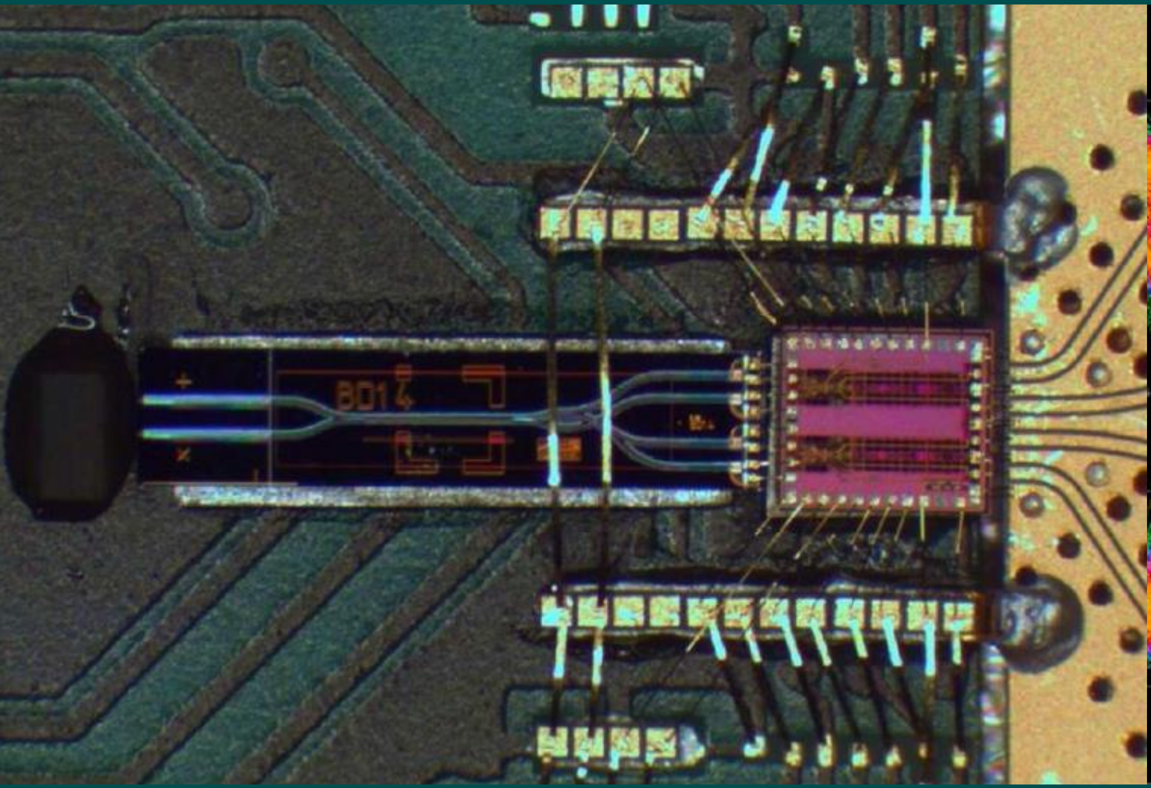
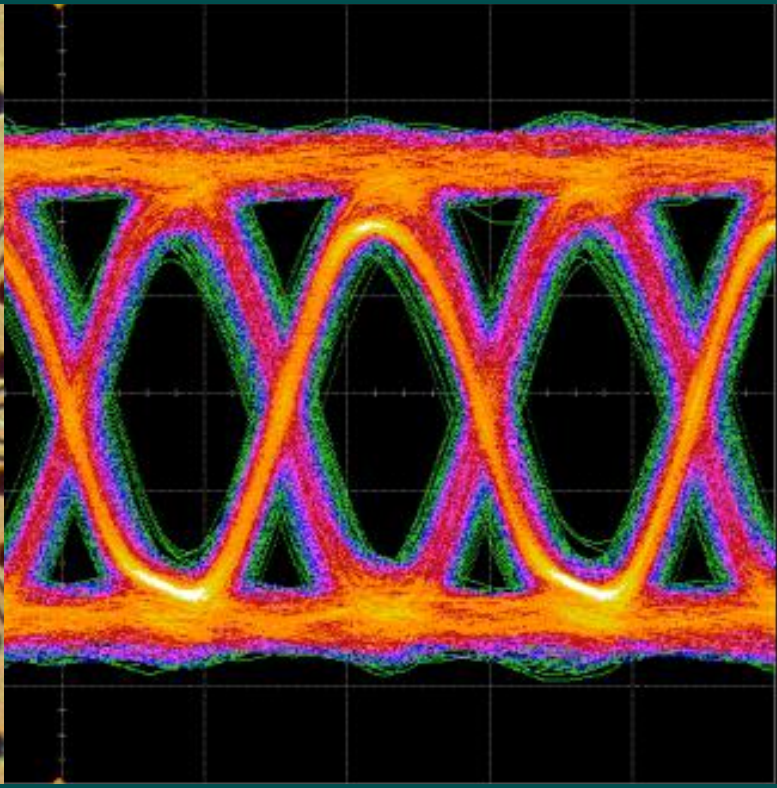
# Broadband Circuits for Wireless and Wireline Communications





# 1. INTRODUCTION

**Institute for RF Engineering and Electronics**
**Prof. Dr.-Ing Ahmet Çağrı Ulusoy**
ulusoy@kit.edu

# BCWW

- Learn about broadband communication systems with an emphasis on “wireline” communications (fiber optics)
- Learn how these systems operate, their performance specifications and hardware requirements
- This lecture will concentrate on the “frontend” electronics, driver and receiver amplifiers
- We will learn broadband circuits types on receivers and transmitters, how they are analyzed and how they are designed
- We will have “hands-on” exercises on designing broadband circuits

# Method

- Lecturer: (https://www.ihe.kit.edu/mitarbeiter_ulusoy.php)

- Slides will be provided that will be annotated during the lecture, students will receive the slides with the notes

- It is recommended that you take your own additional notes

- In the Lab portion, the concepts thought in the lecture will be exercised in “hands-on” design tasks

- Final exam will be based on published literature and a 20 minute presentation, own simulations using the Lab material is encouraged and will be considered as a bonus

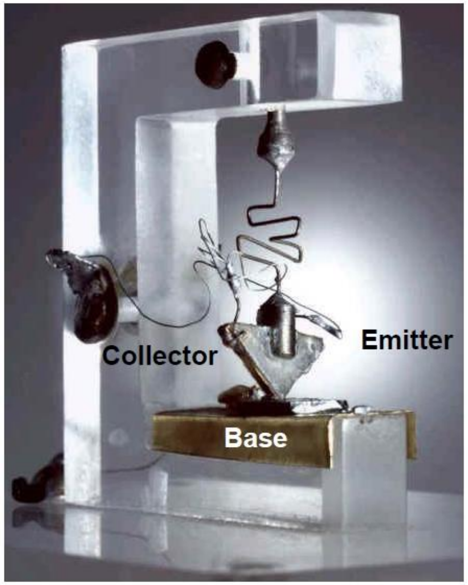
# Additional References

- The slide set with notes from Ulusoy will be sufficient, additional recommended references:

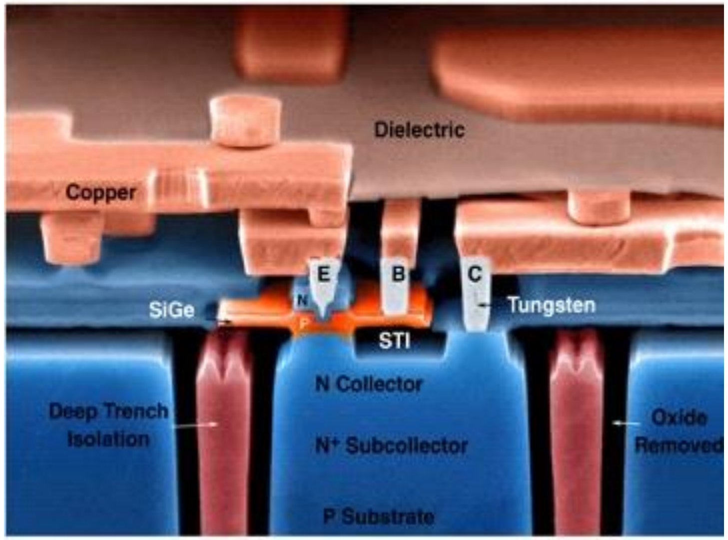
Eduard Säckinger, “Broadband Circuits for Optical Fiber Communications”
John Wiley & Sons, 2005

Behzad Razavi “Design of Integrated Circuits for Optical Communications”
Wiley, 2012

