PUBLIC DEFENSE:
HETEROGENEOUS SILICON PHOTONIC DEVICES AND SUBSYSTEMS FOR MICROWAVE PHOTONICS

Kasper Van Gasse

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

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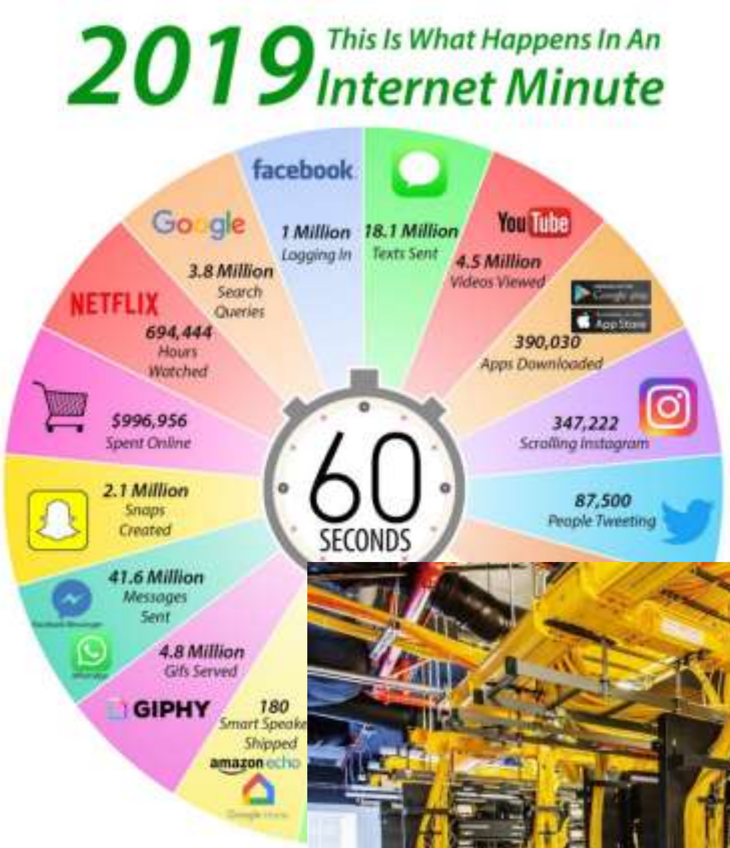
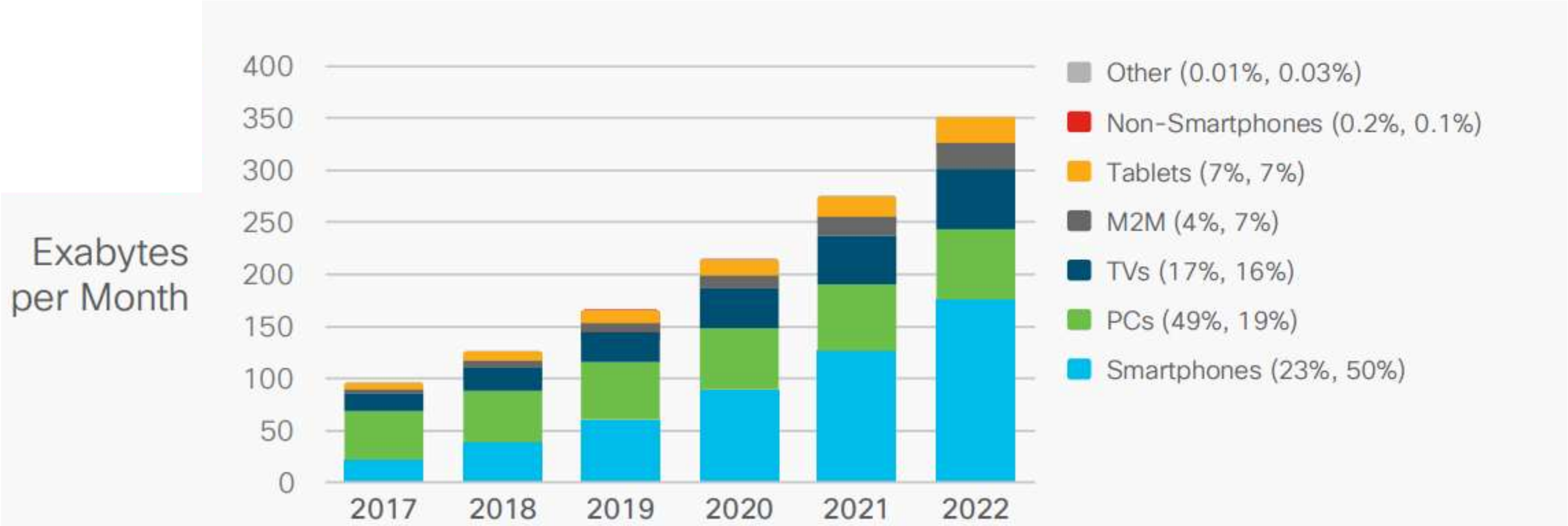
Context and motivation

