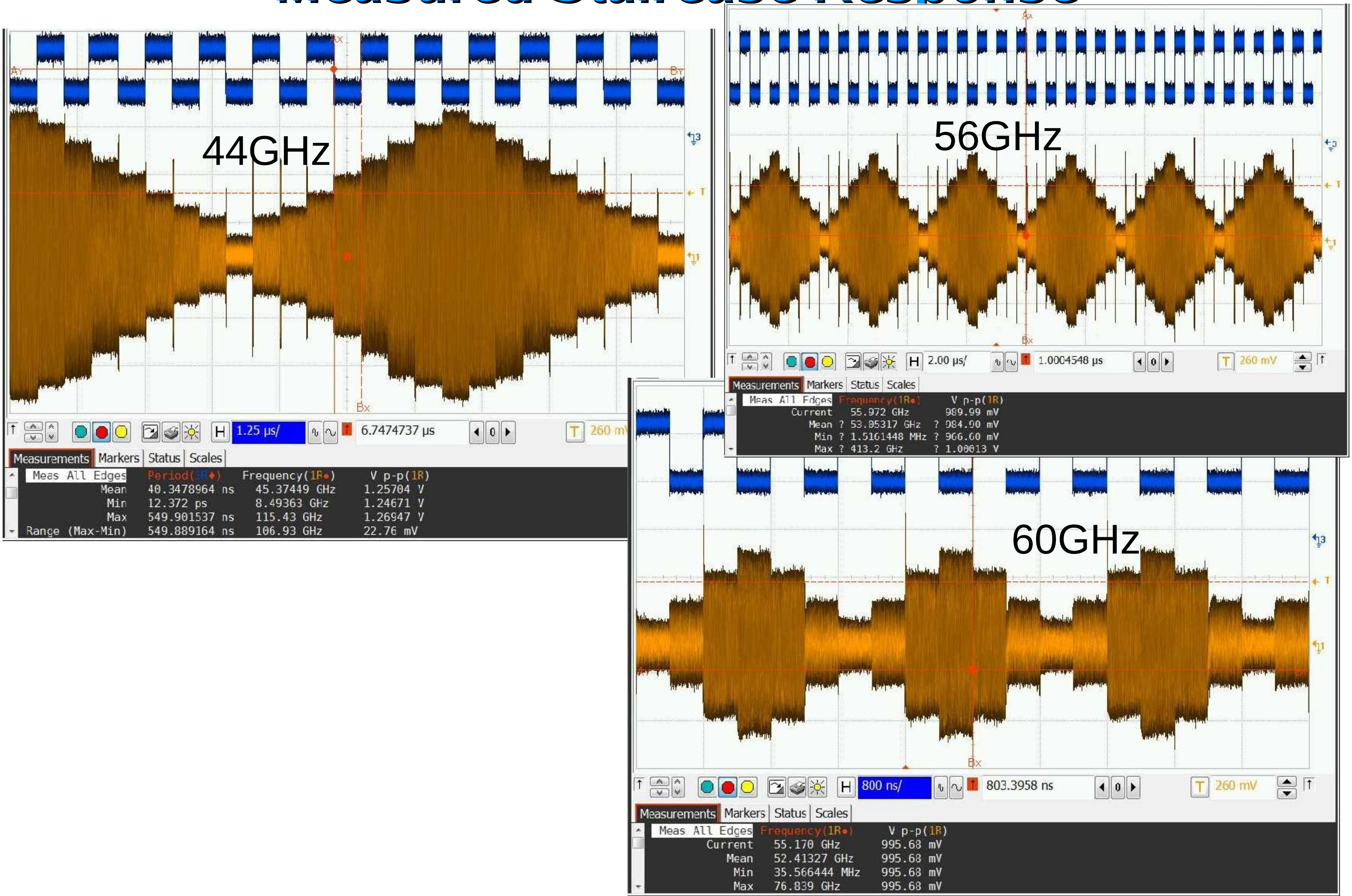


ST 130-nm SiGe BiCMOS process

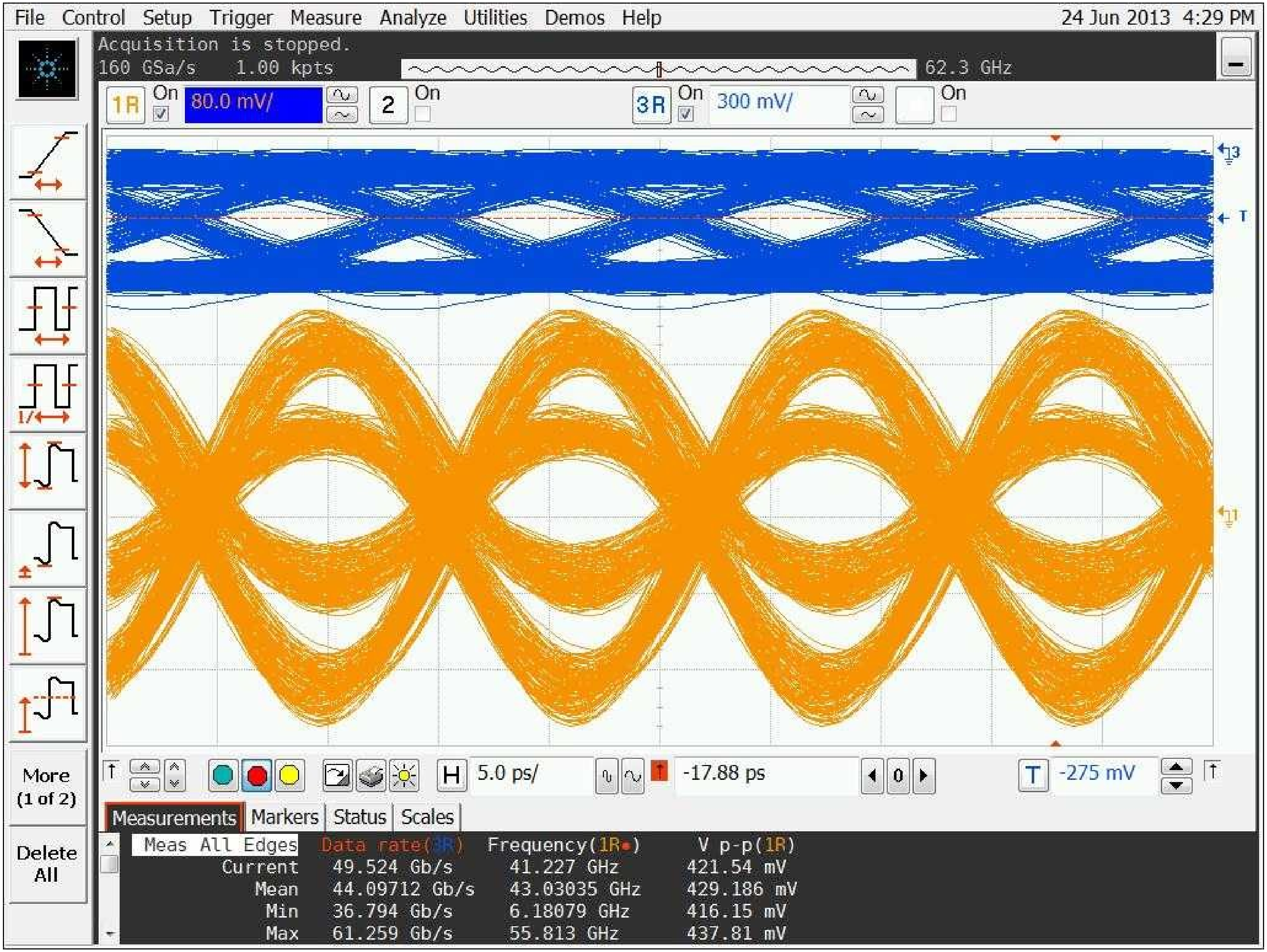
Measured P_{out} over 2^{14} code words



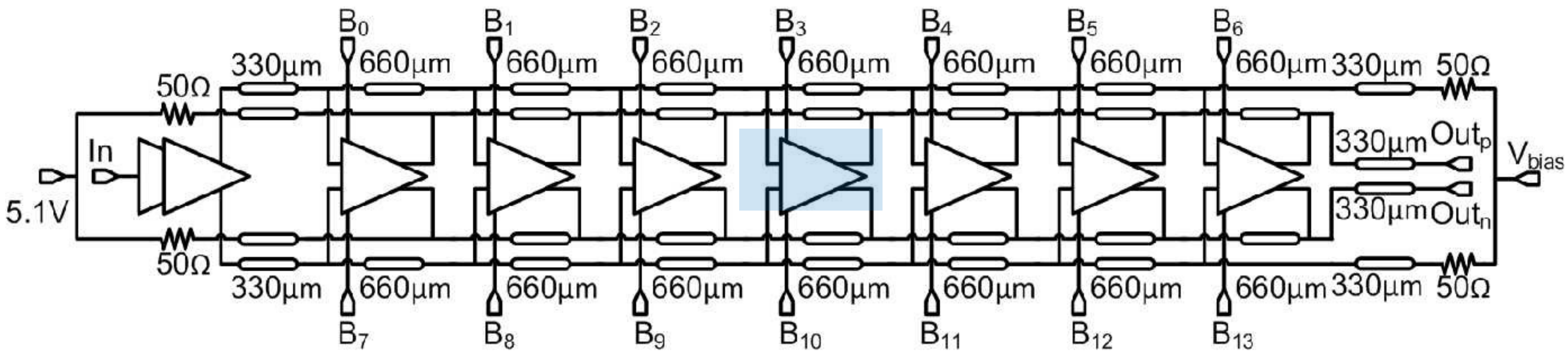
Measured Staircase Response



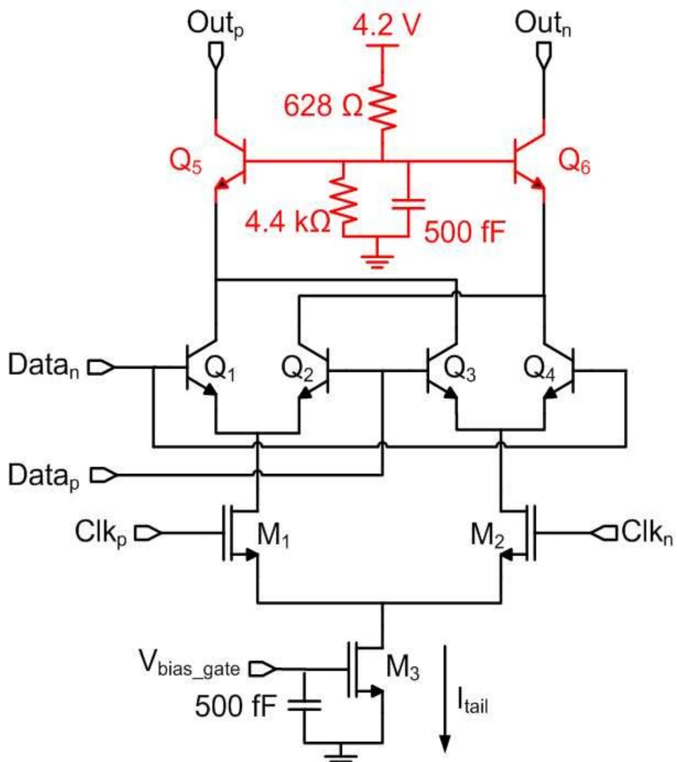
44-GHz Carrier: 1MSB switching @ 44 Gb/s

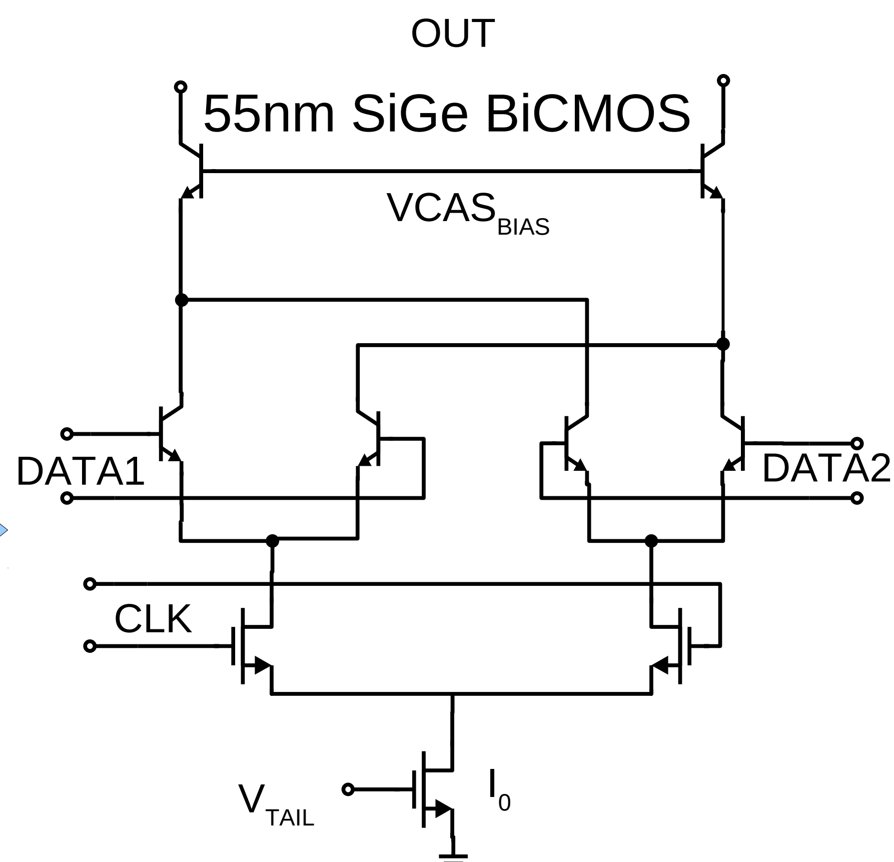


Can we quadruple data rate?

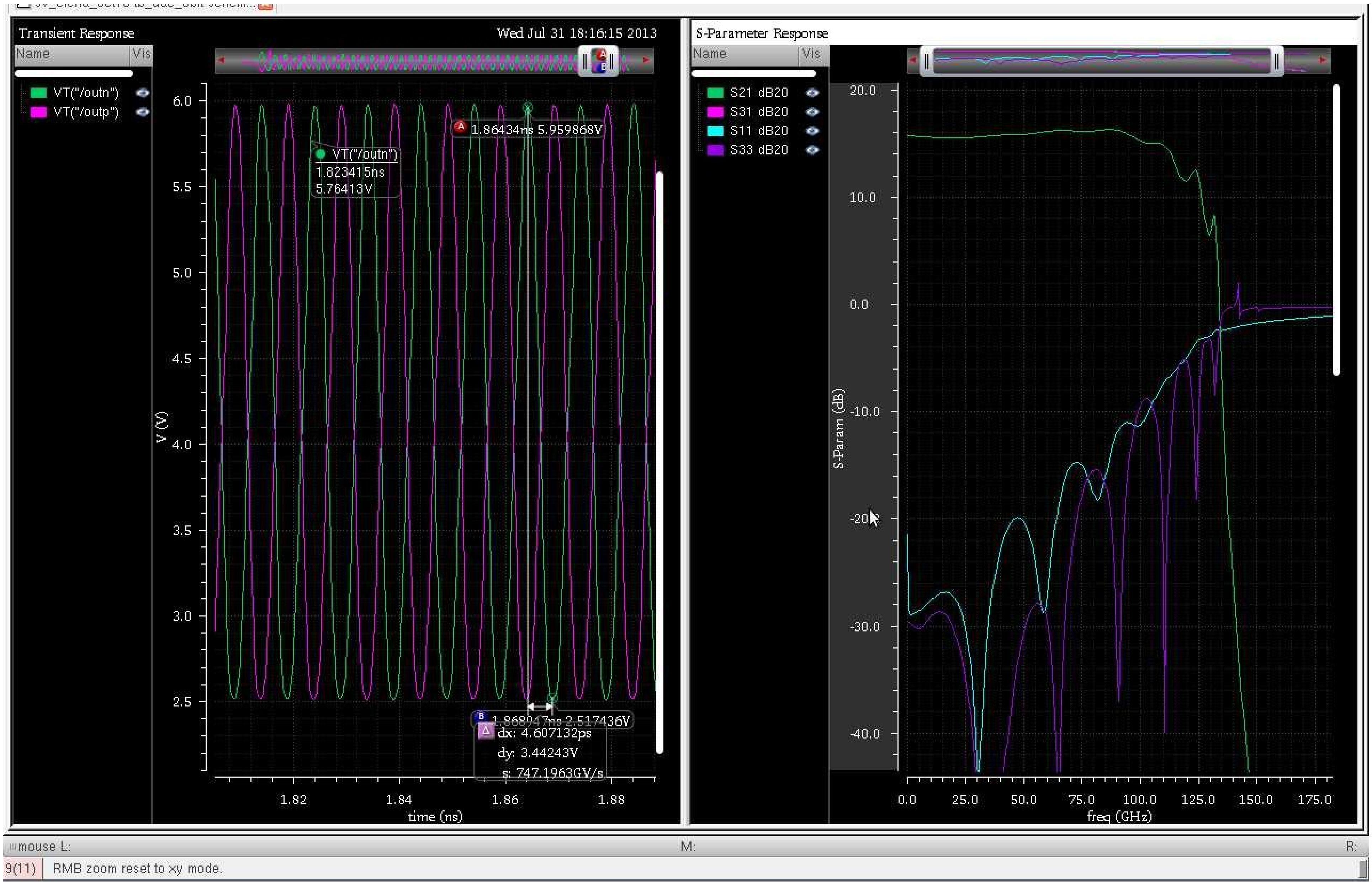


130nm SiGe BiCMOS



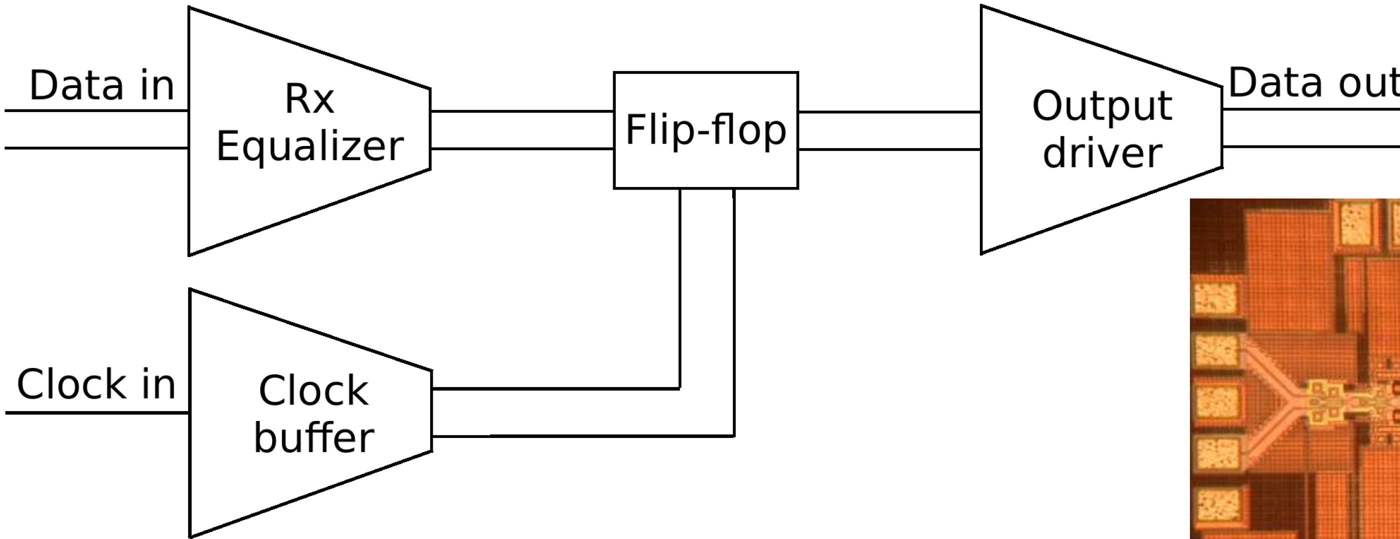


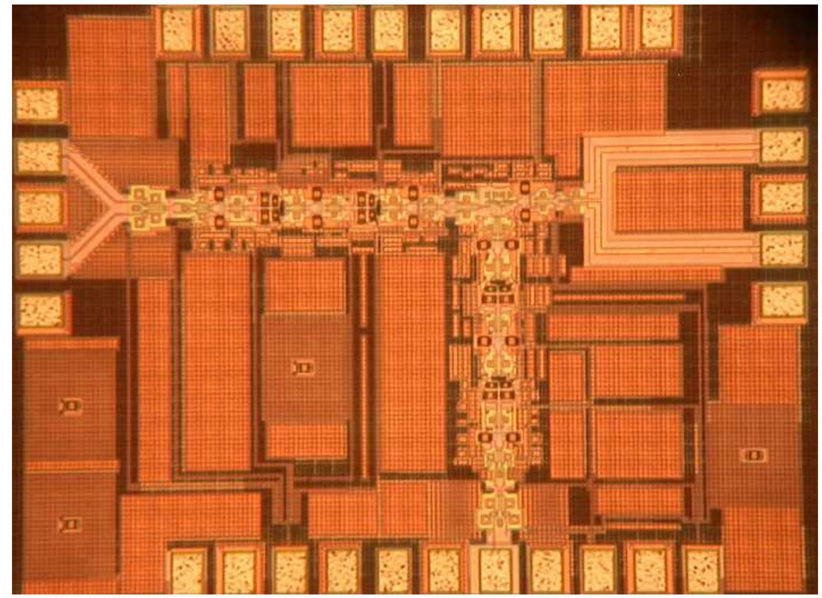
Next Gen: Spar and large signal simulation

