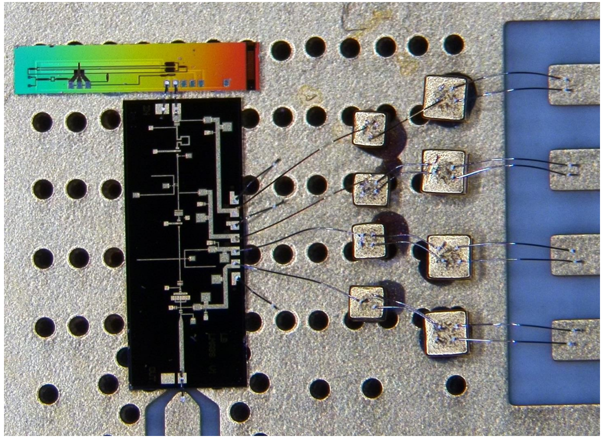

Electronic and Photonic Integrated Circuits for Millimeter Wave-over-Fiber

Laurens Bogaert

Supervisors: Prof. Dr. Ir. Johan Bauwelinck, Prof. Dr. Ir. Gunther Roelkens

IDLab INTERNET & DATA LAB
Photonics Research Group
imec
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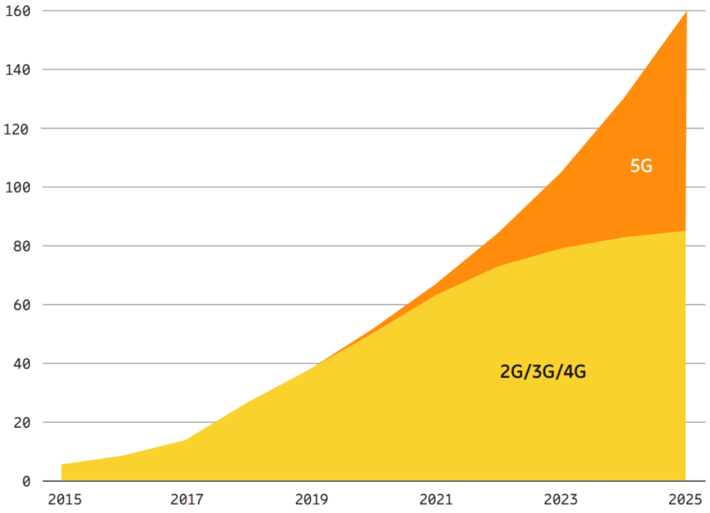
Mobile data traffic increases rapidly

Figure 12: Global mobile data traffic (EB per month)



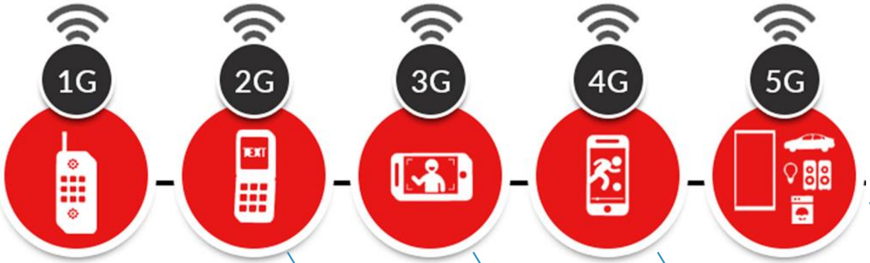
Ericsson Mobility Report, June 2020

- 2015: 9 EB/Mo
- 2020: 51 EB/Mo **(x5.7)**
- 2025: 160 EB/Mo **(x3.1)**

  1 EB = 1 billion gigabytes

- Mainly video-related traffic!
  Streaming, Social network, Video call, (cloud) Gaming, …

1G to 5G



voice

1982 1992 2001 2012 2020

text video livestream ???

1240 min.

Netflix SD
1 GB/h.

≈ 21 GB
≈ 168 Gb

3G (2 Mbps): 1 day

4G (100 Mbps): 28 min.

5G (10 Gbps): 17 sec.

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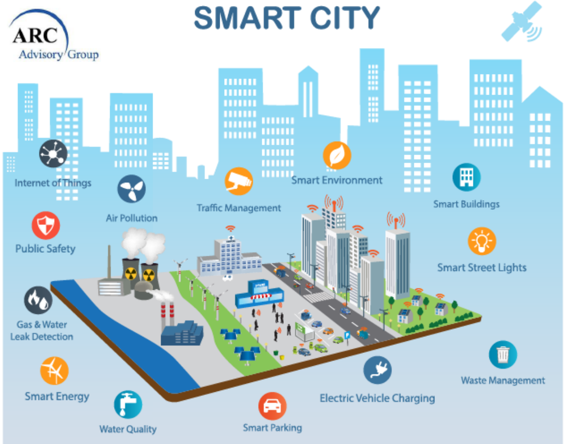
Increasing speed is only part of 5G

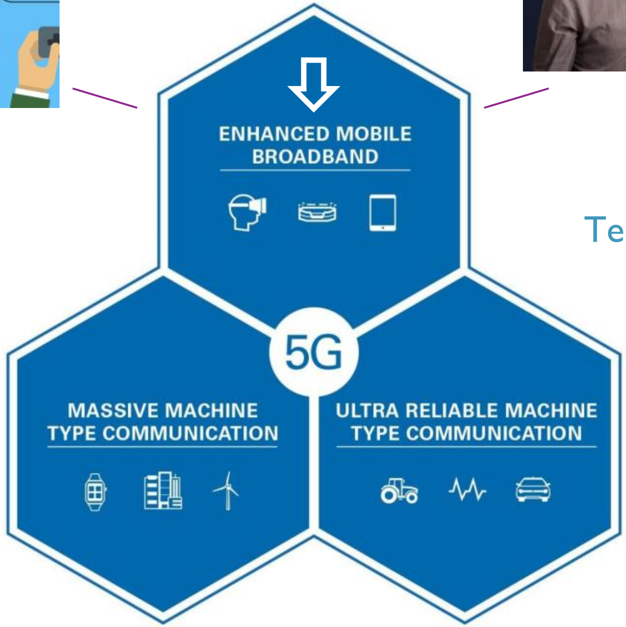
Cloud gaming,
Cloud working,
…

Very high speed,
Everywhere

VR-AR

Smart city, smart home (sensors)





Tele-surgery

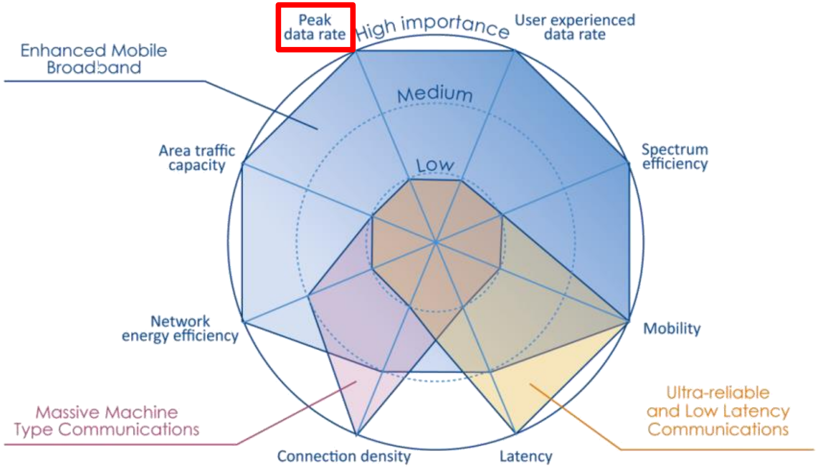
High density,
Low power

Low latency,
high reliability

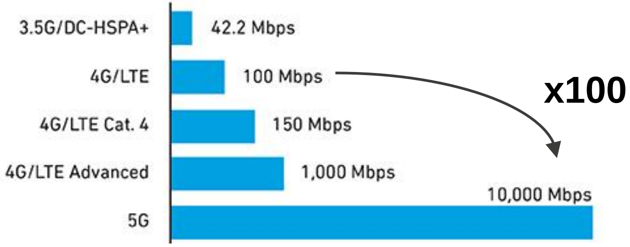
Self driving cars

Enhanced mobile broadband requirements

My Phd: Focus on enhanced mobile broadband

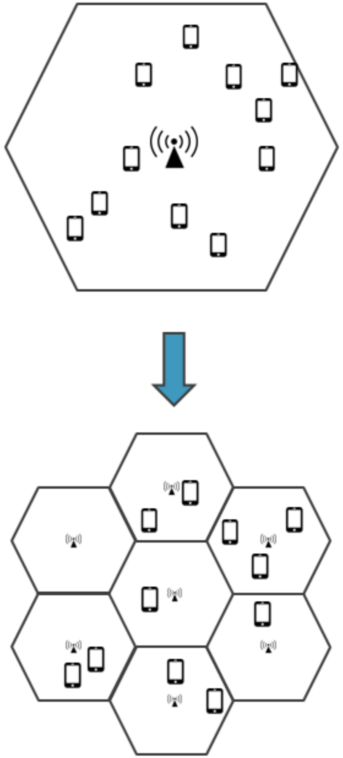


Peak data rate



Three categories with different requirements:
Does not mean “one wireless network to rule them all”

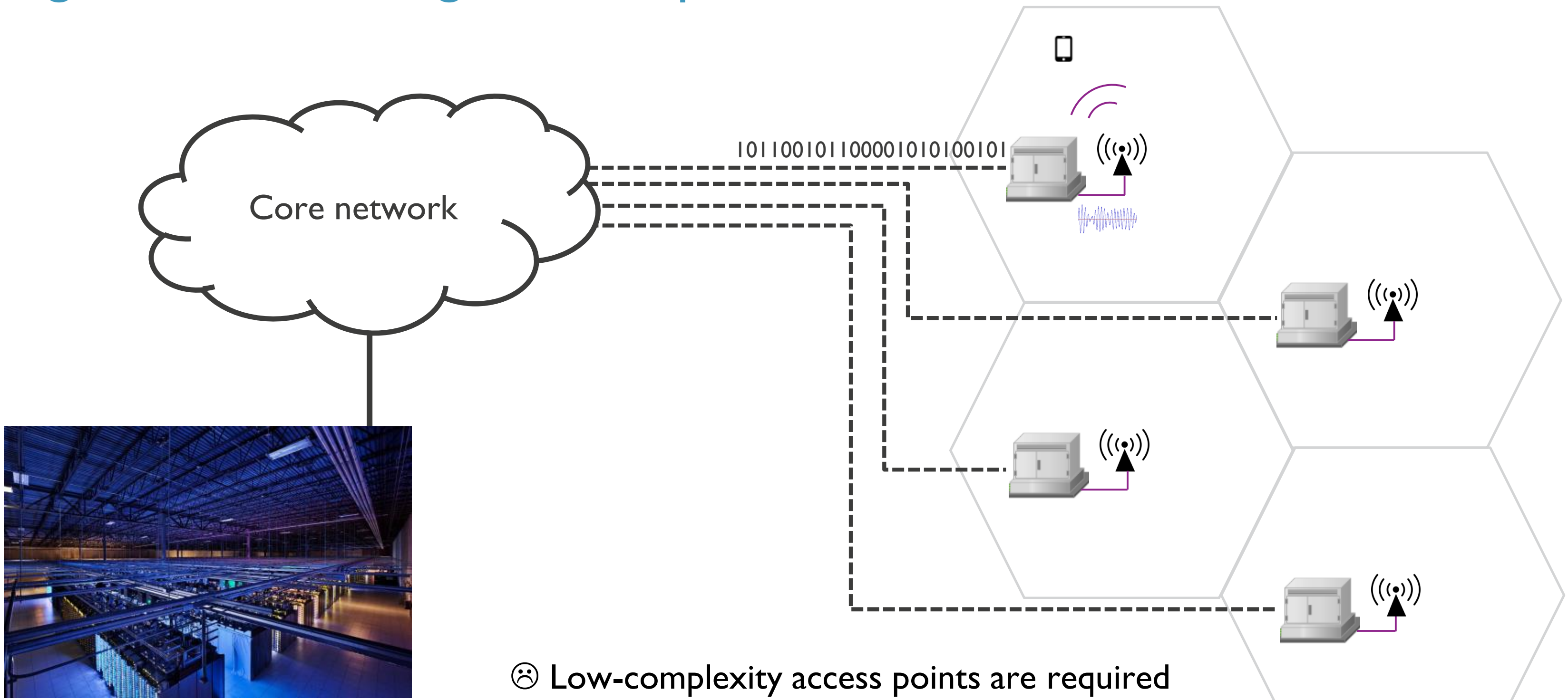
How do we meet these requirements – part 1: Small-cell approach



- Total data capacity ↗ due to reduced users/cell
- Power ↘ due to reduced antenna-user distance

- Cost ↗ due to more cells/area

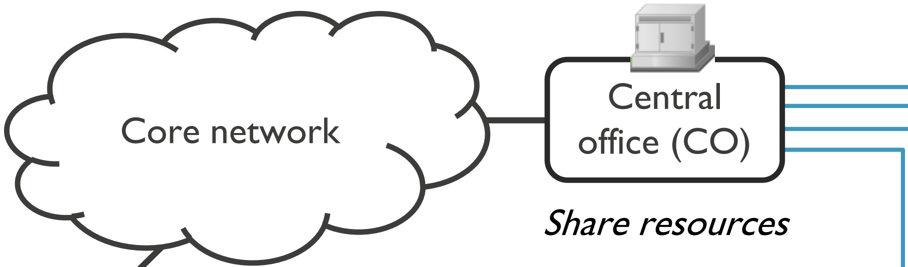
Straightforward scaling is too expensive!