- Internet data traffic is increasing every year
- Popularity of streaming (YouTube and Netflix) keeps pushing demand for bandwidth and data
- All this data needs to be physically transported
- Massive development of datacenters and optical fiber networks
- Google, Facebook, Amazon, ...



CONTEXT AND MOTIVATION: DATA TRAFFIC IS BECOMING MOBILE

- Internet traffic is moving from computers to smartphones
- By 2022 half of all internet traffic through mobile phones
- Need for constant development mobile network



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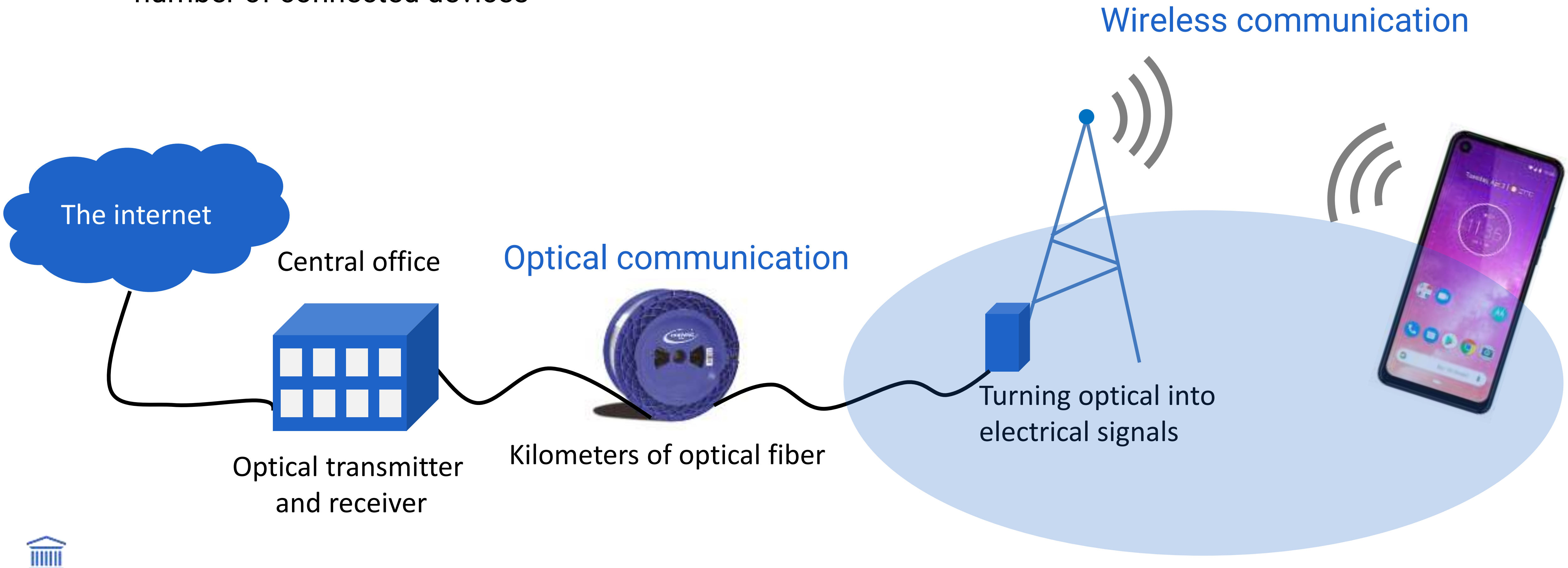
MOBILE RADIO ACCESS NETWORK OF TODAY – 4G