# Broadband Communications




~70 Years

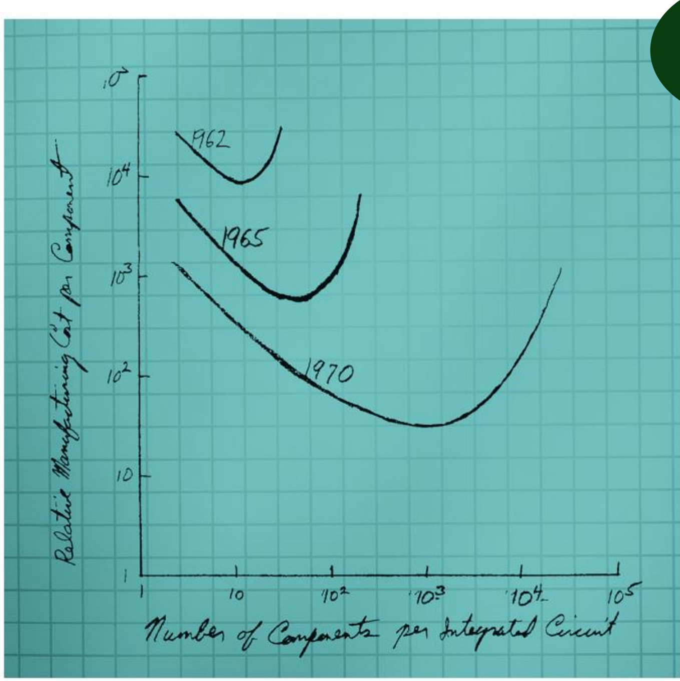


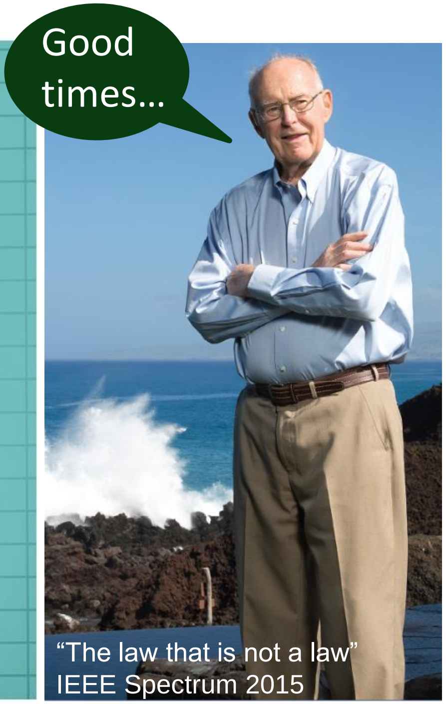

1947: First transistor
Operational in KHz range
60‘s: IC era starts (few transistors)

Cross-section of a SiGe HBT
Operational in THz range
ICs with billions of nanoscale transistors

**Transistor is the most important invention of the 20th century!**

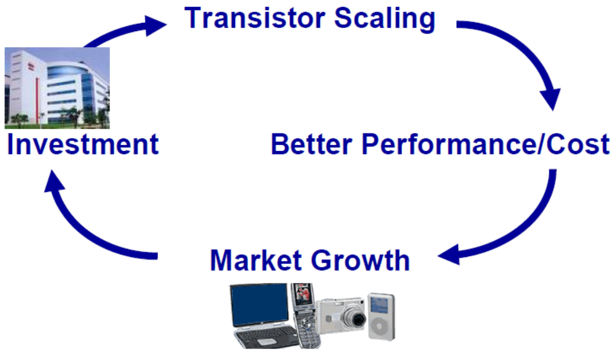
- Like in every other electronics lecture: Moore´s Law




Chris Mack "The multiple lives of Moore's Law"
IEEE Spectrum, vol. 52, issue 4

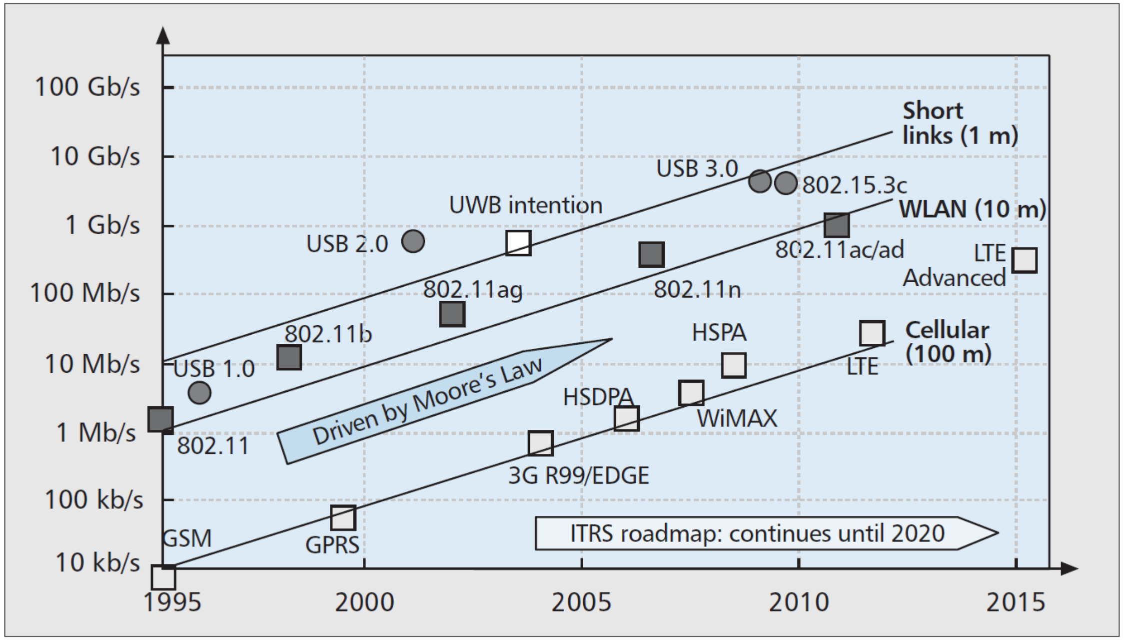
Arden et al. "more-than-Moore"
White paper, ITRS




- **Moore:** Relative manufacturing cost per component decreases for increasing number of components in an IC (1965)
- The # of transistors in an IC doubles every 1.5 years
- Self-fulfilling prophecy, ITRS
  (International Technology Roadmap for Semiconductors)

# Broadband Communications

The incredible growth of semiconductor industry and digital electronics means also more data needs to move from point A to point B

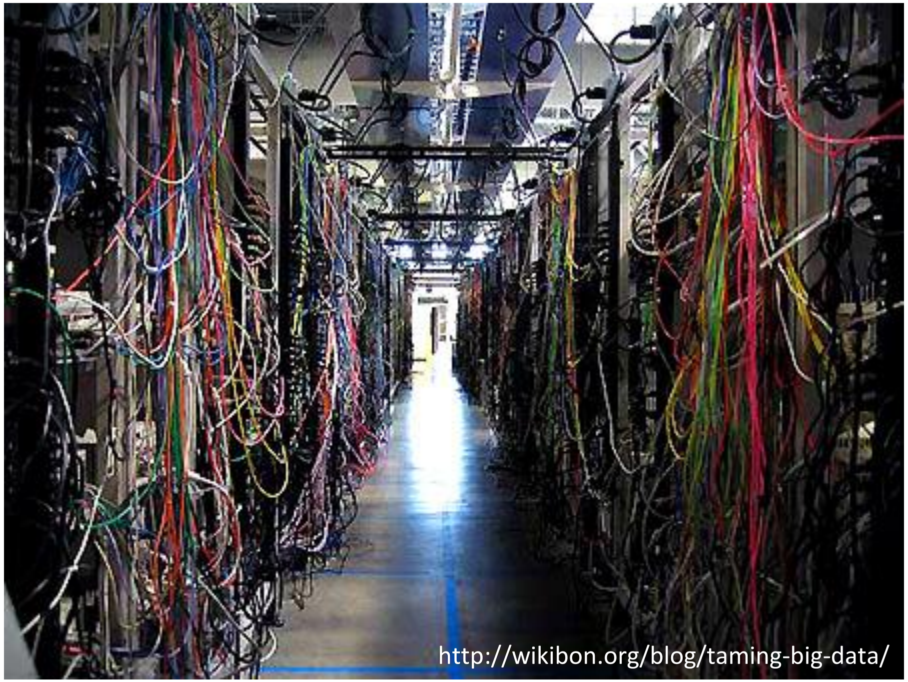



A. Fehske et. Al. "The Global Carbon Footprint of Mobile Communications – The Ecological and Economic Perspective"
IEEE Communications Magazine, Aug. 2011