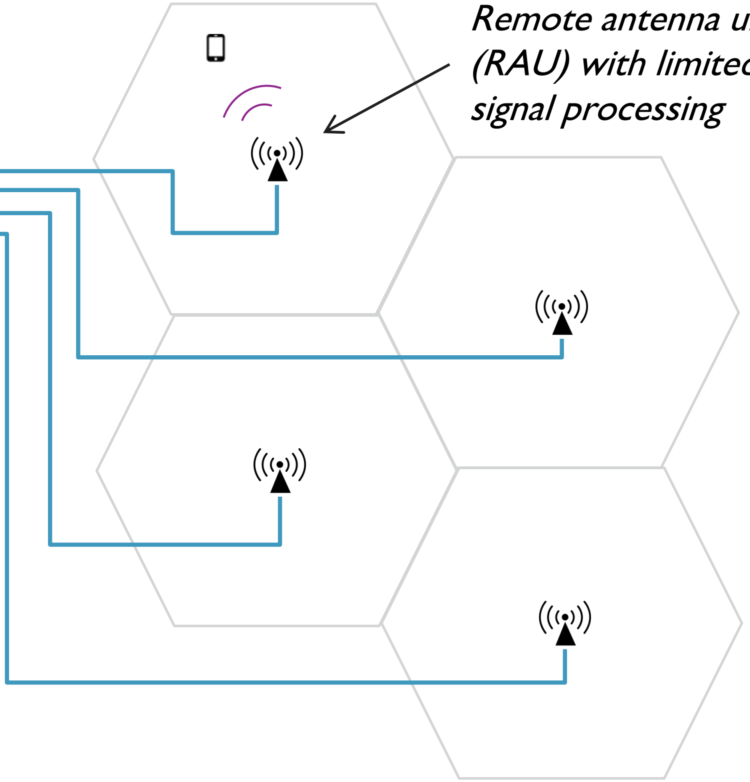


Data Center

☹ Low-complexity access points are required to make them mass-deployable (which is needed for small cell networks)

Re-use infrastructure by centralization!



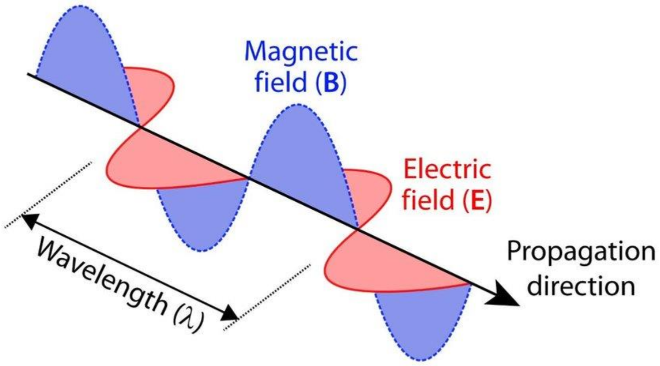


Optical communication to connect the central office to the antennas:

- Low loss
- High bandwidth

How do we meet these requirements? – part II: mmWave frequencies

- Electromagnetic wave: wave of the electric field **E** and magnetic field **B**
  - Propagation of energy
  - Moves at speed of light 300 km/ms (*vacuum*), slows down in material
  - Wavelength: length of 1 cycle
  - Frequency: how many oscillations per second



How do we meet these requirements? – part II: mmWave frequencies

- Millimeter wave frequencies:
  - Above 30 GHz (wavelength < 1 cm)
  - Less congested, more bandwidth available
  - More complex circuitry, more wireless loss, blocked by objects

Data rate ~ Bandwidth

FM: 100 MHz
DAB+: 220 MHZ

1227 MHz,
1575 MHz

2.4 GHz

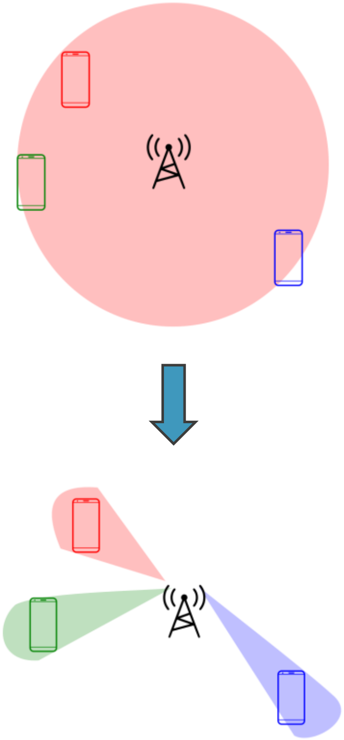
2.4 GHz,
5 GHz

868 MHz

4G: 800 MHz,
1.8 GHz,
2.6 GHz

5G: 700 MHz,
3.5 GHz,
(28 GHz)

How do we meet these requirements? – part III: Beamforming



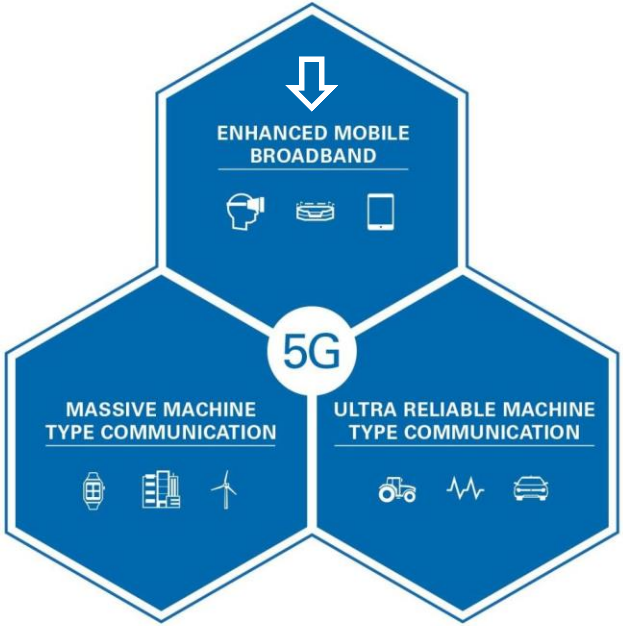
Send to all directions

→ **send to the intended user**

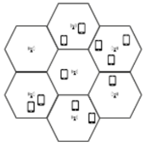
- Power efficiency cellular network ↗
- Interference↘
  - Signal quality ↗
  - Data capacity ↗ because parallel beams are possible

Electronic and Photonic Integrated Circuits for Millimeter Wave-over-Fiber

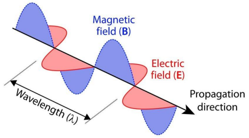
- Mobile data traffic increases rapidly



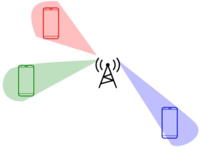
- Small cell: network densification
  - Scalability by centralization
  - Optical communication between central office and remote antennas



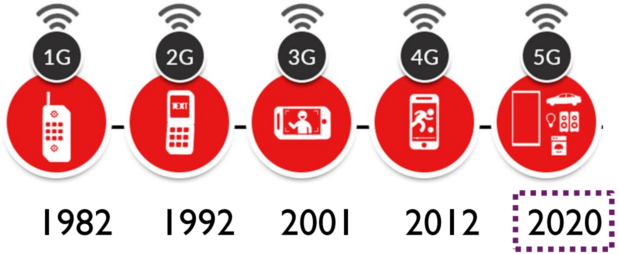
- mmWave frequencies
  - Less congested, more bandwidth
  - Higher losses, more complex

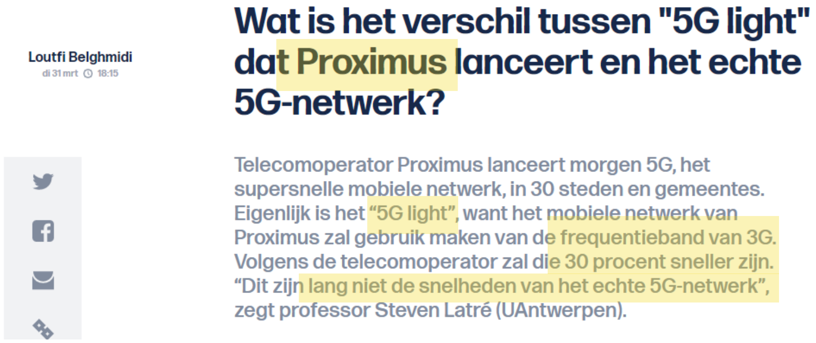


- Beamforming
  - Improved power efficiency
  - Lower interference



But what about 5G already being deployed?

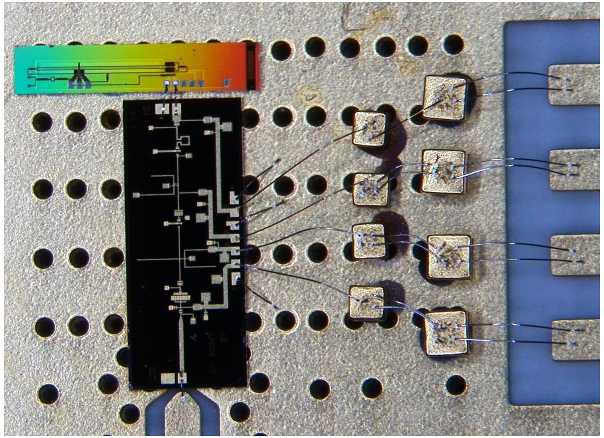



Loutfi Belghmidi
di 31 mrt 18:15

Wat is het verschil tussen "5G light" dat Proximus lanceert en het echte 5G-netwerk?

Telecomoperator Proximus lanceert morgen 5G, het supersnelle mobiele netwerk, in 30 steden en gemeentes. Eigenlijk is het "5G light", want het mobiele netwerk van Proximus zal gebruik maken van de frequentieband van 3G. Volgens de telecomoperator zal die 30 procent sneller zijn. "Dit zijn lang niet de snelheden van het echte 5G-netwerk", zegt professor Steven Latré (UAntwerpen).

"5G" nowadays uses traditional spectrum (< 6 GHz)
5G light is about 30% faster than current 4G
5G light is not nearly as fast as real 5G



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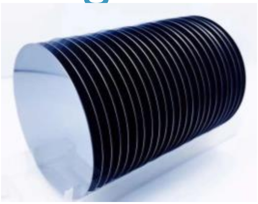
Integrated Electronics (Electrical chips) = combine complex electrical functionality in a single device

Ingot

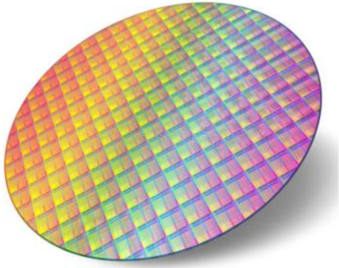


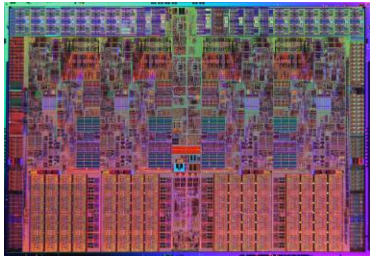
Wafers

Processing at cleanroom

Design

Integrated electronic circuits on wafer





Cut wafer in dies

Packaging

Product (e.g. computer)

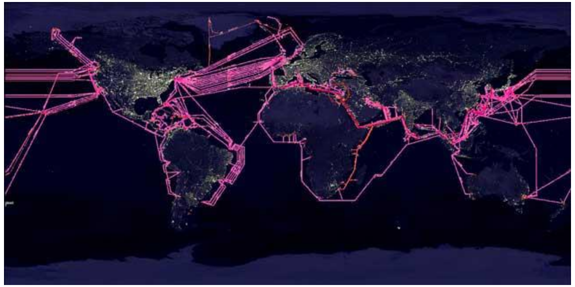
Measurement

What is photonics and what are the applications?

- The word 'photonics' is derived from the Greek word "phos - φως" meaning **light**
- Optics and photonics is the study of the **fundamental properties of light** and harnessing them in **practical applications**. *(Nature)*
- A branch of physics that deals with the properties and applications of photons especially as a medium for **transmitting information** *(Merriam-Webster)*

Sensors (e.g. heart rate)

Lidar (for self-driving cars)



Datacom/Telecom:
Data centers, trans-oceanic, …

Integrated photonics (Optical chips) = combine complex optical functionality in a single device

+

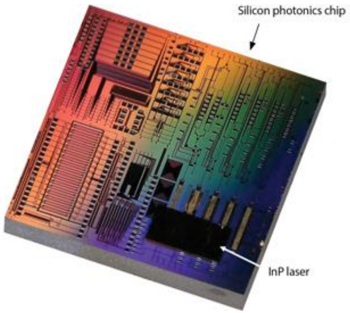
+

Filter

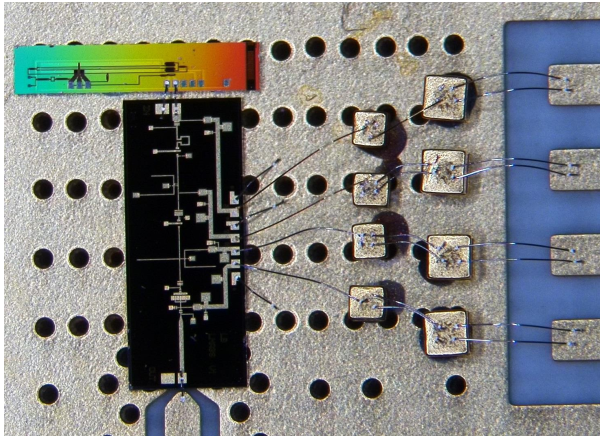
+

Photodetector

=



- Integrate many **optical** functions on a chip (~Electronic integrated circuit)
- Low cost
- Compact