- Current networks offer speeds up to 100s Mbps
- New technologies needed to handle demand for bandwidth and number of connected devices



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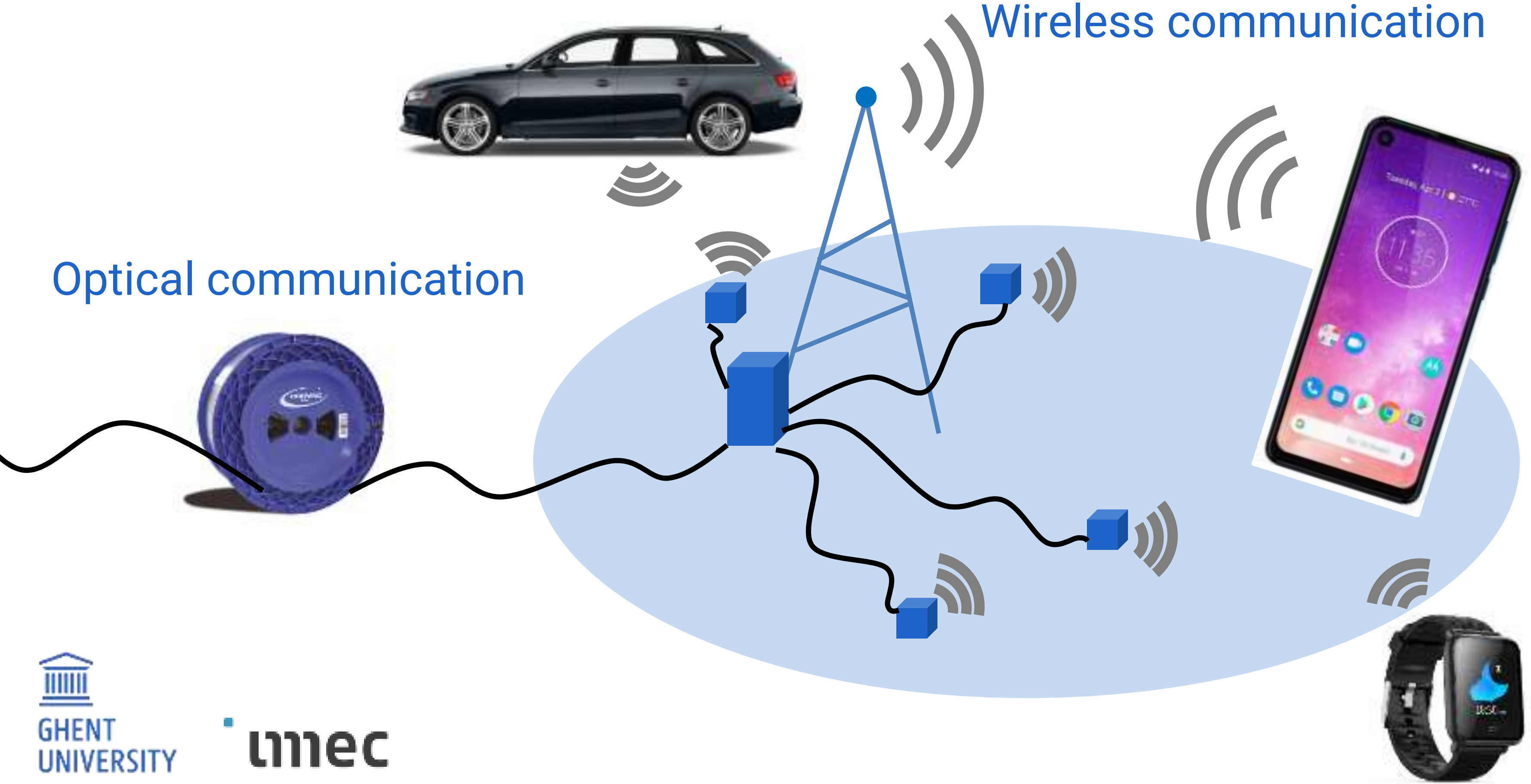
MOBILE RADIO ACCESS NETWORK OF TOMORROW – 5G