**Big Data is Coming !** **Also internet of things, smart cities, body area networks, intelligent mobility, 5G & 6G….**

By 2022 global IP traffic will reach 396 exabytes per Month

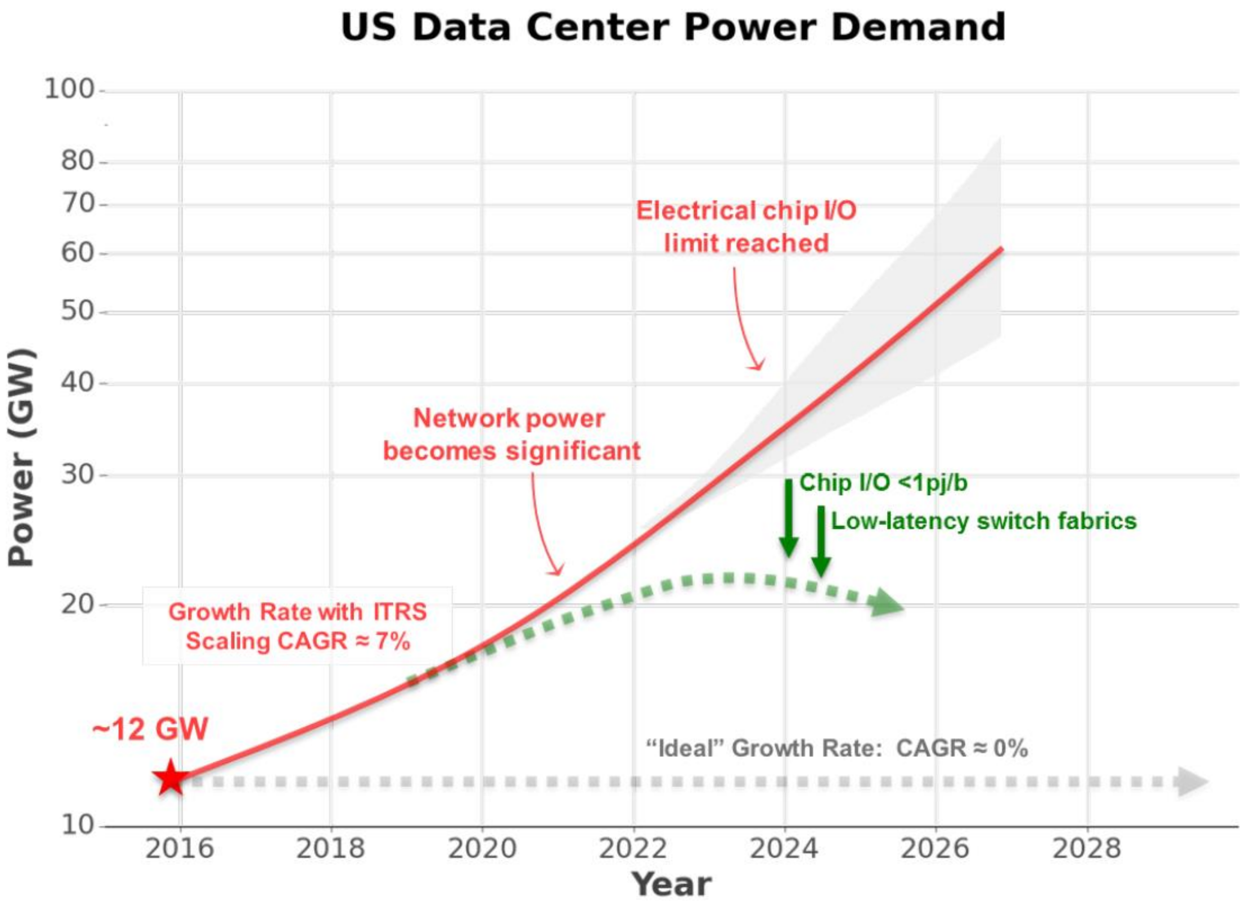
It would take one person over 5 million years to watch the amount of video that will cross global IP networks each month in 2018



http://wikibon.org/blog/taming-big-data/

# Broadband Communications

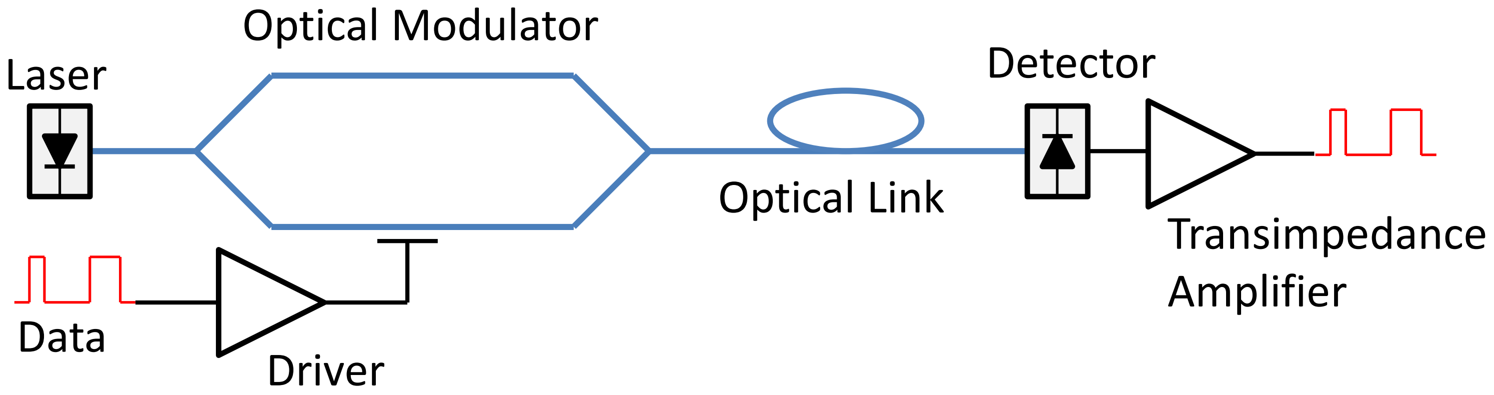
- The energy consumption in data centers alone is significant! Currently 2.5% of all energy in the US, expectation x2 in the next 8 years




Advanced Research Projects Agency – Energy (ARPA-E): Energy Efficient Light Wave Integrated Technology Enabling Networks that Enhance Datacenters

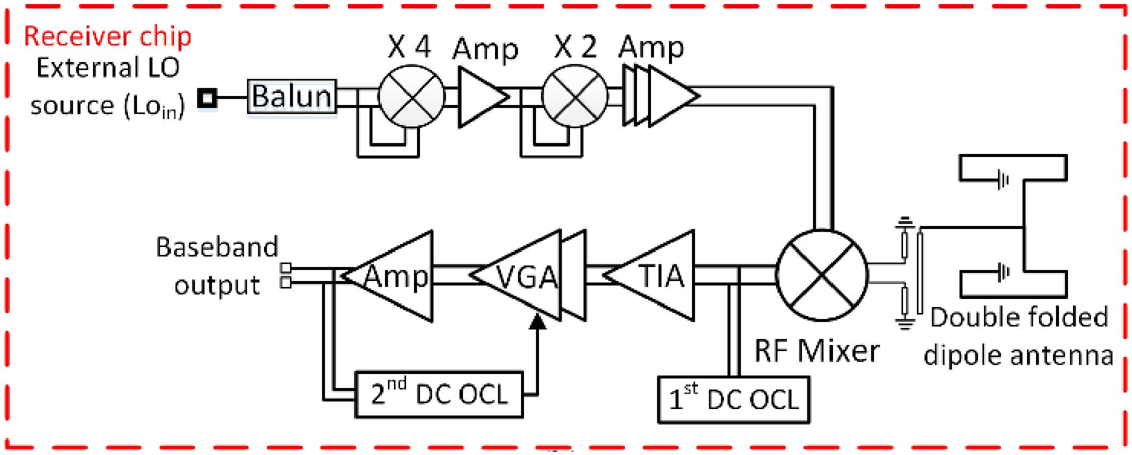
# Broadband Circuits

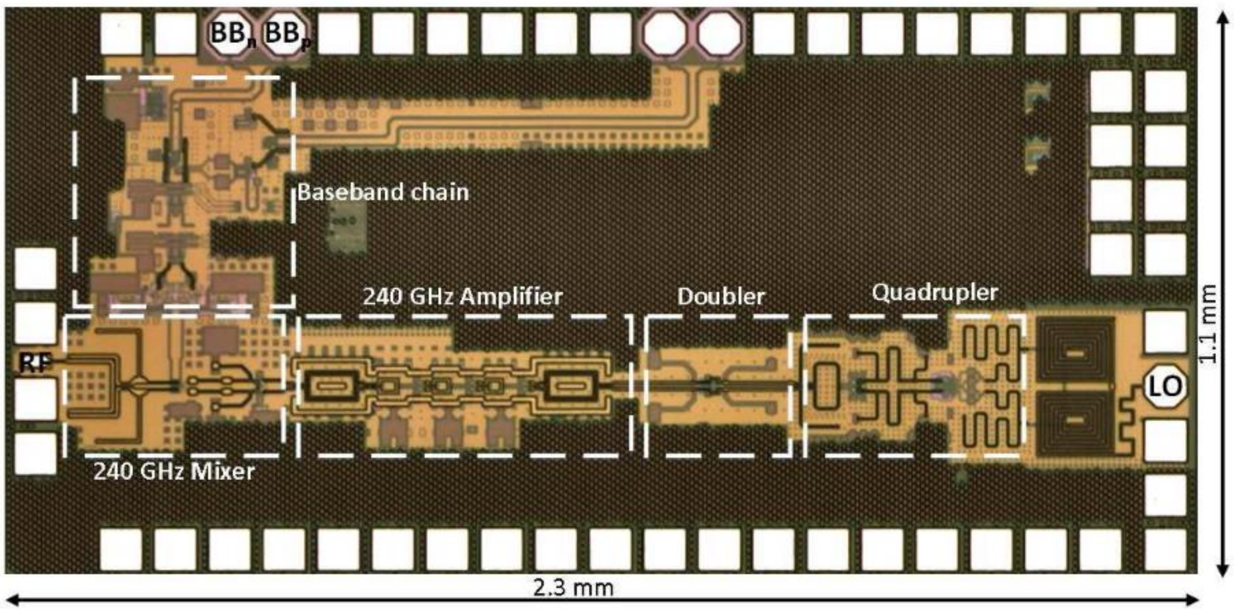
- The receiver and transmitter electronics play a crucial role in the overall system budget of wireline communications
- This is an area of intensive research, the overall goal is to improve link efficiency expressed in pJ/bit
- In fiber optics, electronic/photonic interfaces are a typical bottleneck in terms of data rate per lane and power consumption



# Broadband Circuits

- In wireless communications baseband electronics start to become more and more like a photonic frontend




M. H. Eissa *et al.*, "Wideband 240-GHz Transmitter and Receiver in BiCMOS Technology With 25-Gbit/s Data Rate," in *IEEE Journal of Solid-State Circuits*, vol. 53, no. 9, pp. 2532-2542, Sept. 2018.