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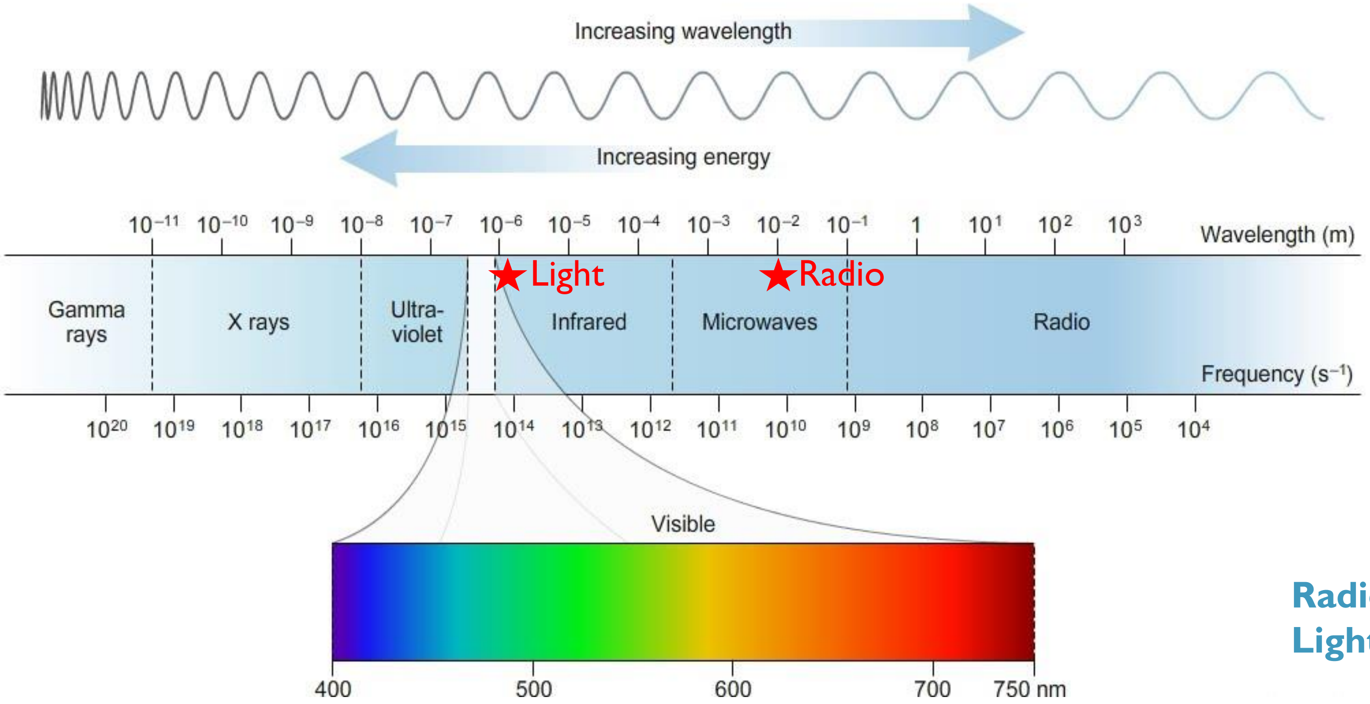
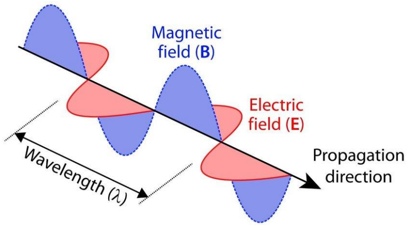
Light is also an electromagnetic wave … with a much higher frequency

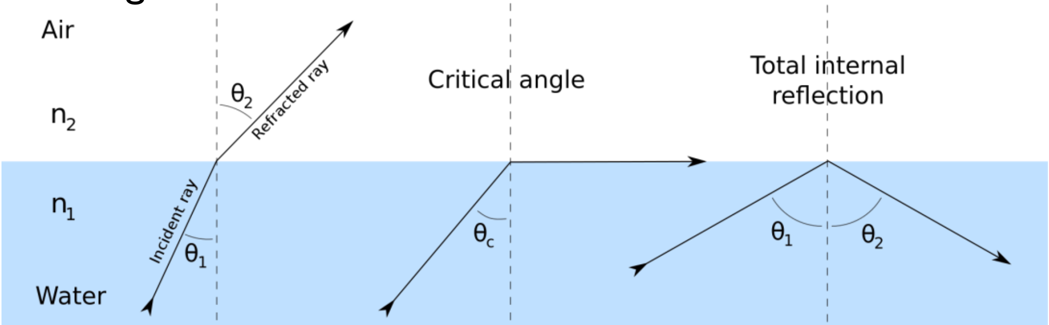


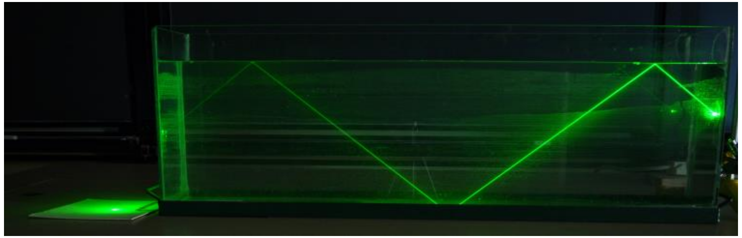


Radio: 30 GHz (1 cm)
Light: 193 THz (1.55 μm)

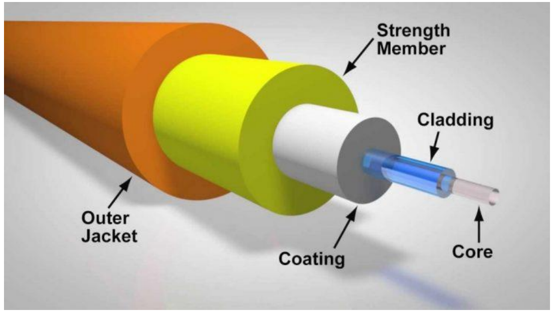
Light rays: refraction and total internal reflection

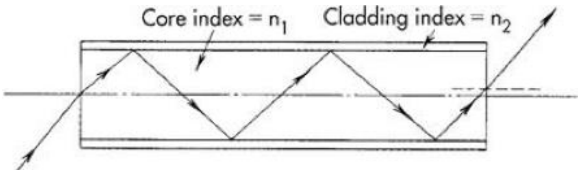
- Light bends at an interface with different refractive index
  - Refractive index: measure for density of the material
  - Refractive index air < refractive index water
  - Angle in air > angle in water



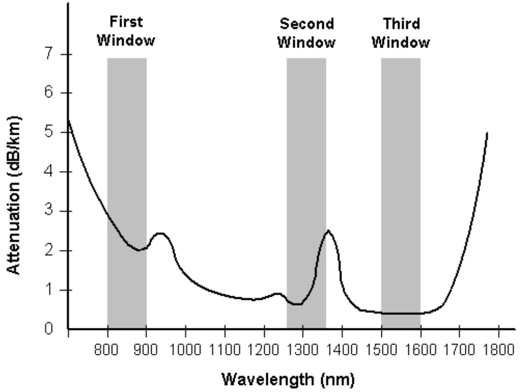


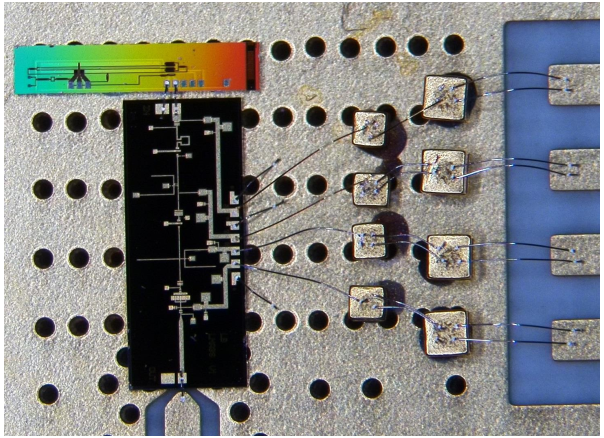
Optical communication using glass fibers





- Core = higher refractive index than cladding
- If launch angle is right → Total internal reflection
- Low loss propagation of light (trapped in core)
  - 50% of power lost after 15km (1550 nm)
  - Direct 28 GHz transmission (electrical):
    50% of power lost after approximately 1m





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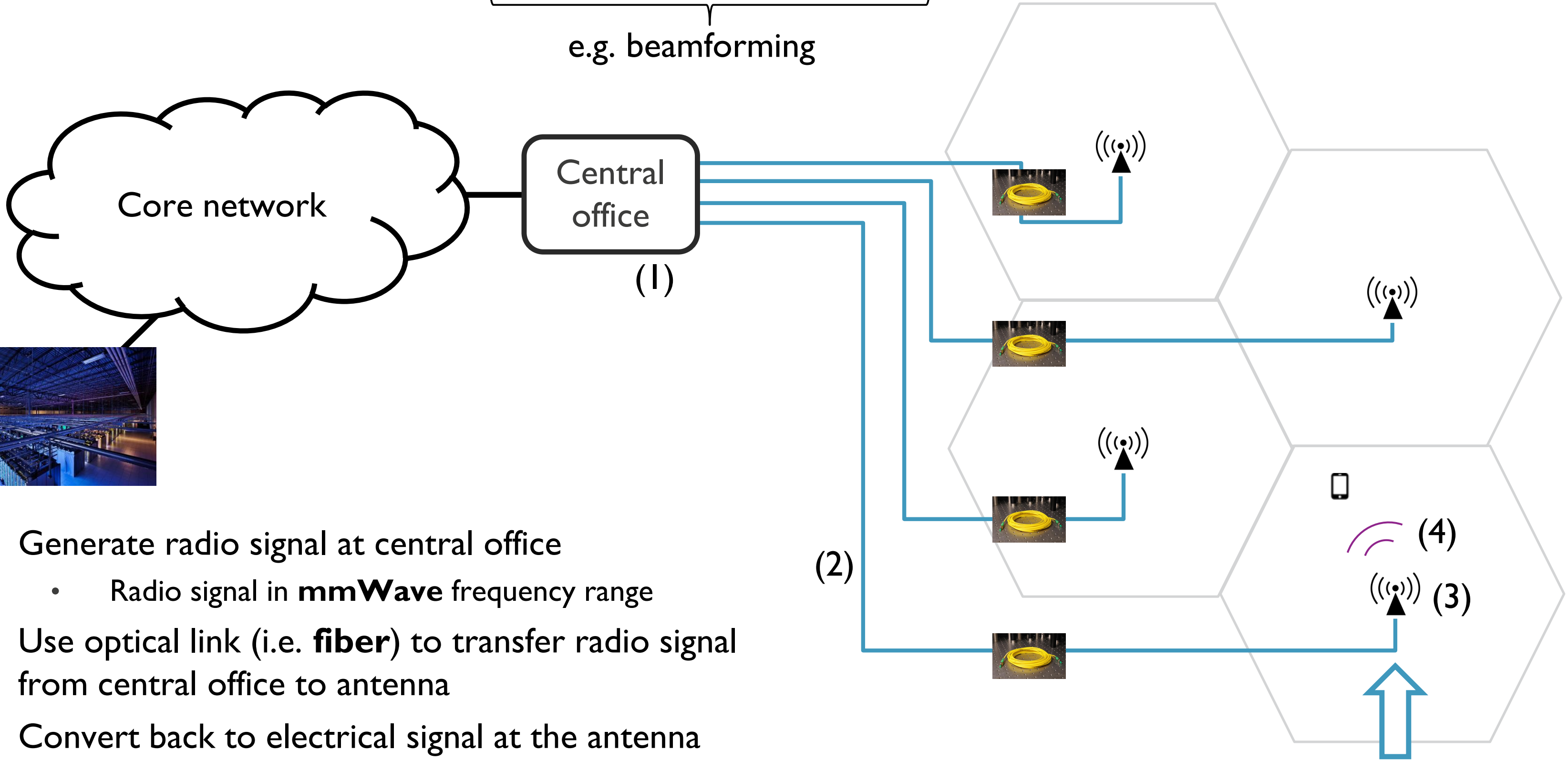
Electronic and Photonic $\underbrace{\text{Integrated Circuits}}_{\text{e.g. beamforming}}$ for mmWave-over-Fiber



1. Generate radio signal at central office
   - Radio signal in **mmWave** frequency range
2. Use optical link (i.e. **fiber**) to transfer radio signal from central office to antenna
3. Convert back to electrical signal at the antenna
4. Send signal wirelessly from antenna to user

\# antenna >> # central office
→ focus research on optimizing antenna side of the link

Generate radio signal at central office …

Movie

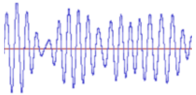
Frames

Pixel (RGB)
101100101100001010100101

Datacenter

Central office

mmWave signal



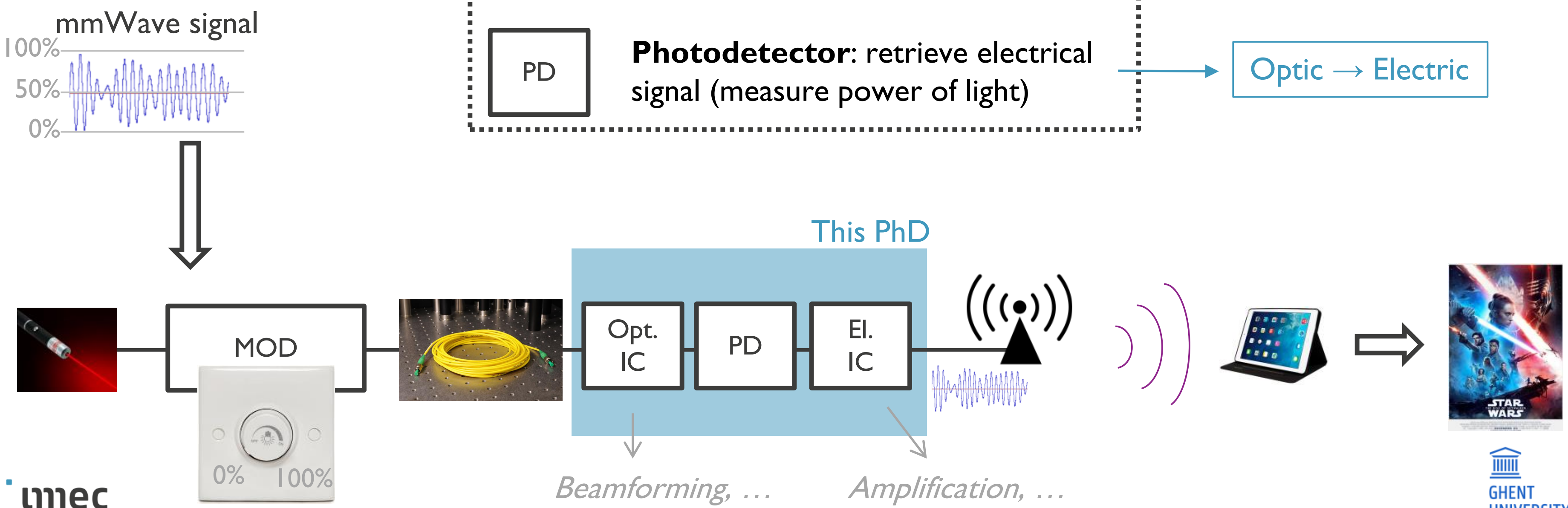
bit sequence → radio signal
(*centralized*)