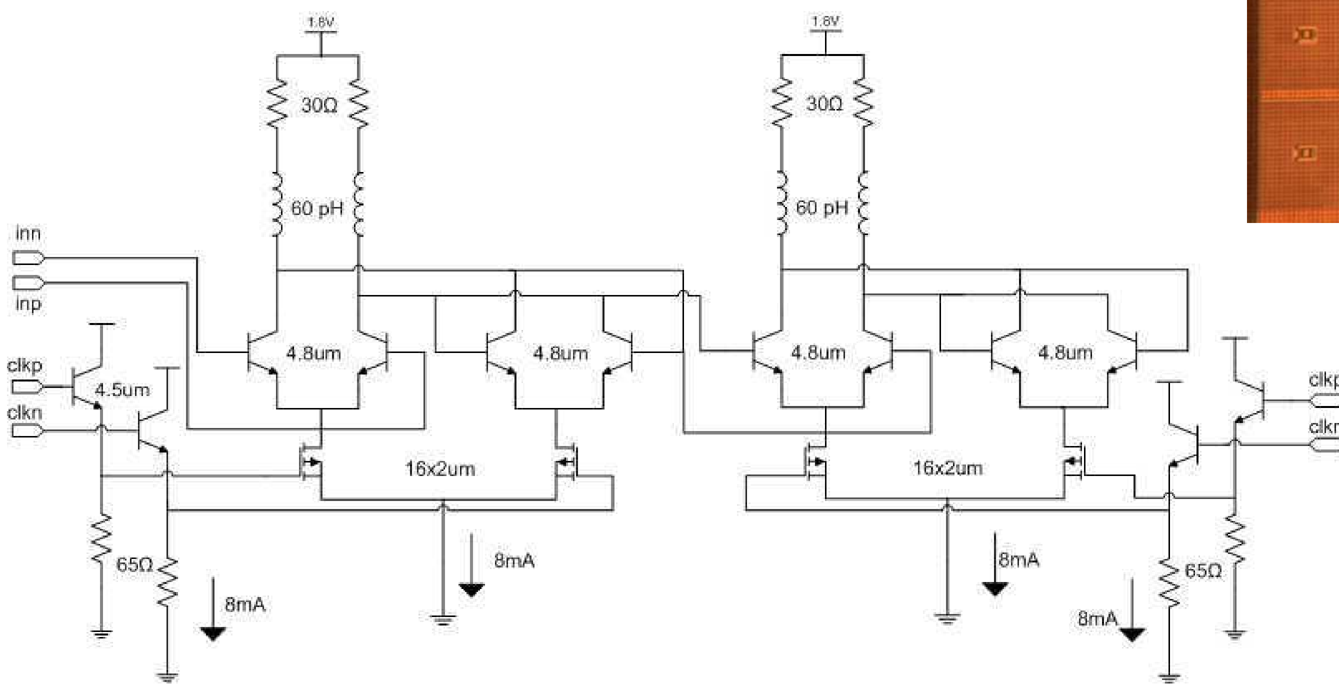


108-GHz Clock Quasi-ECL 1.8V Logic

[Y. Fu CSICS 2013]





