Karlsruhe Institute of Technology

# *Energy-efficient high-speed optical transmission for detector systems*

Institute for Data Processing and Electronics

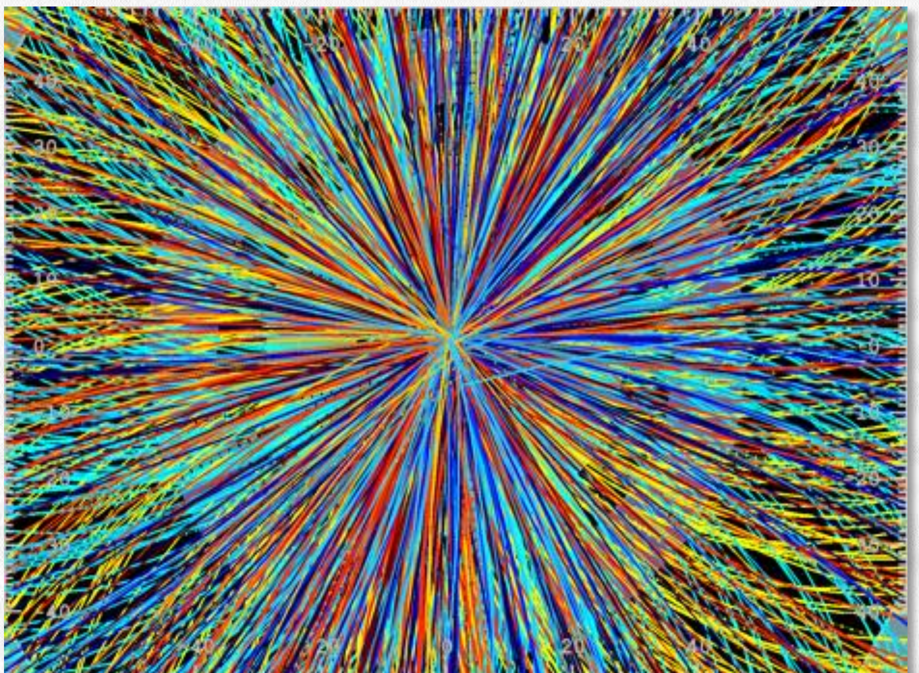
**Marc Schneider**

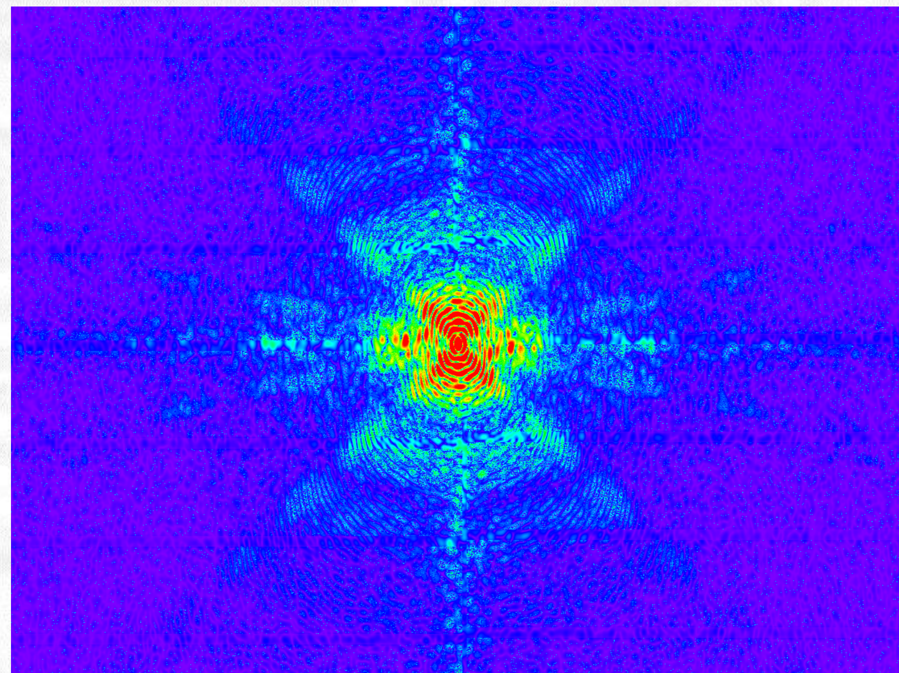
**International Workshop on Radiation Imaging Detectors iWoRID 2014**

**2014-06-26**

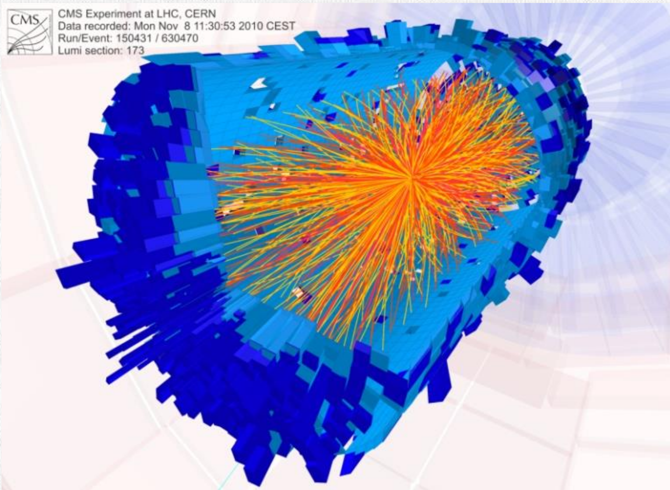
# Future detectors

- Several million up to a billion electrical signal channels
- Higher rates from each channel
- ➡ Massive increase of amount of data generated





# Example: Silicon Tracking at HL-LHC




*How to deal with ≈ 4 trillion hits/second ?*

*How to deal with ≈ 400 billion tracks/second ?*

- *Five-fold increase of track density and thus channels*
- *Massive challenge for power distribution and cooling*
- *Ten-fold increase in radiation levels*
- *Track-based trigger decision within ≈ 6 µs*
- *Ideal: „mass-less“ detector with micrometer precision*

# We ask for

- Lower power consumption
- Lower power dissipation
- Lighter cabling
- Higher bandwidth

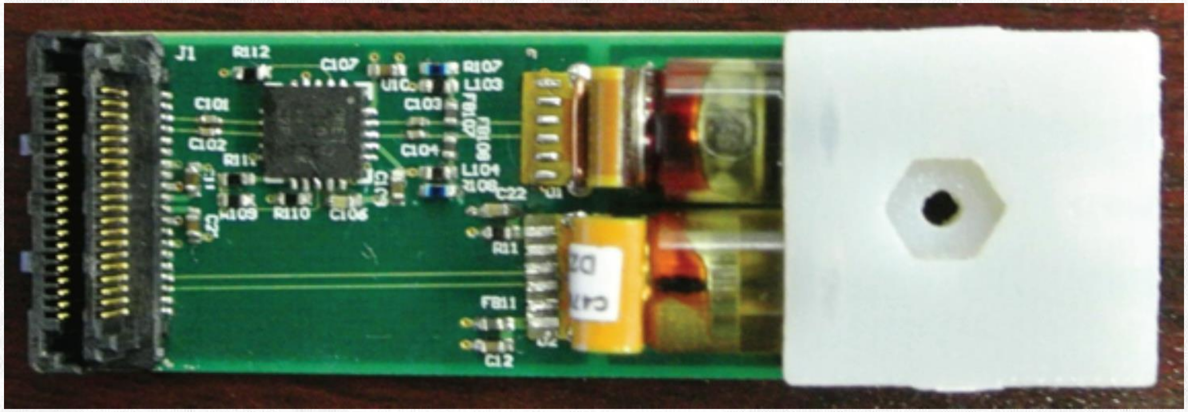
➔ Optical data transmission

# Current solutions

- *Electrical transmission over coaxial cables*
  - *Slow (relatively)*
  - *High energy consumption (line drivers)*
  - *Limited length (attenuation, distortion)*
- *Optical transmission over glass fibers with directly modulated laser diodes*
  - *Sensitive*
  - *High energy consumption*
  - *One channel per glass fiber with <<10 Gb/s (CMS Tracker 40 Mb/s, radiation hard)*

# Projected solutions *(random choice)*

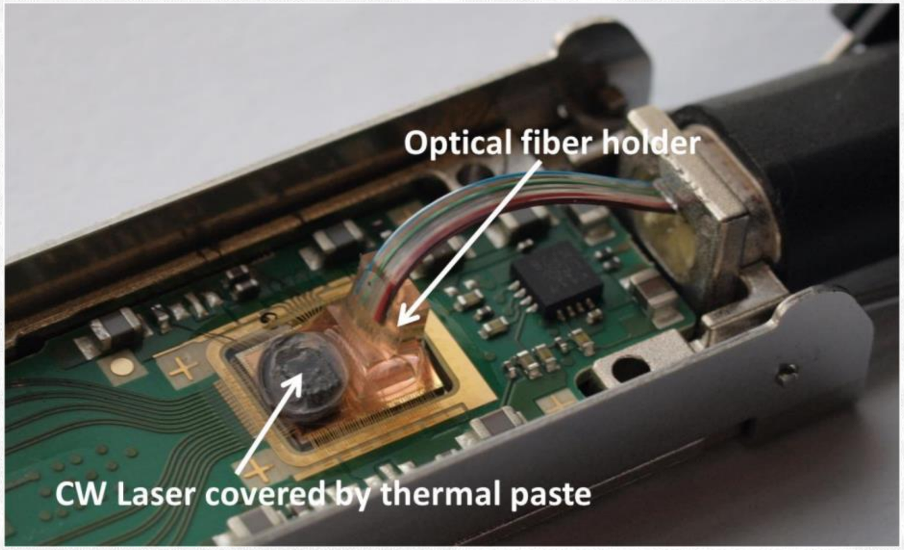
- *Optical transmission over fibers with directly modulated laser diodes*
  - *Sensitive*
  - *High energy consumption*
  - *One channel per fiber with 10 Gb/s*
  - *Multiple parallel fibers*