# Broadband Circuits: Challenges

- On the receiver side,
  - The noise generated at the receiver amplifier
    **input referred noise current, sensitivity**
  - The receiver amplifier determines E/O bandwidth, hence the data rate per lane.
    **electro/optical bandwidth**
  - The linear response of the receiver amplifier
    **inter-symbol interference, linear distortion**
  - Non-linear response of the receiver amplifier
    **total harmonic distortion, dynamic range**
  - Power consumption
    **efficiency**

# Broadband Circuits: Challenges

- On the transmitter side,
  - Capacitive load with high voltage (or current) swing
    **output voltage or current swing**
  - The driver amplifier determines E/O bandwidth, hence the data rate per lane.
    **electro/optical bandwidth**
  - Dynamic turn-on/turn-off behavior of the amplifier
    **extinction ratio**
  - The linear response of the driver amplifier
    **inter-symbol interference, linear distortion**
  - Non-linear response of the driver amplifier
    **total harmonic distortion**
  - Power consumption & **efficiency**

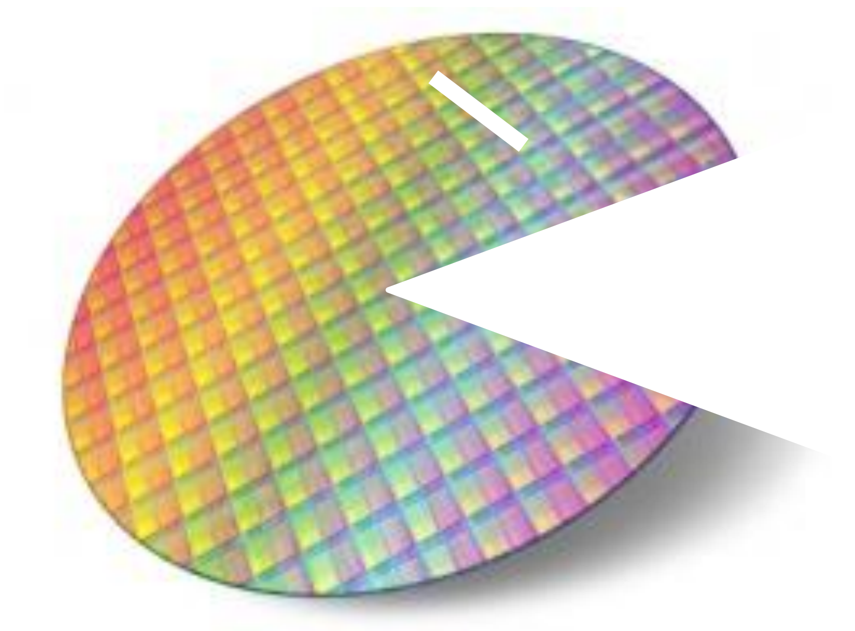
# IC Technologies

**Law of Semiconductors:**

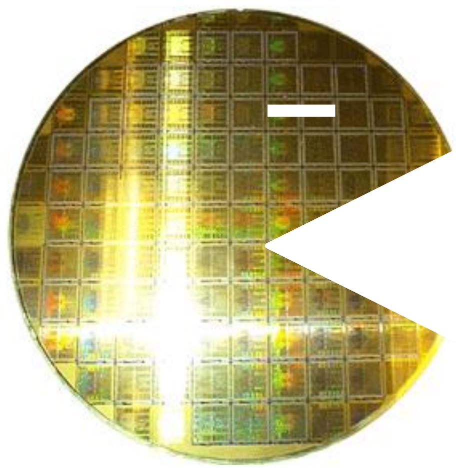
“What can be done in silicon, shall be done in silicon…
And, what can be done in CMOS shall be done in CMOS.”

*Anonymous*

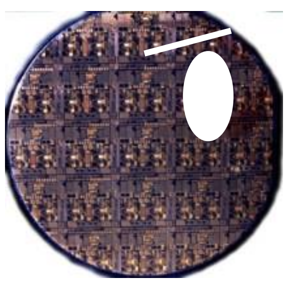
**CMOS**



**SiGe**



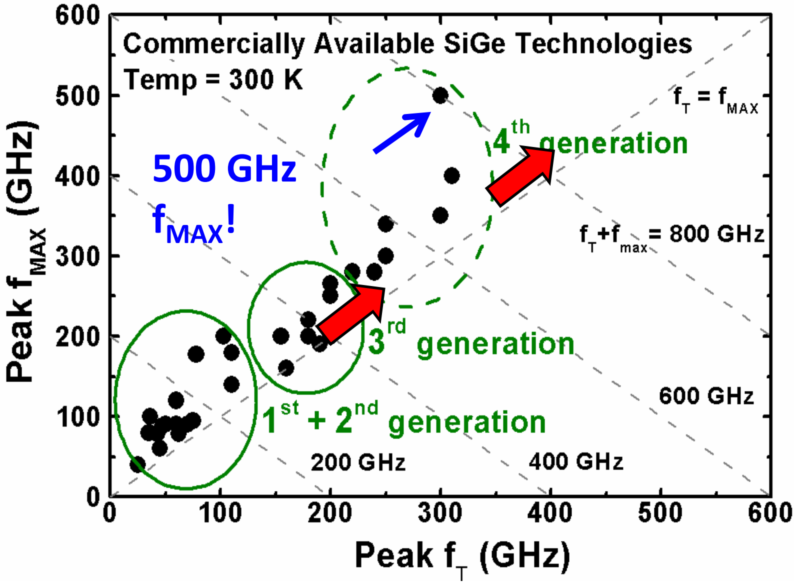
**III-V**



(if there is a business case)

# IC Technologies

- Moore's Law is typically quoted for digital ICs (memories, CPUs…)
- However, similar trends observed for analog ICs, especially in terms of performance



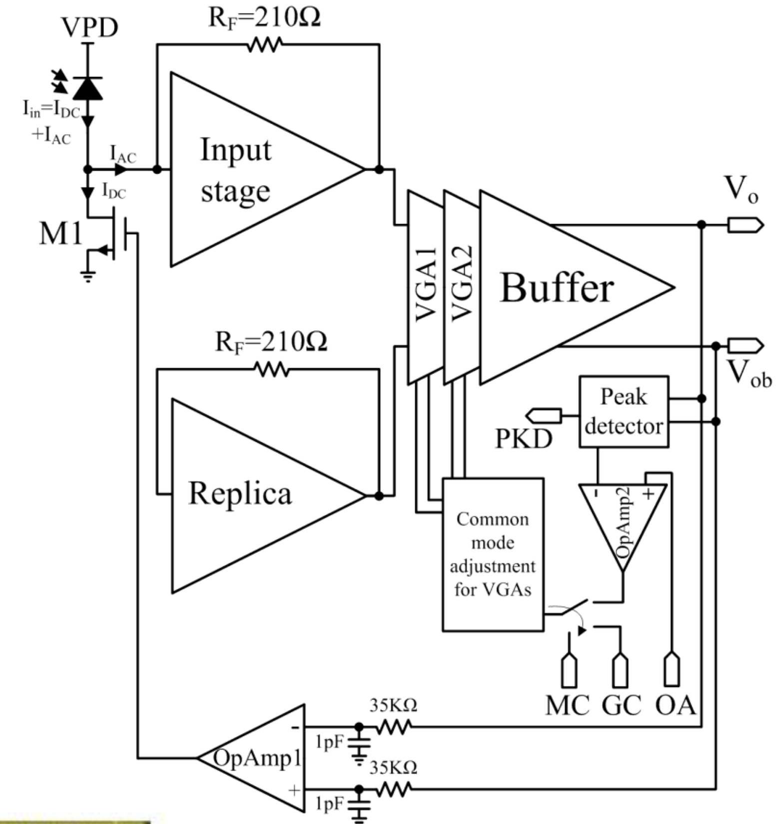

- # of transistors remain relatively fixed for analog ICs
- Tremendous improvement in performance e.g. SiGe approximately x5 within 20 years
- $f_T$: Transit frequency
  Frequency current gain (**H21**) equals 1
- $f_{max}$: Maximum frequency of oscillation
  Frequency **maximum available gain** equals 1

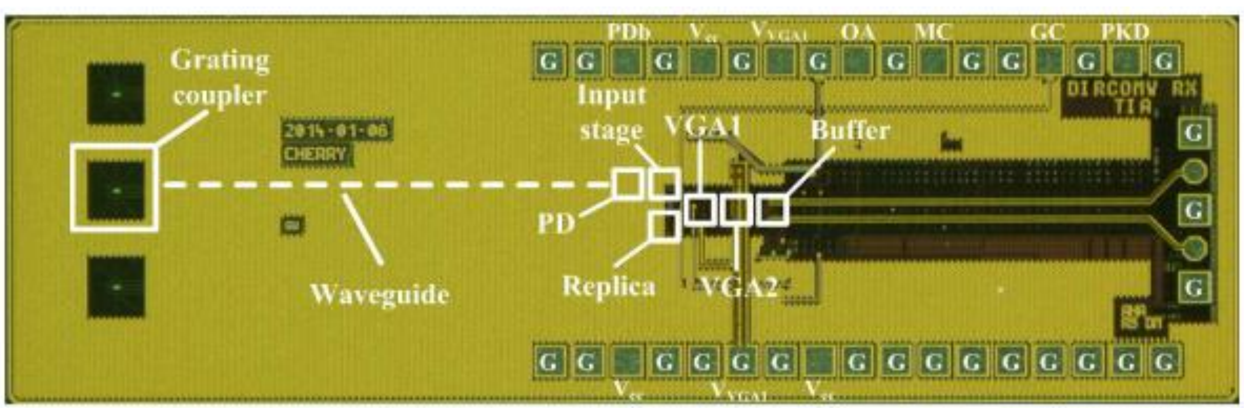
…We will learn about these terms

- Understanding transistor limitations is absolutely essential to achieve desired broadband circuit performance
- Device capacitances, transconductance, breakdown mechanisms, non-linearity, dynamic behaviour etc.