… Use optical link to transfer radio signal to antenna

Laser: continuous, unmodulated light

MOD — **Modulator**: put electrical signal on optical carrier (~dimmer) → Electric → Optic

PD — **Photodetector**: retrieve electrical signal (measure power of light) → Optic → Electric



Outline

Introduction

- 5G
- Photonics

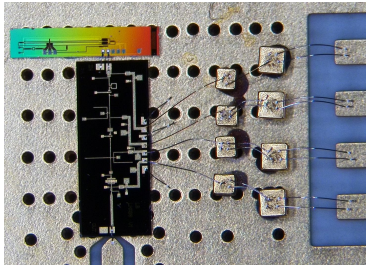
Detection and modulation + amplification

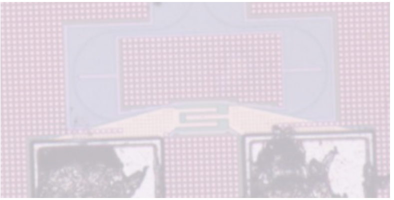
High power detectors

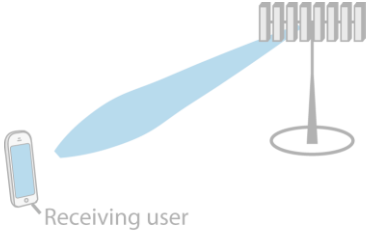
Beamforming

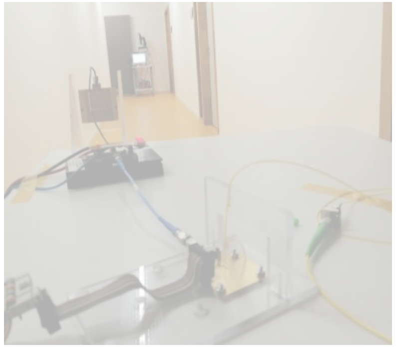
Link experiments

Summary





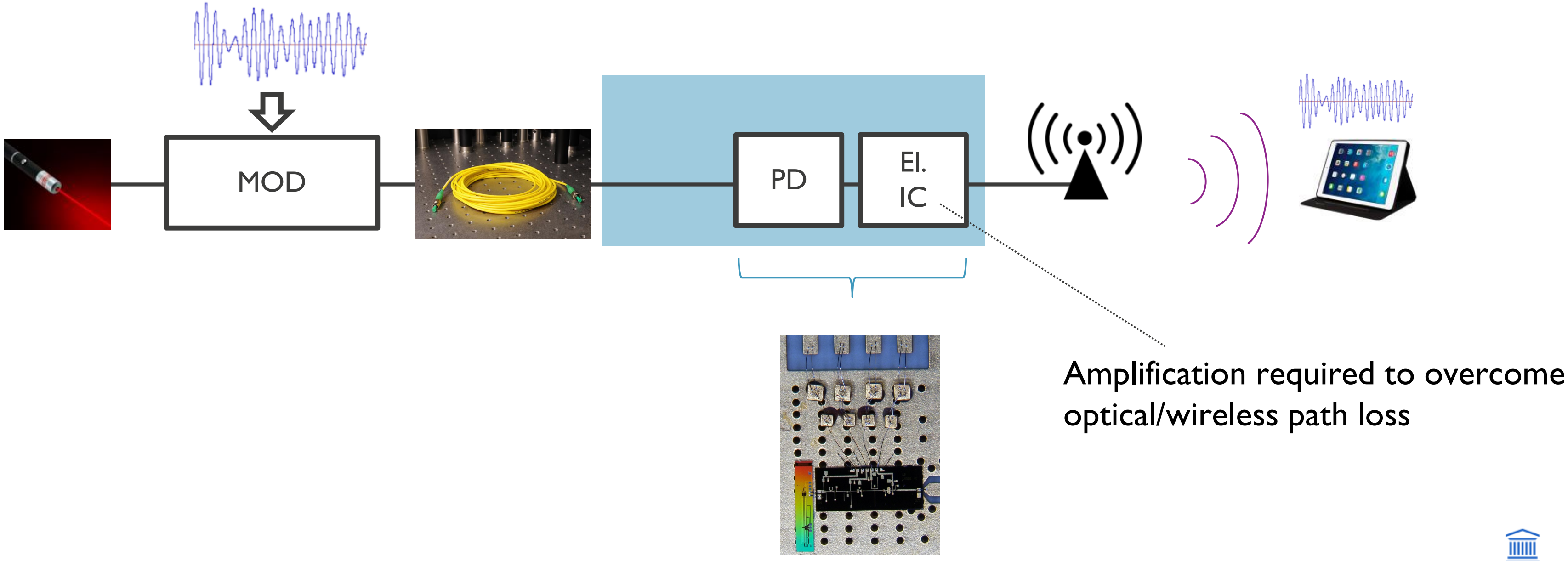




Downlink (= to end user)

Central office: generate radio signal and convert to optical domain

Remote antenna unit: convert to electrical domain, narrowband amplification and transmit over wireless path (+ processing)



Photoreceiver combines O/E-conversion with narrowband amplification

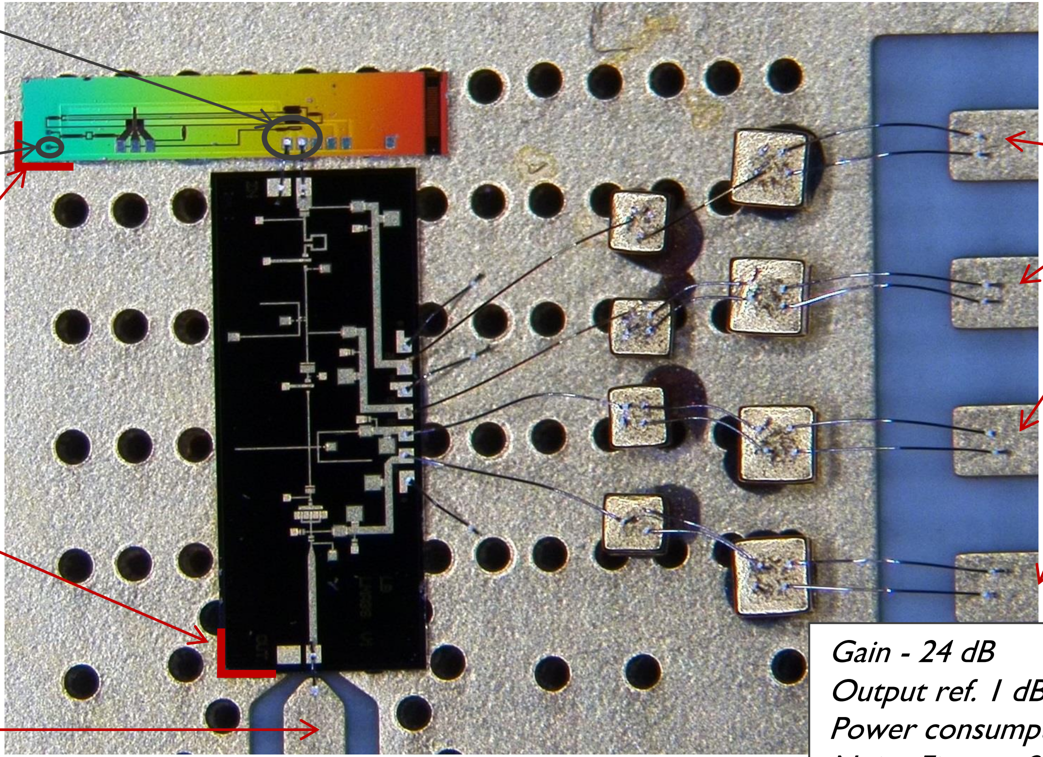
Photodetector:
Converts to optical
to electrical signal

Optical coupling:
from fiber to chip

Photonic chip
(Si)

Electronic chip
(GaAs) –
1.4 x 3.4 mm

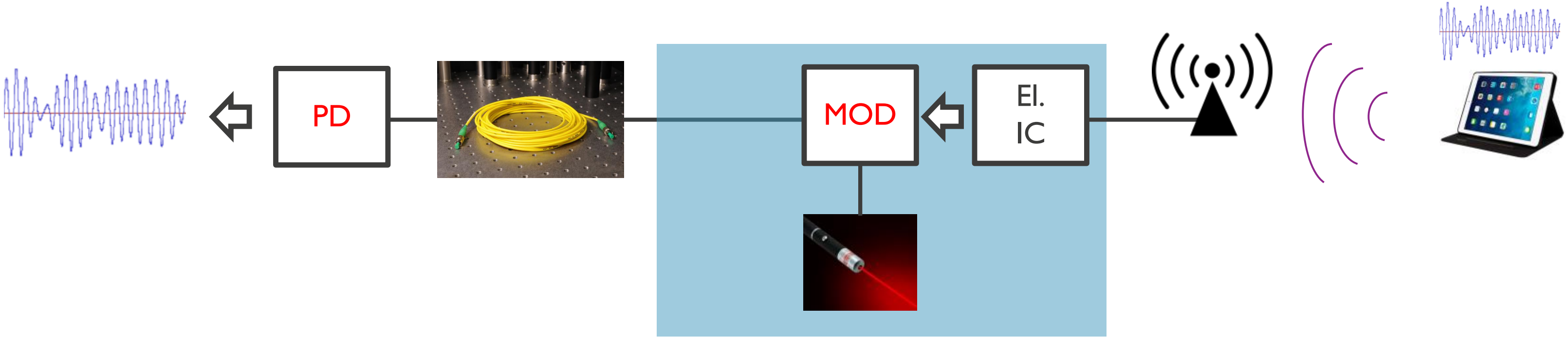
Connection
to antenna



Supply lines

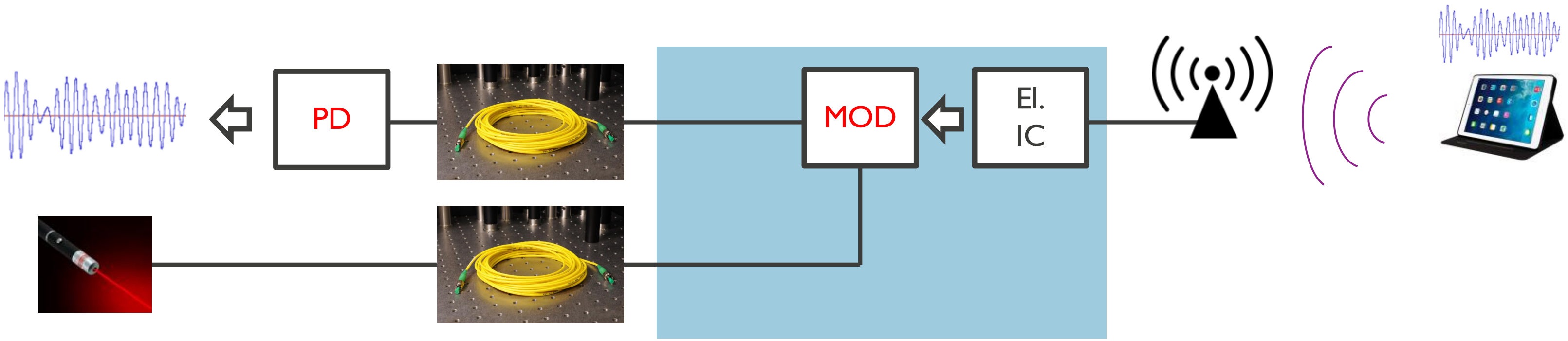
Gain - 24 dB
Output ref. 1 dB compression – 13.9 dBm
Power consumption - 303 mW
Noise Figure - 2.1 dB
3 dB bandwidth - 23.5 to 31.5 GHz

Uplink (= from end user)