C. Liu *et al.*, A Small-Footprint, Dual-Channel Optical Transmitter for the High-Luminosity LHC (HL-LHC) Experiments, TWEPP 2013

# *Projected solutions (random choice)*

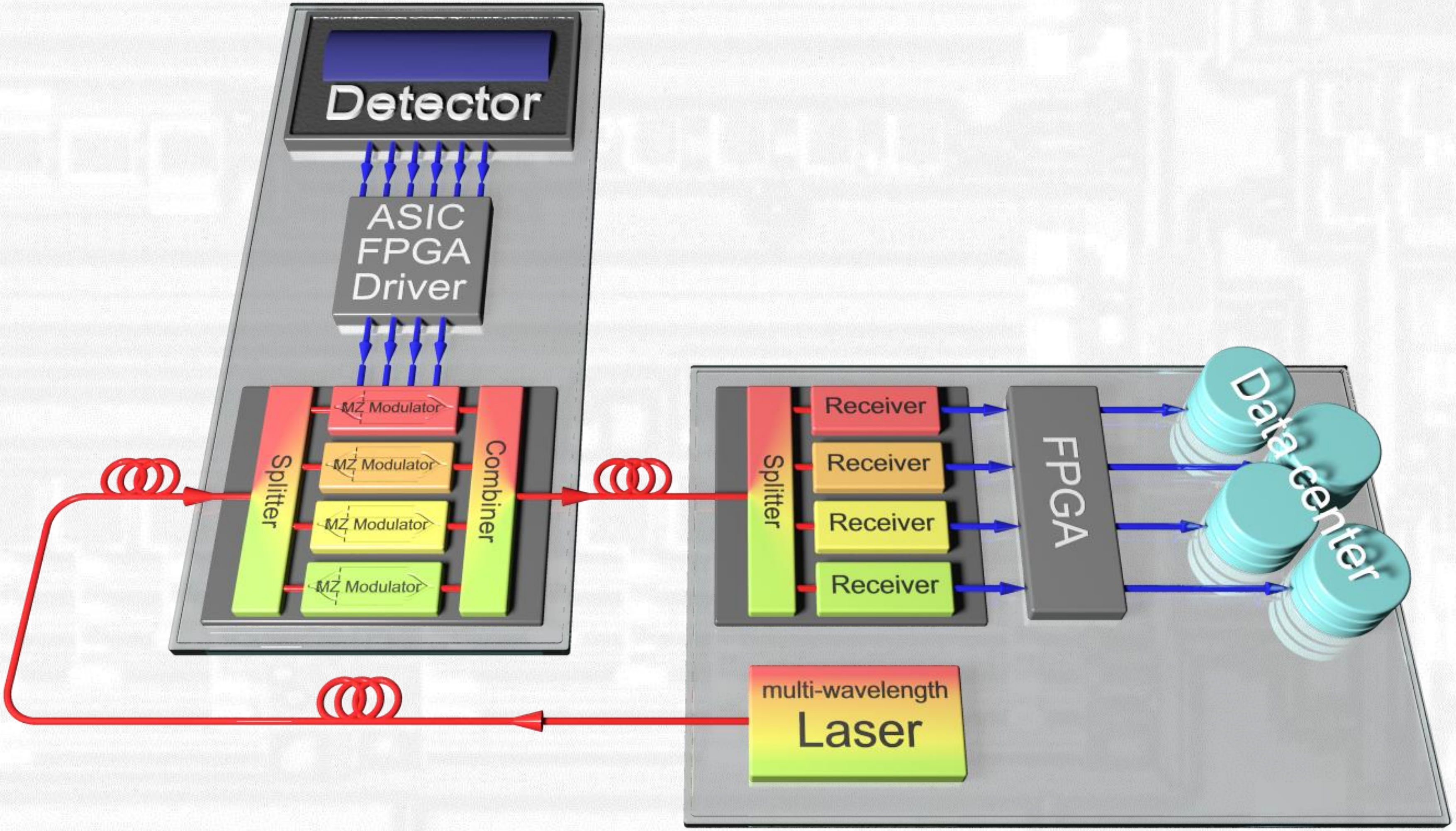
- *Externally modulated laser diodes*
  - *Sensitive*
  - *High energy consumption*
  - *One channel per fiber with 10 Gb/s*
  - *Multiple parallel fibers*




G. Drake *et al.*, A new high-speed optical transceiver for data transmission at the LHC experiments, TWEPP 2013

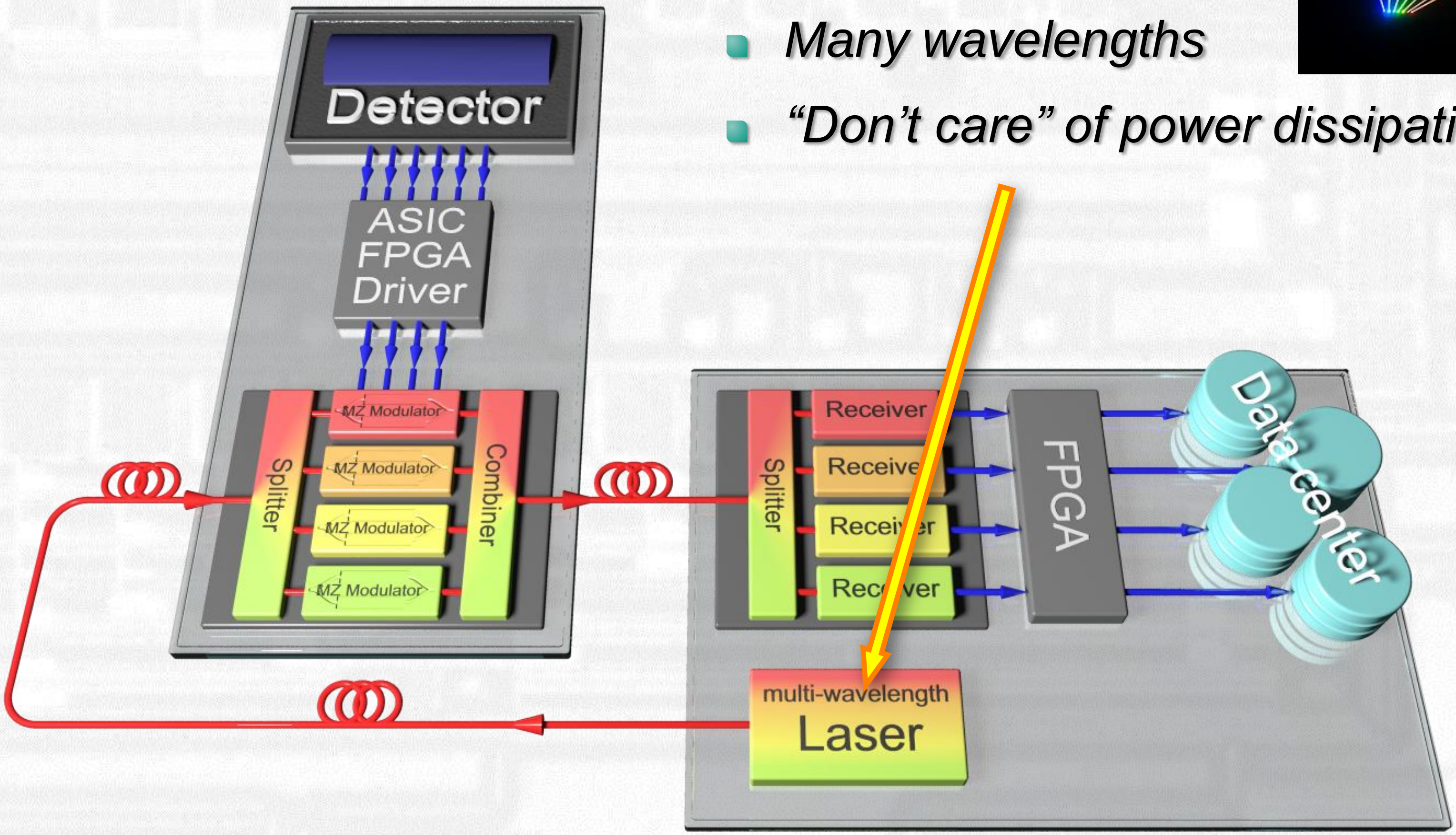
- *QSFP+ module*
- *CW Laser*
- *External Mach-Zehnder modulator (Si photonics)*

# Our concept


Detector
ASIC
FPGA
Driver
Splitter
MZ Modulator
MZ Modulator
MZ Modulator
MZ Modulator
Combiner
Splitter
Receiver
Receiver
Receiver
Receiver
FPGA
Data-center
multi-wavelength
Laser