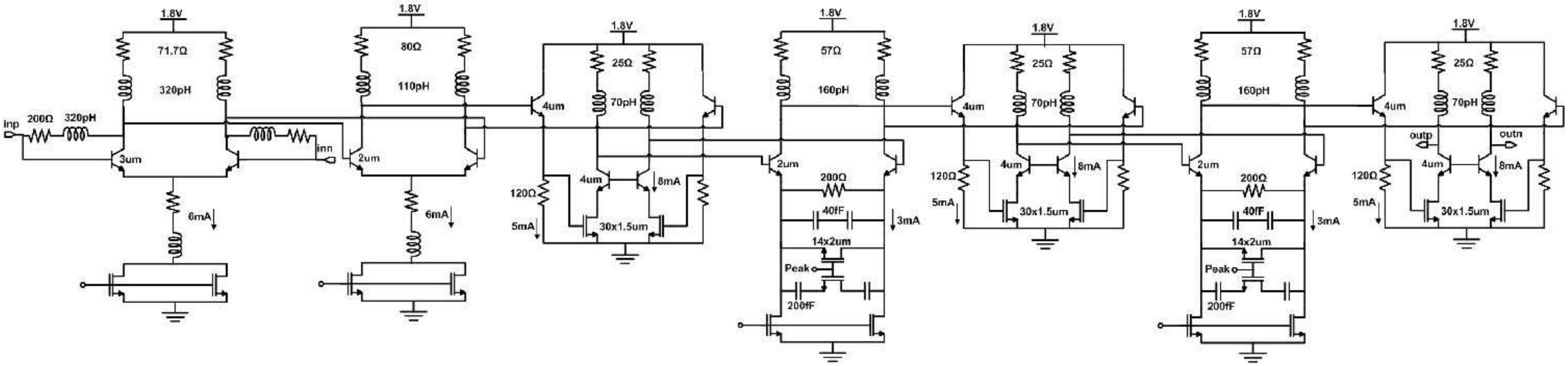


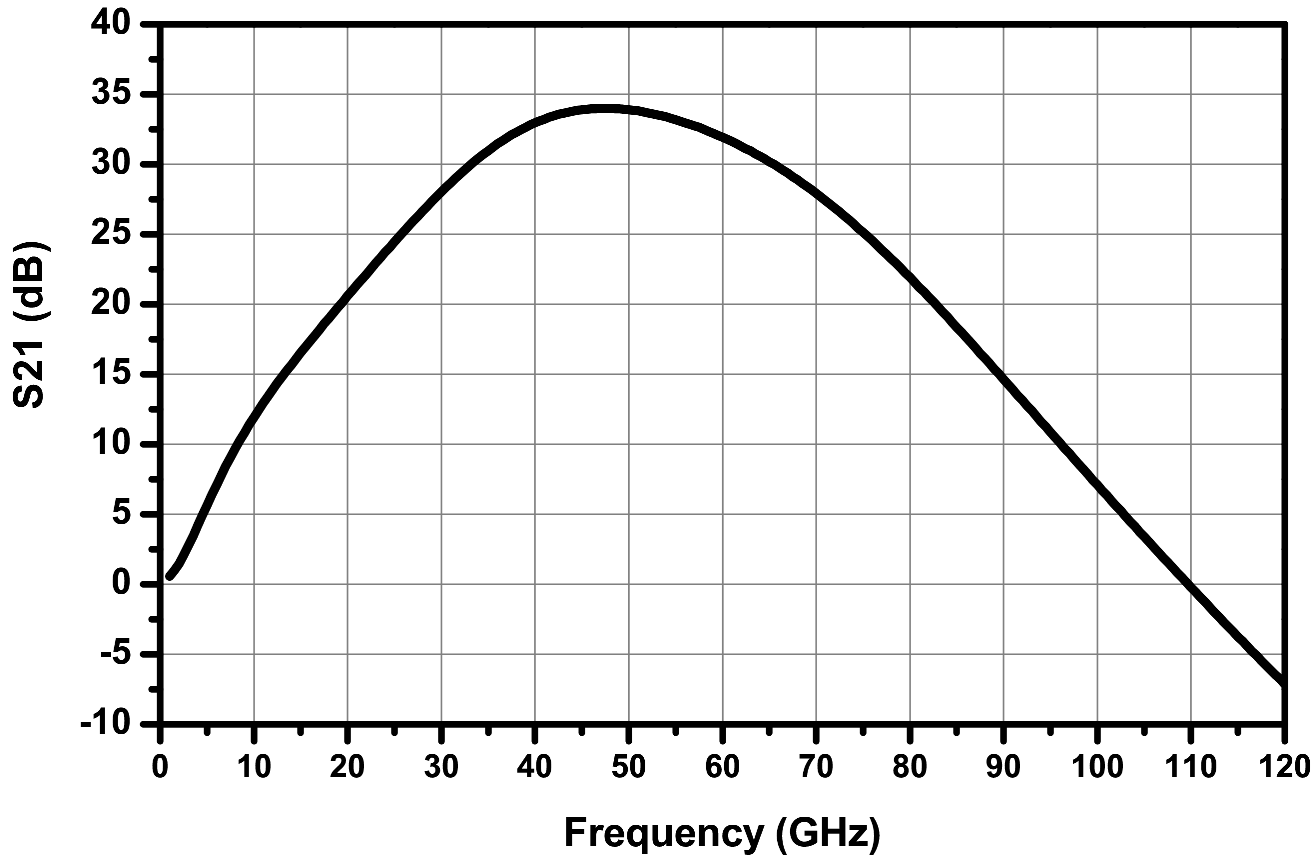
New 1.8V Quasi-CML Family

BiCMOS9MW

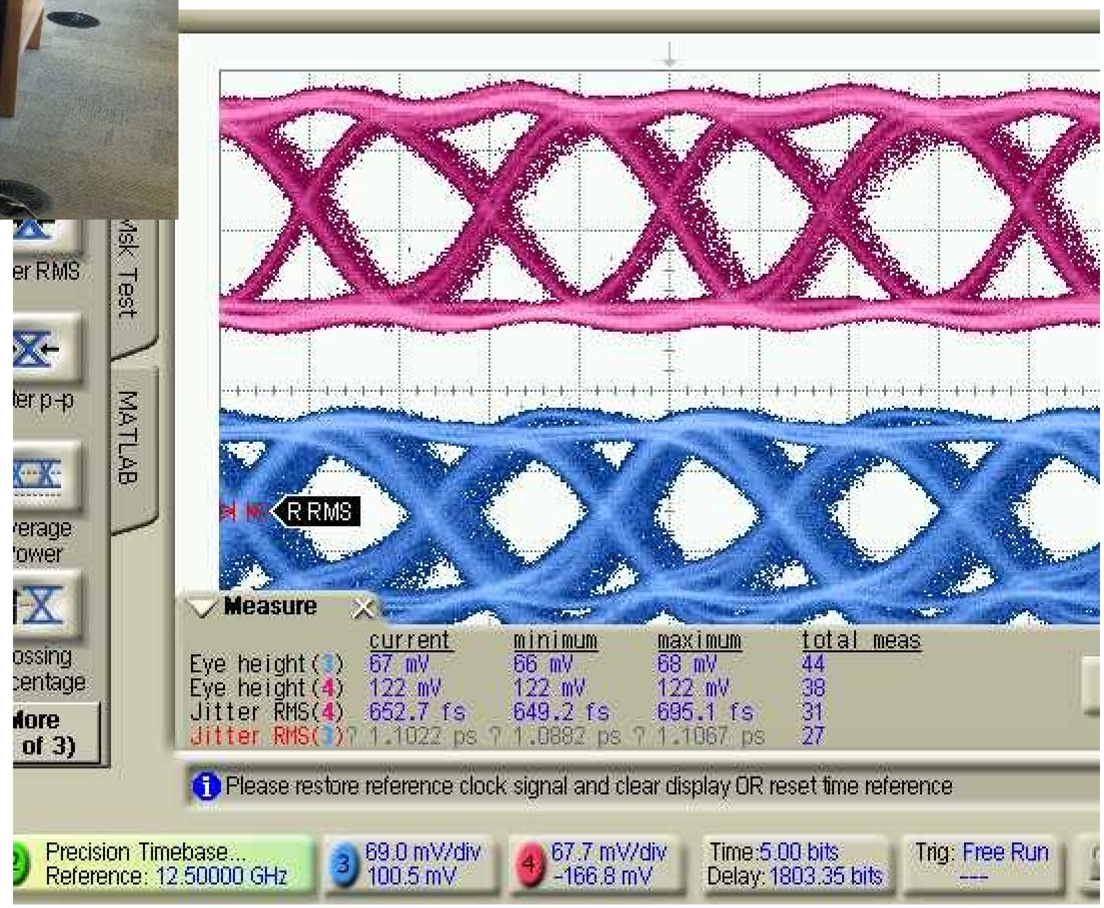
1.8V MOS-HBT Quasi-ECL

108-GHz, 1.8V Lumped Clock-Path

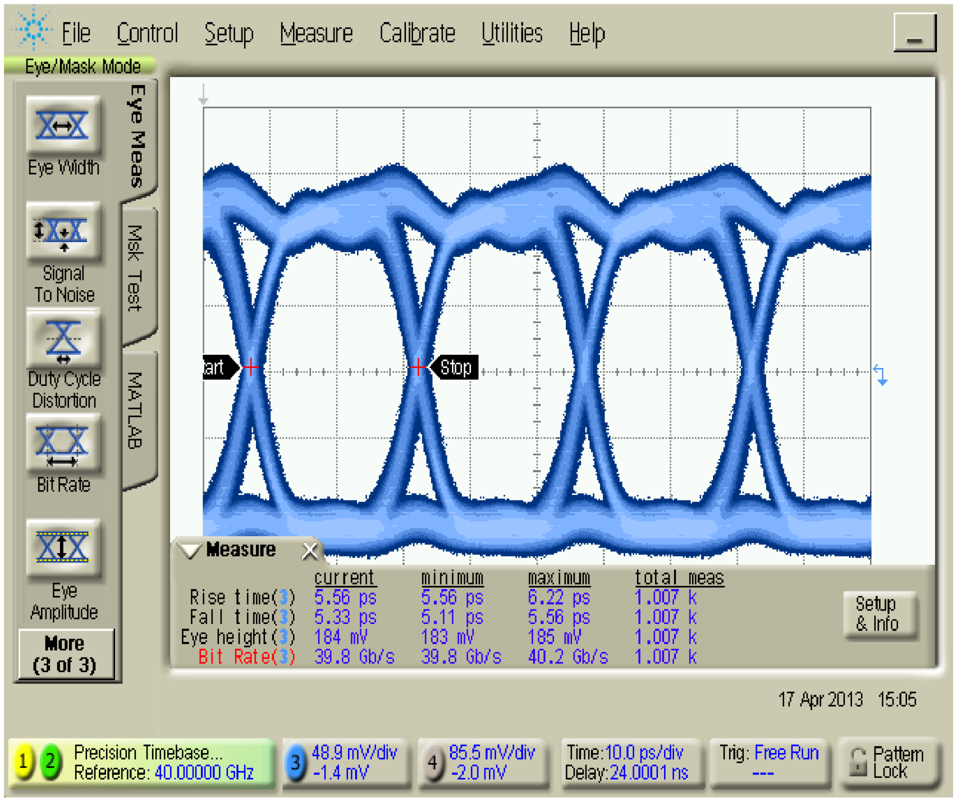


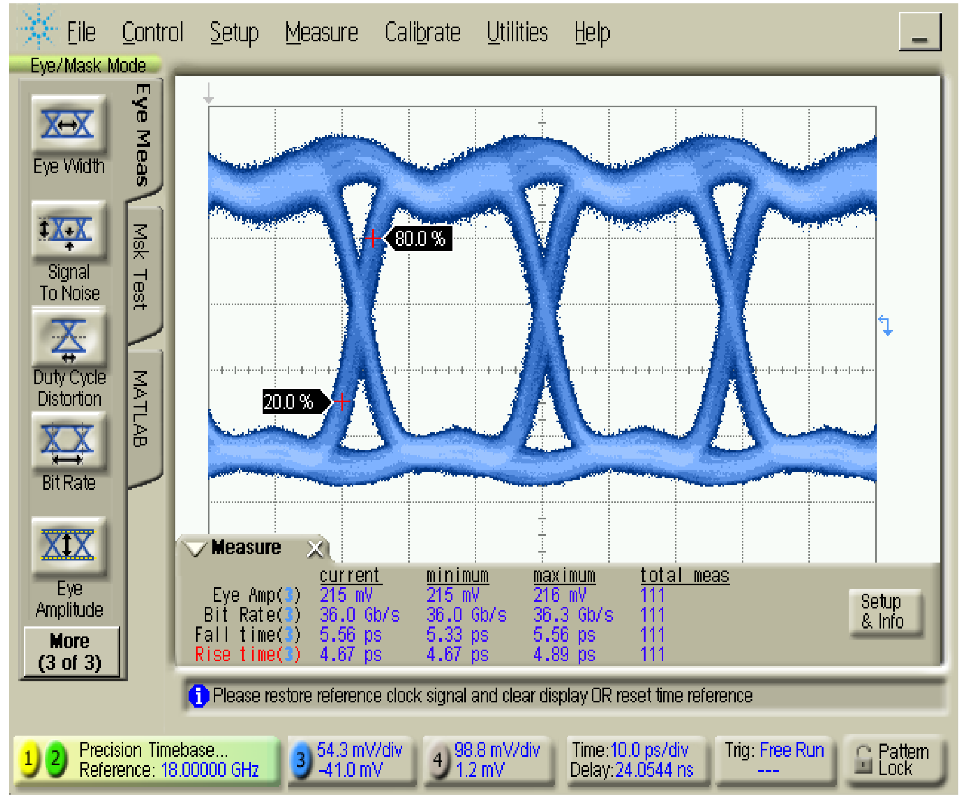


75-Gb/s retimed equalization of a 3-m long cable



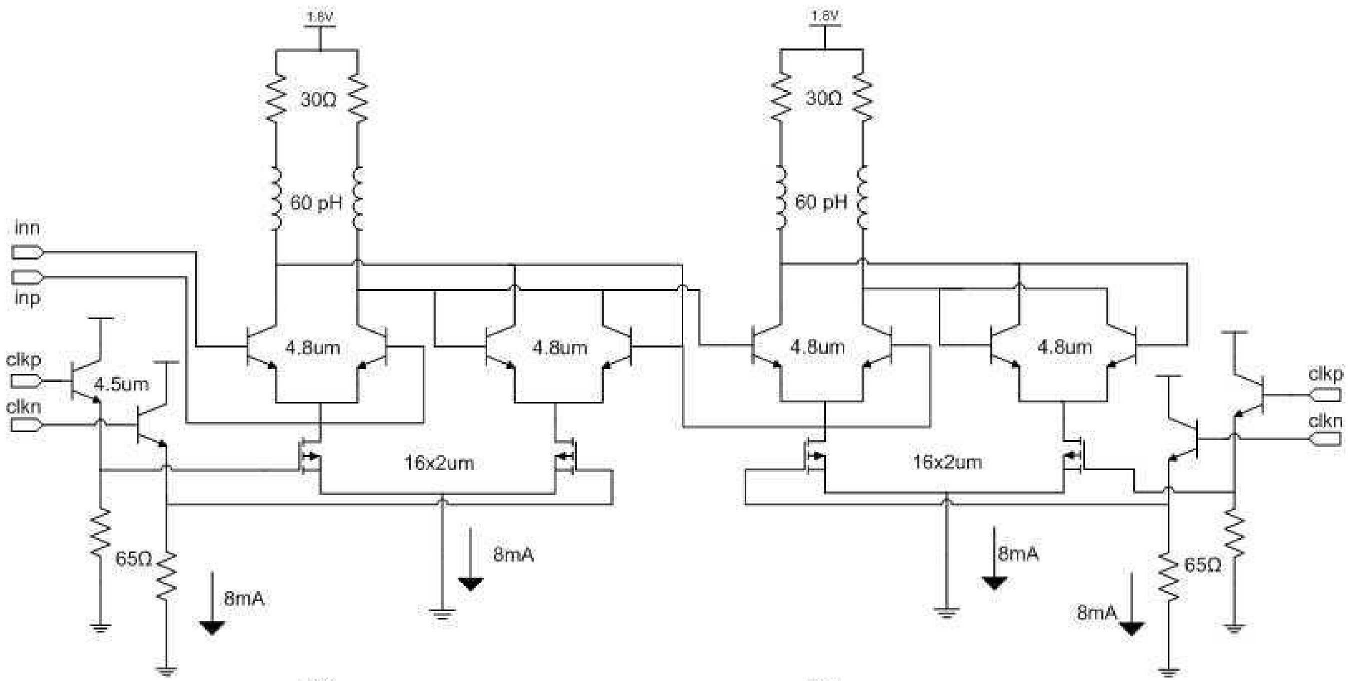
Retimed Cable Equalization Demos

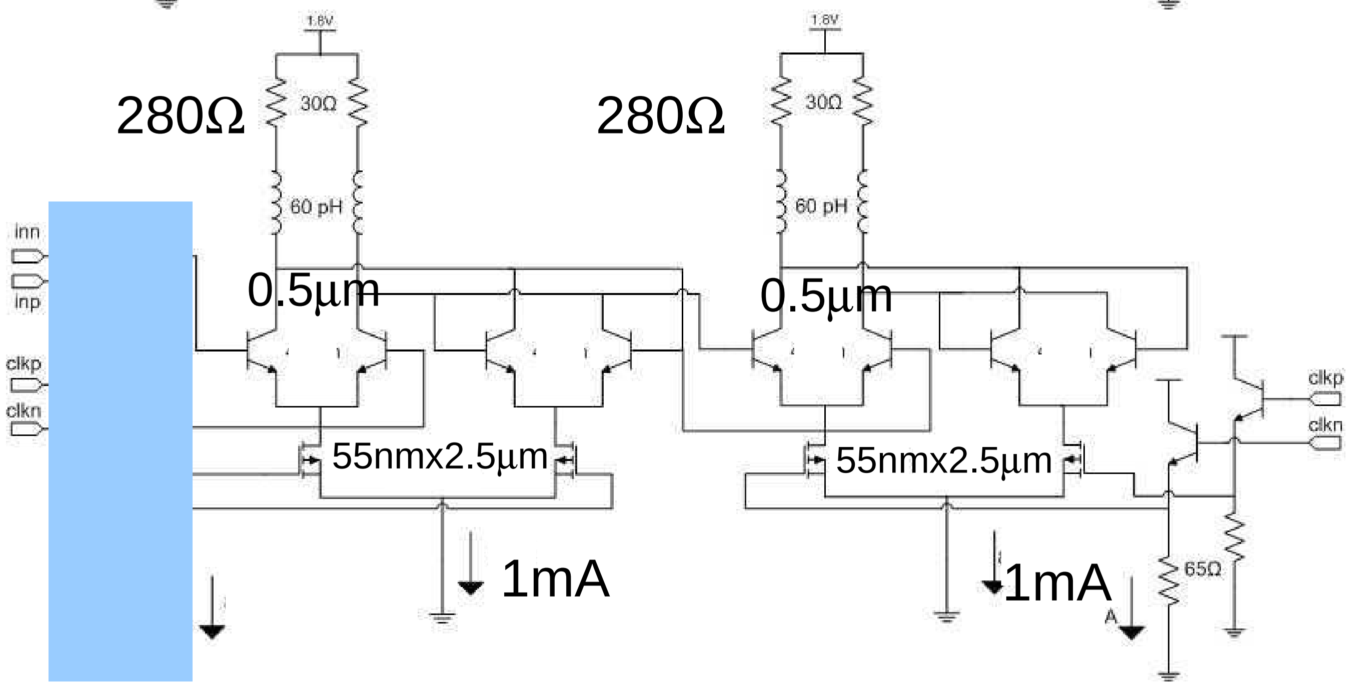




40 Gb/s retimed with 40-GHz clock 36 Gb/s retimed with 108-GHz clock

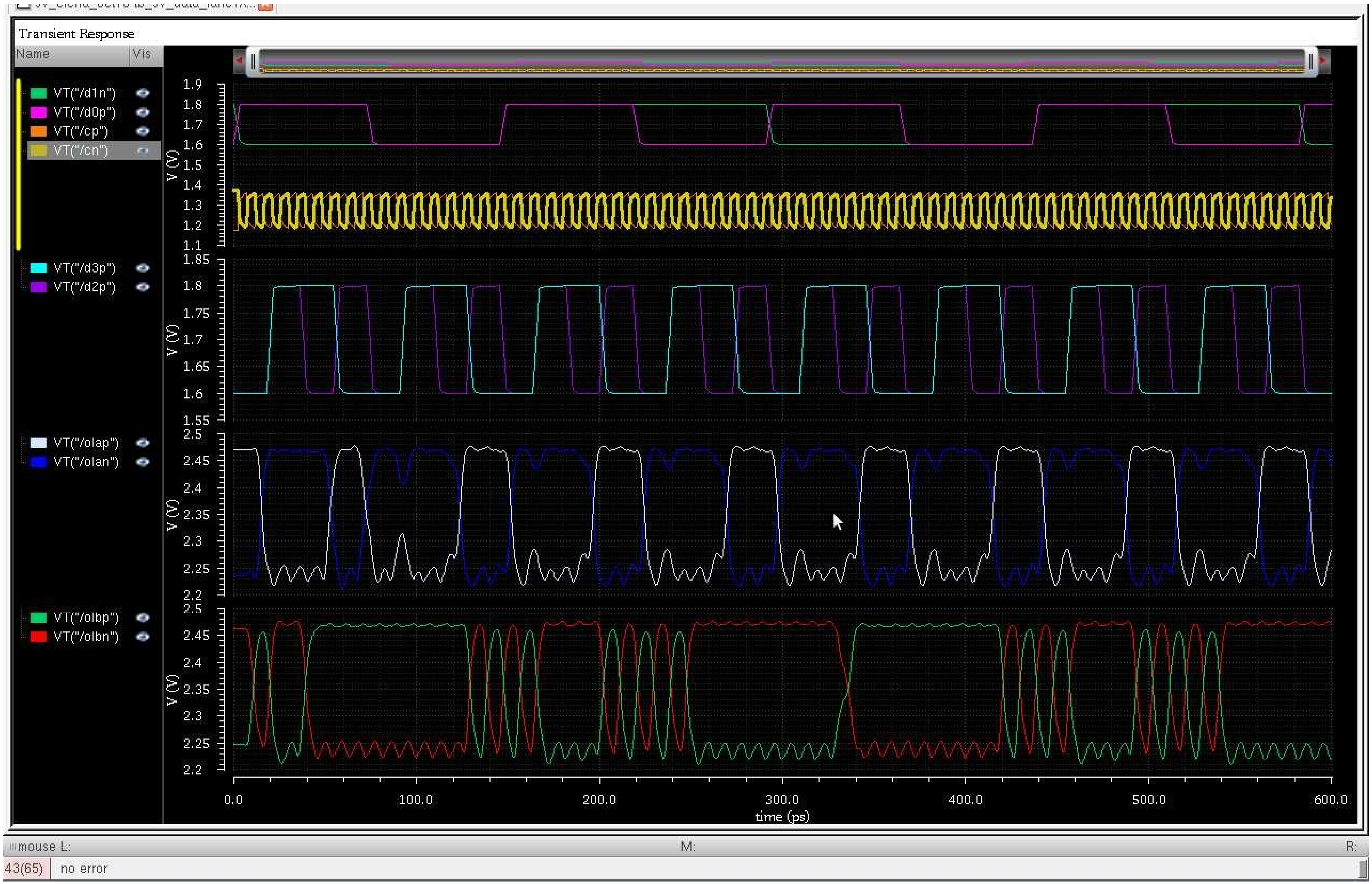
Scaling to 55nm BiCMOS55





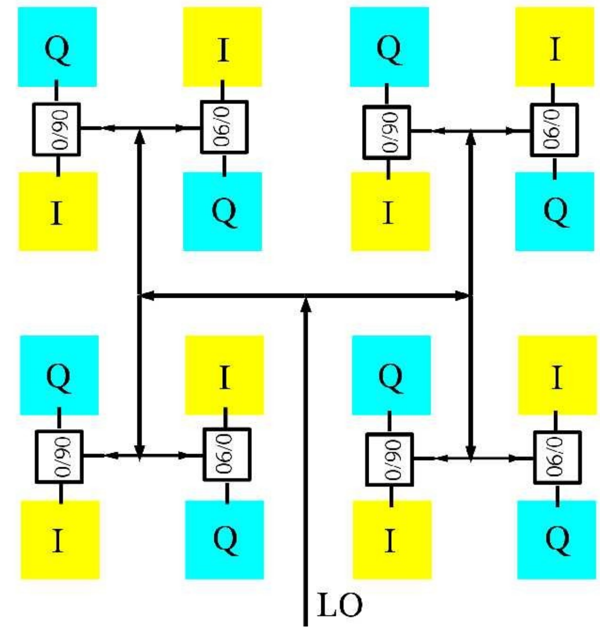
- 8x lower power consumption
- higher speed
- 36 fJ/bit

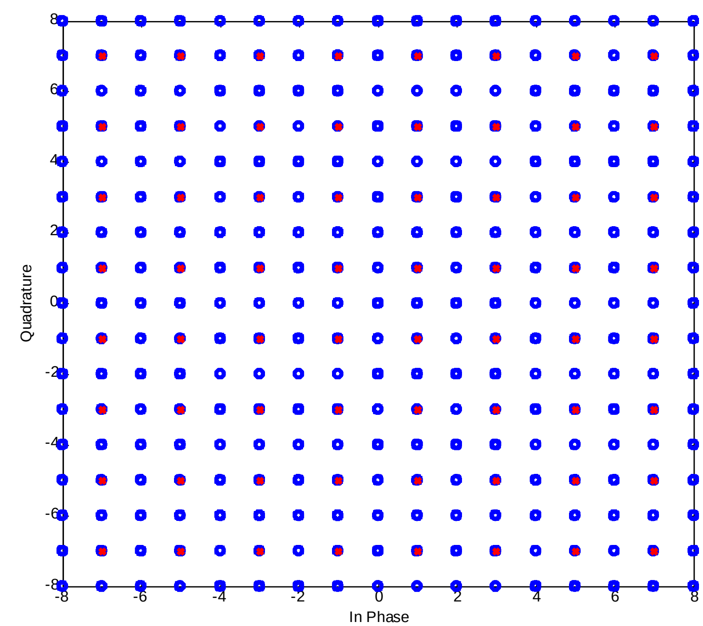
120-Gb/s 4:2 MUX Retimed Lane Simulation



TX IQ Array with Antenna Segmentation

- Array element
  - Merged DAC with PA
  - Saturated PA
  - 2 bits: for OOK and BPSK modulation at up to 44 GBaud
  - Optional bits in each element
- Adaptable QPSK/m-ary QAM
- Max. PAE at each constellation point
- No back-off needed for linearity

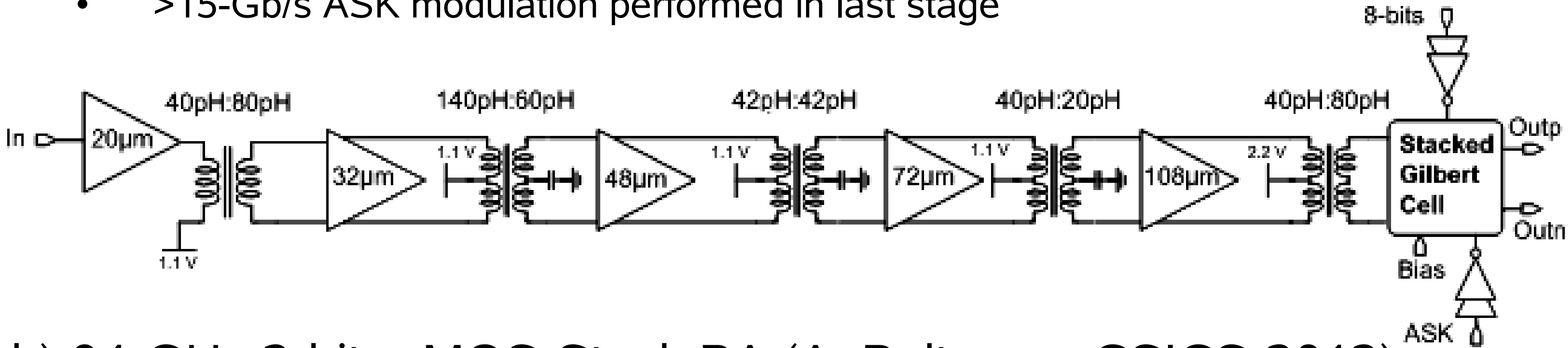




Two solutions for 94-GHz Power DAC

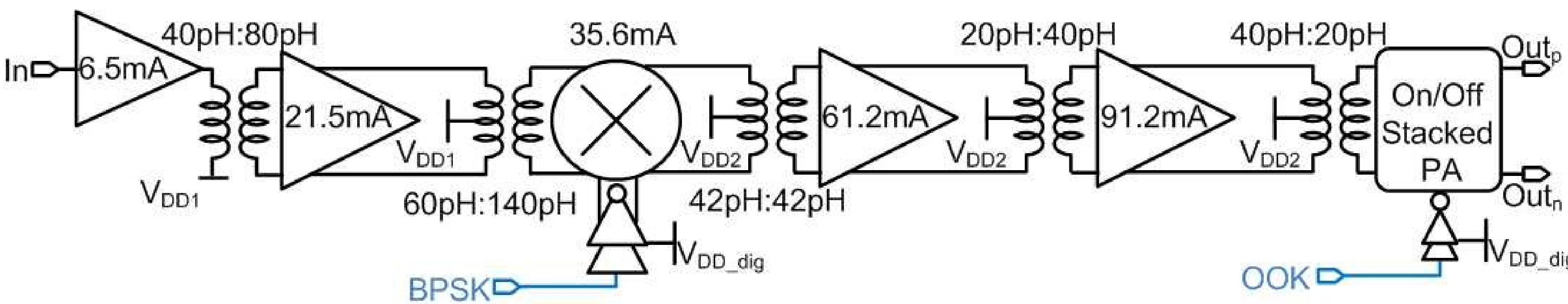
a) 94-GHz 9-bit Stacked Gilbert Cell (S. Shopov, ESSCIRC 2013)

- >15-Gb/s BPSK modulation performed in last stage
- >15-Gb/s ASK modulation performed in last stage