# Current Research Examples

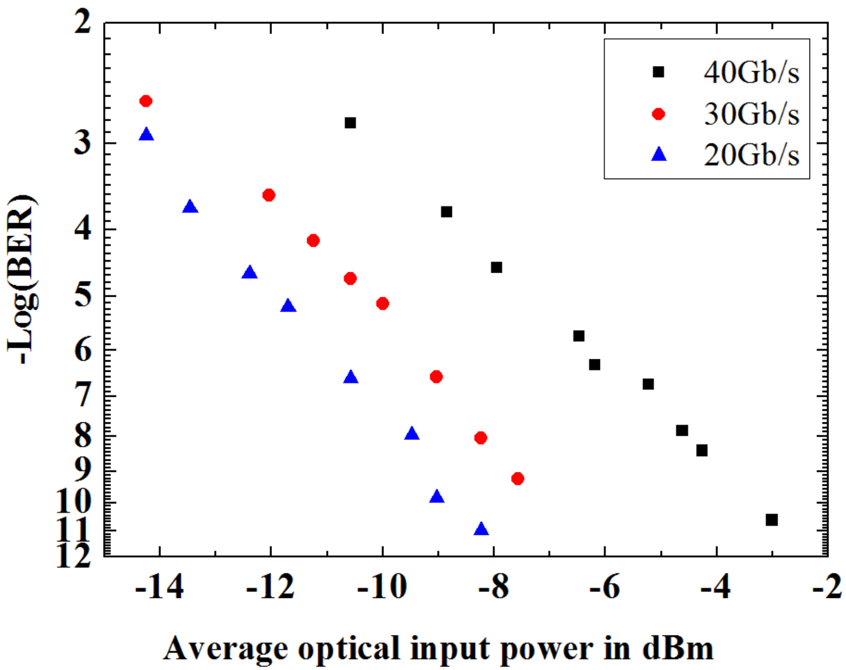
- Implemented in SiGe EPIC 0.25 µm technology
- Single-ended linear TIA with integrated Ge photo diodes constituting a direct detection receivers for OOK and PAM modulation techniques
- Two modes of operation: manual gain control and automatic gain control
- Input overload current compensation up to 4mA and DC offset cancellation circuitry
- The fastest integrated Si photonics receiver

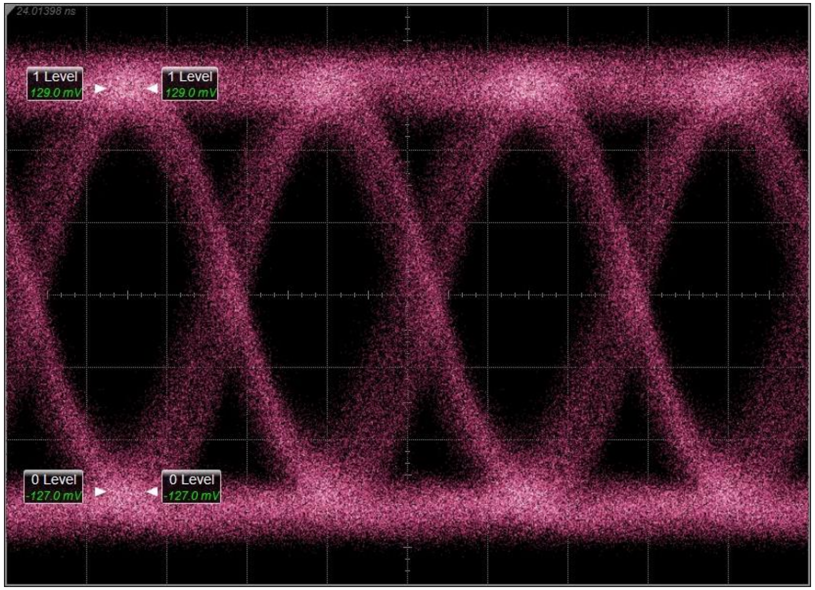



# Current Research Examples

- **Measurements**

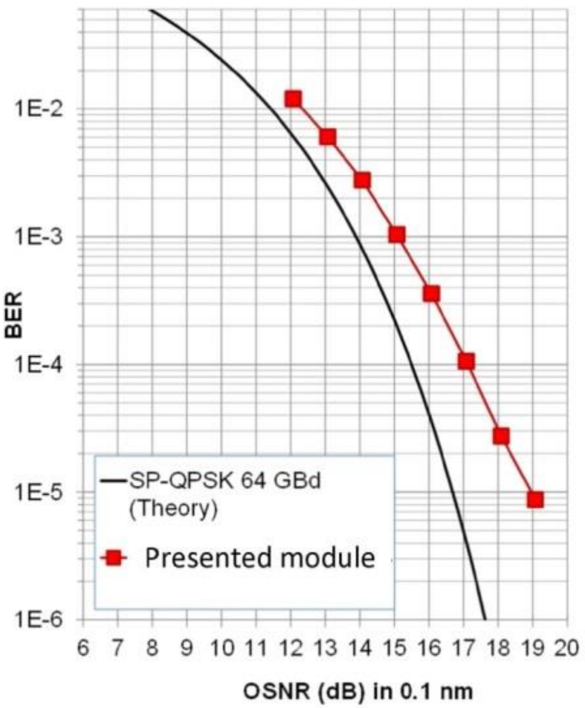


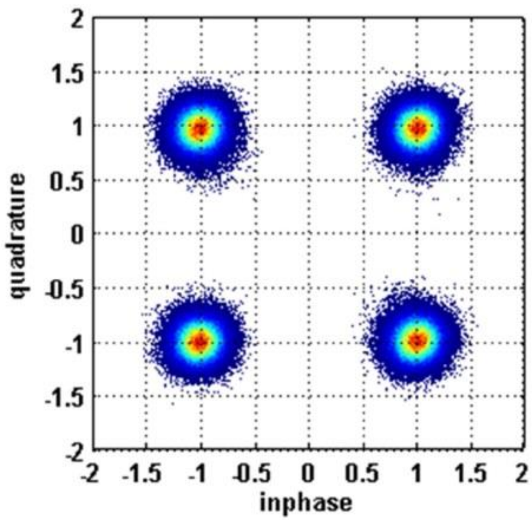



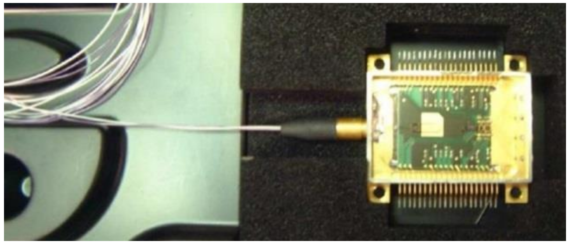

Eye diagram at a photo current of 300 µA at 40 Gb/s

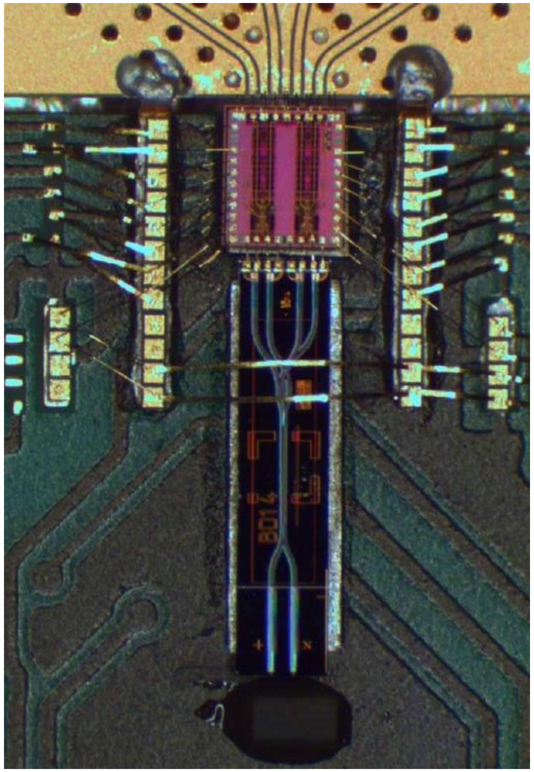
A. Awny, R. Nagulapalli, G. Winzer, M. Kroh, D. Micusik, S. Lischke, D. Knoll, G. Fischer, D. Kissinger, A. C. Ulusoy, L. Zimmermann, L., "A 40 Gb/s Monolithically Integrated Linear Photonic Receiver in a BiCMOS SiGe:C Technology," in *Microwave and Wireless Components Letters, IEEE* , vol.25, no.7, pp.469-471, July 2015