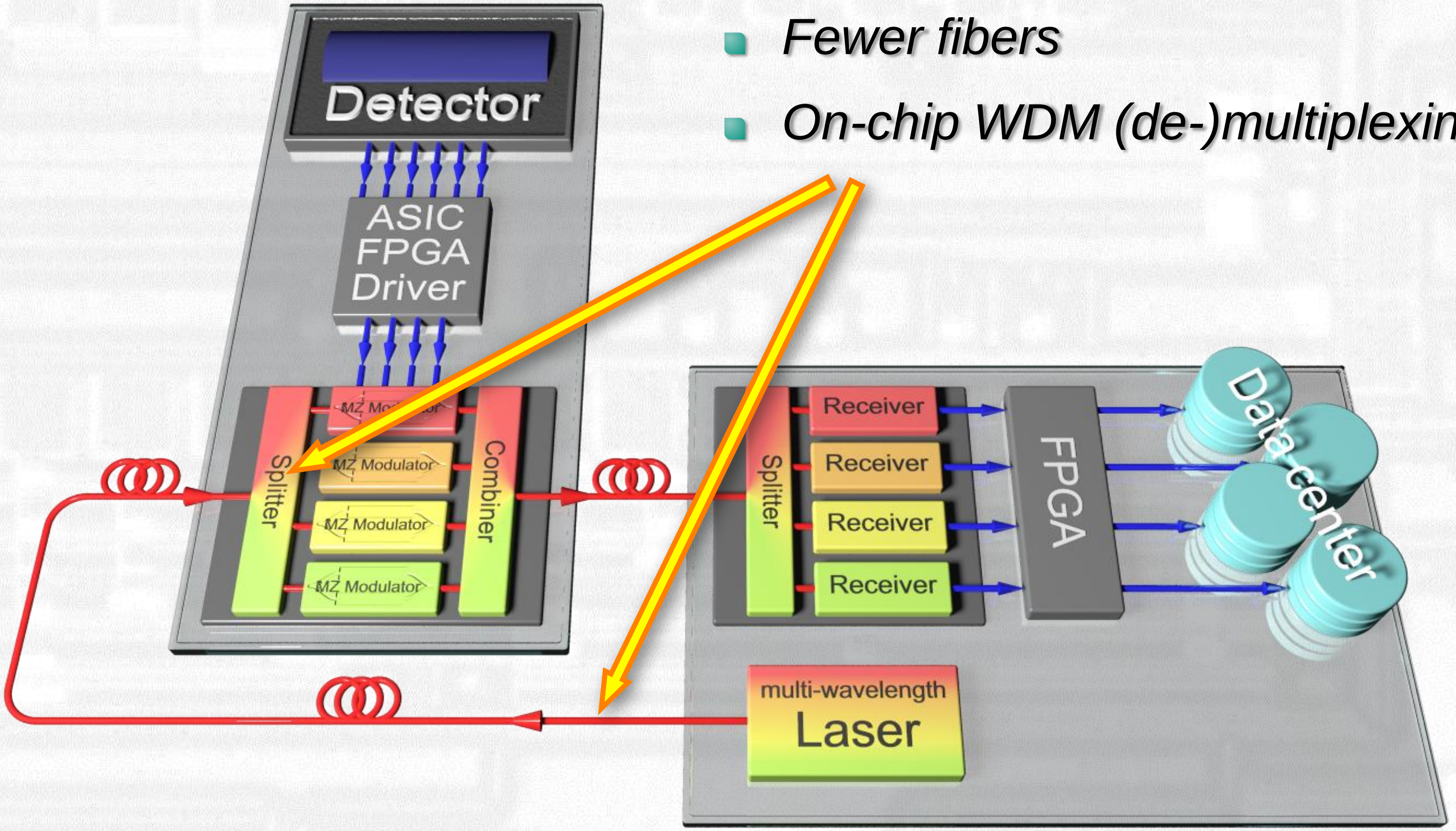
# *What are we doing differently?*

- *External lasers*
  - *Stable wavelengths*
  - *Many wavelengths*
  - *“Don’t care” of power dissipation*



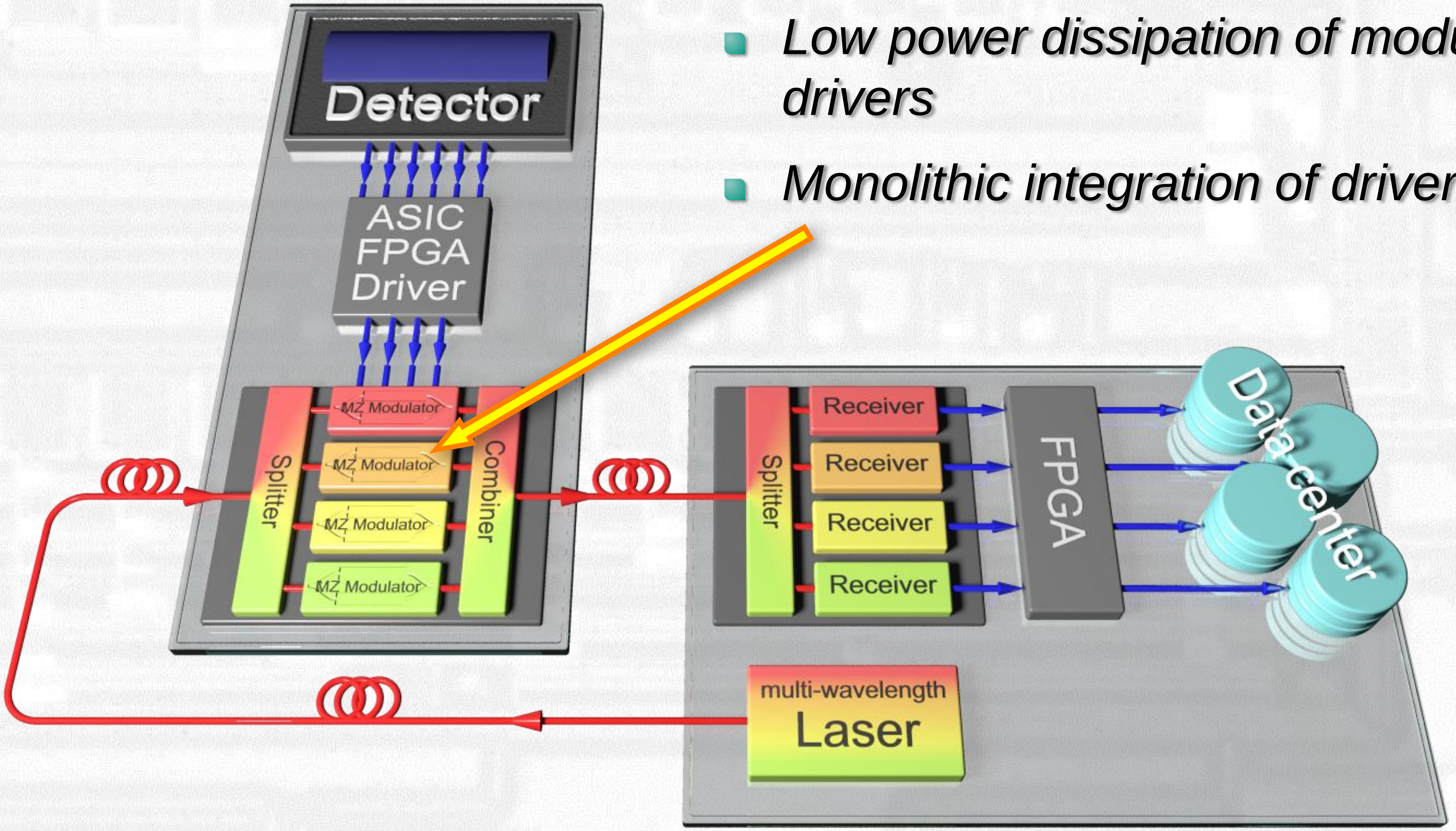
# What are we doing differently?

- Multiple wavelength channels per fiber
  - Wavelength division multiplexing (WDM)
  - Fewer fibers
  - On-chip WDM (de-)multiplexing