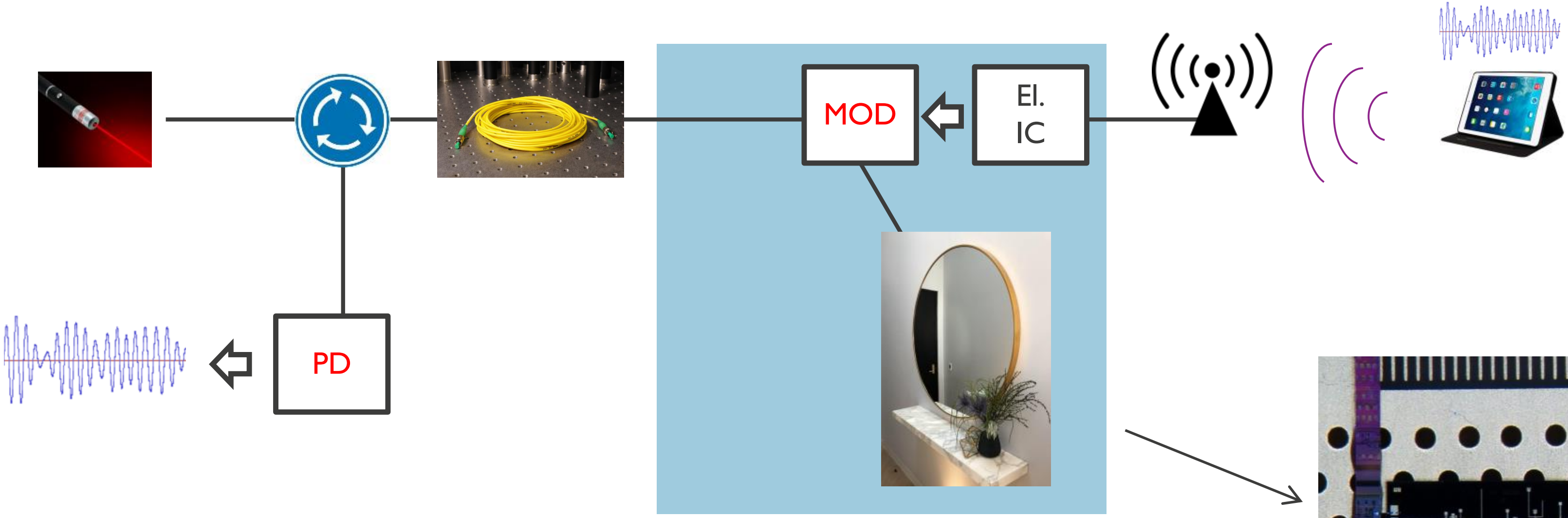
Turn the link around? Requires laser at every antenna – Scalability ☹

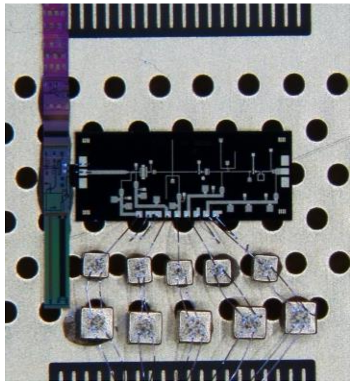
Uplink (= from end user)



Push laser back to central office? Requires two fibers

Uplink (= from end user)

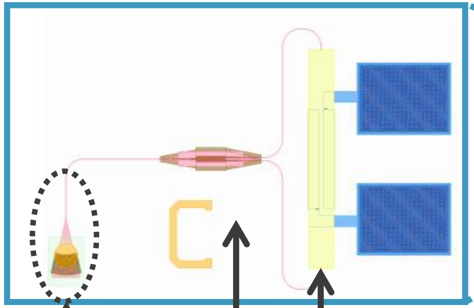


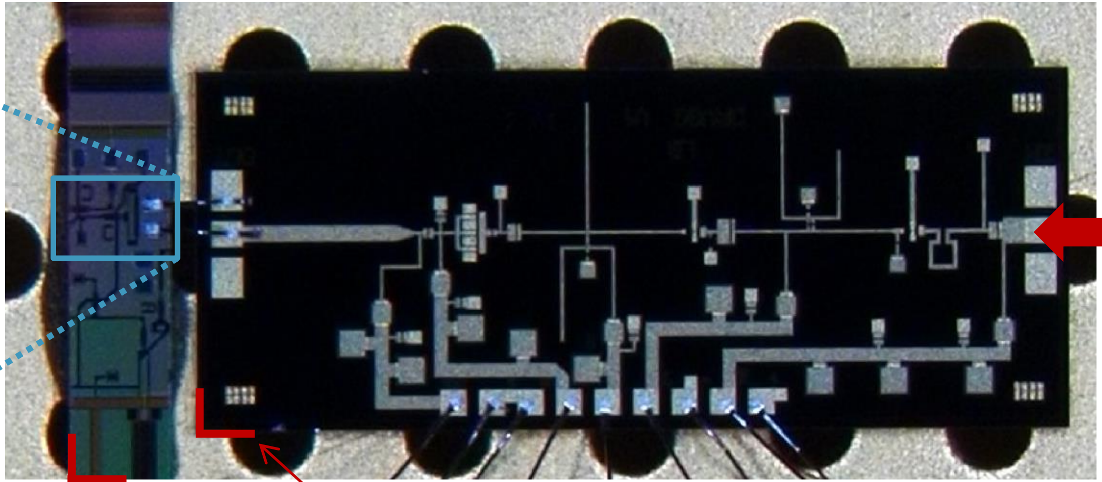


Use reflective modulator!

Same frequency range: Largely re-use downlink amplifier

Reflective modulator and narrowband amplification





Radio signal from antenna (el.)

Light in/out

Modulator (EAM)

Reflective loop mirror

Photonic chip (Si)

Electronic chip (GaAs) – 1.4 x 3.4 mm

Gain – 25.5 dB
Input ref. 1 dB compression – -20 dBm
Power consumption – 124 mW
Noise Figure – 2.0 dB
3 dB bandwidth – 24.4 to 29.5 GHz

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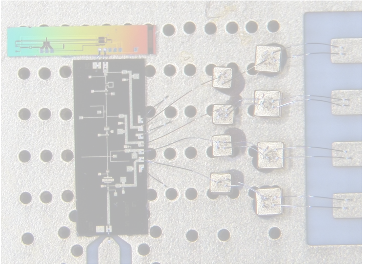
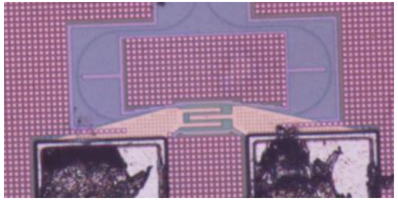
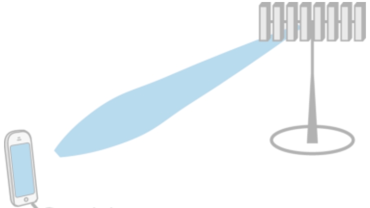
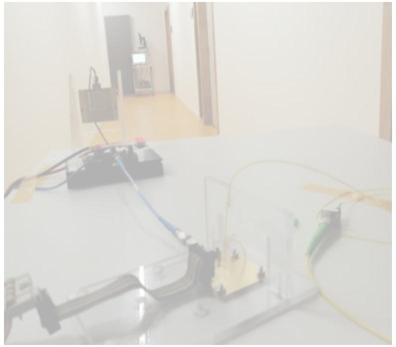
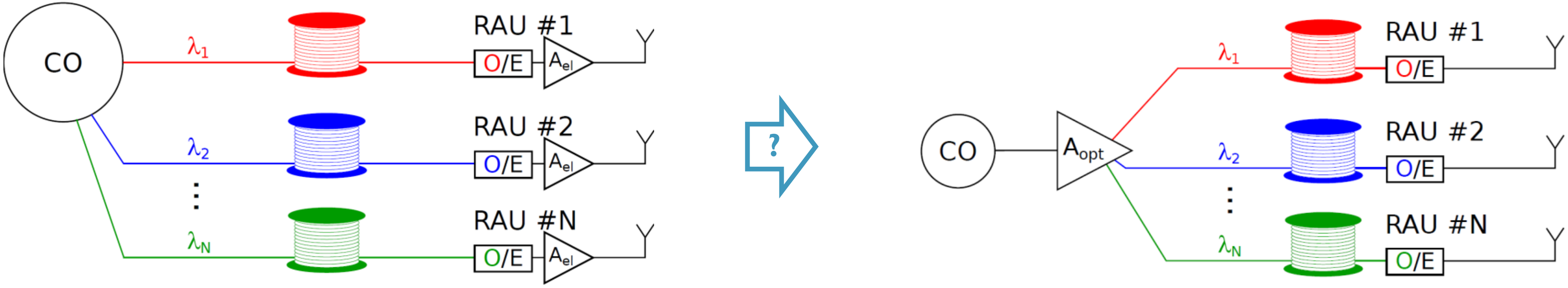






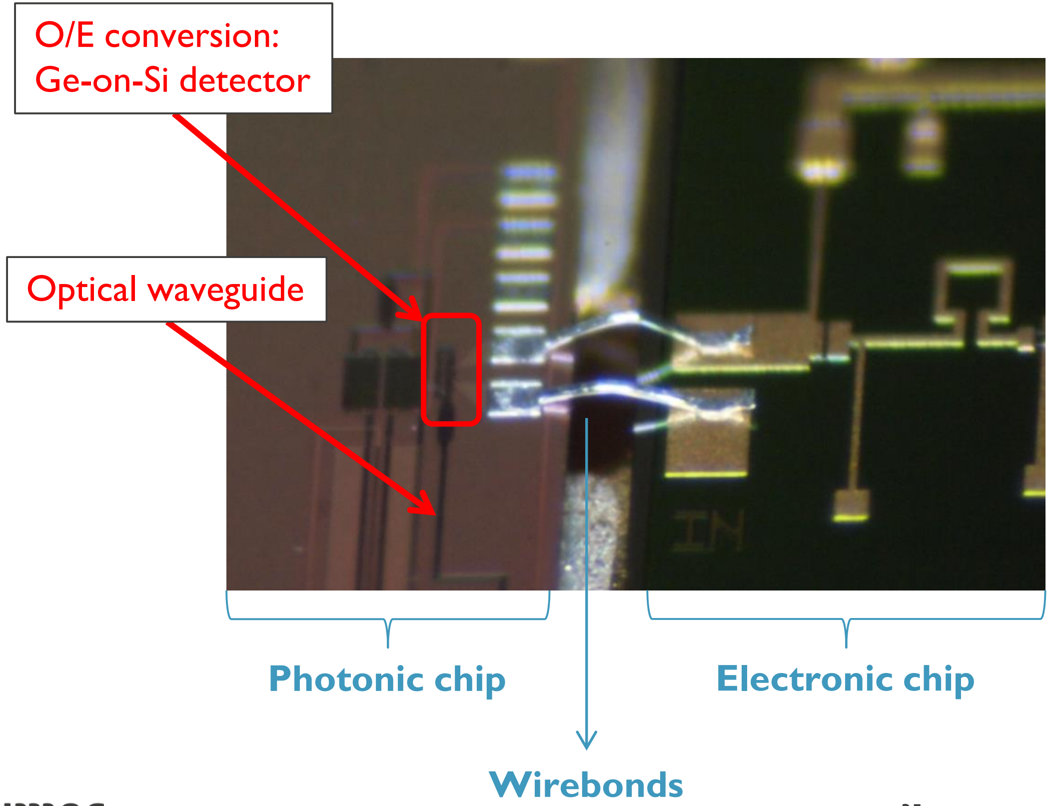


Optical amplification allows for centralization



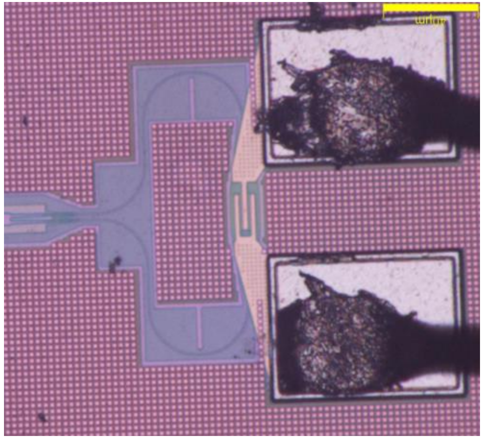
- Shared optical amplification
  - Noise: typically lower
  - Complexity: no scaling with #RAUs + centralized maintenance
- Individual electrical amplification
  - Linearity: challenging (fiber, amplifier, photodetector)
    → **My focus:** high power photodetector (O/E conversion of high power optical signal without distortion)