# Current Research Examples





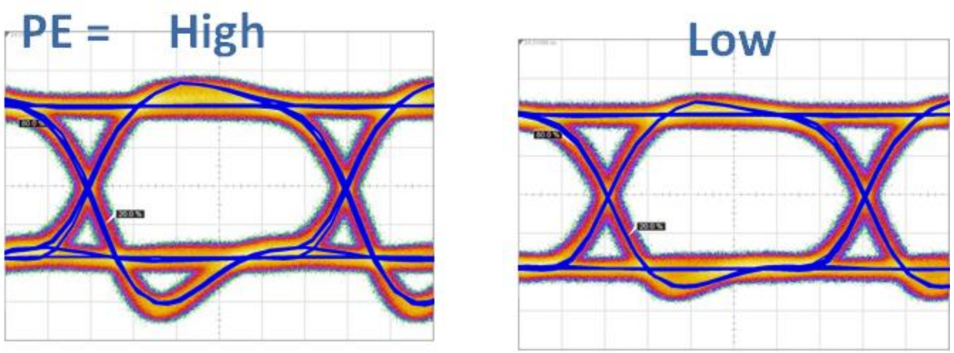
- The shown TIA integrated in a two channel electro/optical module
- Measured BER and constellation diagram at 128 Gbit/s data transmission
- State of the art electro/optical performance

A. Awny, A. C. Ulusoy et al., "23.5 A dual 64Gbaud 10k 5% THD linear differential transimpedance amplifier with automatic gain control in 0.13um BiCMOS technology for optical fiber coherent receivers," 2016 IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, 2016

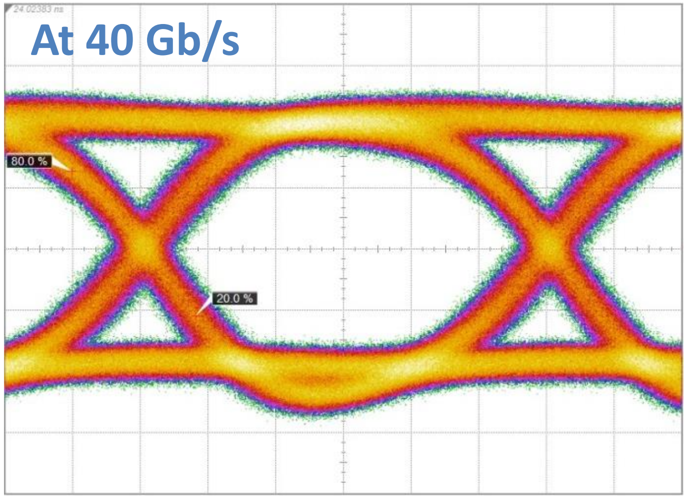
# Current Research Examples

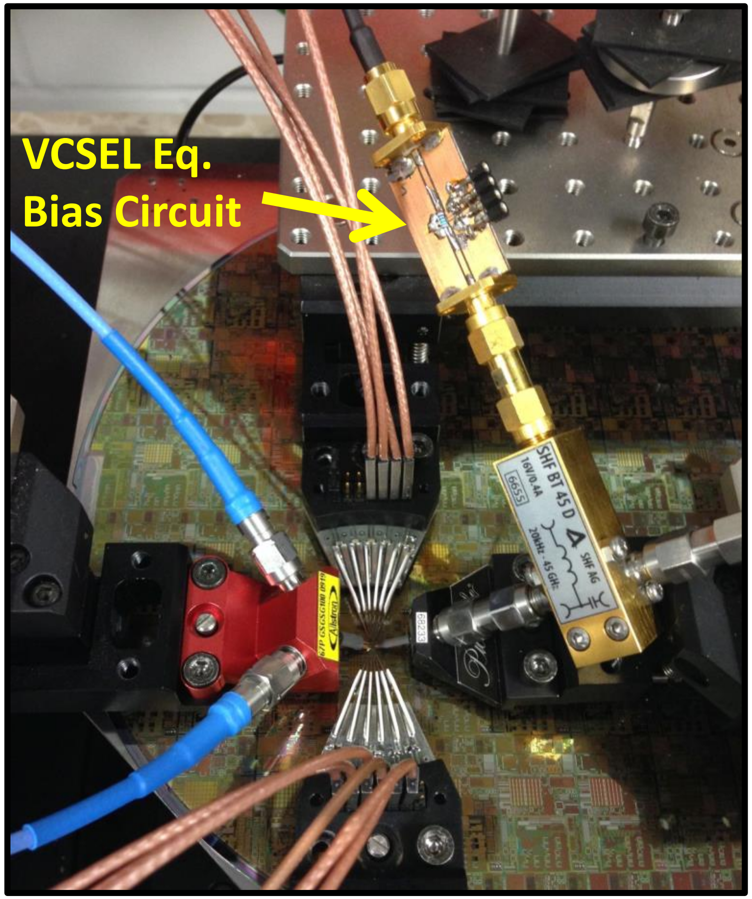
- **VCSEL Driver**

Conditions: 25 Gb/s, $I_{B/M}$ = 4/4 mA ($VCC_o$ = 3.7 V, $V_{REF}$ = 130 mV)