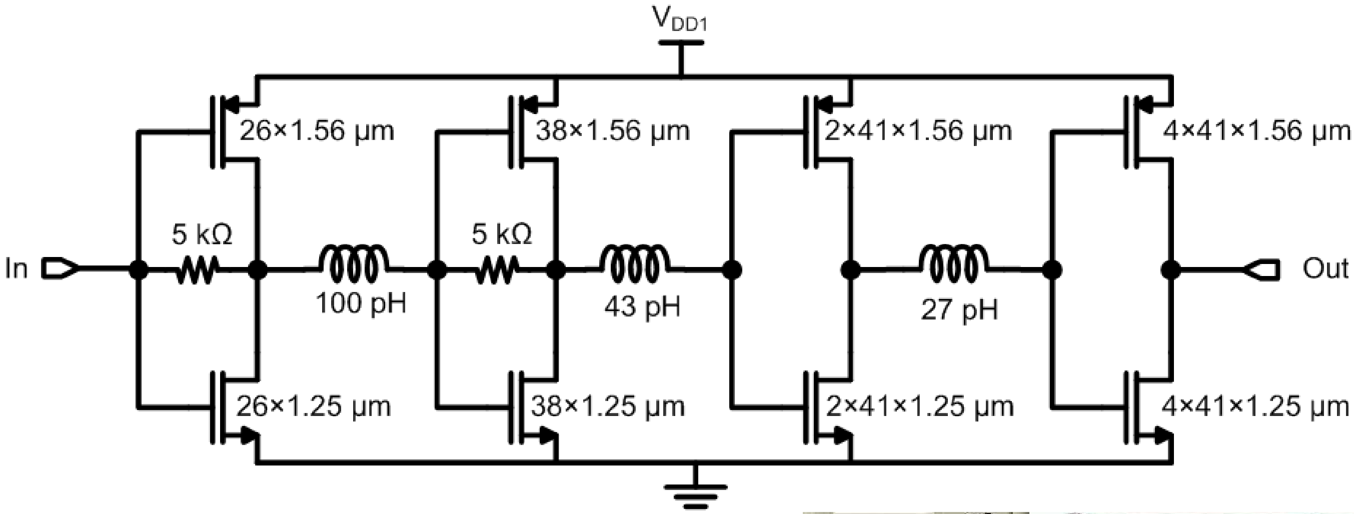


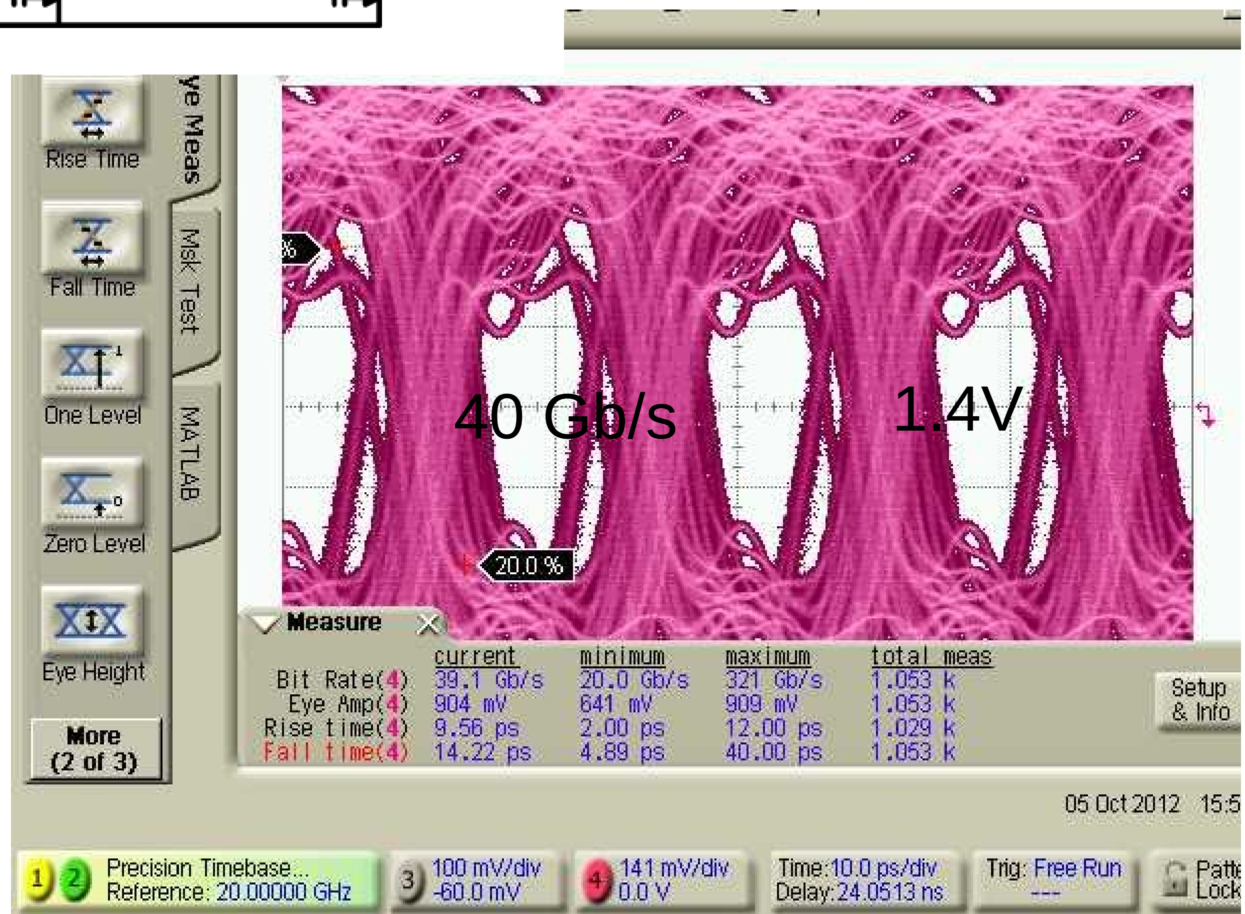
b) 94-GHz 2-bit n-MOS-Stack PA (A. Balteanu, CSICS-2013)

- >44-Gb/s BPSK modulation performed in mixer
- >44-Gb/s OOK modulation performed in last stage



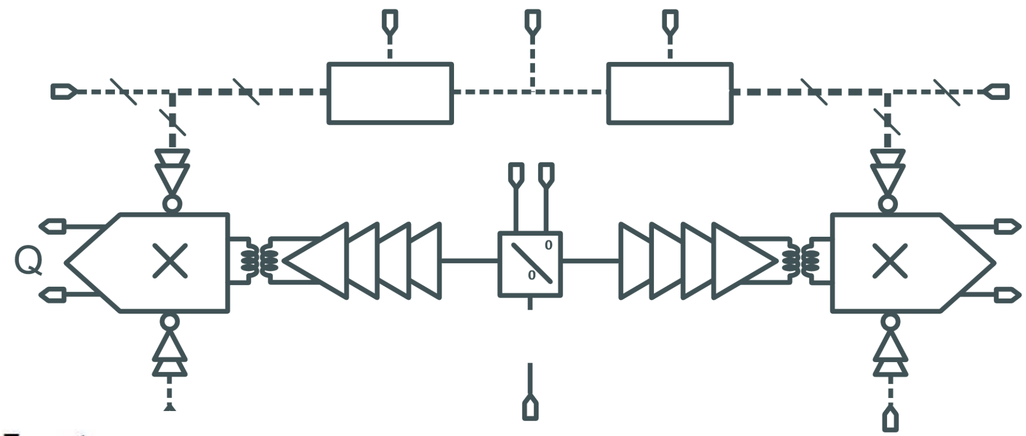
40+ Gb/s inductively-peaked CMOS logic

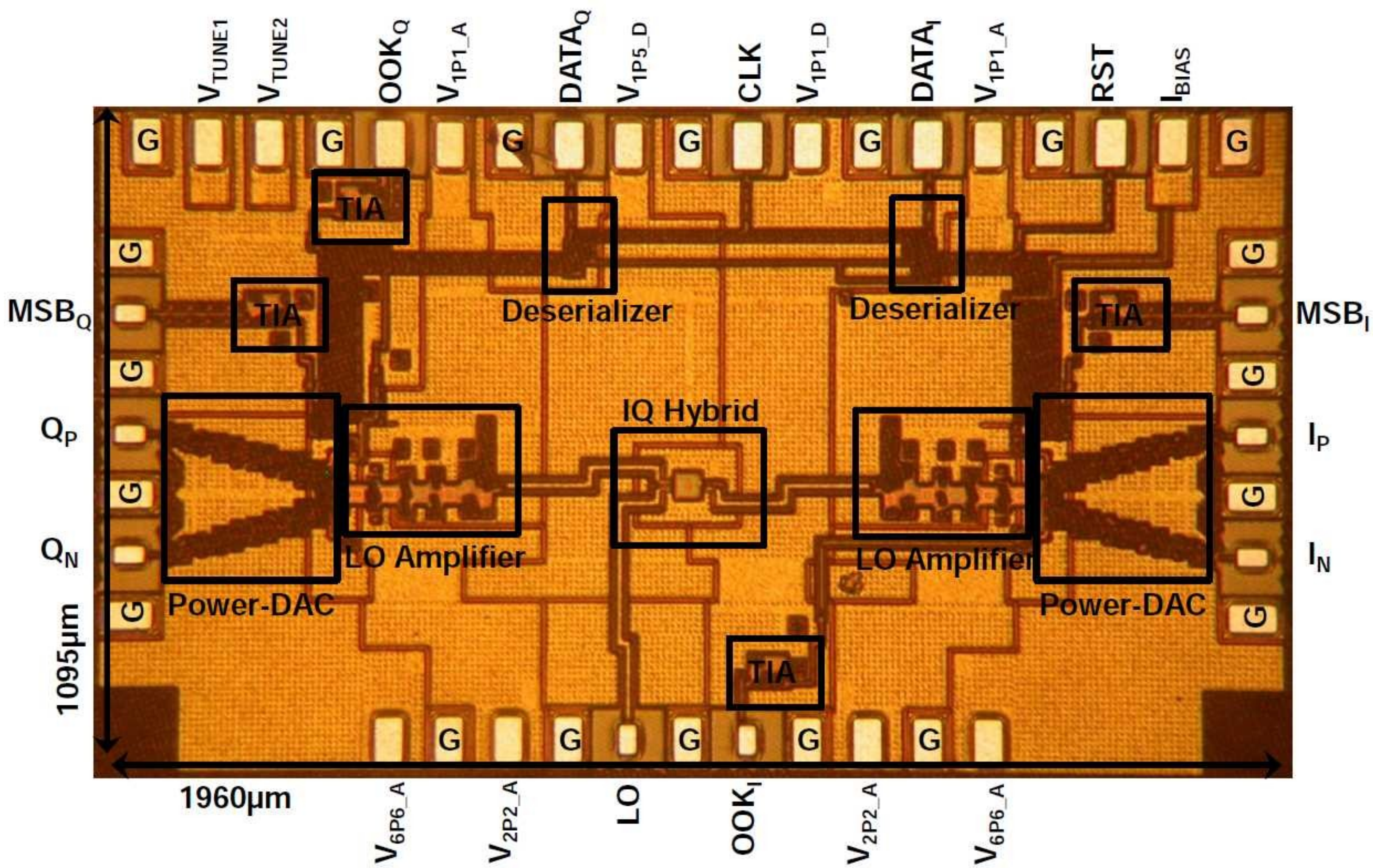




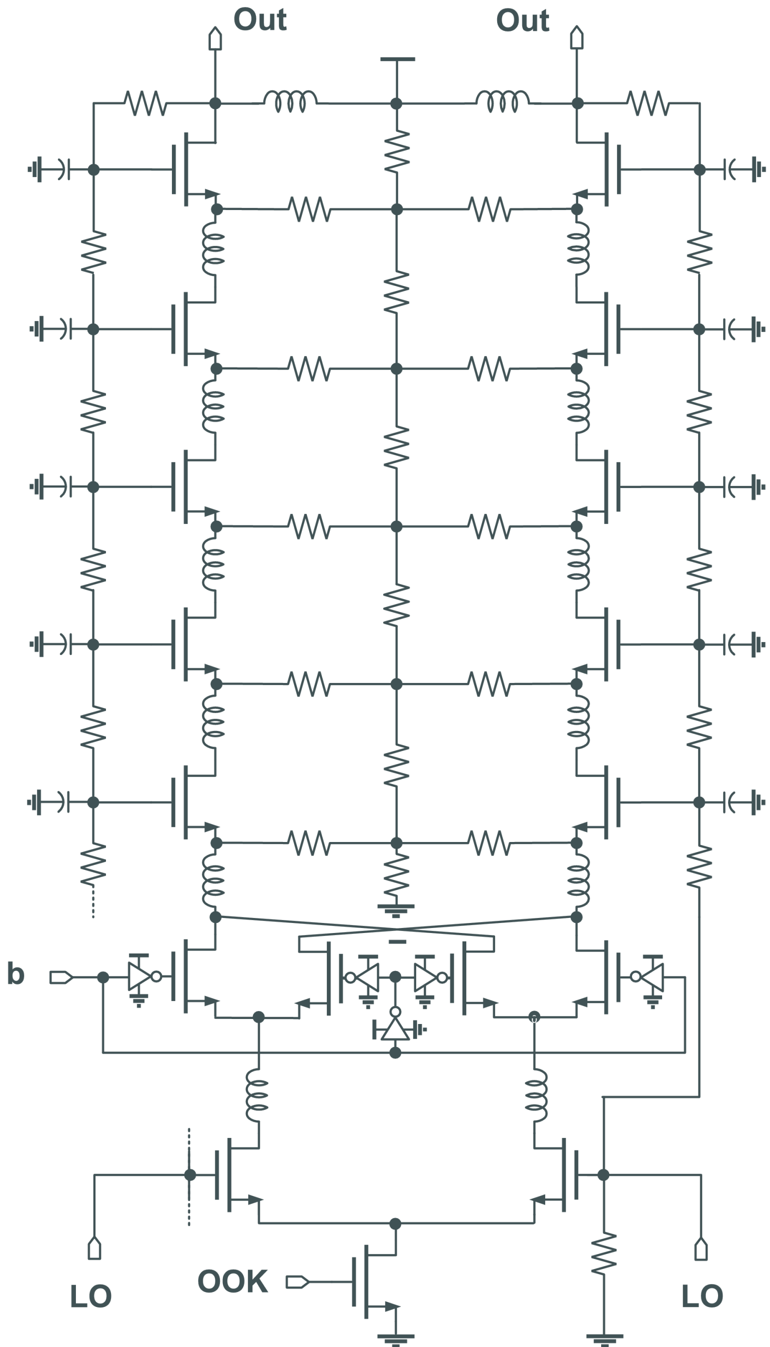
94-GHz Gilbert-Cell Based IQ DAC

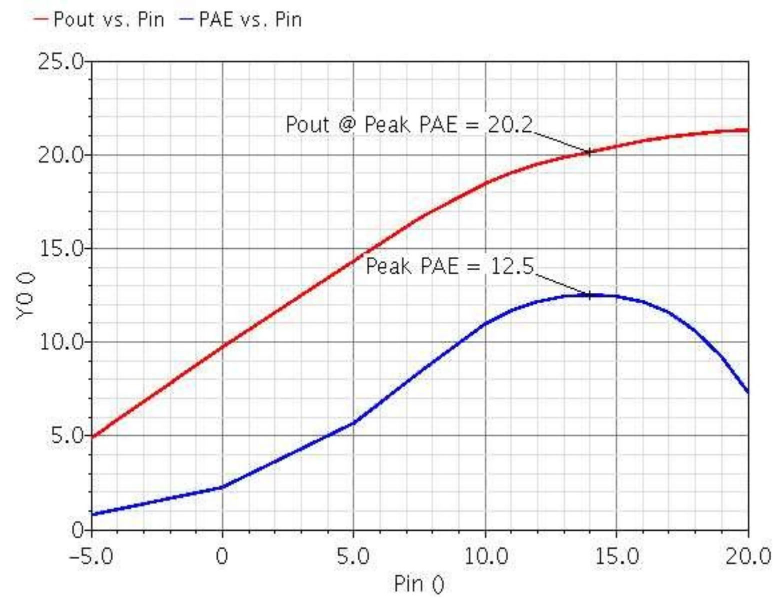
[S. Shopov et al. ESSCIRC 2013]