- Next generation targets 10 Gbps for end users
- 100-fold increase in number of connected devices
- New technologies and applications needed to realize 5G



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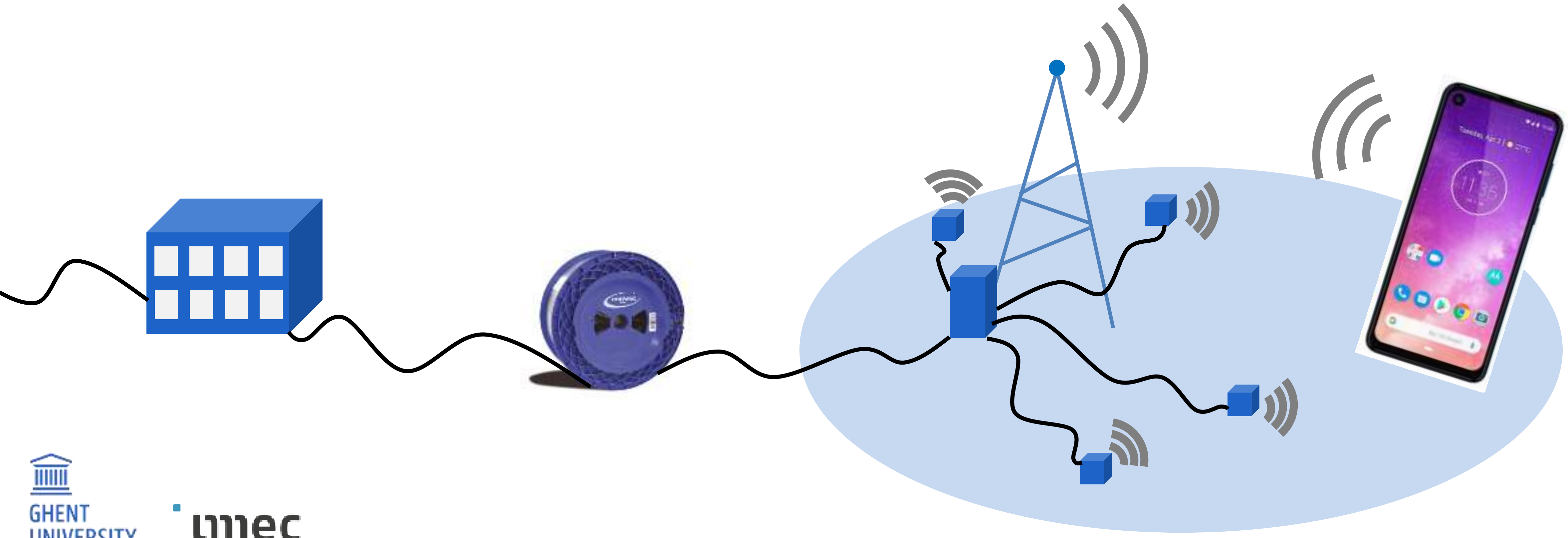
HETEROGENEOUS SILICON PHOTONIC DEVICES AND SUBSYSTEMS FOR MICROWAVE PHOTONICS