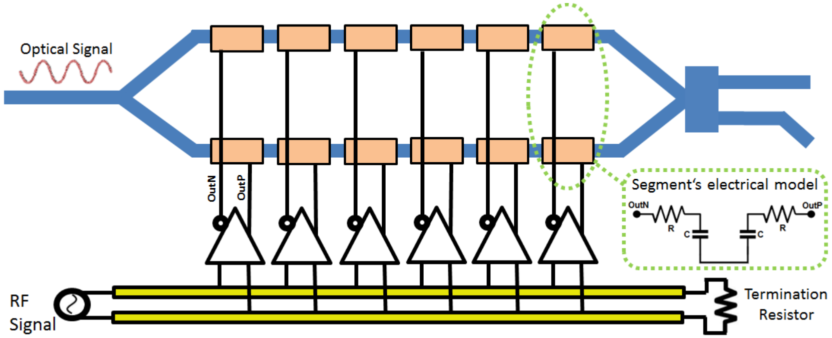

25 Gb/s Eye at Low and High Pre-emphasis Settings of the VCSEL Driver

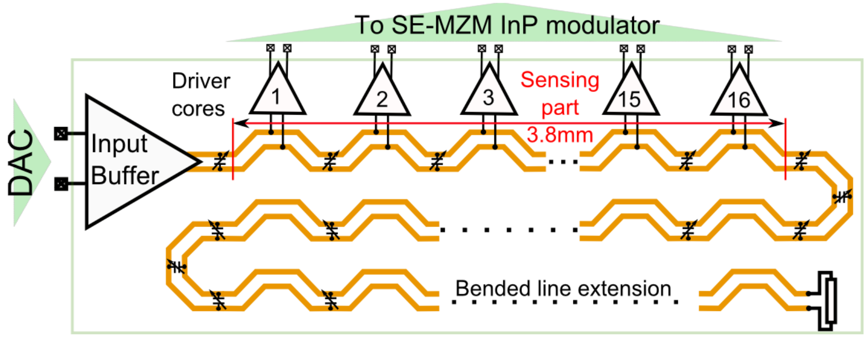


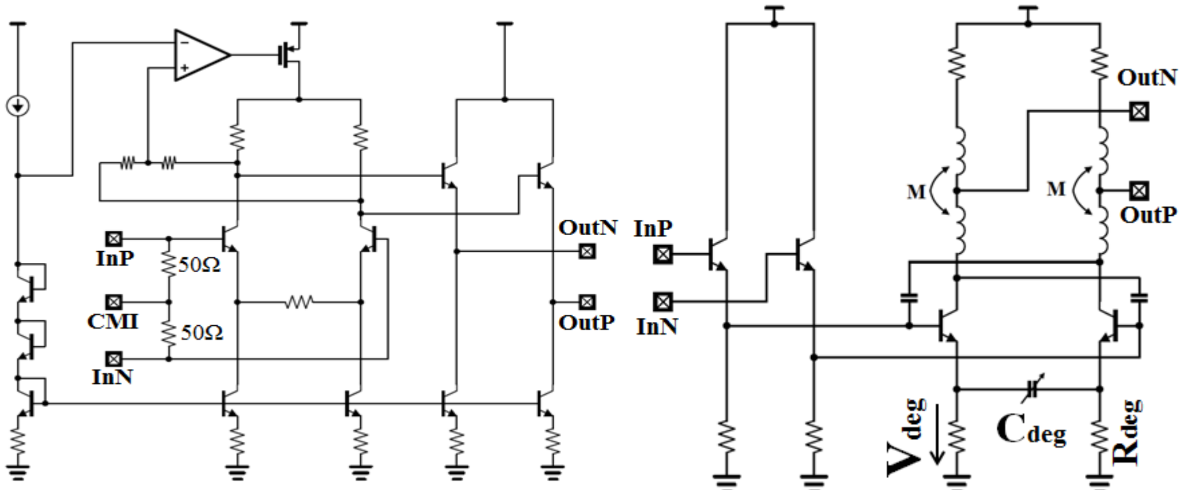



# Current Research Examples

- **MZM Driver**



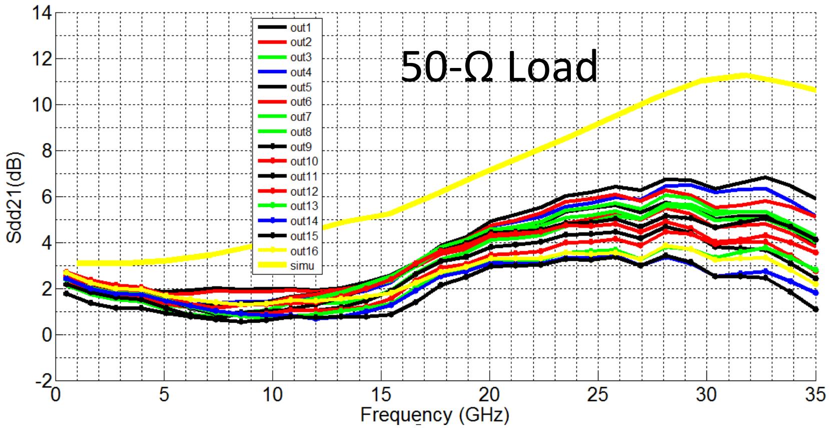



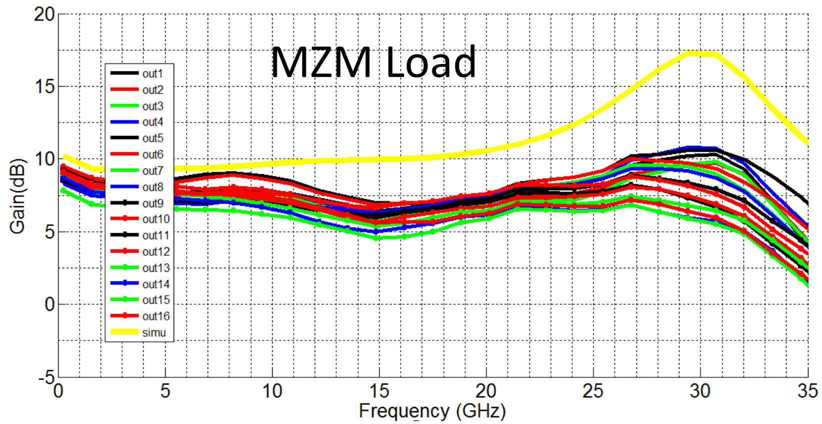

Input buffer

- 2.5 V $V_{pp}$
- BW 32 GHz
- PDC 1.6 W
- Tunable group delay for Optical/electrical matching

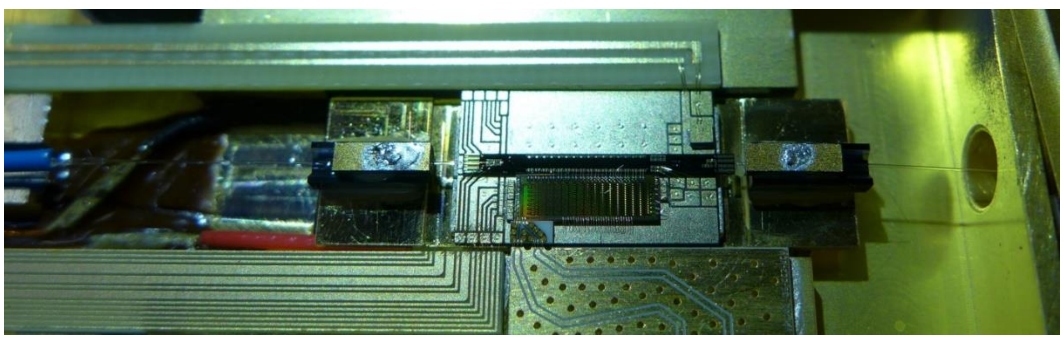
# Current Research Examples

Gain measurement of each channel

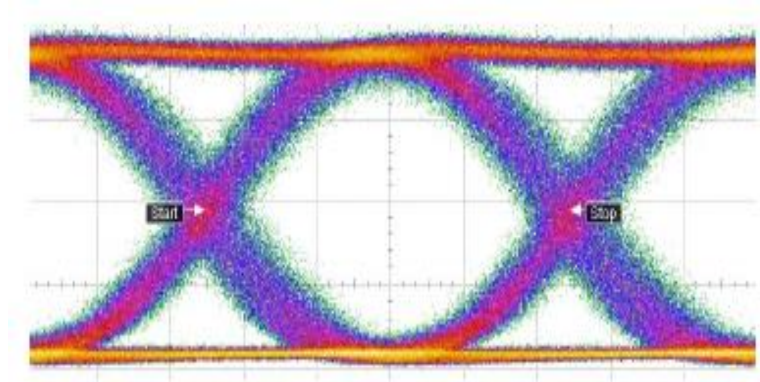



Electrical large signal performance was verified as well



Segmented driver in electro/optical module

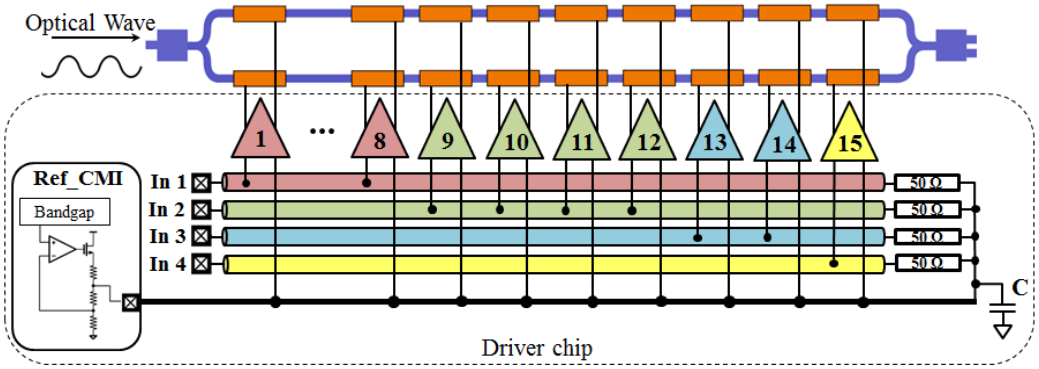


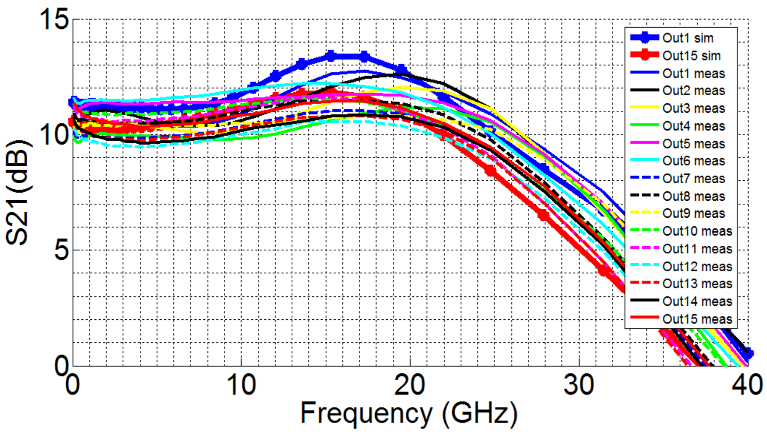
40 Gbps electro/optical eye diagram

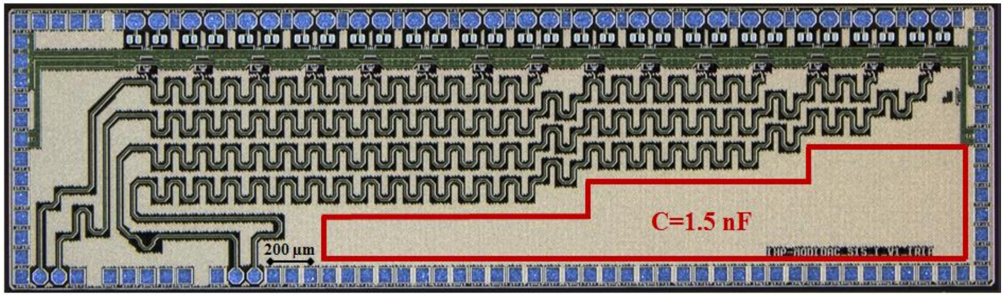
I. G. López, A. C. Ulusoy *et al.*, "A 2.5 Vppd broadband 32 GHz BiCMOS linear driver with tunable delay line for InP segmented Mach-Zehnder modulators," *2015 IEEE MTT-S International Microwave Symposium*, Phoenix, AZ, 2015, pp. 1-4.