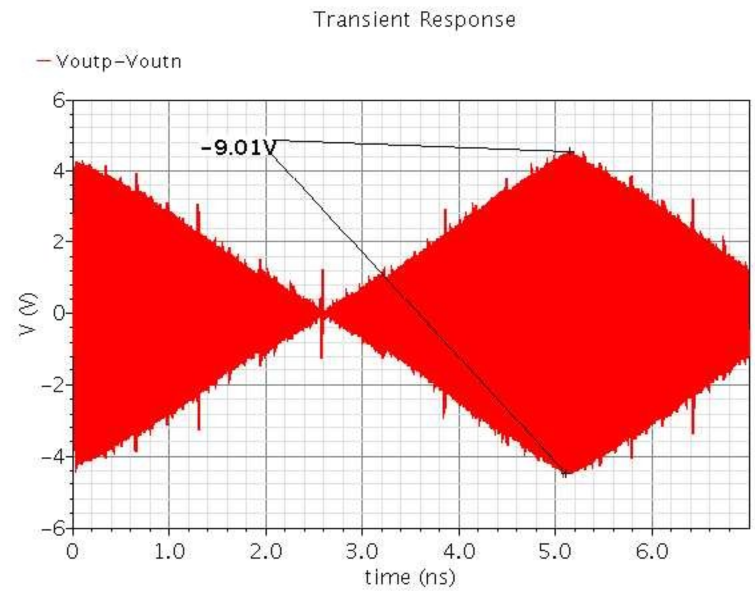




94-GHz 9-bit stacked Gilbert cell

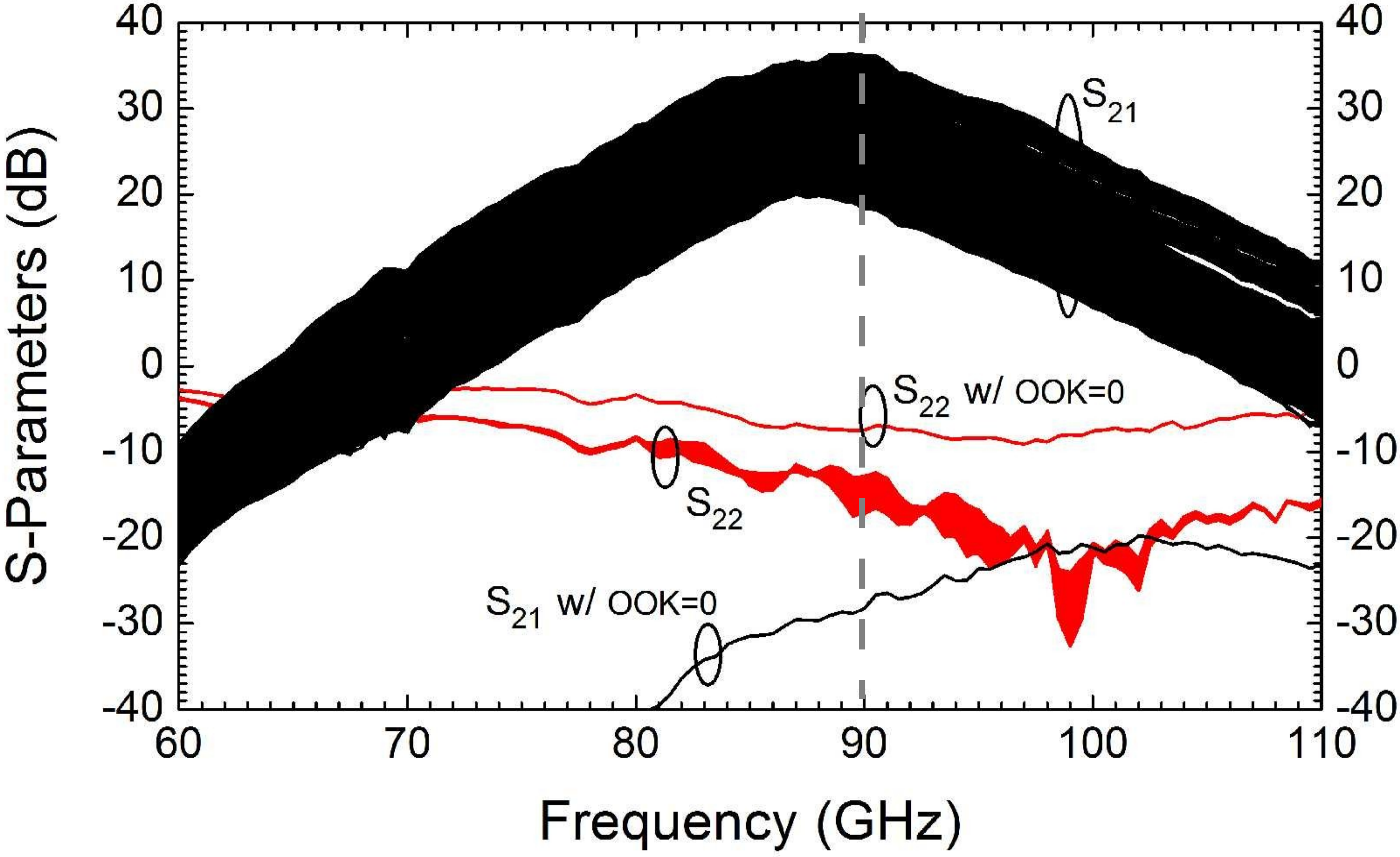




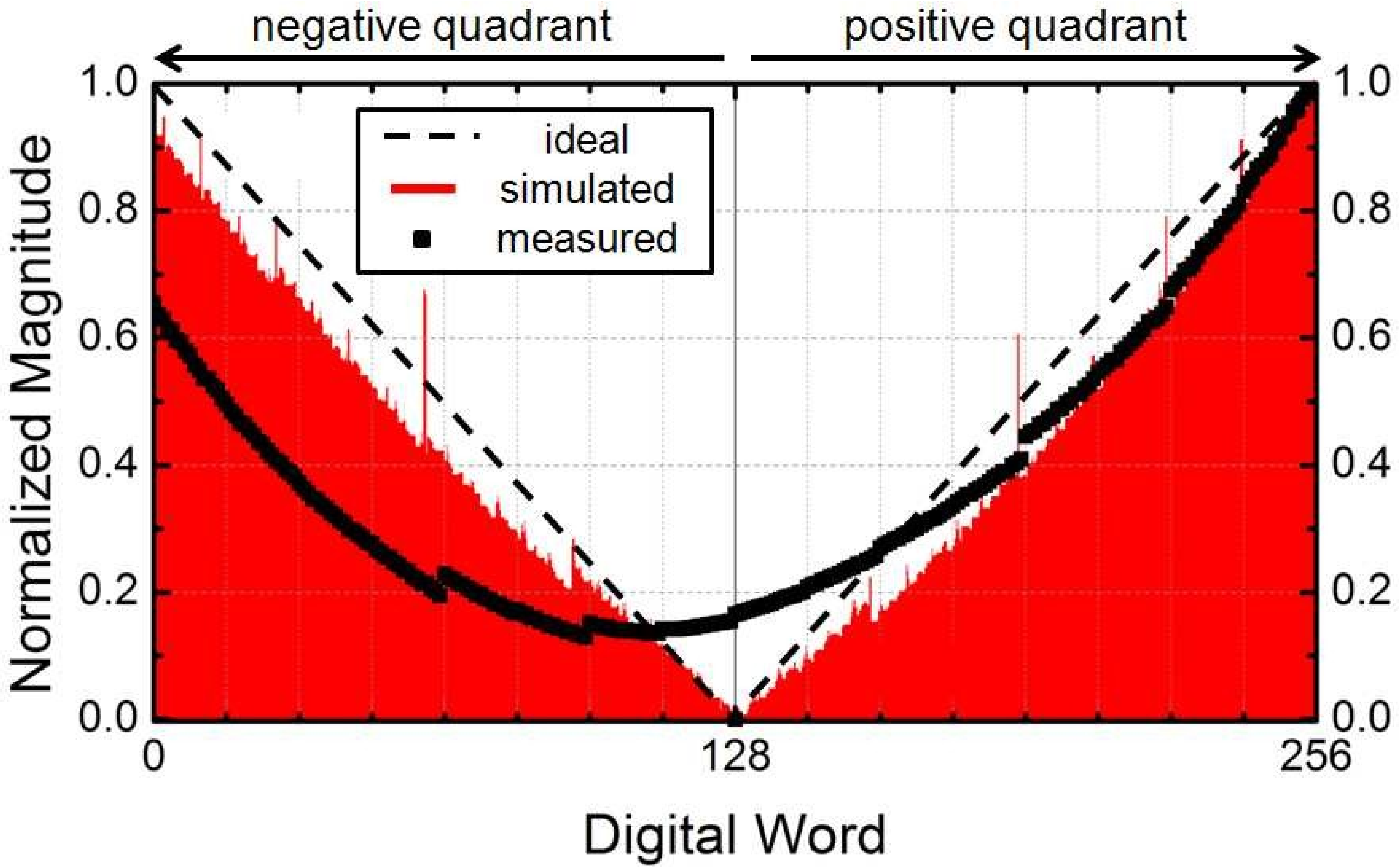


I_{DC} = 56.4 mA, $R_{OPT,diff}$ = 100Ω

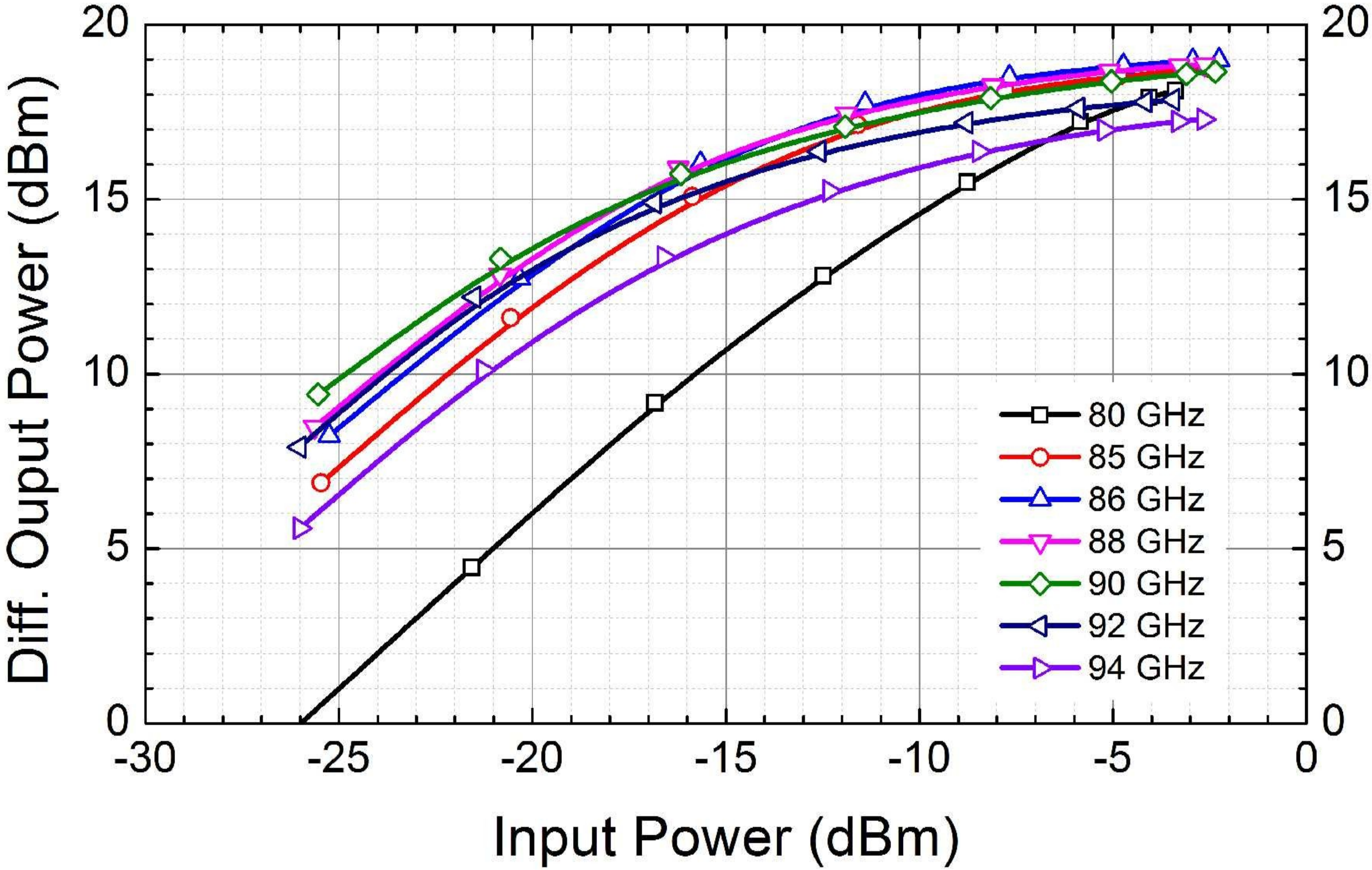
S-par. measurements for all 255 code words



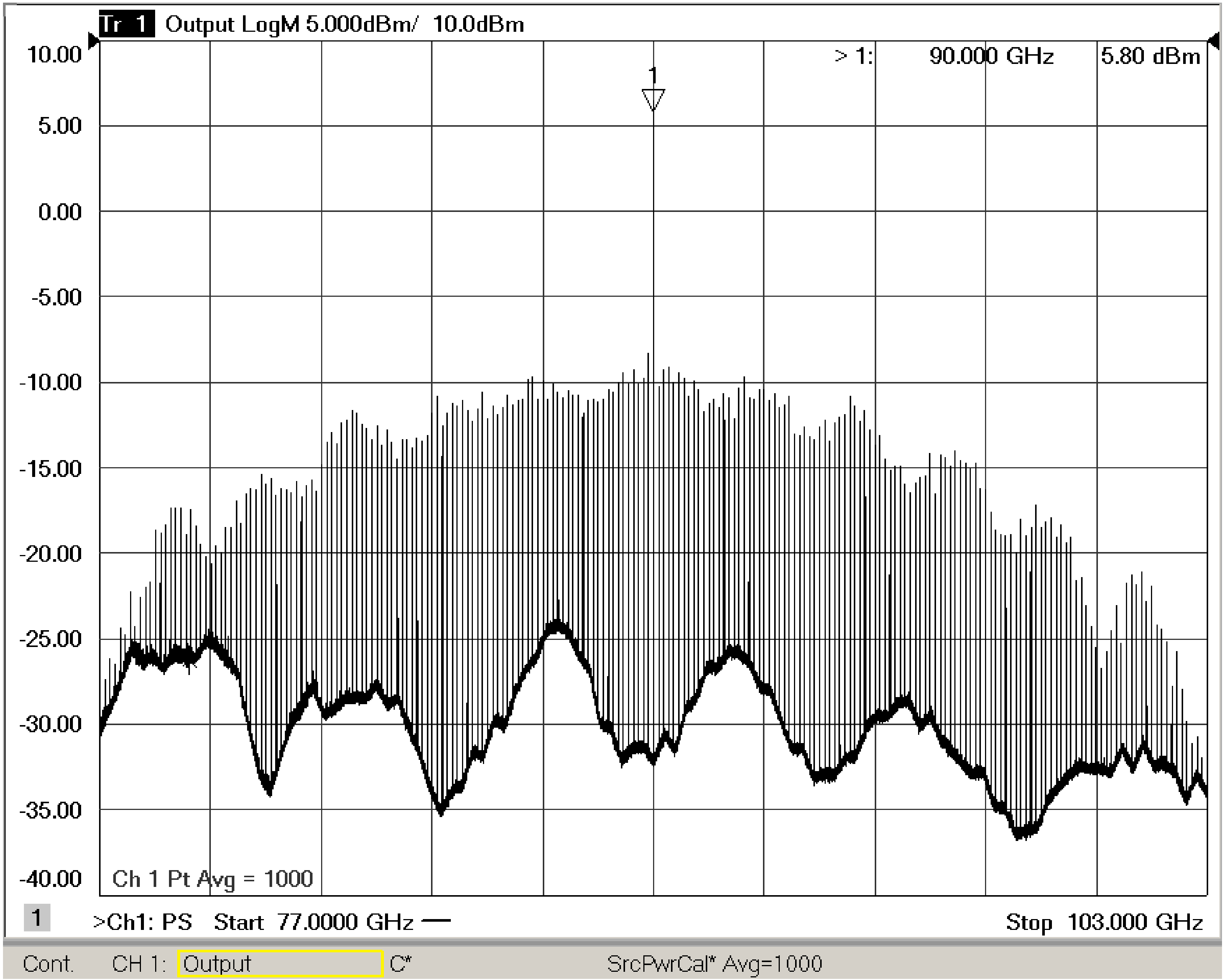
INL-DNL at 90 GHz from S-par. measurements



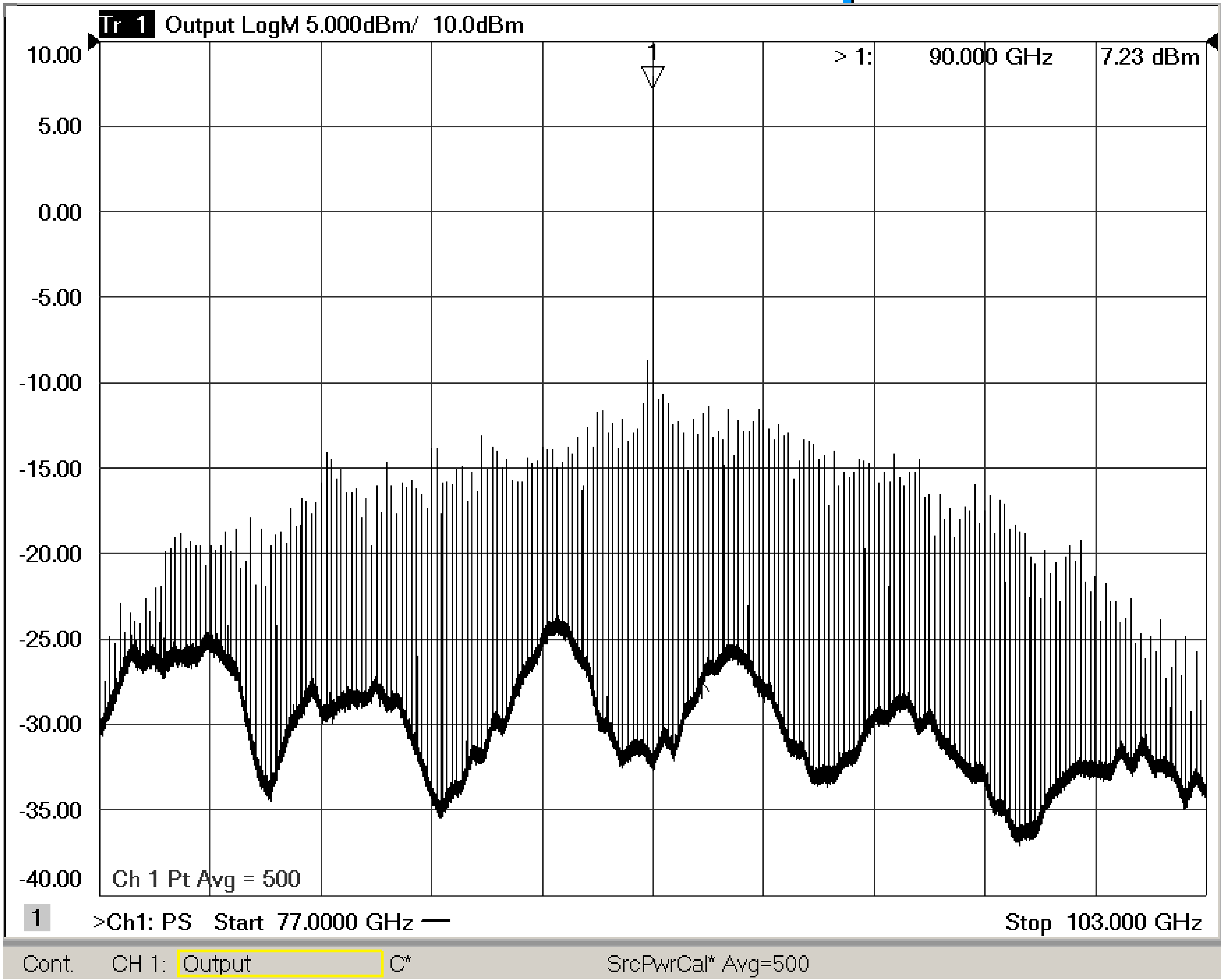
Large signal P_{out} vs. P_{in} for different frequencies