Photodetector: converts optical signal to electrical signal

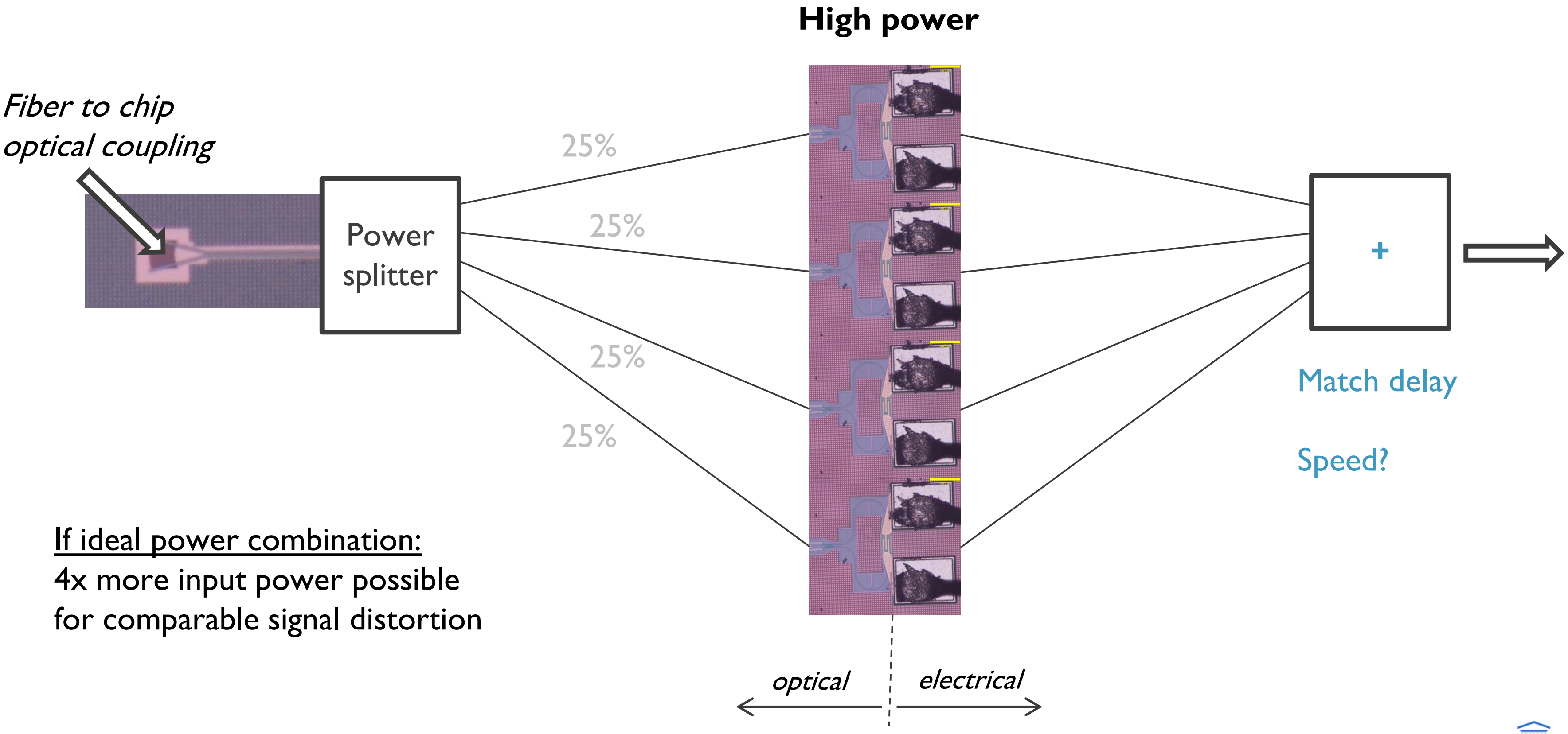


Ge-on-Si photodetector

- CMOS compatible
- Fast (bandwidth > 50 GHz)
- Limited linearity/power handling



Divide and conquer to reduce power per detector

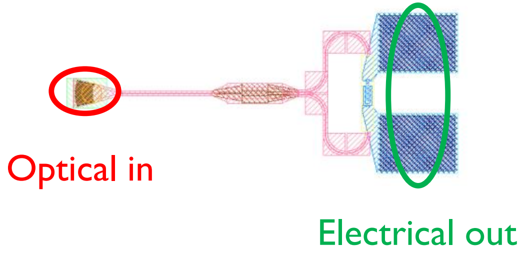


<u>If ideal power combination:</u>
4x more input power possible
for comparable signal distortion

Try to achieve high-speed, high-linearity O/E conversion

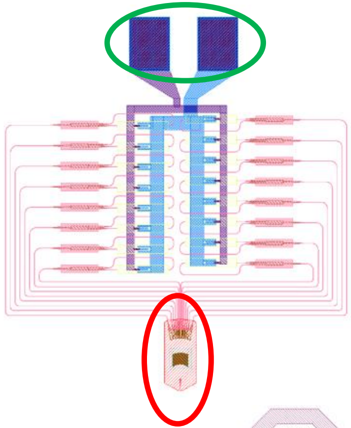
<u>Single photodetector</u>

- High speed
- Low linearity



<u>Parallel photodetector</u>

- Low speed
- High linearity

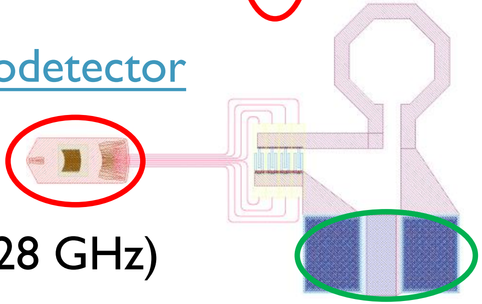


<u>Traveling wave photodetector</u>

- High speed
- High linearity
- Broadband

<u>LC matched photodetector</u>

- High speed
- High linearity
- Narrowband (28 GHz)



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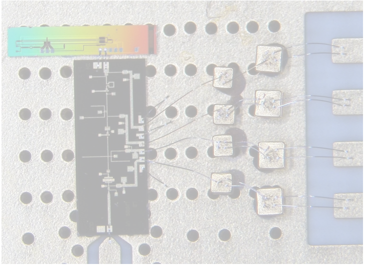
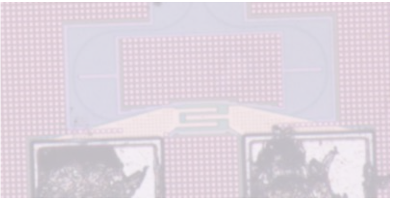
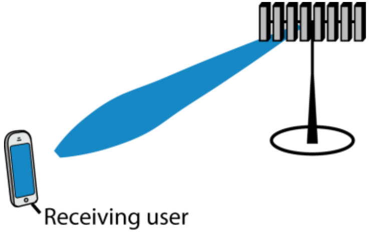
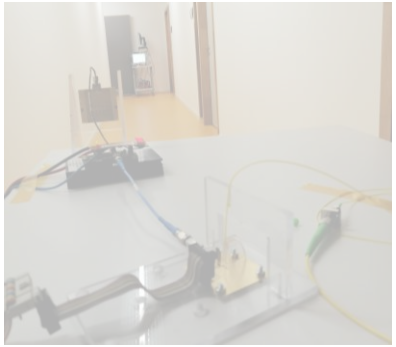
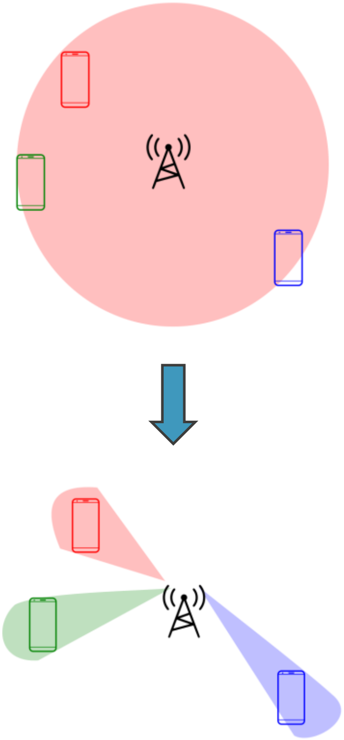








Remember: *How do we meet these requirements? – part III: Beamforming*

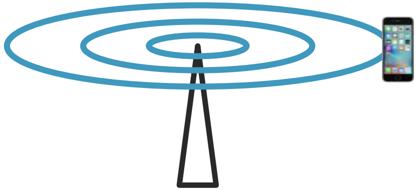


Send to all directions

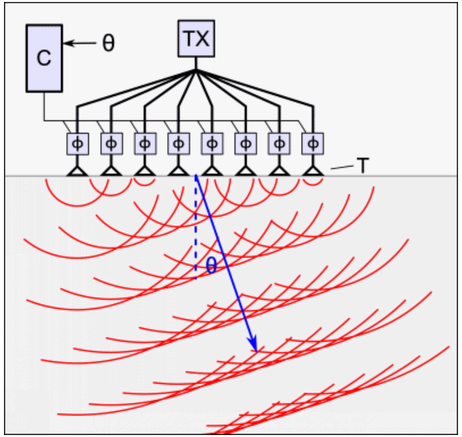
→ **send to the intended user**

- Power efficiency cellular network ↗
- Solves increased wireless loss at mmWave frequencies (focus energy in beam direction)
- Interference ↘
  - Signal quality ↗
  - Data capacity ↗

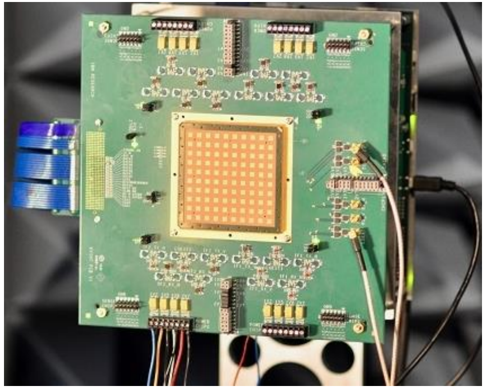
How to form and steer the beam?



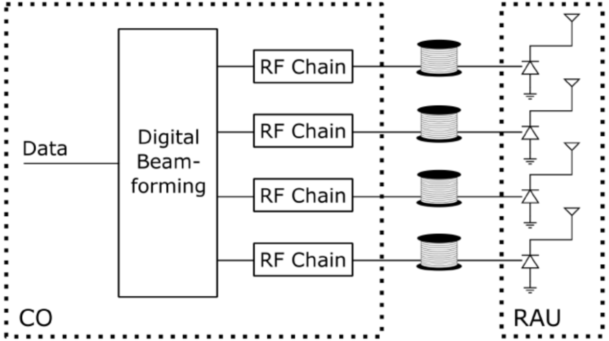
- One antenna ~ circular wave front (omnidirectional)
- Multiple antenna's with variants of the same signal
  - Individual antennas still show circular wave fronts
  - Antenna array results in combined propagation in direction of blue arrow (unidirectional)

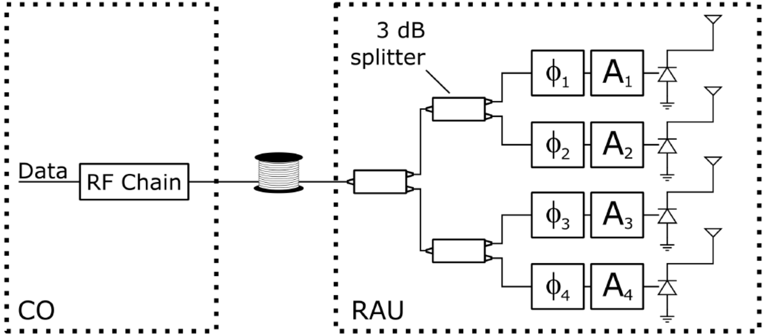


To centralize or not to centralize?

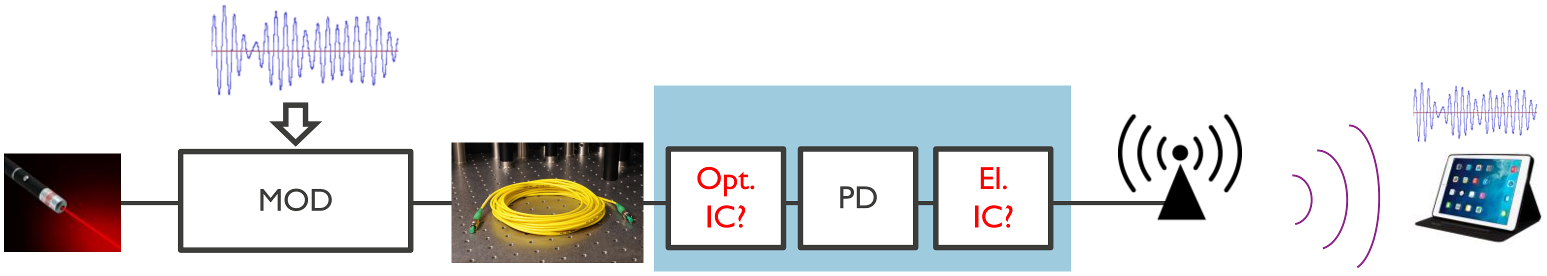


- Beamforming antenna (RAU) = combination of multiple radiating elements (set of antennas)
  - Beamforming = Each antenna gets a slightly different variant of the same signal
  - Don’t centralize (scalability)





Optical or electrical beamforming?

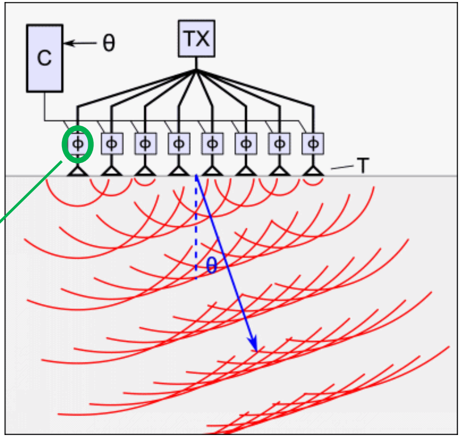


Optical beamforming because:

- High bandwidth **possible**
- Lower loss
- Lower loss variation with different beam steering settings
- Reduced electromagnetic interference

Tunable delay via switchable delay line

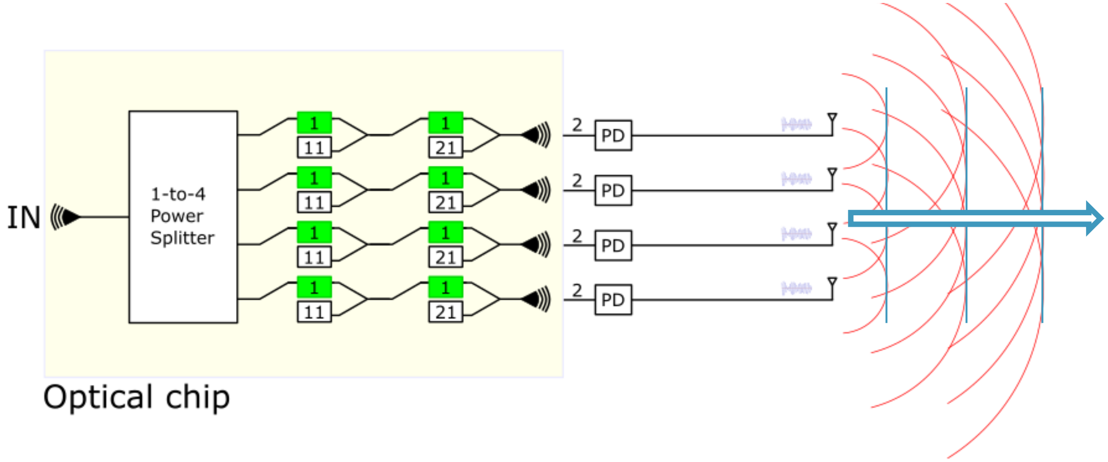
- Same signal but different delay to each element
- Tunable delay in the photonics IC

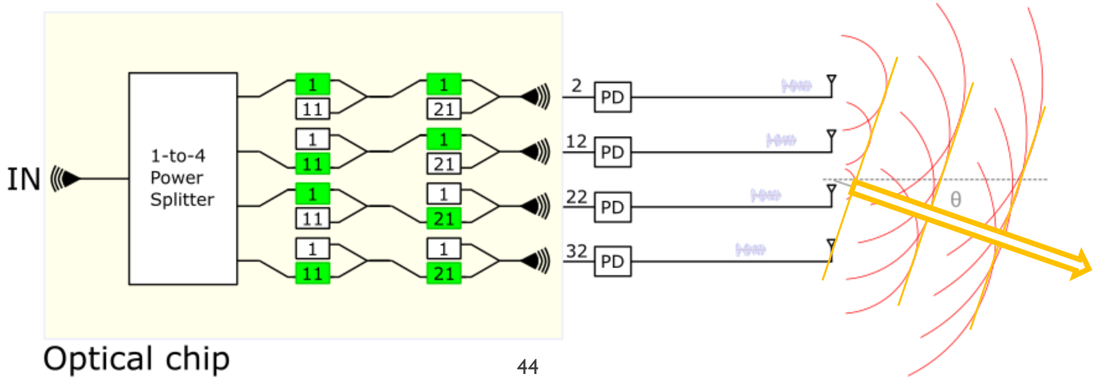


60 km/h

2 min.
12 min.
22 min.
32 min.