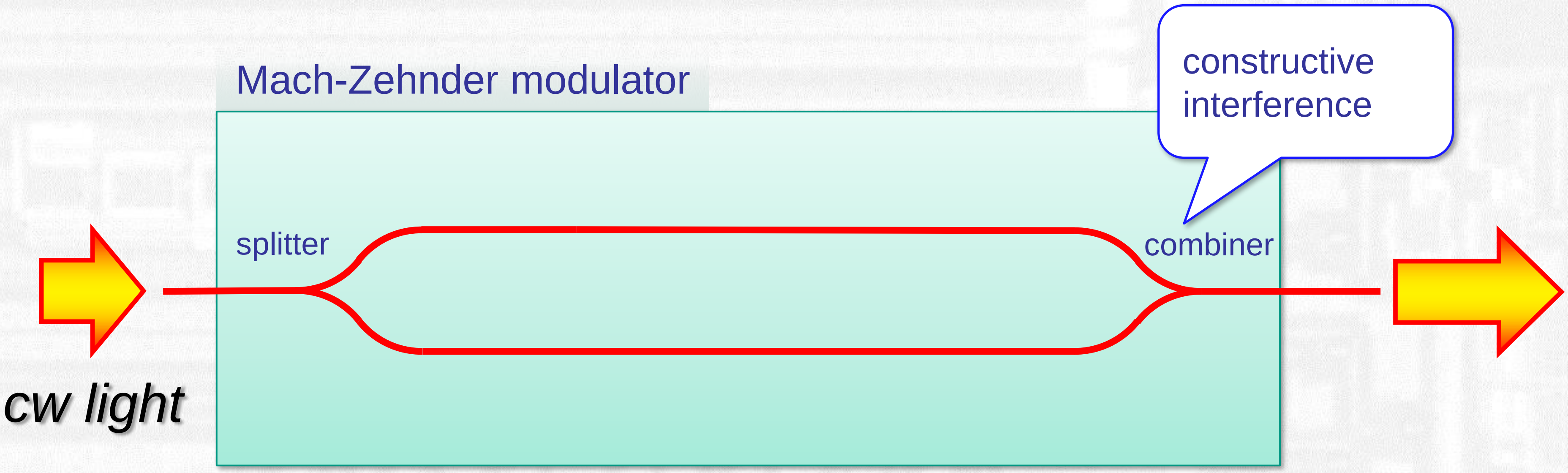


# What are we doing differently?

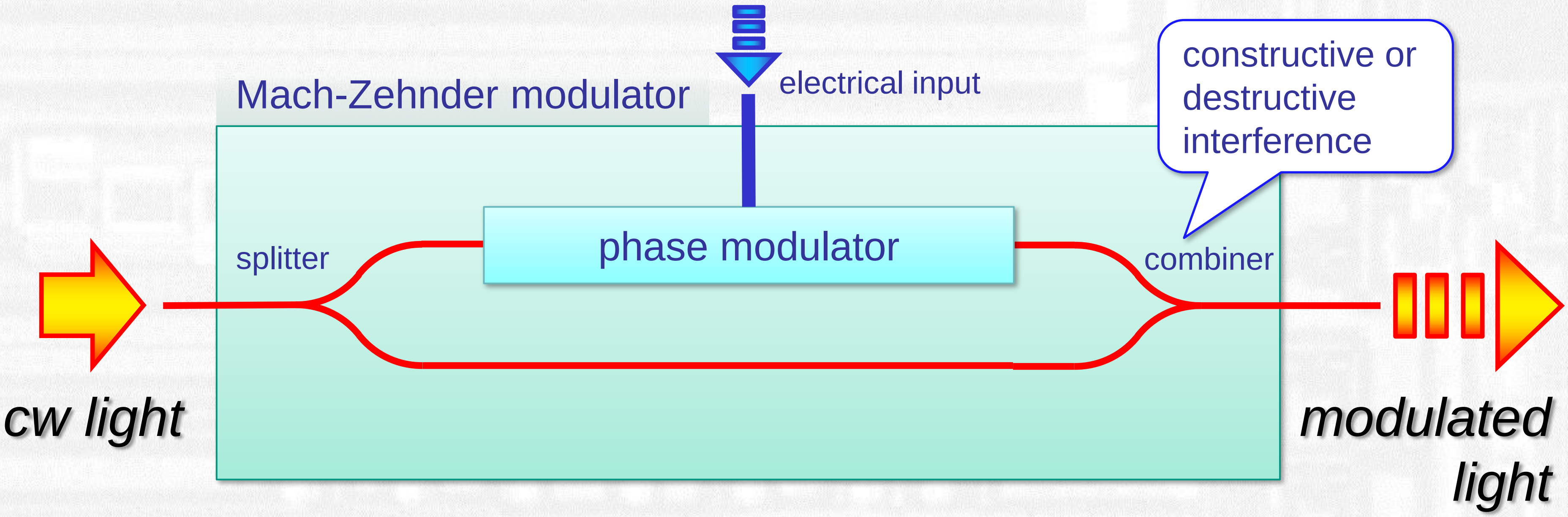
- Efficient silicon photonics modulators
  - Mach-Zehnder modulators
  - Low power dissipation of modulators and drivers
  - Monolithic integration of driver electronics



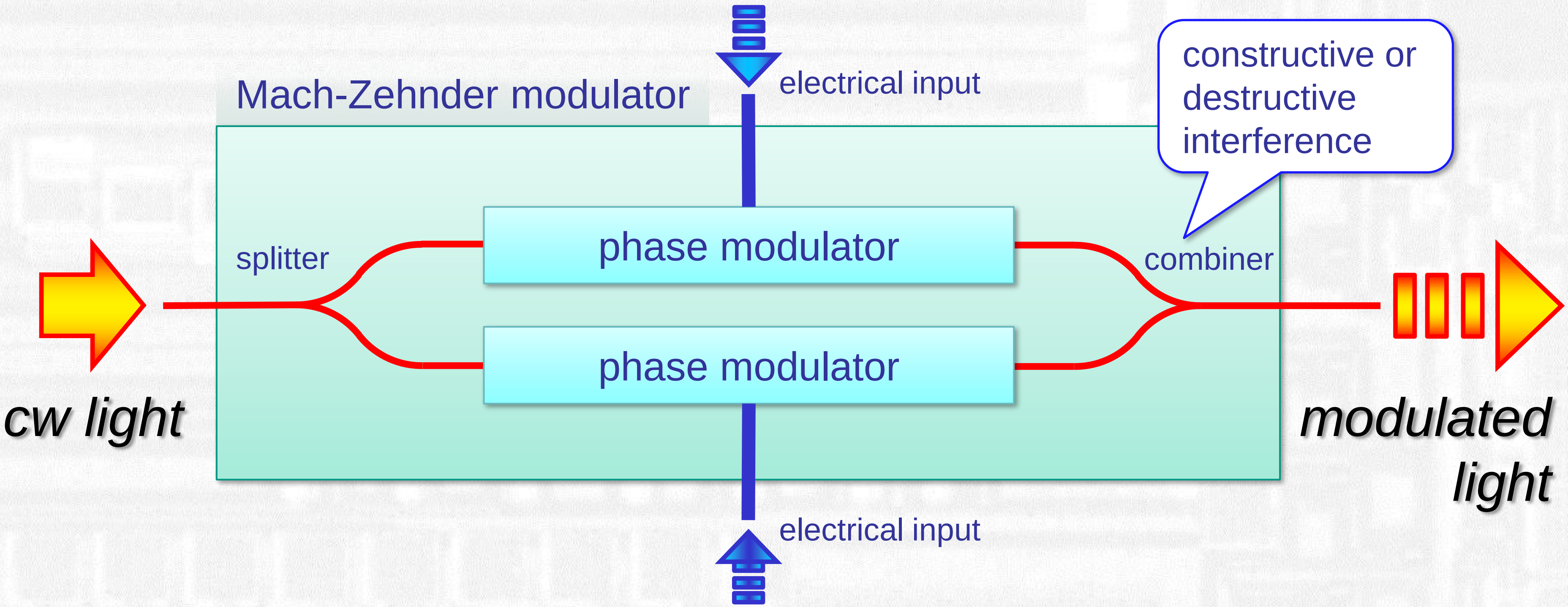
# Mach-Zehnder modulator?