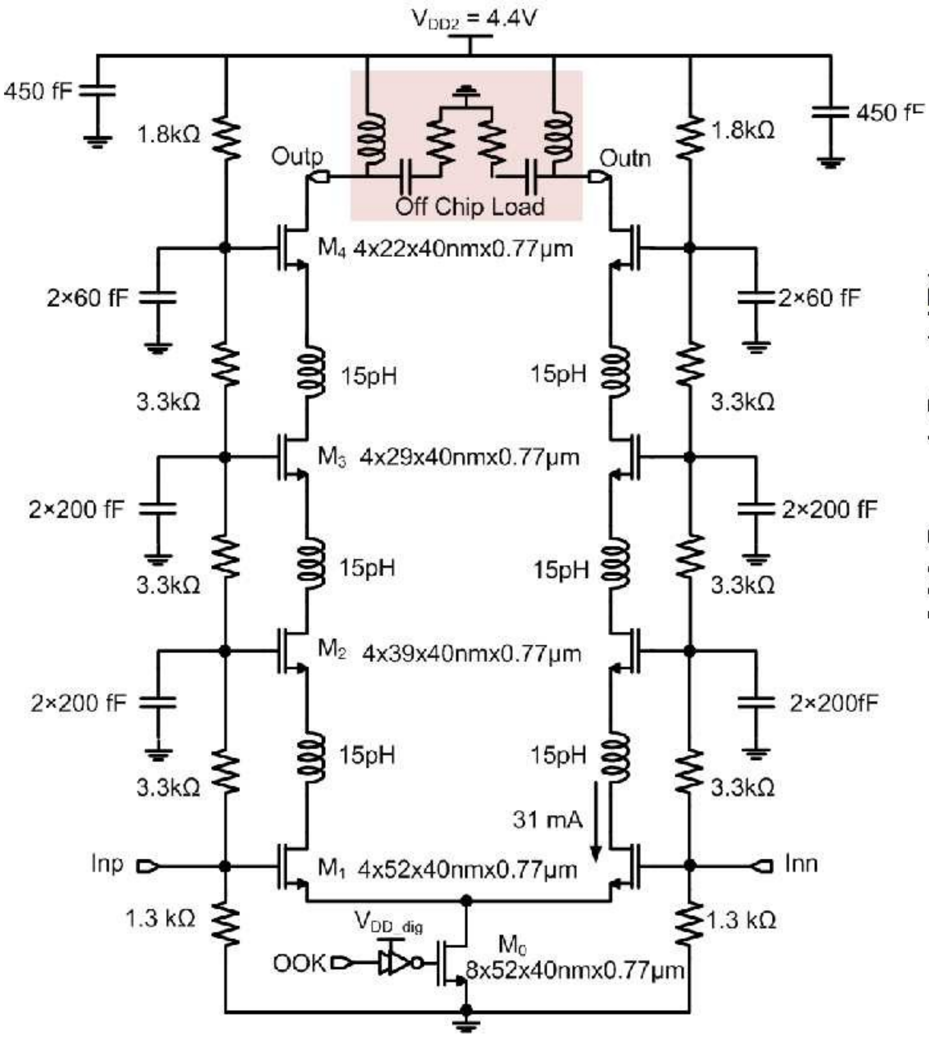
MSB, 15-Gb/s PRBS ASK/BPSK Spectra

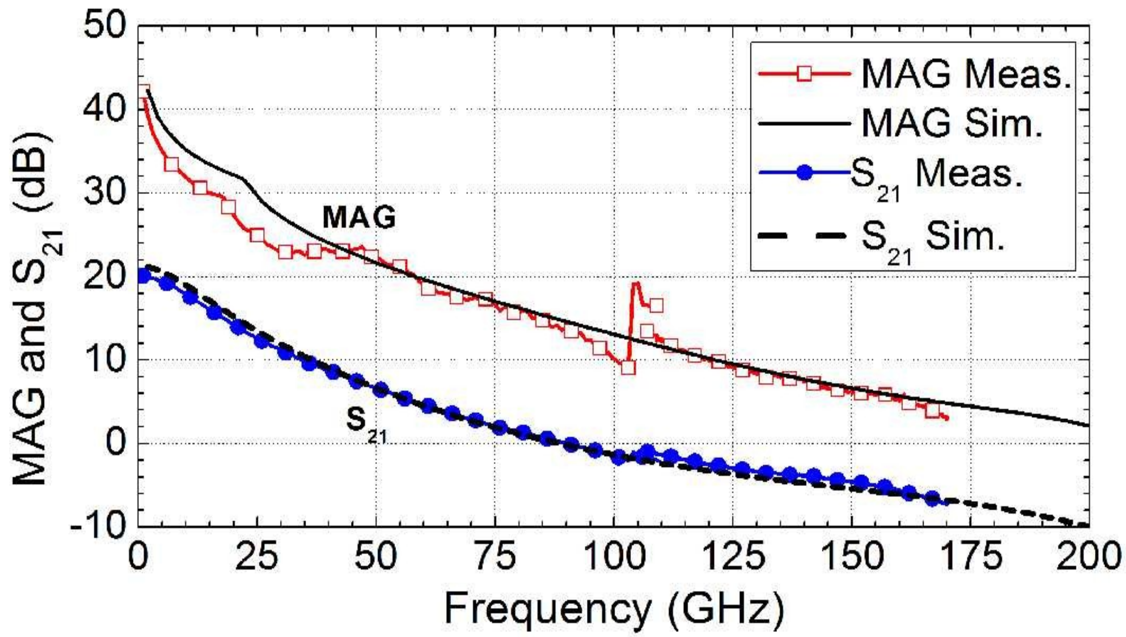


15-Gb/s PRBS OOK Spectra

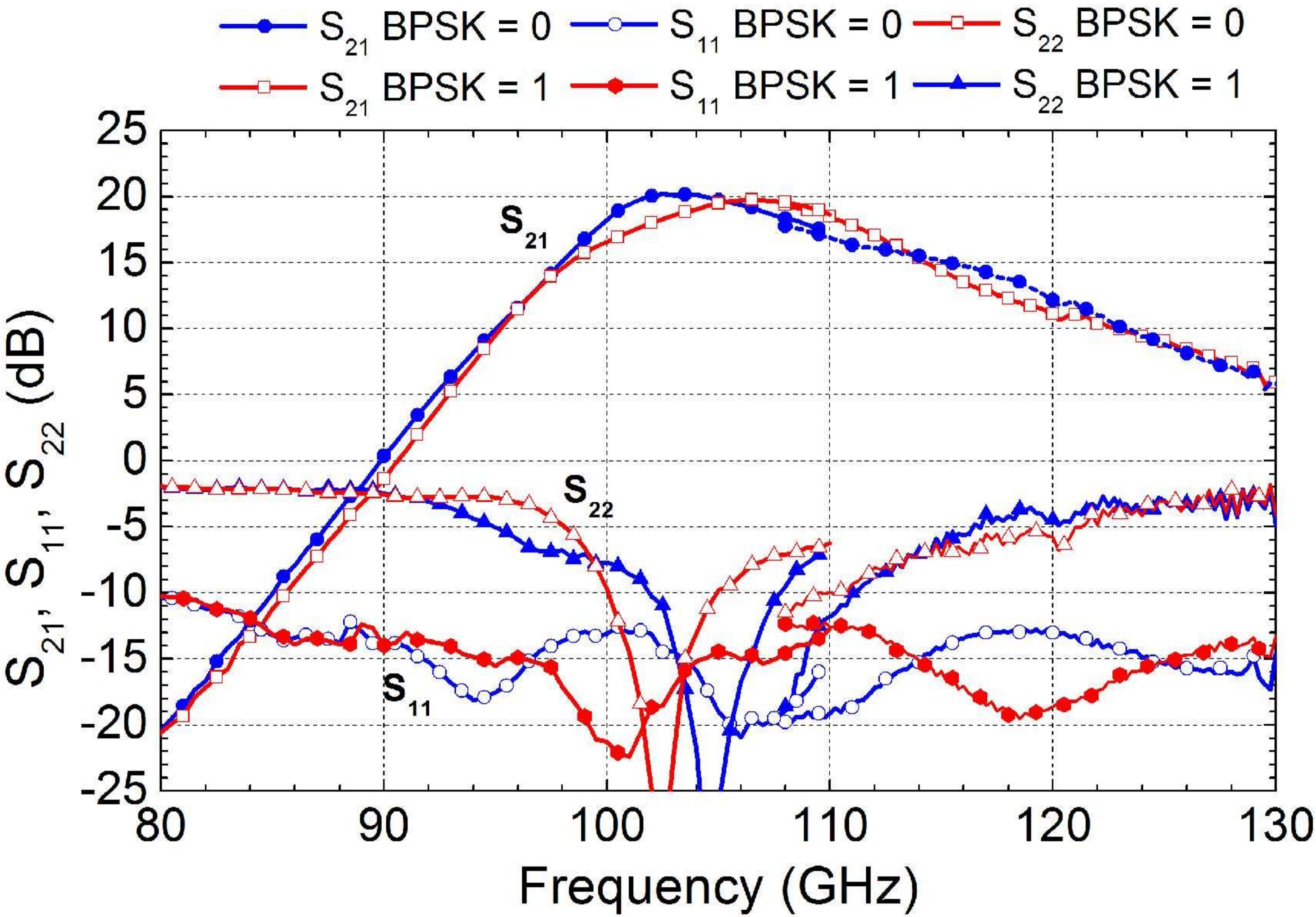


94-GHz n-MOS-Stack PA with OOK Modulation

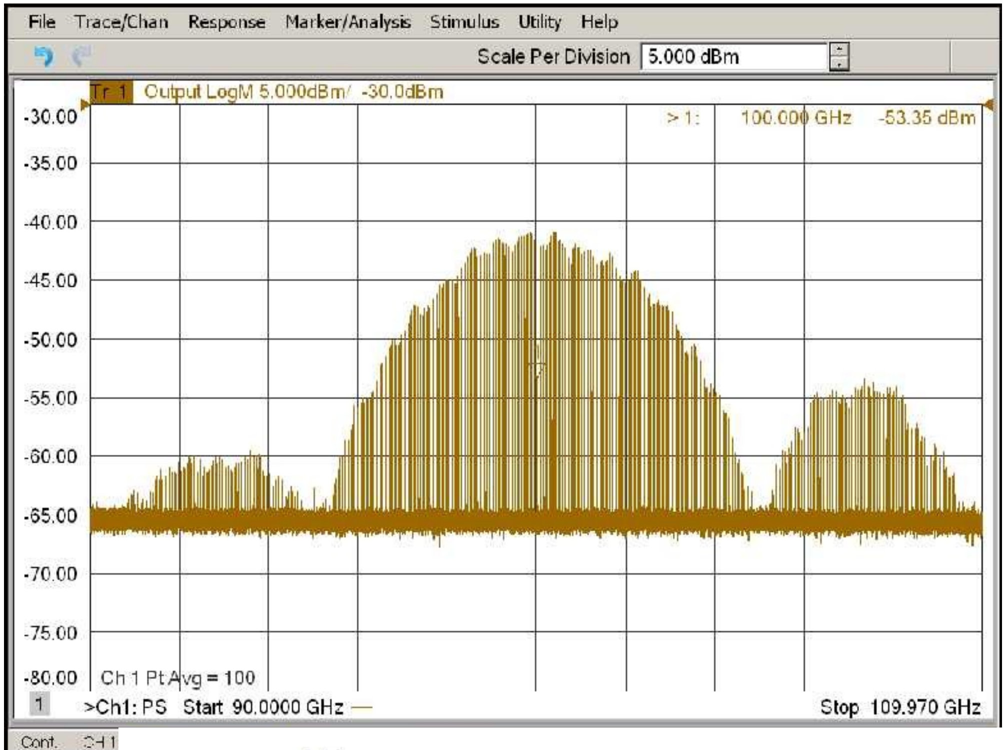


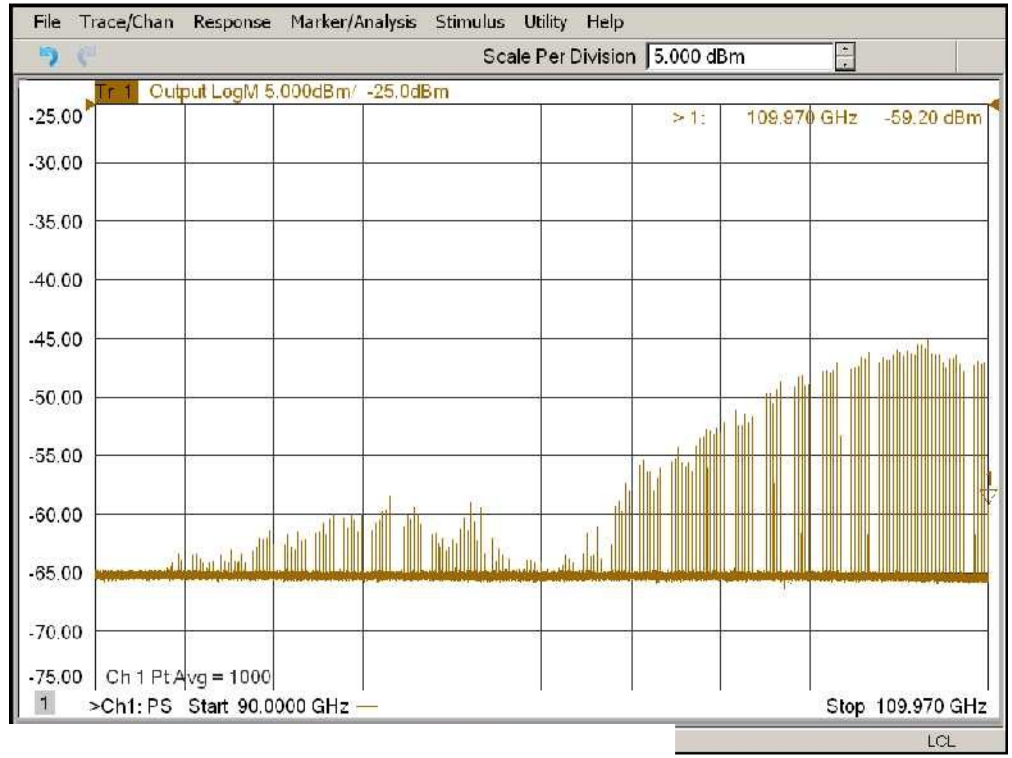


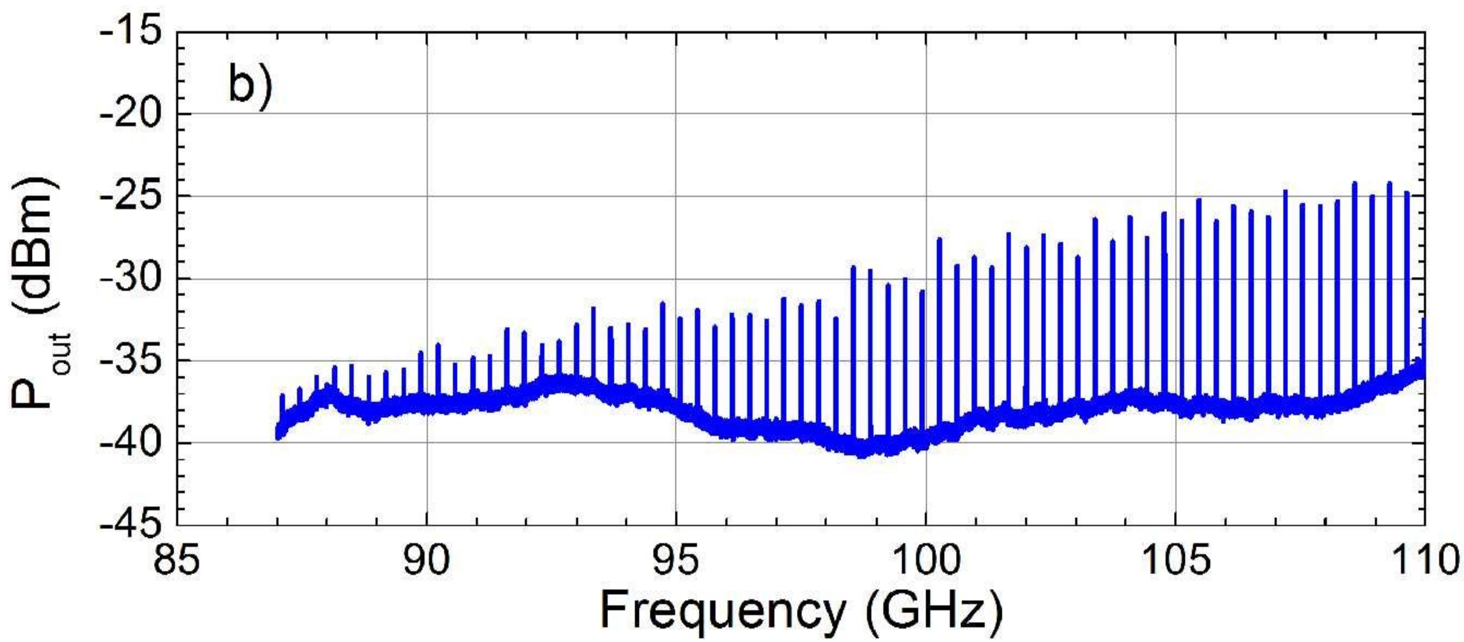
LO Amplifier S-parameters



100/110 GHz: BPSK at 5/10/44Gb/s







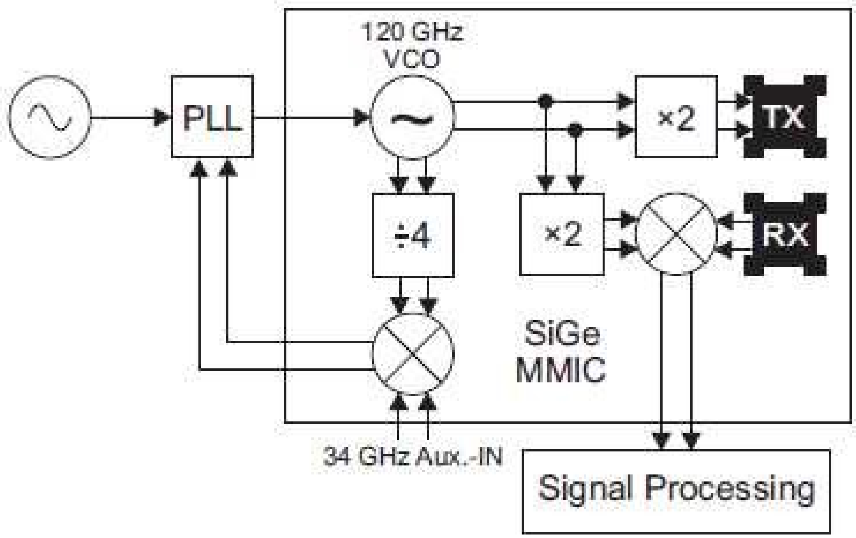
Conclusions

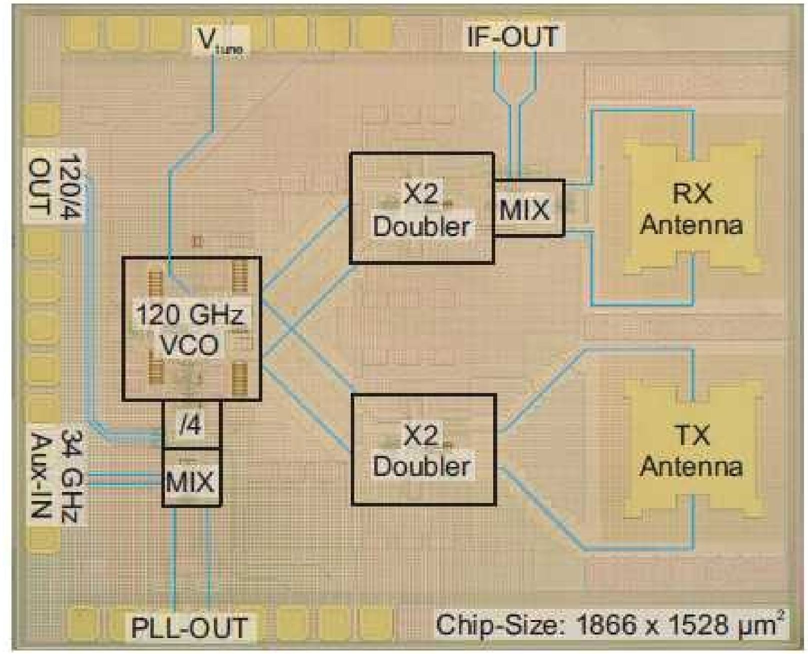
- Power DAC transmitters with antenna/modulator segmentation
- Convergence of digital with THz techniques
  - 44-Gbaud (88G b/s) 2-bit Power-DAC at 100-110 GHz
  - 15-Gbaud (120 Gb/s) 19 dBm, 18-bit IQ Power DAC
  - 60GS/sec $6V_{pp}$ 6-bit Distributed Power DAC
- 200+ Gb/s radio at 240 GHz feasible in silicon
- 100-Gb/s electronics for 1Tbs/carrier fiberoptics
- Need progress in modulators and electronic-photonic integration

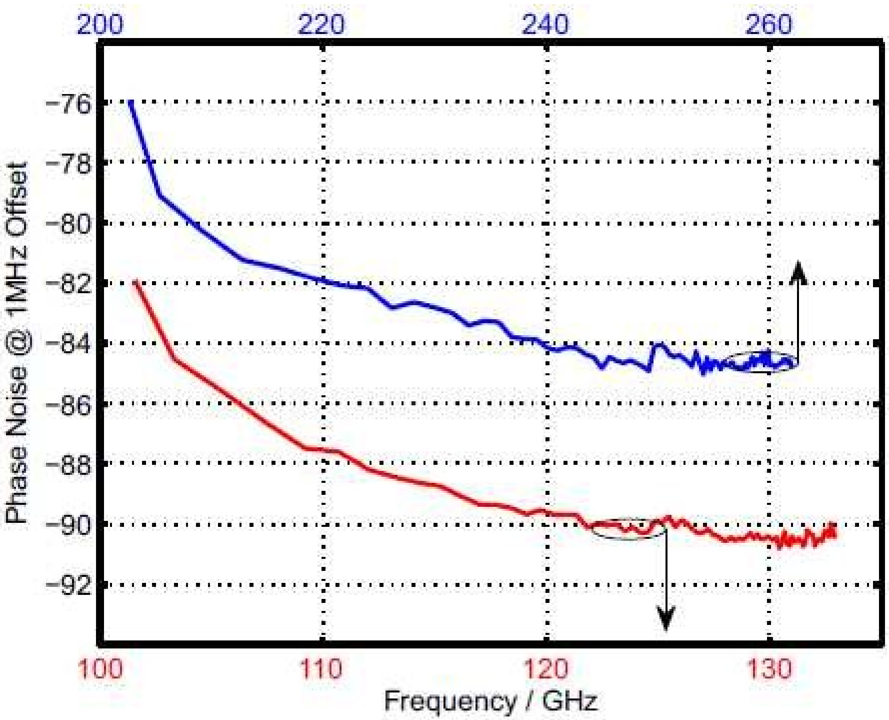
Credits

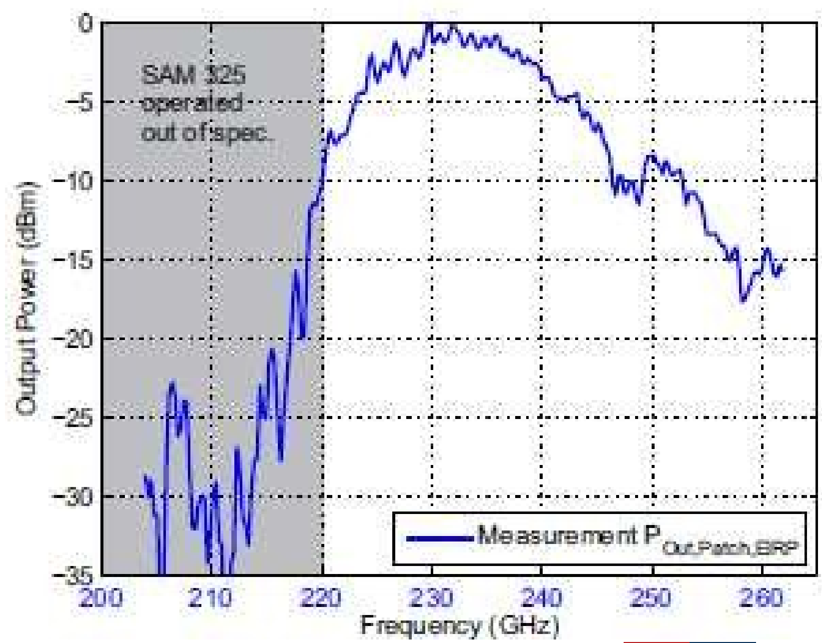
- Graduate students
  - Andreea Balteanu
  - Stefan Shopov
  - Yingying Fu
  - Ioannis Sarkas
  - Alex Tomkins
  - Eric Dacquay
  - Ivan Krotnev
- Funding
  - NSERC,
  - OCE,
  - Robert Bosch,
  - DARPA,
  - Ciena,
  - Gennum
- Chip donations
  - STMicroelectronics,
  - DARPA
  - Ciena