Different beam steering angle when tuning delay difference





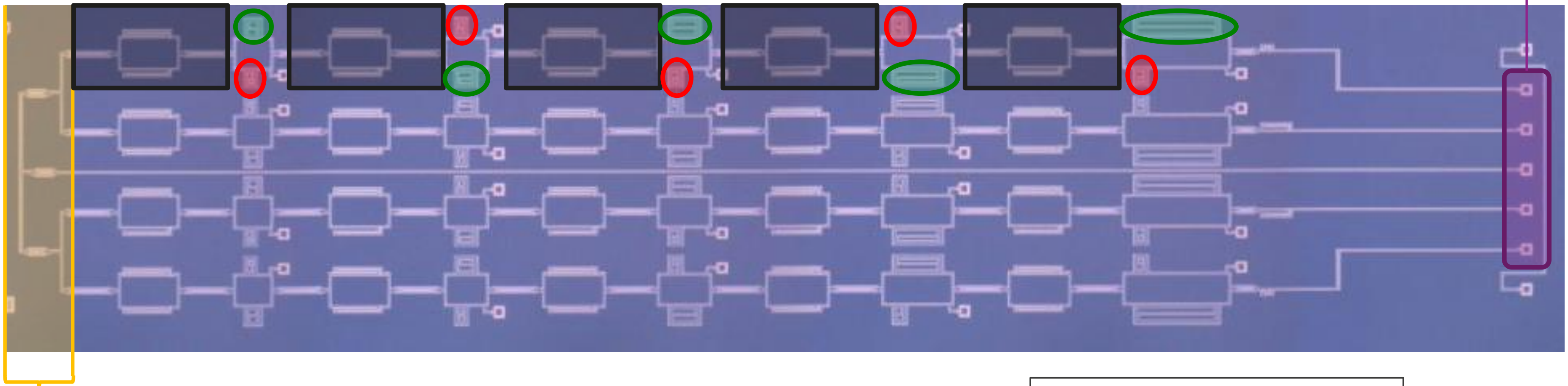
Photonic integrated circuit (before adding electronics)

“Railway switch” – lacks control electronics in this image

“Short railway track”, i.e. small delay

“Long railway track”, i.e. large delay

Light out (antenna 1)
Light out (antenna 2)
Light in
Light out (antenna 3)
Light out (antenna 4)



1-to-4 Splitter

5 bit, 1.6 ps resolution
Max delay = 49.6 ps
Antenna array with 4 antennas

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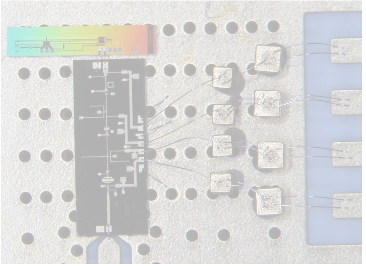
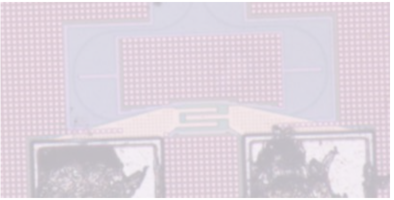
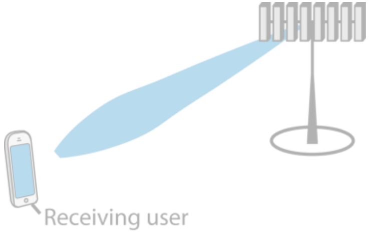
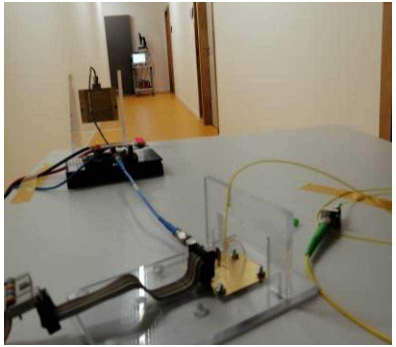








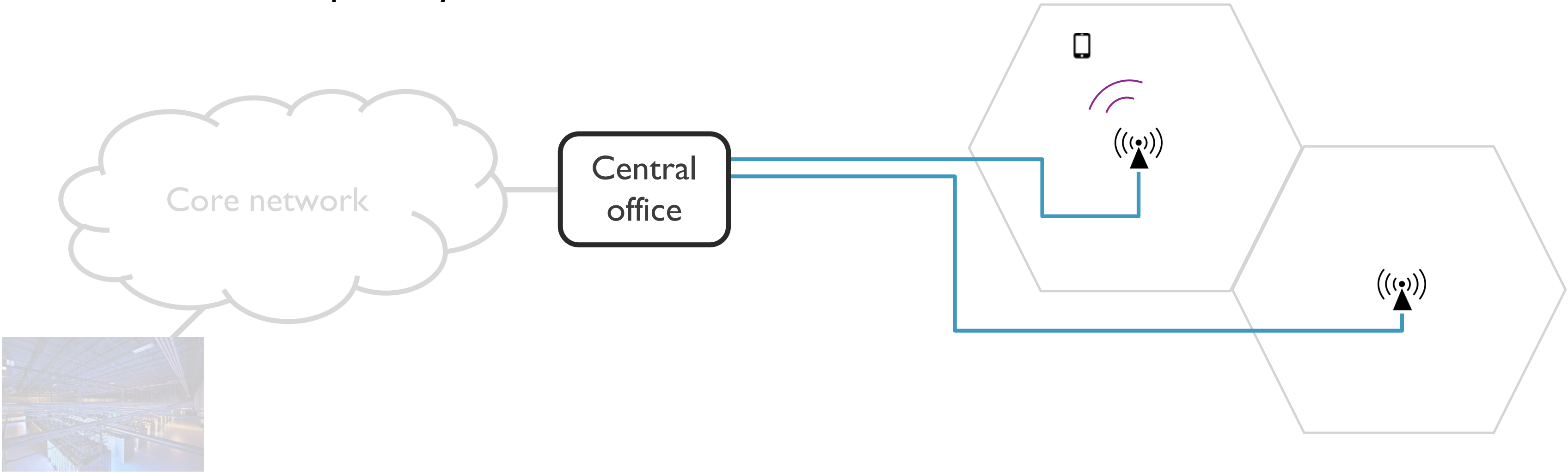
Fiber-wireless experiments

Fiber: separation between central office and remote antenna units (2 km)

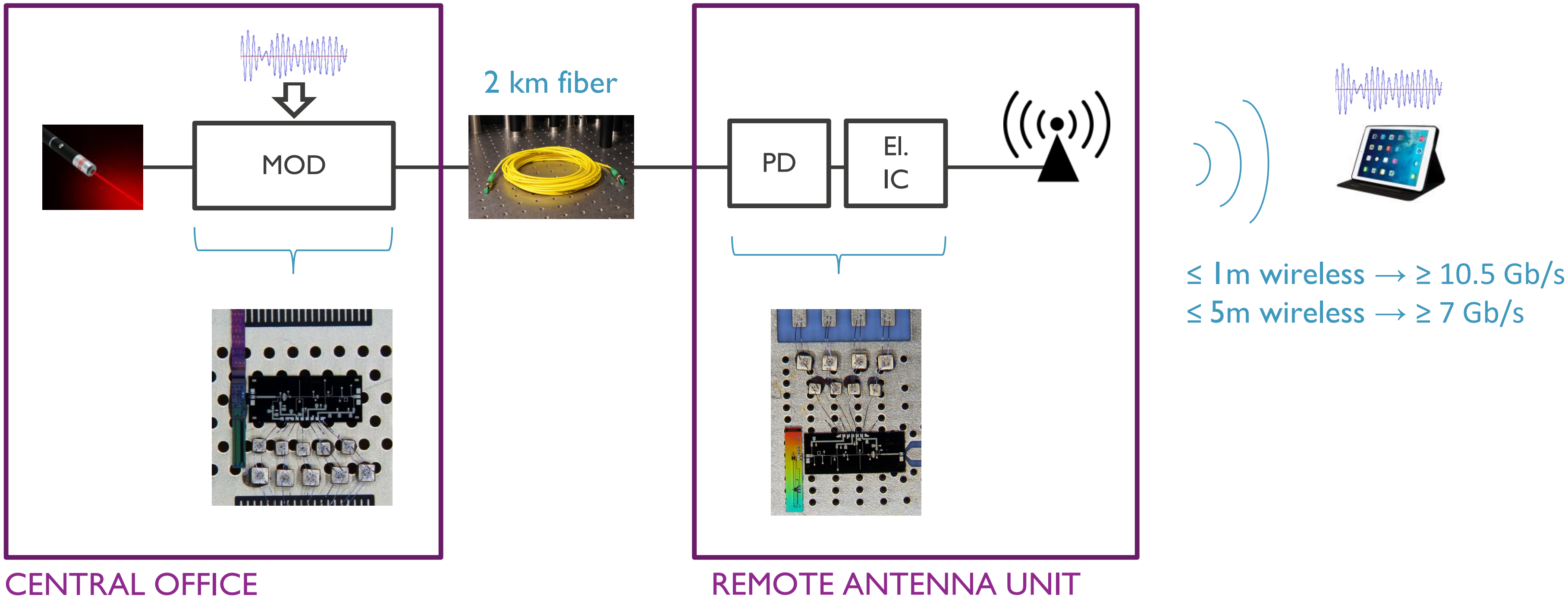
Wireless: distance between antenna unit and user equipment

Downlink and uplink: time division duplexing, i.e. different time slot (~Walkie Talkie)

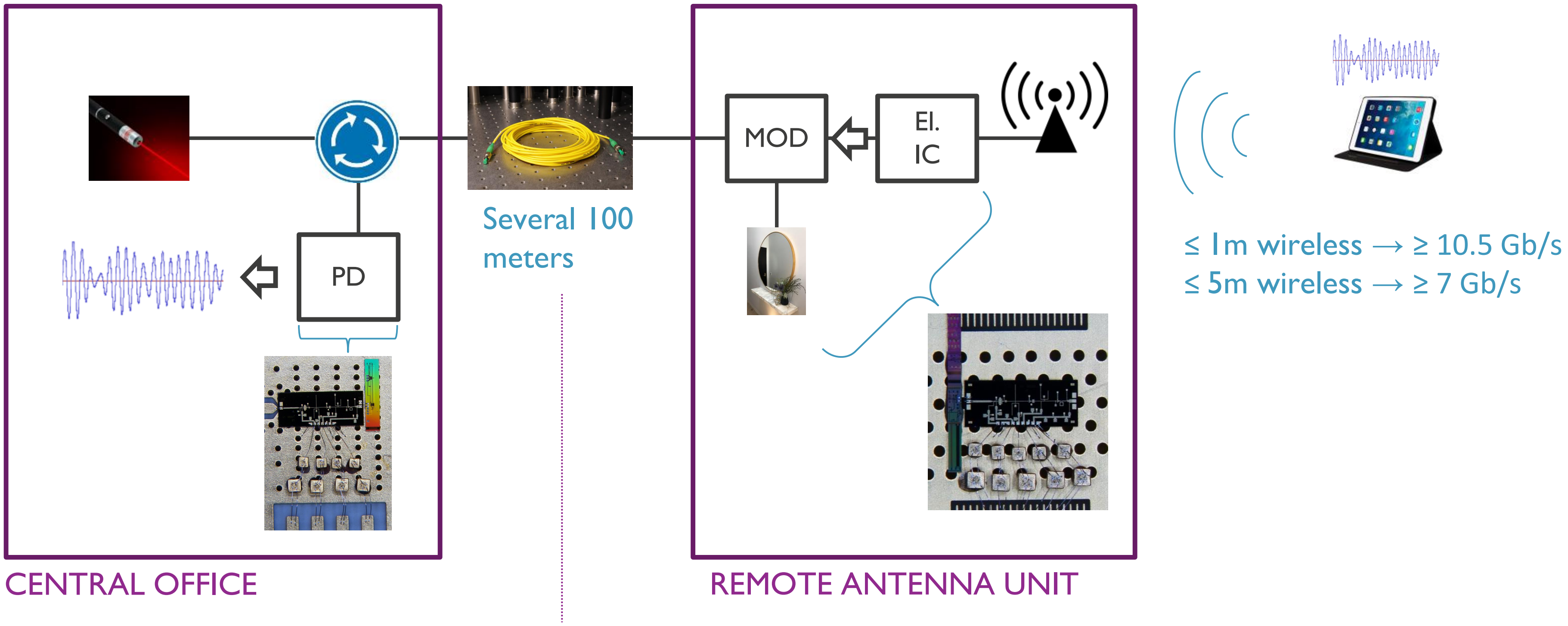
Hence tested separately



Fiber-wireless experiments to the user (downlink)