# Mach-Zehnder modulator?



# Mach-Zehnder modulator?



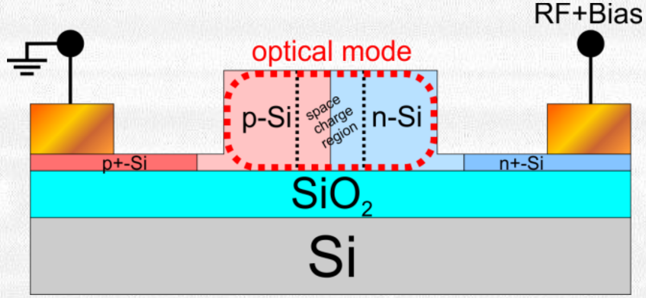

*Simple and power efficient modulation*

**1 pJ/bit** power consumption with potential go down to 10 fJ/bit

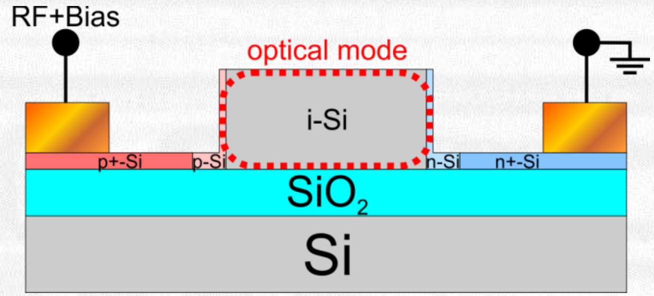
# Mach-Zehnder modulator

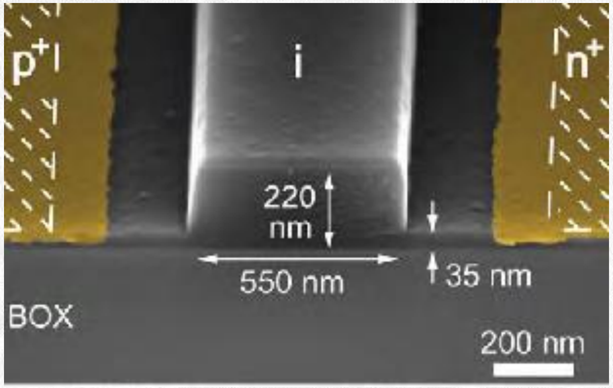
## *Phase modulators*

- ***pn-modulator:***
  *(reverse biased)*

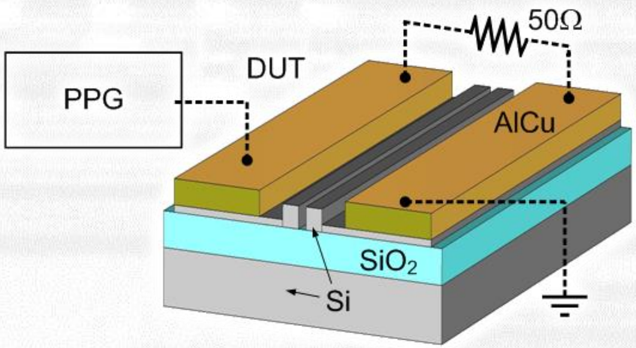


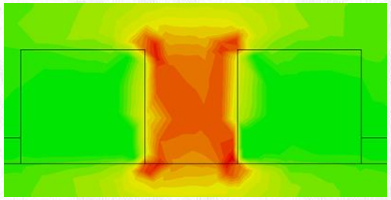

- ***pin-modulator:***
  *(forward direction)*



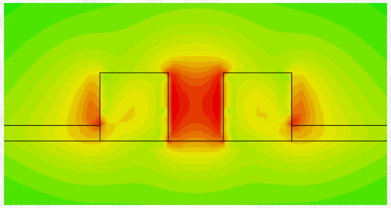




- ***SOH-modulator:***
  *(Slot waveguide with electroopic active polymer)*



Sim. electr. field

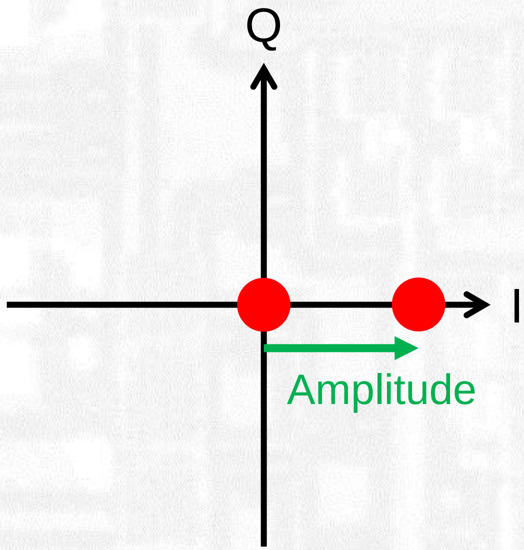


Sim. optical field

# Mach-Zehnder modulator

## *ASK (Amplitude Shift Keying)*

- *2 possible states ⇒ 1 bit per symbol (0, 1)*




*Output signal:*

$$z(t) = I(t) \cdot \cos(\omega_c t) - Q(t) \cdot \sin(\omega_c t)$$

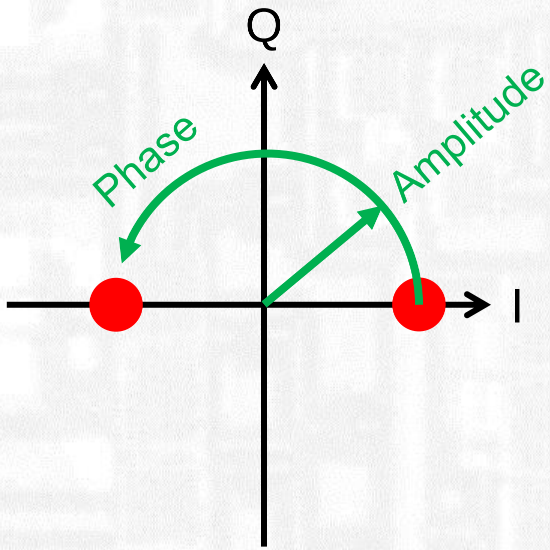
# Mach-Zehnder modulator

*ASK (Amplitude Shift Keying)*

- *2 possible states ⇒ 1 bit per symbol (0, 1)*

*PSK (Phase Shift Keying)*

- *2 possible states ⇒ 1 bit per symbol (0, 1)*




*Output signal:*

$$z(t) = I(t) \cdot \cos(\omega_c t) - Q(t) \cdot \sin(\omega_c t)$$

# Mach-Zehnder modulator

ASK (Amplitude Shift Keying)

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PSK (Phase Shift Keying)

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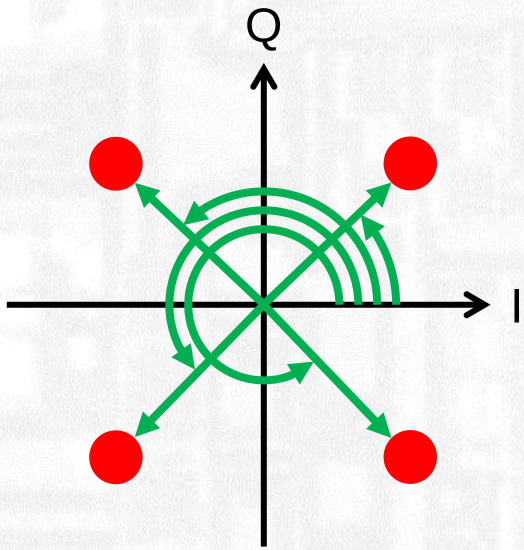


High-order modulation formats

- QPSK (4PSK) ⇒ 2 bits per symbol (00, 01, 10, 11)

# Mach-Zehnder modulator

ASK (Amplitude Shift Keying)

- 2 possible states ⇒ 1 bit per symbol (0, 1)

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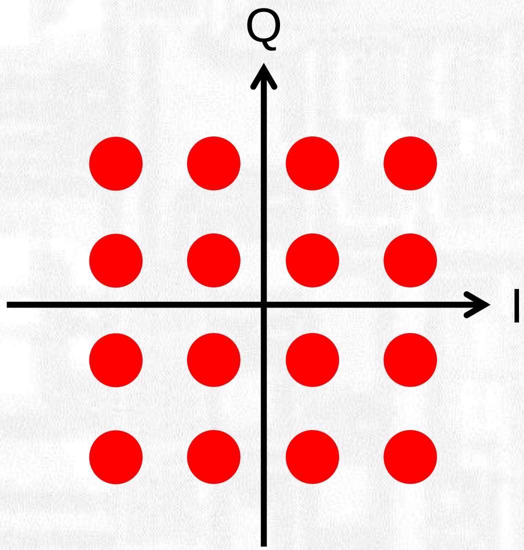



High-order modulation formats

- QPSK (4PSK) ⇒ 2 bits per symbol (00, 01, 10, 11)
- 16-QAM ⇒ 4 bits per symbol (0000, 0001, …, 1111)