240-GHz SiGe HBT Radar Transceiver



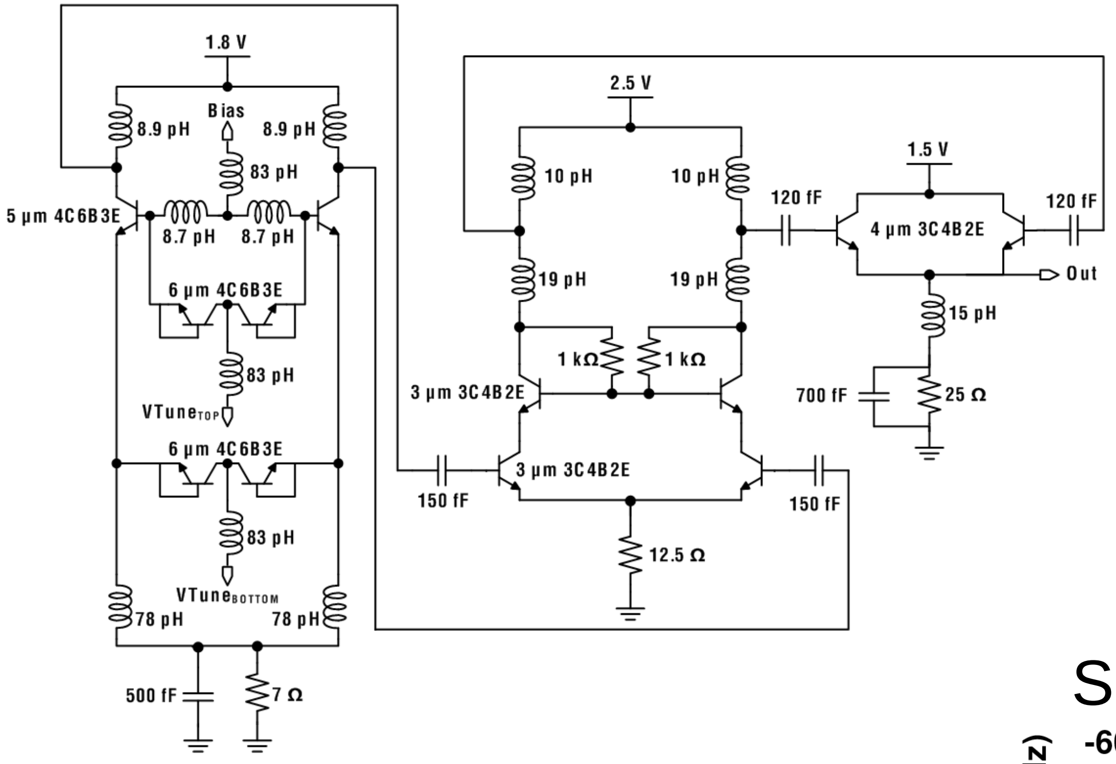


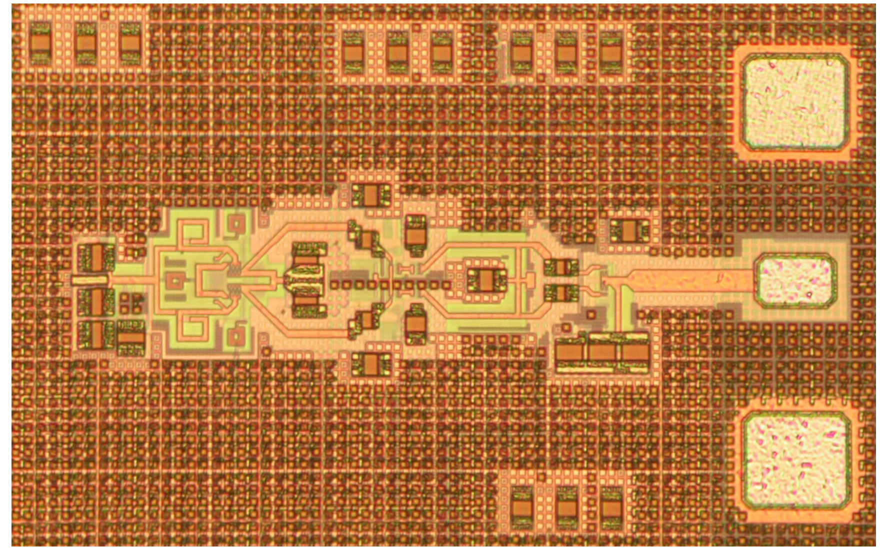




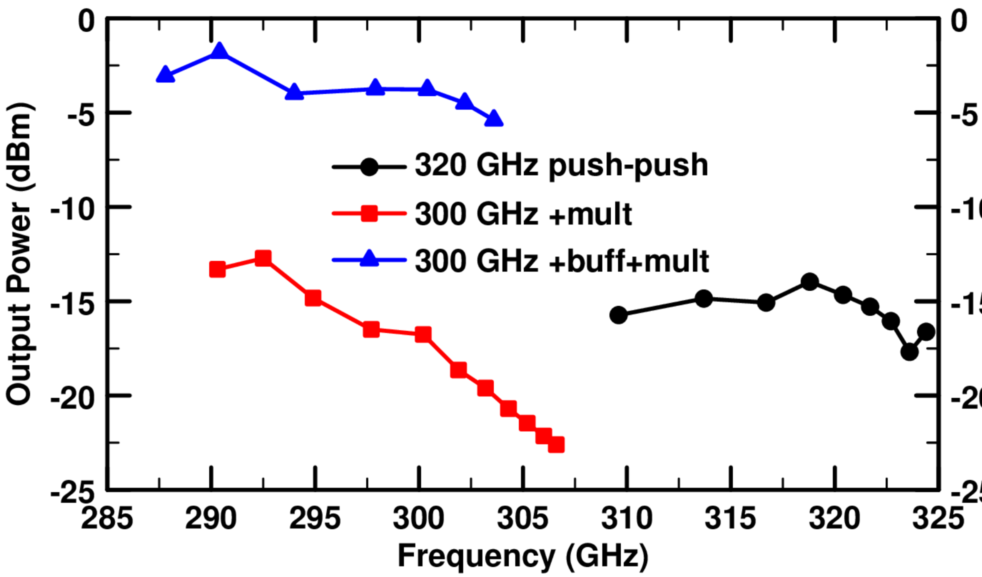
Bredendiek et al, IMS 2013

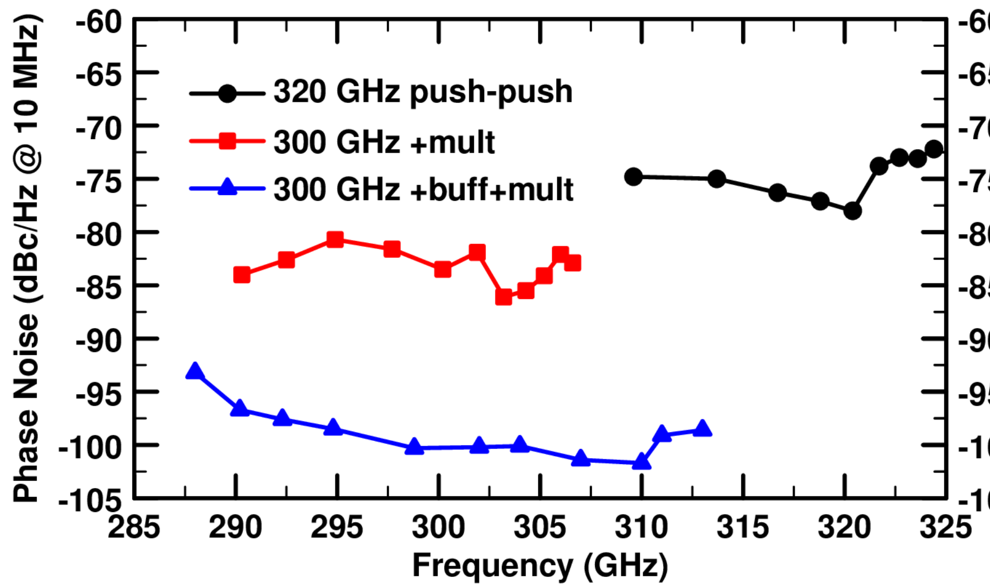
300-GHz SiGe HBT VCO-Doubler Source





S. Voinigescu et al., JSSC 2013





InP HBT Integrated Circuits: 600 GHz & Beyond

TELEDYNE SCIENTIFIC COMPANY
A Teledyne Technologies Company
UCSB

614 GHz fundamental VCO

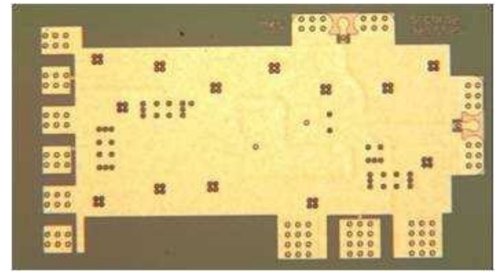
M. Seo, TSC / UCSB

M. Seo, TSC / UCSB

Vtune
Vtune
VEE
VBB
VEE
VBB
Vout
Vout

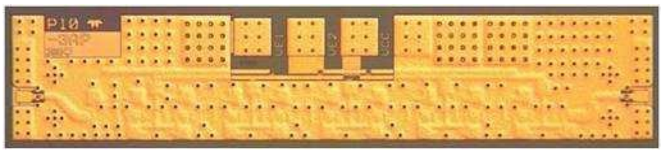
340 GHz dynamic frequency divider

M. Seo, UCSB/TSC
IMS 2010



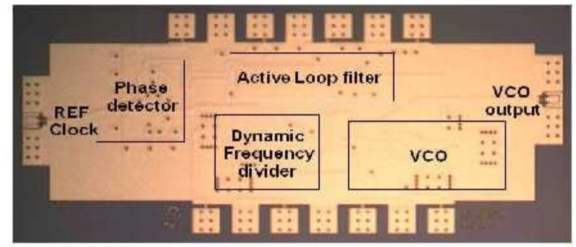
585-600 GHz amplifier, > 34 dB gain, 2.8 dBm output

M. Seo, TSC
IMS 2013



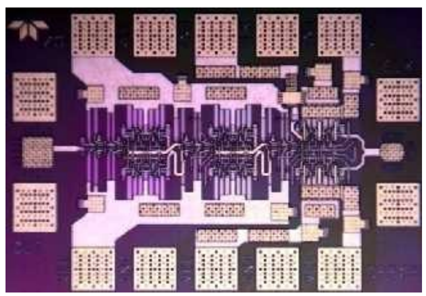
300 GHz fundamental PLL

M. Seo, TSC
IMS 2011



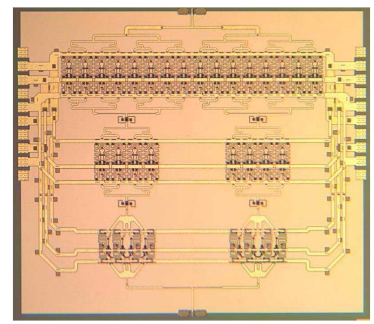
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC
CSIC 2010



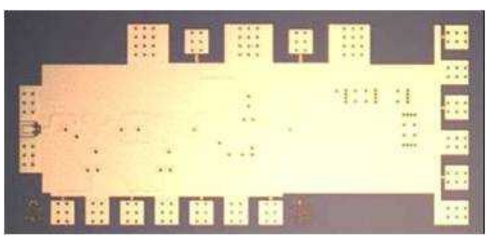
220 GHz 180 mW power amplifier

T. Reed, UCSB
Z. Griffith, Teledyne
CSICS 2013



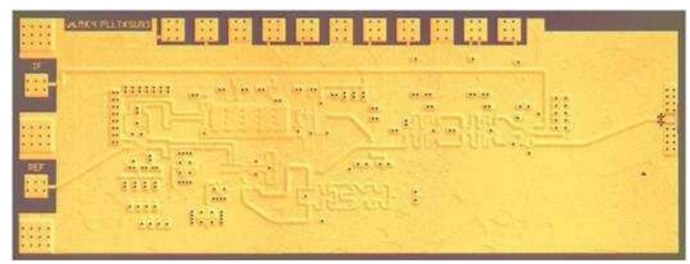
Integrated 300/350GHz Receivers:
LNA/Mixer/VCO

M. Seo TSC



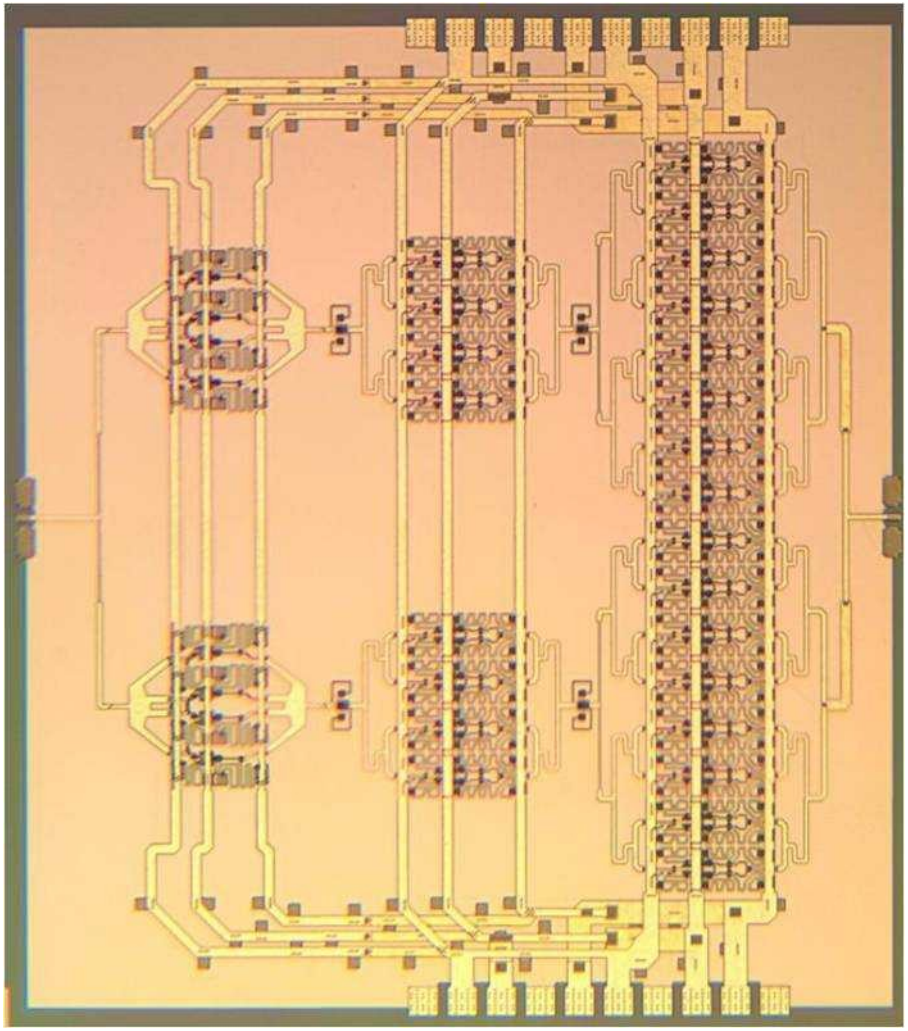
600 GHz Integrated Transmitter
PLL + Mixer

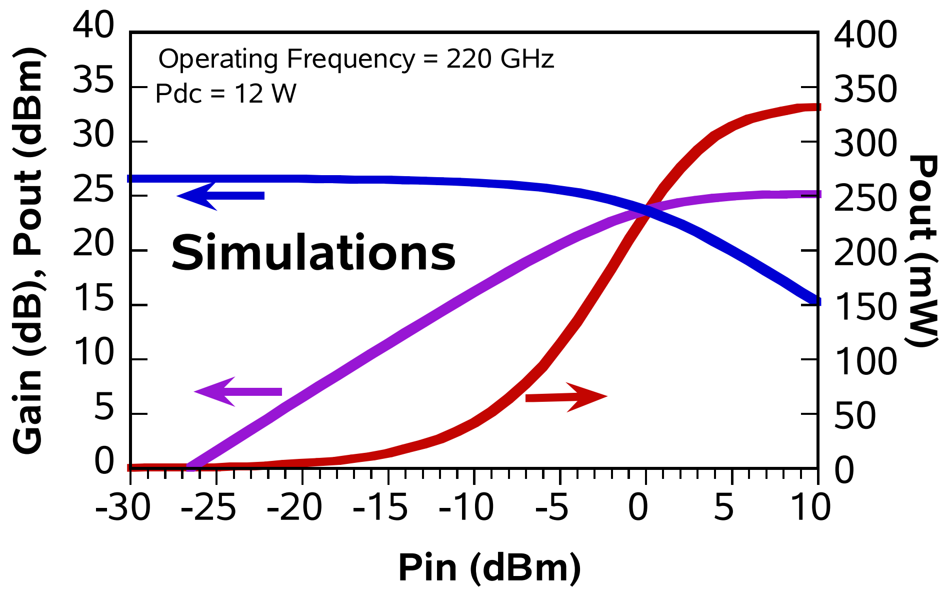
M. Seo TSC



Courtesy of Mark Rodwell

220 GHz, 180mW Power Amplifier





Simulations:

320 mW ouput @ P1dB

Measurements to date:

180 mW @ 220 GHz

T. Reed, UCSB
Z. Griffith, Teledyne
Teledyne 256 nm InP HBT

A 180mW InP HBT Power Amplifier MMIC at 214 GHz
(To be presented, CSICS 2013)