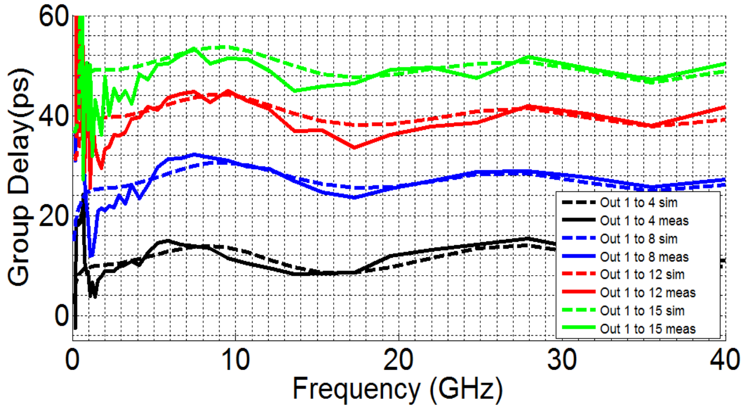
# Current Research Examples

- **Driver with 4-bit DAC**



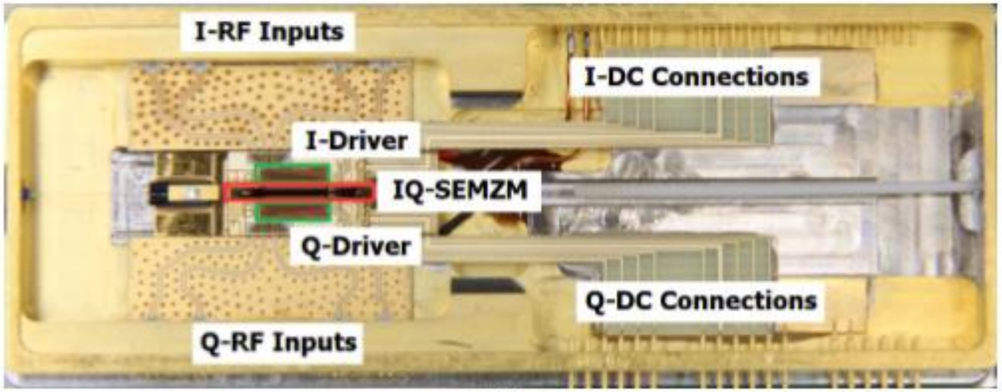



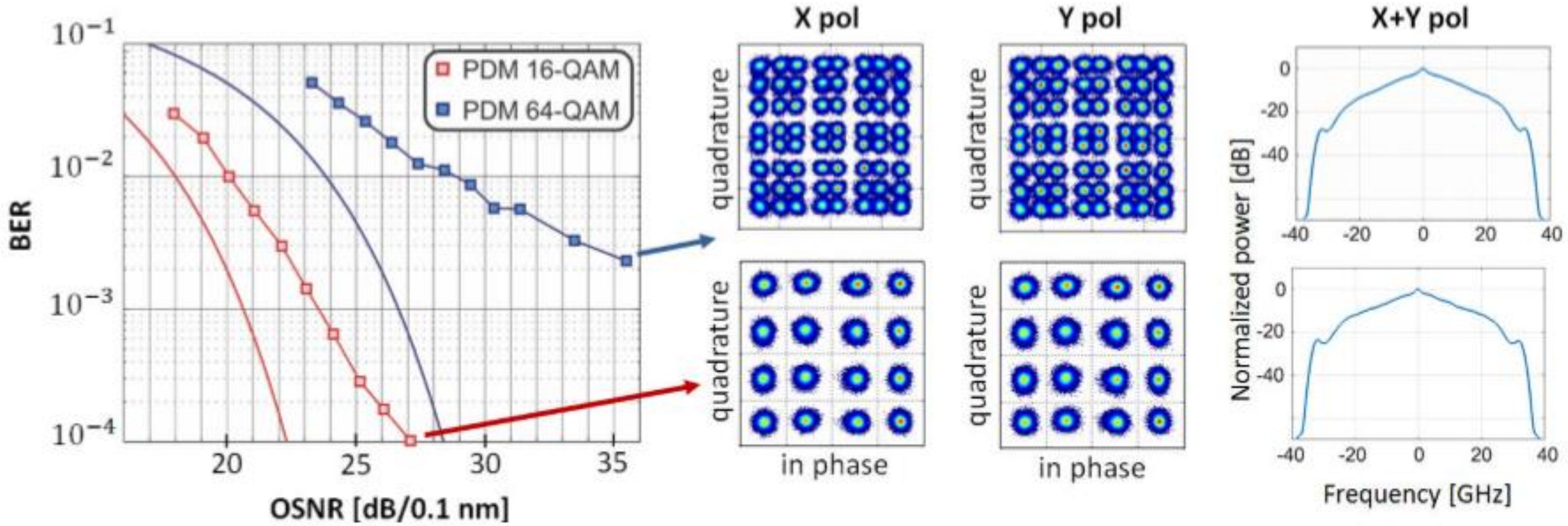

I. G. López, A. C. Ulusoy *et al.*, "A 40 Gbaud SiGe:C BiCMOS Driver for InP Segmented MZMs with Integrated DAC Functionality for PAM-16 Generation“ IMS 2016

# Current Research Examples

Segmented concept extended with 4-bit DAC functionality




Characterized in an electro/optical module
Presented at OFC as a post-deadline paper

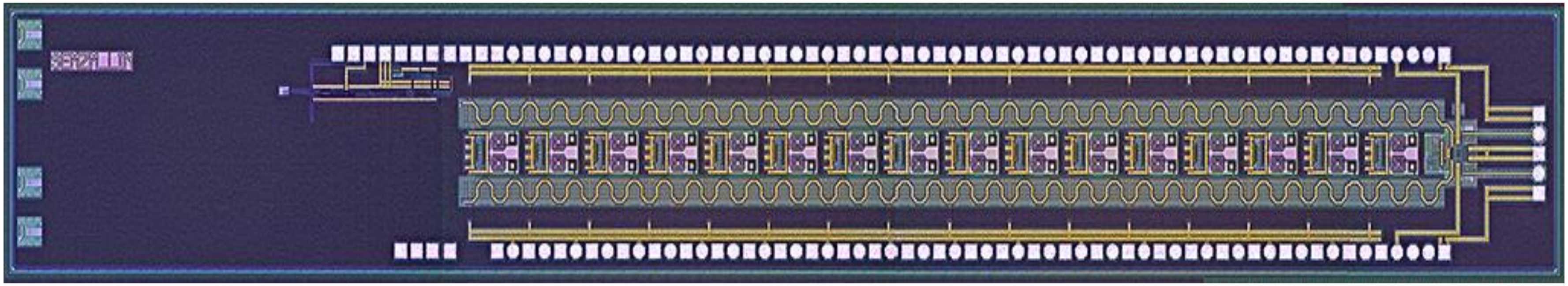


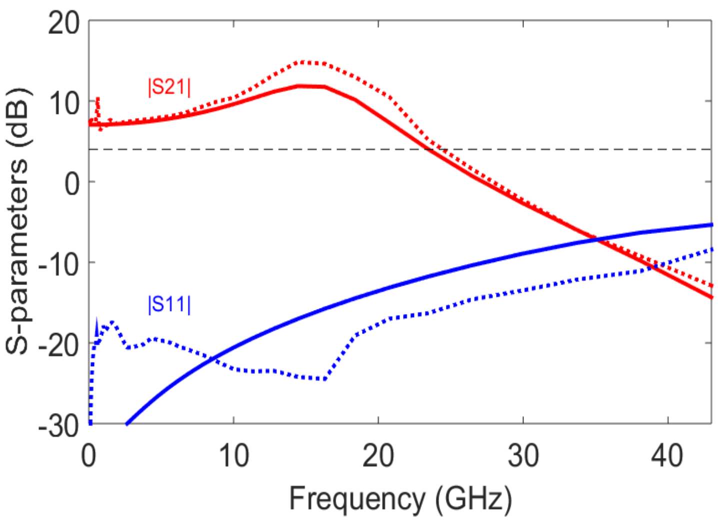

I. G. López, A. C. Ulusoy *et al.*, "DAC-free Ultra-Low-Power Dual-Polarization 64-QAM Transmission with InP IQ Segmented MZM Module " OFC 2016

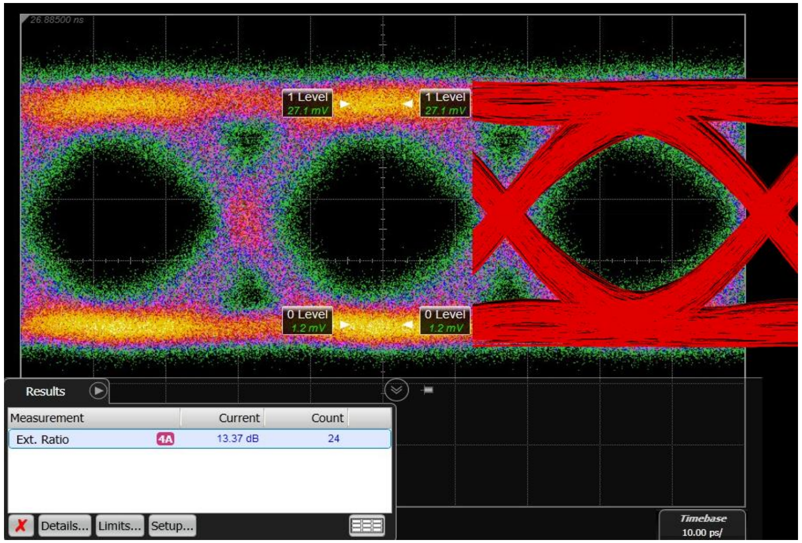
# Current Research Examples

- **EPIC Driver**

13 dB extinction ratio achieved at 28 Gb/s, 2-W power consumption, IC size 9.8x1.3 $mm^2$






P. Rito, A. C. Ulusoy *et al.*, "A Monolithically Integrated Segmented Driver and Modulator in 0.25 µm SiGe:C BiCMOS with 13 dB Extinction Ratio at 28 Gb/s," IMS 2016

# Lecture Plan

| | | | |
|---|---|---|---|
| 29. Apr | | Introduction/Basics Communications | |
| 06. Mai | | Basics Communications/Photonic Components | Lab1 |
| 13. Mai | | Photonic Components | |
| 20. Mai | | Transistors | Lab2 |
| 27. Mai | | TIA Design | |
| 03. Jun | | TIA Design (Advanced Topics) | Lab3 |
| 10. Jun | Pfingstmontag | | |
| 17. Jun | | Driver Design | Lab4 |
| 24. Jun | | Driver Design (Advanced Topics) | |
| 01. Jul | | Bandwidth Enhancement Techniques | Lab5 |
| 08. Jul | | DC Offset Compensation / Stability | |
| 15. Jul | | Gain Control and other advanced concepts (CLK data Recovery), Jitter | Lab6 |
| 22. Jul | | Link imperfections, Optical Fibers, Equalizers | |

# Broadband Circuits for Wireless and Wireline Communications

Karlsruher Institut für Technologie

- We went over main topics to be covered in BCWW and lecture structure
- Motivation and importance of Broadband Circuits for Wireless and Wireline Communications
- Recent research examples on this topic

4-channel version of EPIC TIA capable of 160 Gb/s