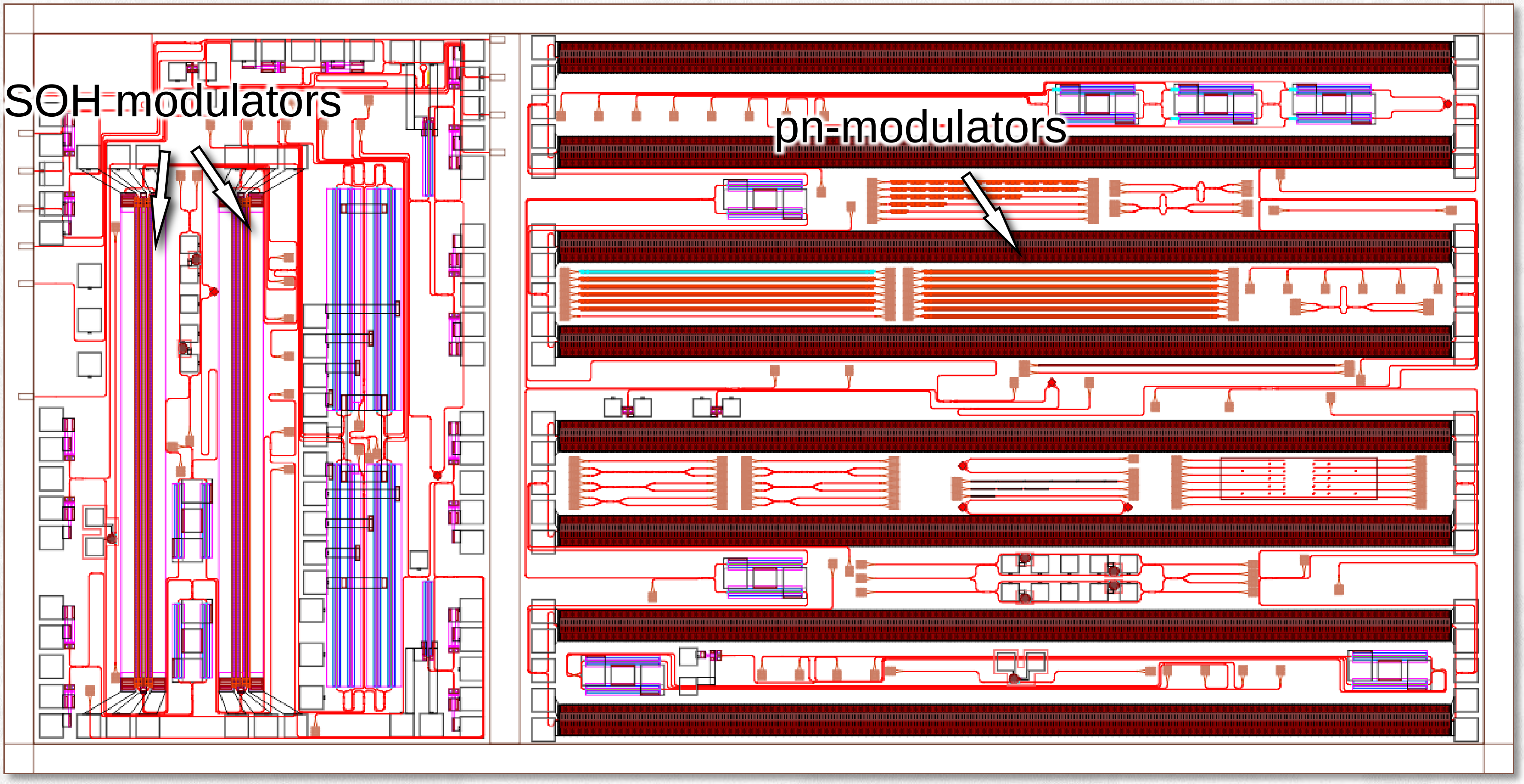
⋮

*Efficient modulation schemes possible for lower signaling frequencies*

# *What have we done?*

# Modulator Chip

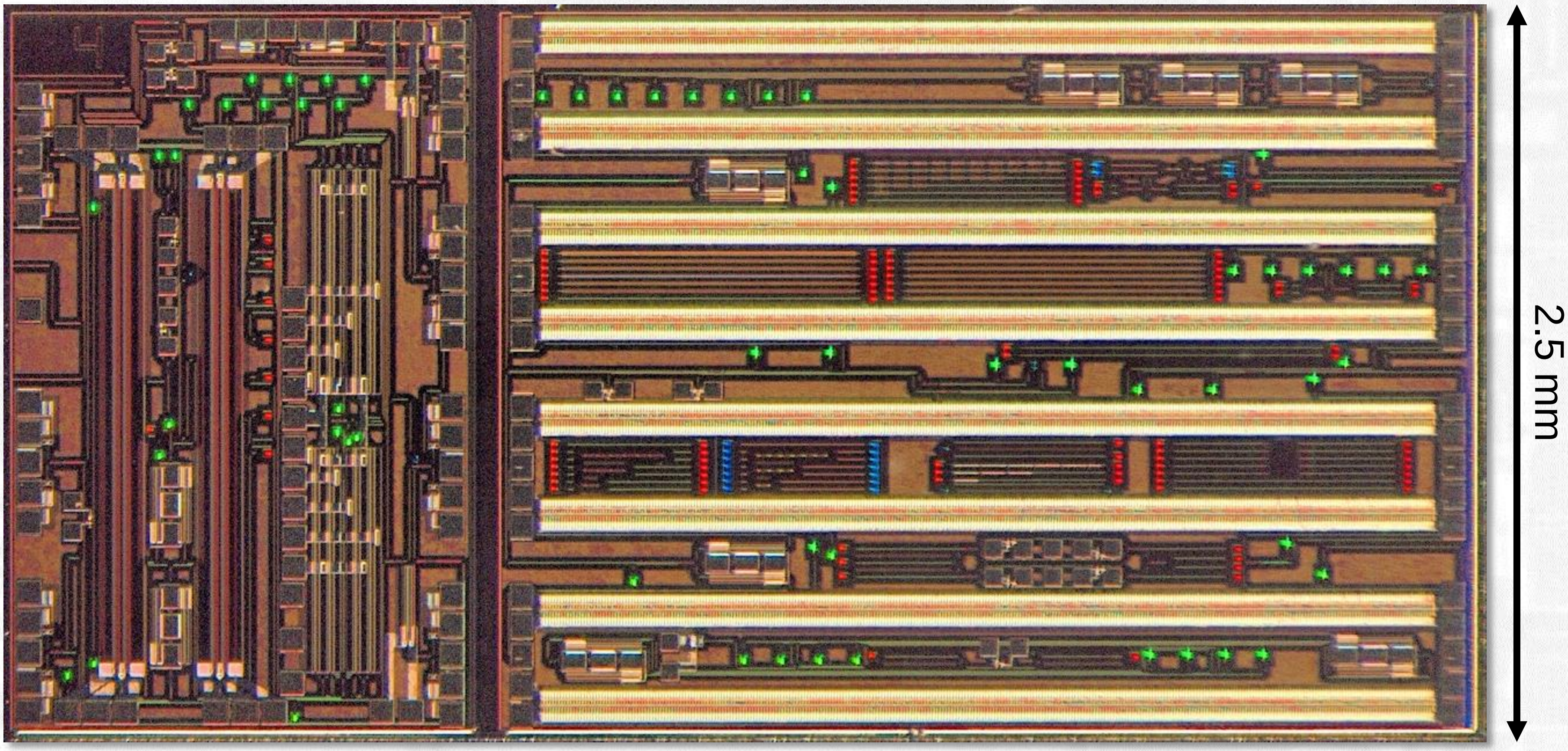
*Chip with different modulator types and Ge-Photodiodes*




*Layout*

# Modulator Chip

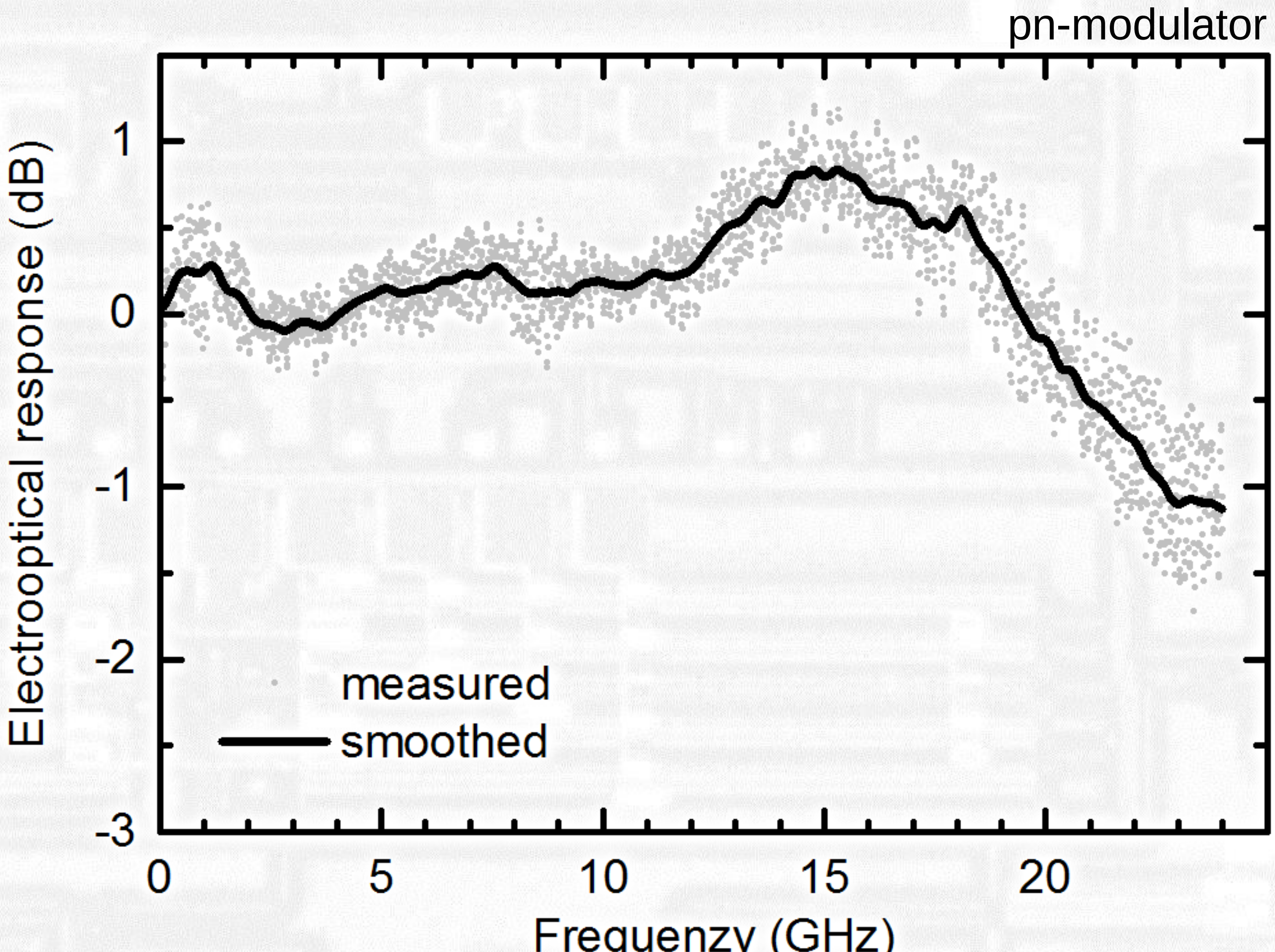
*Chip with different modulator types and Ge-Photodiodes*