Thomas B. Reed[1], Zach Griffith[2], Petra Rowell[2], Mark Field[2], Mark Rodwell[1], *Fellow, IEEE*
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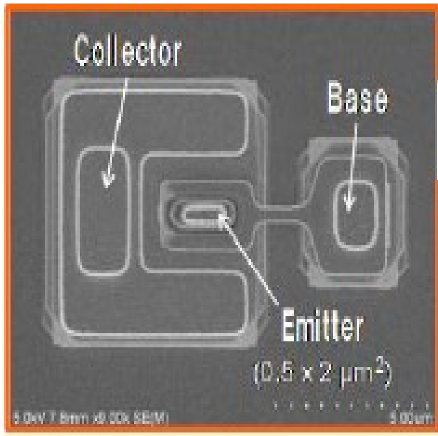
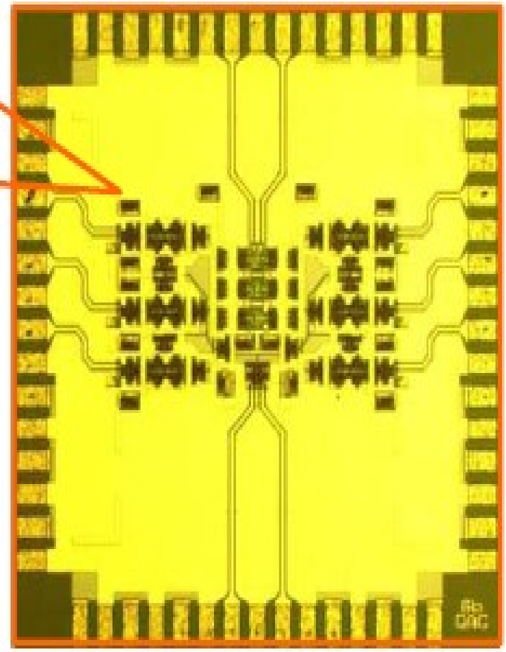
Department of Electrical and Computer Engineering
Santa Barbara, CA, 93106-9560 USA
treed314@gmail.com
[2]Teledyne Scientific and Imaging
1049 Camino Dos Rios, Thousand Oaks, CA, USA 91360
zgriffith@teledyne-si.com

60-GS/s 6-bit broadband DAC in InP HBT



f_t=290 GHz
f_{max}=320 GHz



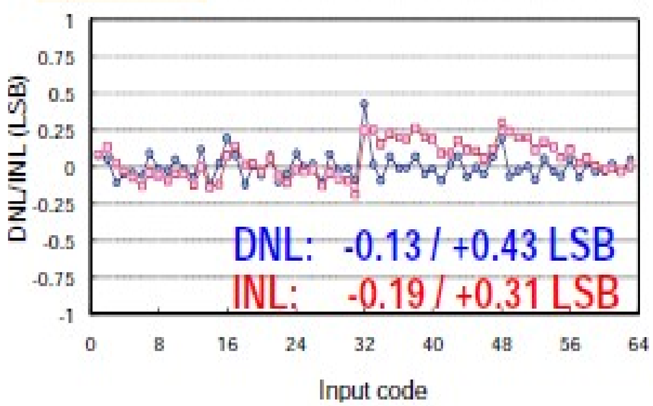
(3 mm x 3 mm)

Technology: InP HBT
Sampling rate: 60 GS/s
Resolution: 6 bit
Analog bandwidth: > 30 GHz
INL/DNL: < 0.5 LSB
SFDR: ~ 30 dB up to 30 GHz
Power Cons.: 1.8 W

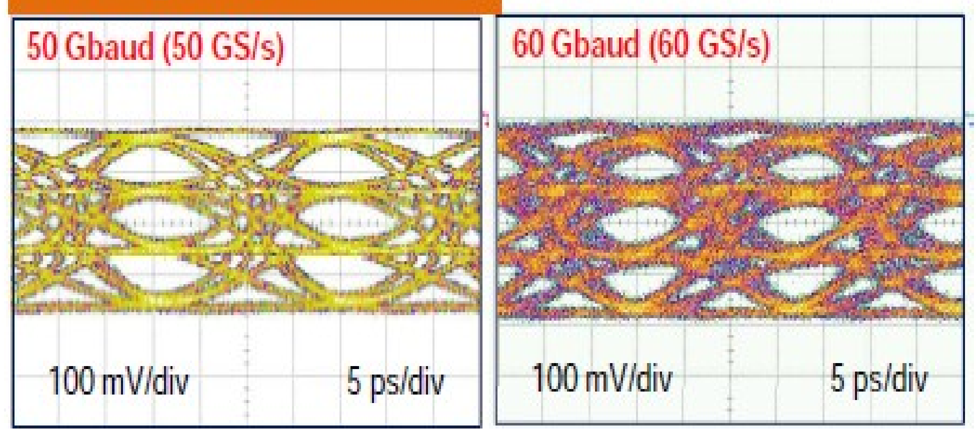
M. Nagatani et al. CSICS 2011

Measured Performance

DNL/INL

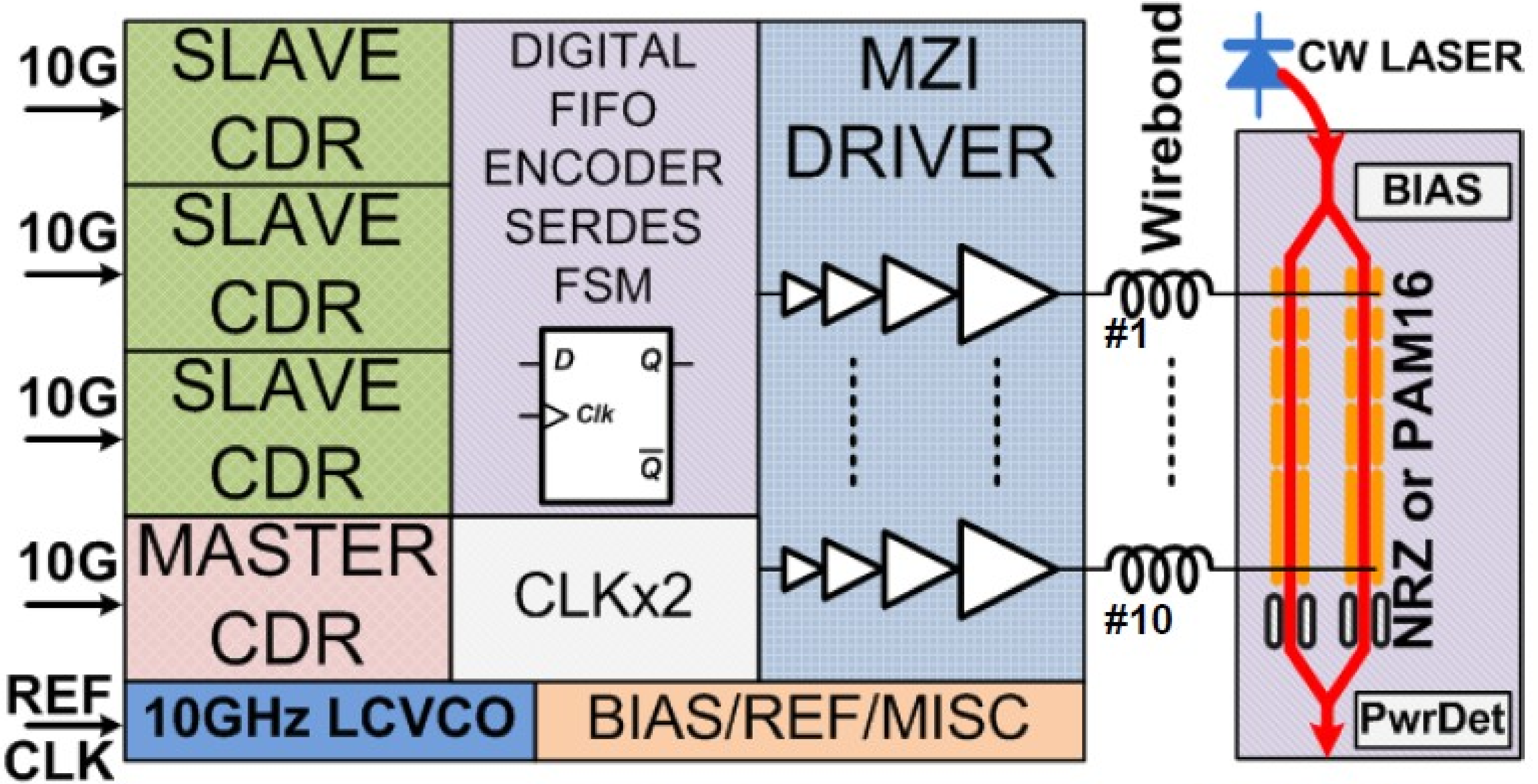


4-level signal output (for 16-QAM)



Courtesy of Koichi Murata, NTT

Example: Binary-Weighted Optical DAC

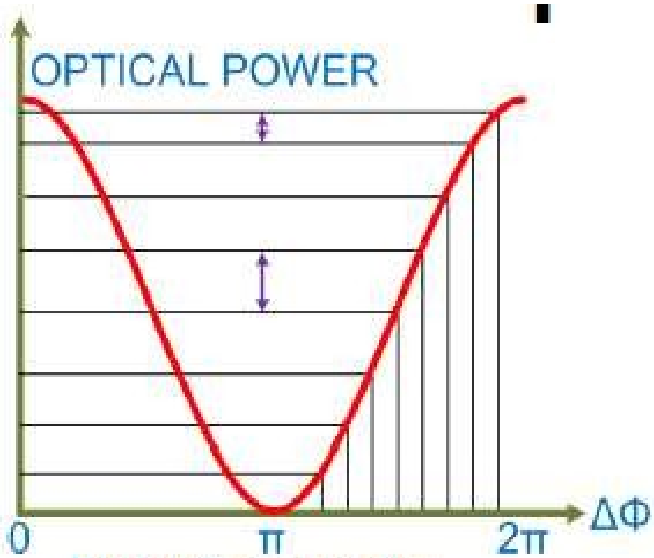


Electrical driver IC in 40nm CMOS

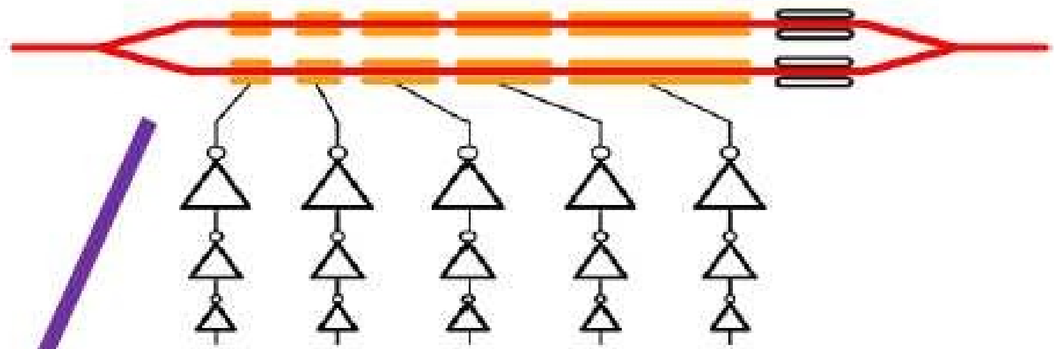
Optical IC in 0.13μm SOI CMOS

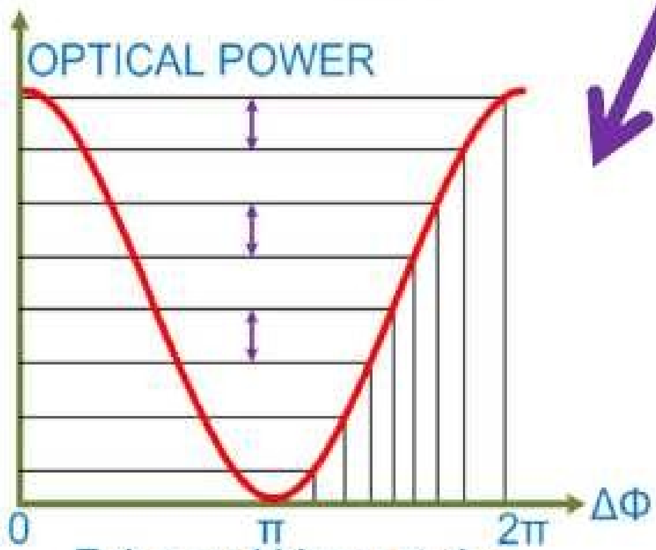
[X. Wu et al, ISSCC 2013]

Optical 16-PAM Eye Diagram

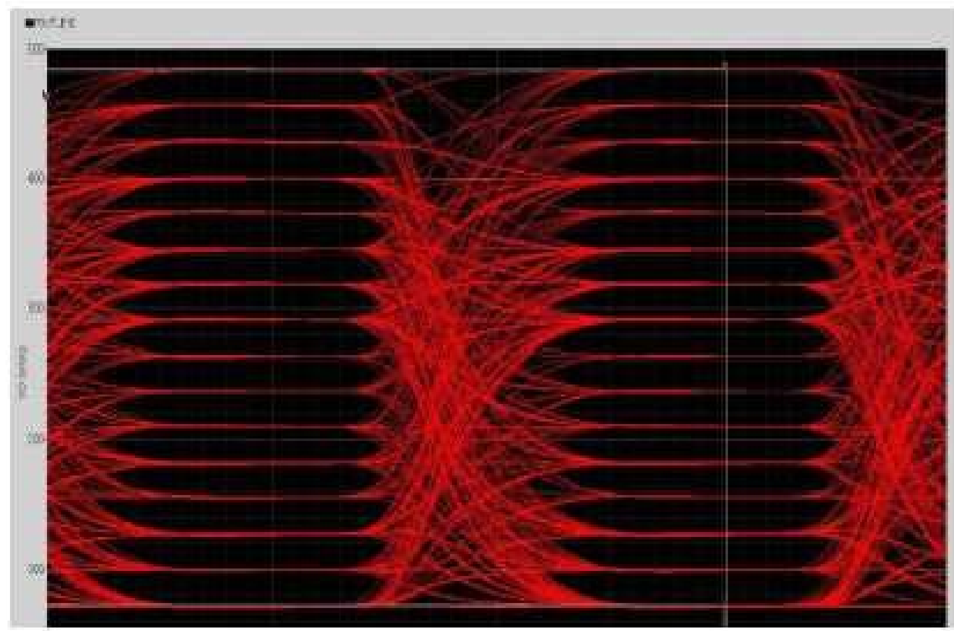


Binary/thermometer code weighted PAM-16



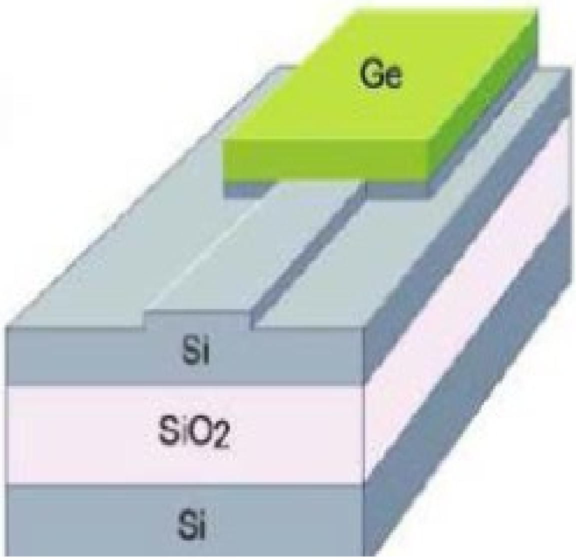


Enhanced binary code weighted PAM-16

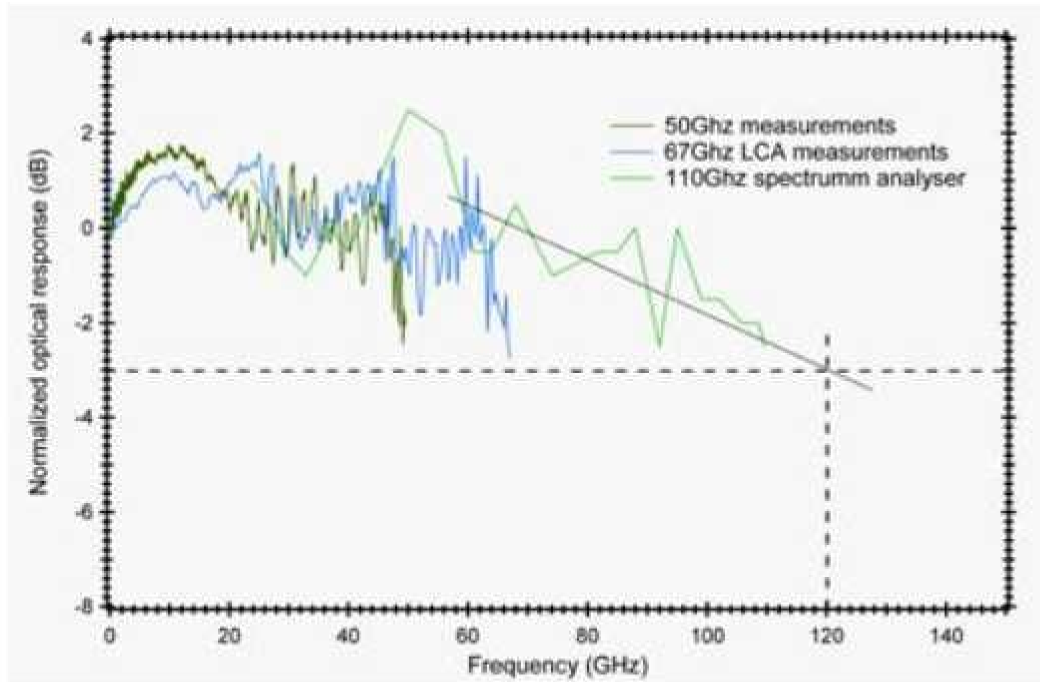


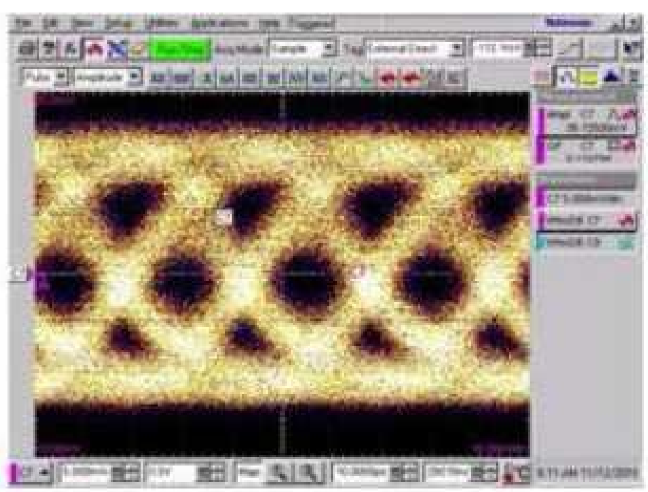
Simulated eye for Enhanced binary code weighted PAM-16

100-GHz Ge PIN Photodiodes on SOI

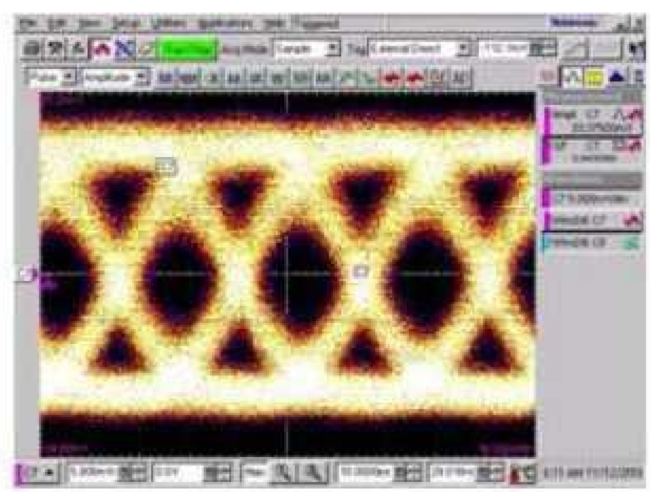


LETI





40 Gbit/s



94-GHz BPSK Modulator