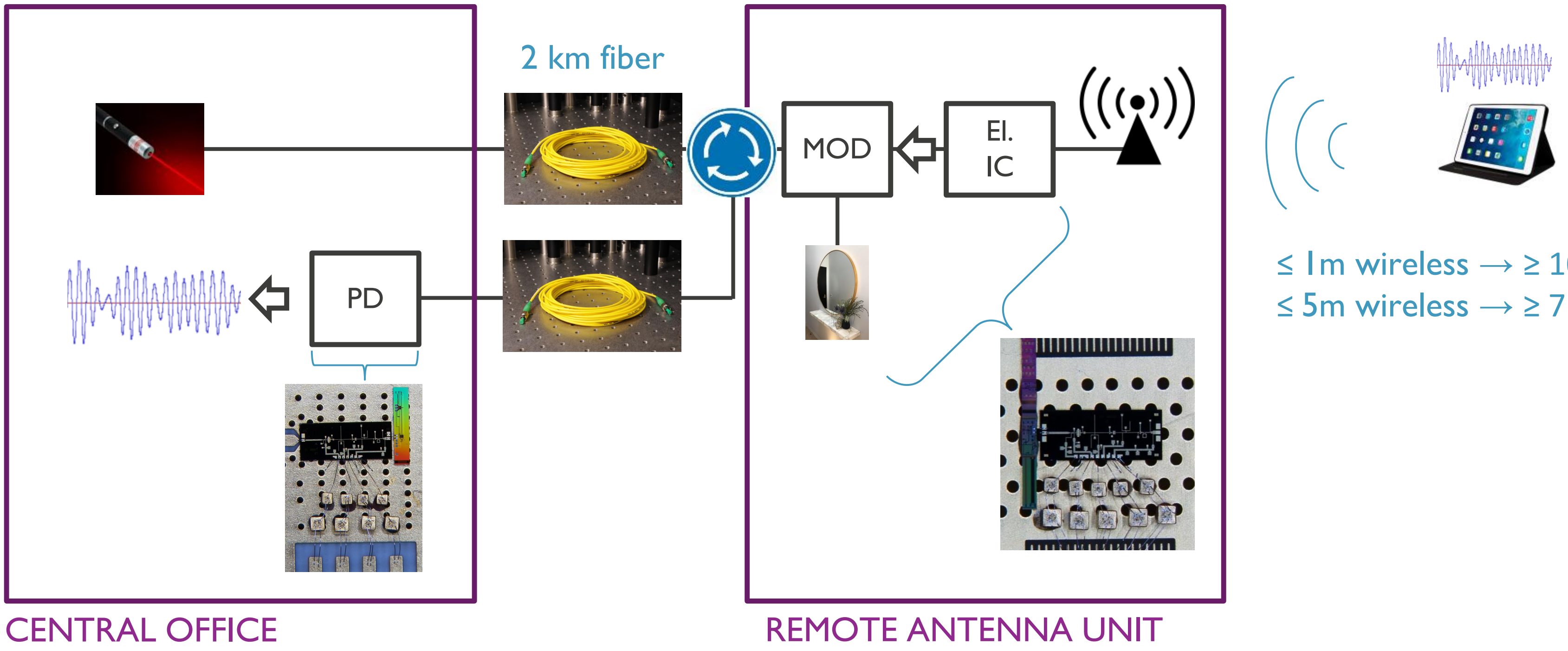


Fiber-wireless experiments from the user (uplink) – short fiber



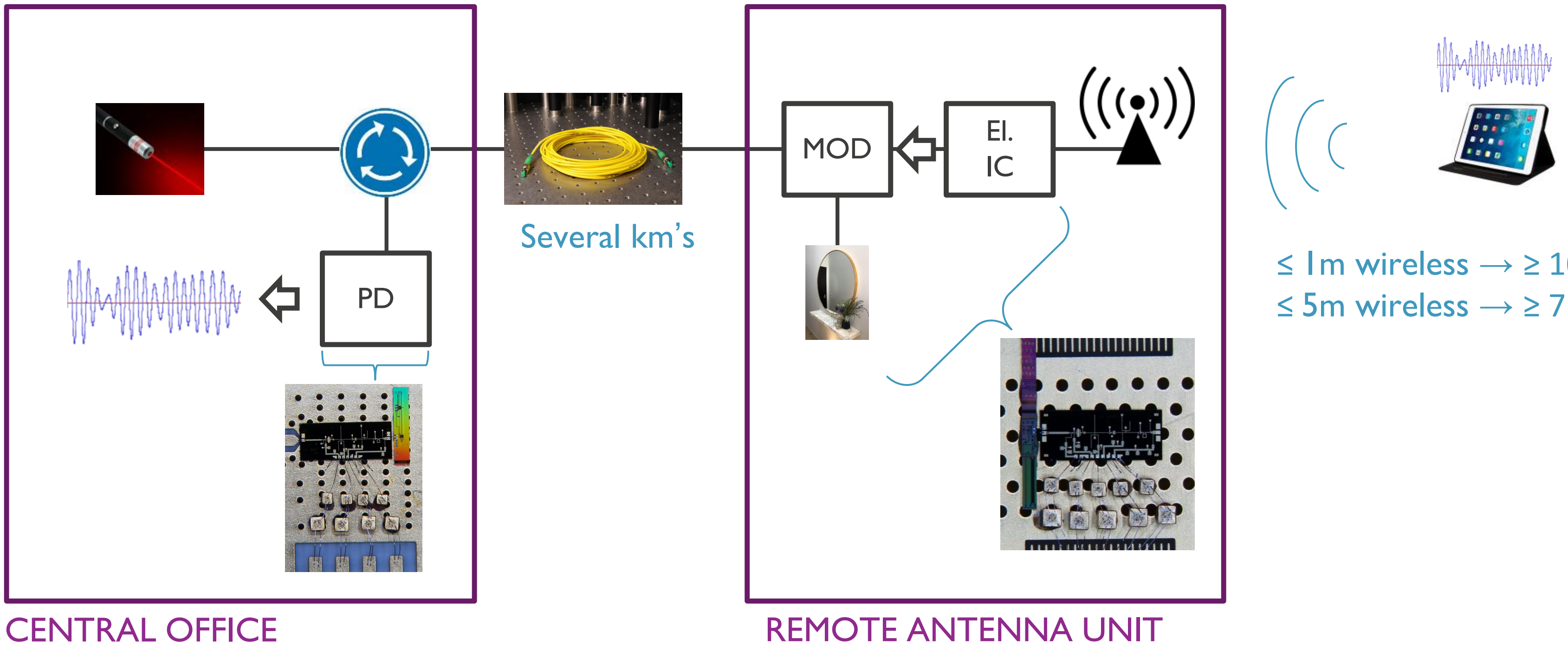
Over longer distances of fiber: reflections in the fiber make a one-fiber solution more complex (signal gets distorted)

Fiber-wireless experiments from the user (uplink) – long fiber



≤ 1m wireless → ≥ 10.5 Gb/s
≤ 5m wireless → ≥ 7 Gb/s

Future work: longer distances over single fiber



≤ 1m wireless → ≥ 10.5 Gb/s

≤ 5m wireless → ≥ 7 Gb/s

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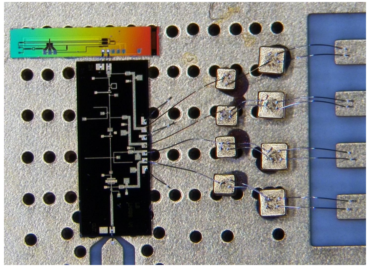
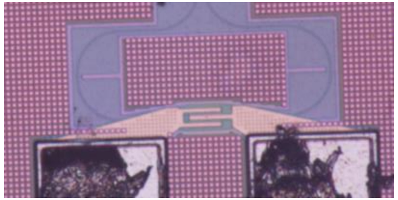
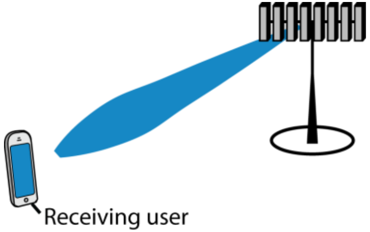
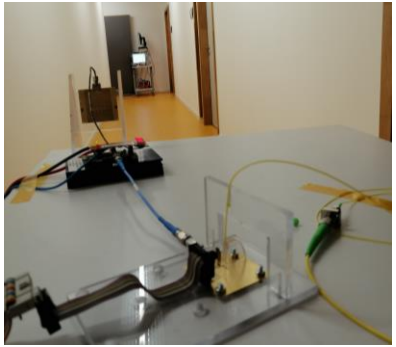
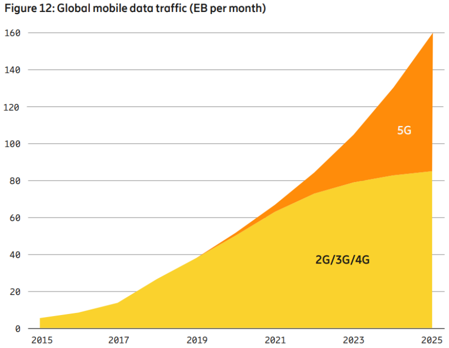


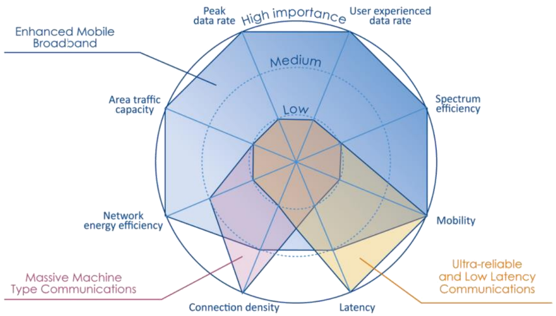






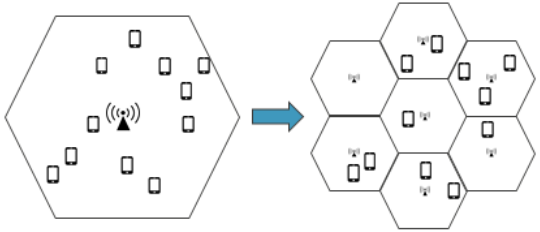
High data rate by small-cell, mmWave and beamforming



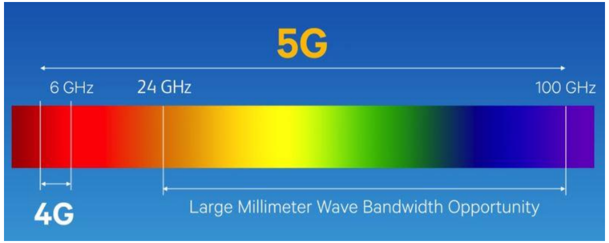


5G is extreme mobile broadband,
massive machine type
and ultra reliable low latency

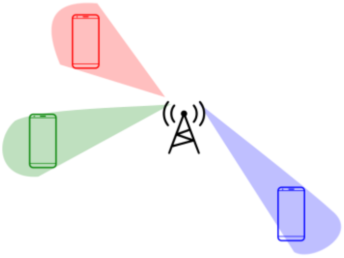
Peak data rate:10 Gb/s



Small-cell requires centralization (*optical backbone*)

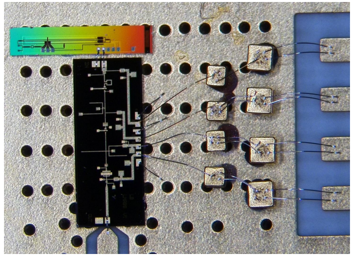


mmWave frequencies offer higher bandwidth and are less congested

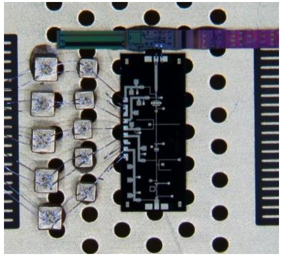


Beamforming improves power efficiency and reduces interference, hence increase in data capacity

Integrated optics and electronics

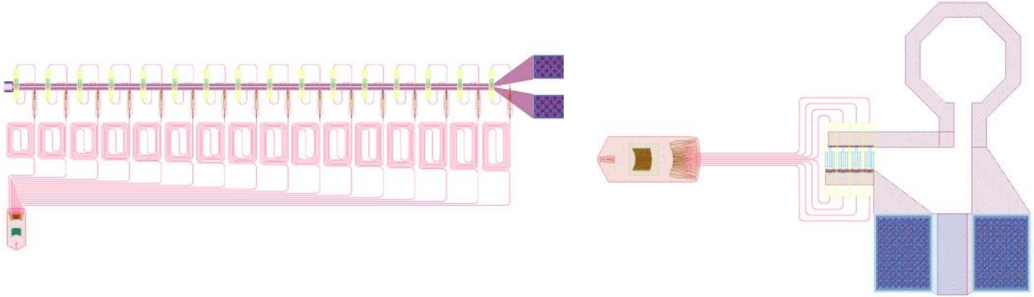


28 GHz photoreceiver:
O/E conversion + amplification

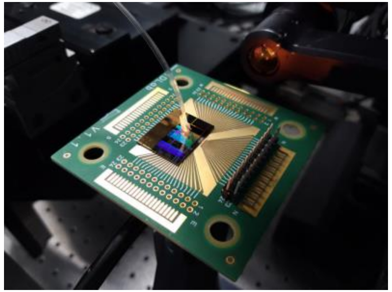


28 GHz transmitter:
amplification + modulation
of external laser

Link experiments show >7 Gbps
downlink and uplink speeds
for 2km fiber / 5m wireless



High power detector to allow for centralized shared
optical amplification: Broadband and narrowband



Optical beamforming
Broadband and narrowband

embracing a better life