*Real chip*

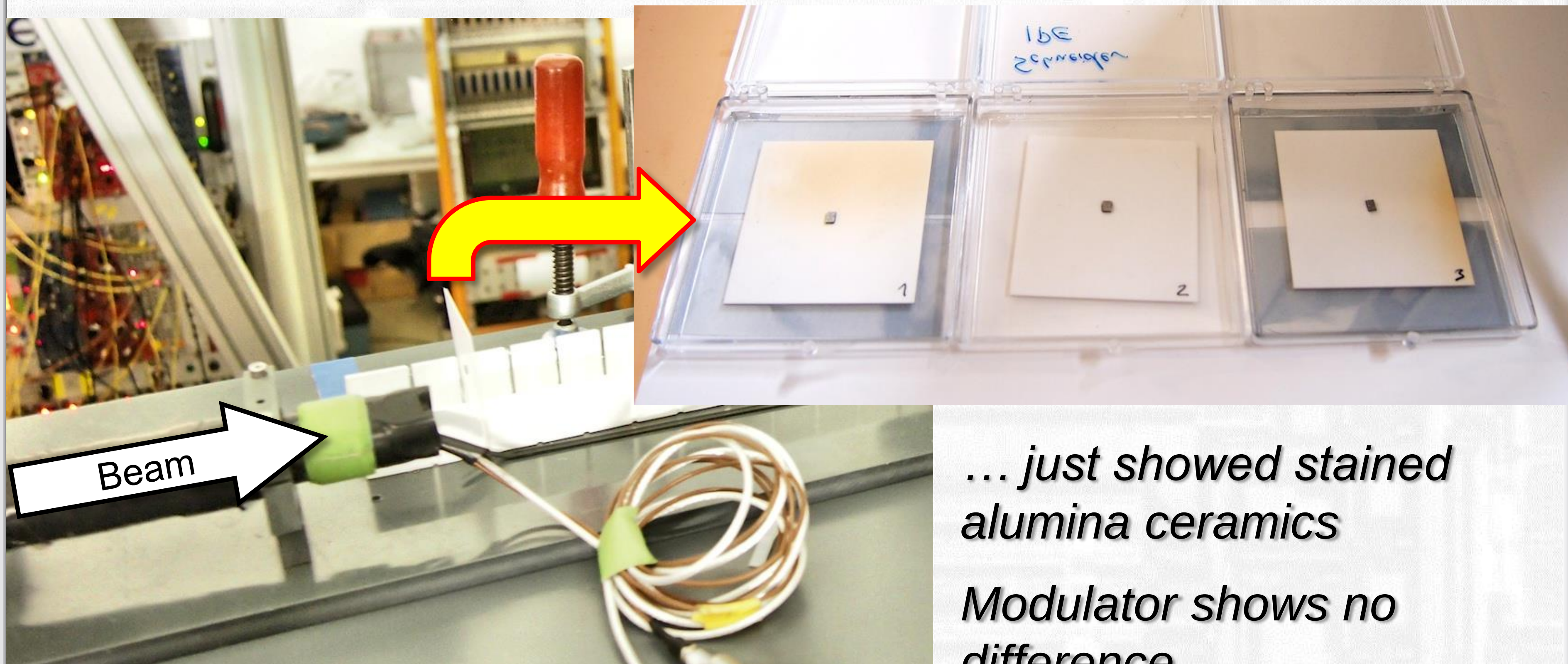
# Modulator Chip

*… and it works:*



# Modulator Chip

*First irradiation experiments…*




5.33×10$^{8}$ Ni ions @ 1400 AMeV ⇒ 12 krad

*… just showed stained alumina ceramics*

*Modulator shows no difference*

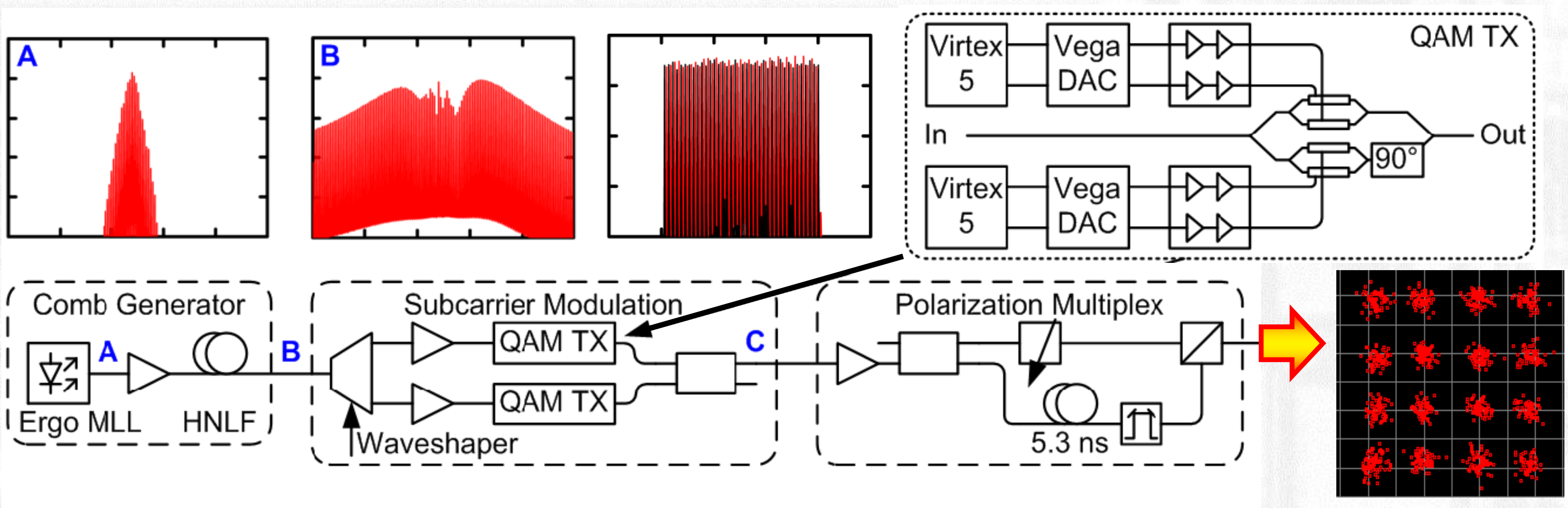
*⇒ Higher doses for next experiments!*

# *Wavelength Division Multiplexing*

*Multiple wavelength channels*

*Frequency comb source: 325 channels, 12.5 GBd, 16-QAM, polarization multiplex ⇒ 32.5 Tbit/s over 50 km*

*BUT: All discrete elements*

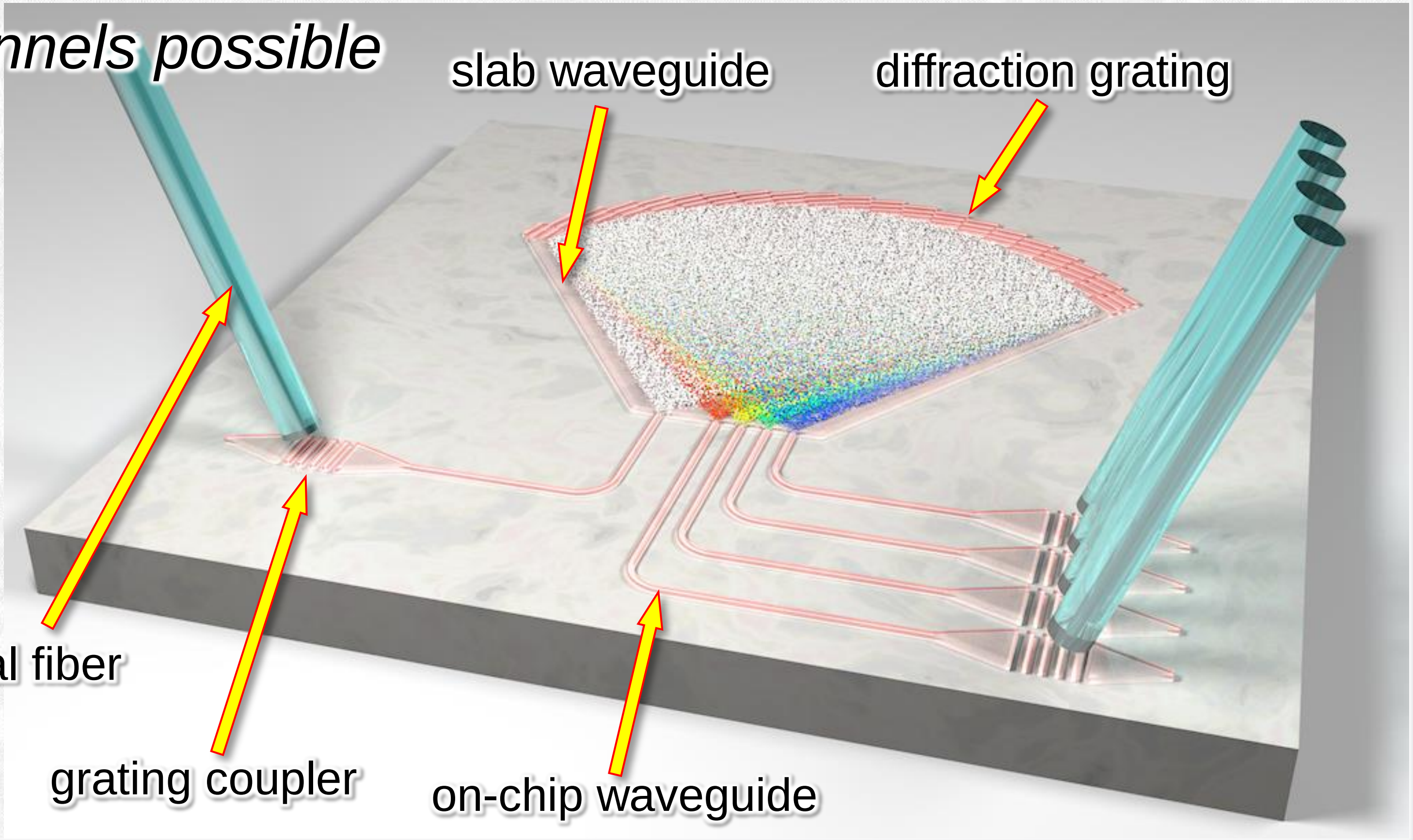



Hillerkuss *et al.*, Nature Photonics 5, 364–371 (2011)
(KIT: Institute of Photonics and Quantum Electronics (IPQ))

# Wavelength Demultiplexer

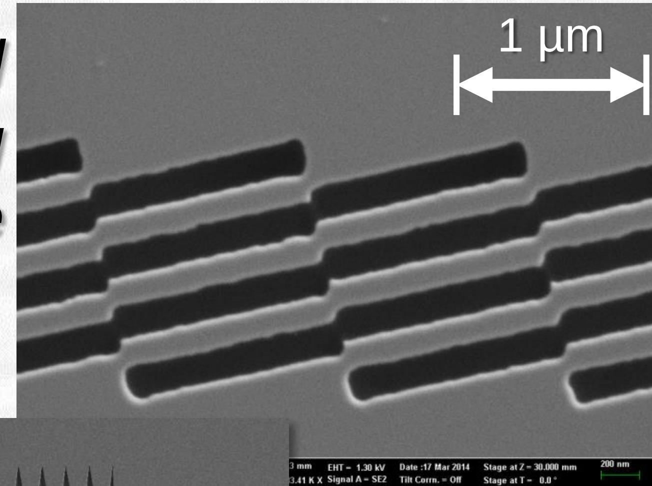
Echelle gratings

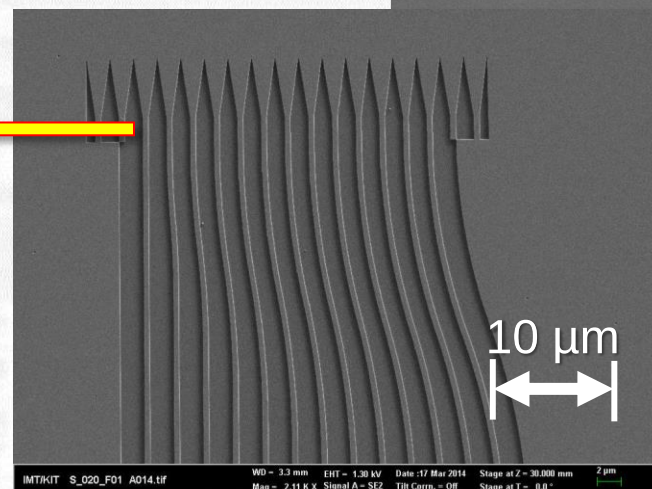
- Less sensitive to edge roughness than arrayed waveguide gratings (AWG)
- Many channels possible
- Compact



# Wavelength Demultiplexer

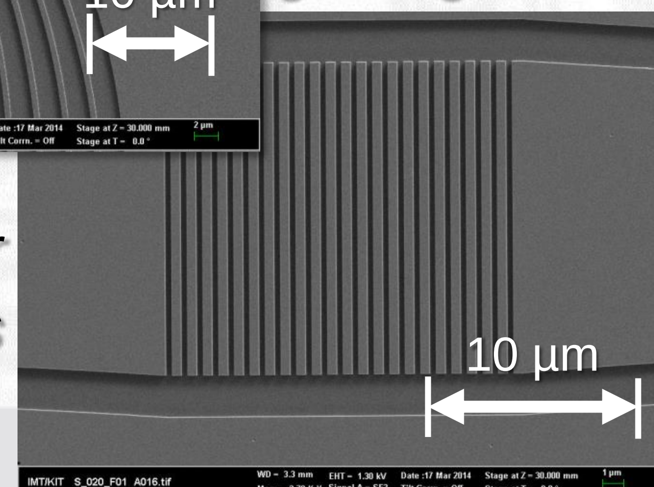

Curved grating structure



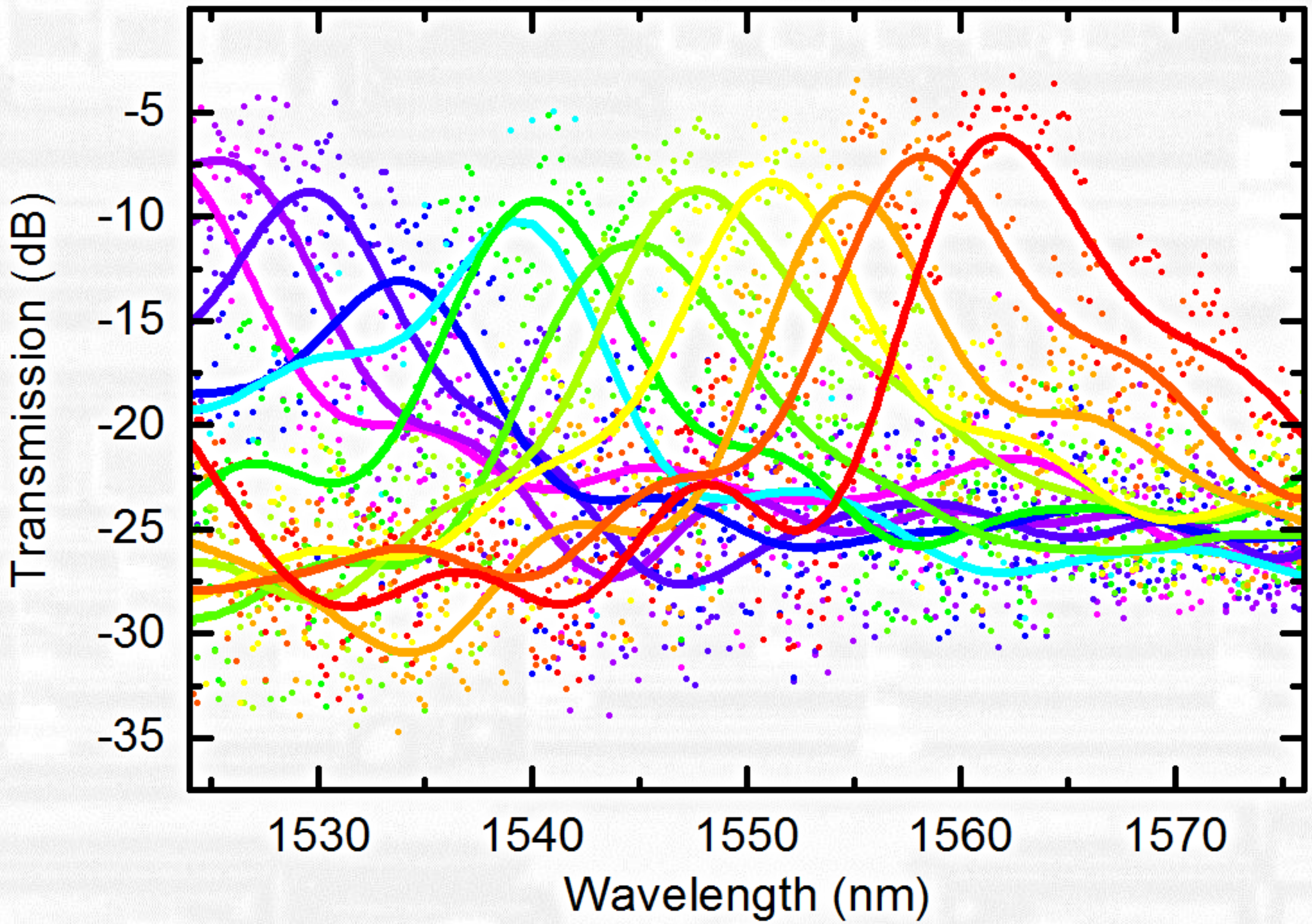

Ports of Echelle grating

Fiber couplers



# *Wavelength Demultiplexer*

*Optical transmission measurement of our very first Echelle-grating demultiplexer*




Silicon thickness deviates from design

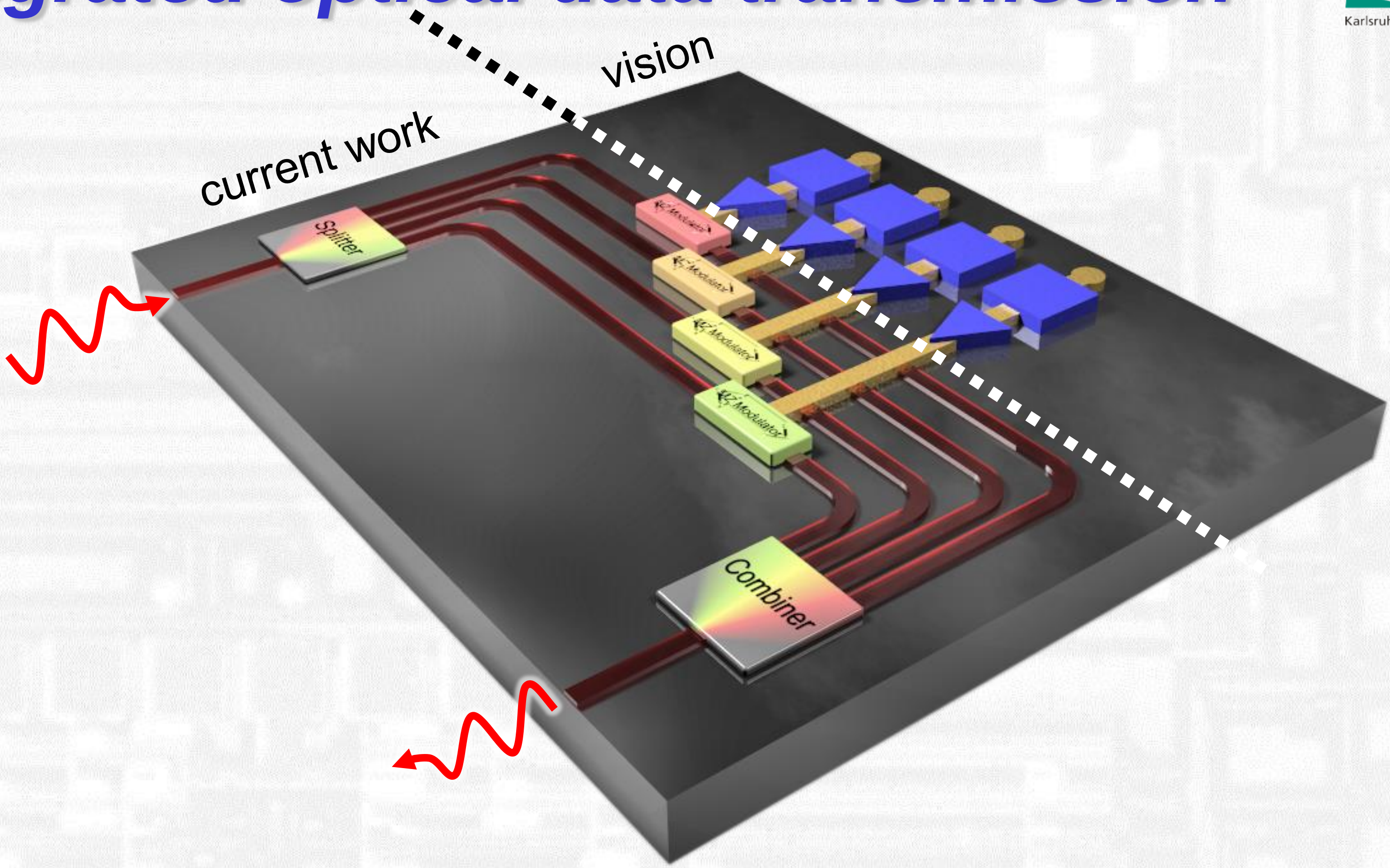
⇒ Different effective refractive index

⇒ Focal points of grating not on output waveguides

⇒ Poor channel separation / high crosstalk

⇒ Modify design…

# Integrated optical data transmission




*Long term vision:*

*Monolithic integration of detectors (bulk), interface electronics, optoelectronics, and optical waveguide devices (surface)*

# *Thank you for your attention!*