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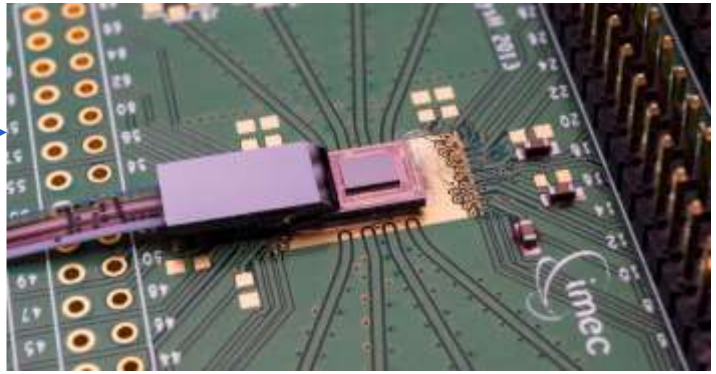
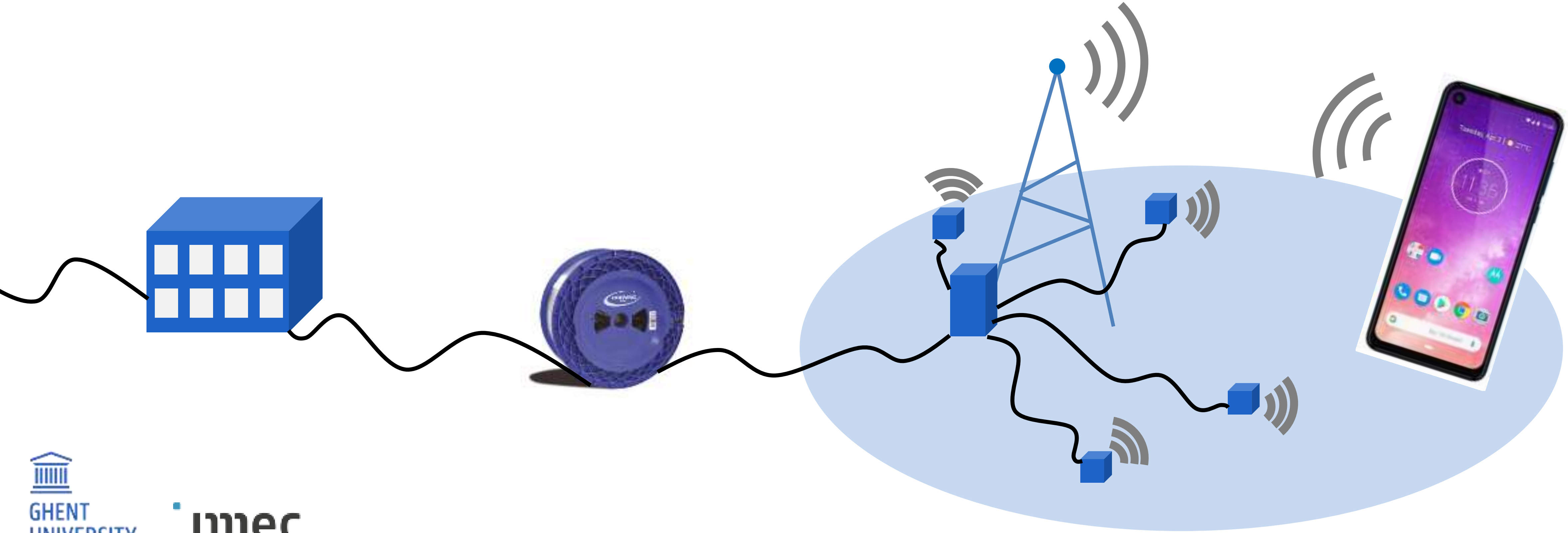
HETEROGENEOUS SILICON PHOTONIC DEVICES AND SUBSYSTEMS FOR MICROWAVE PHOTONICS

Technology





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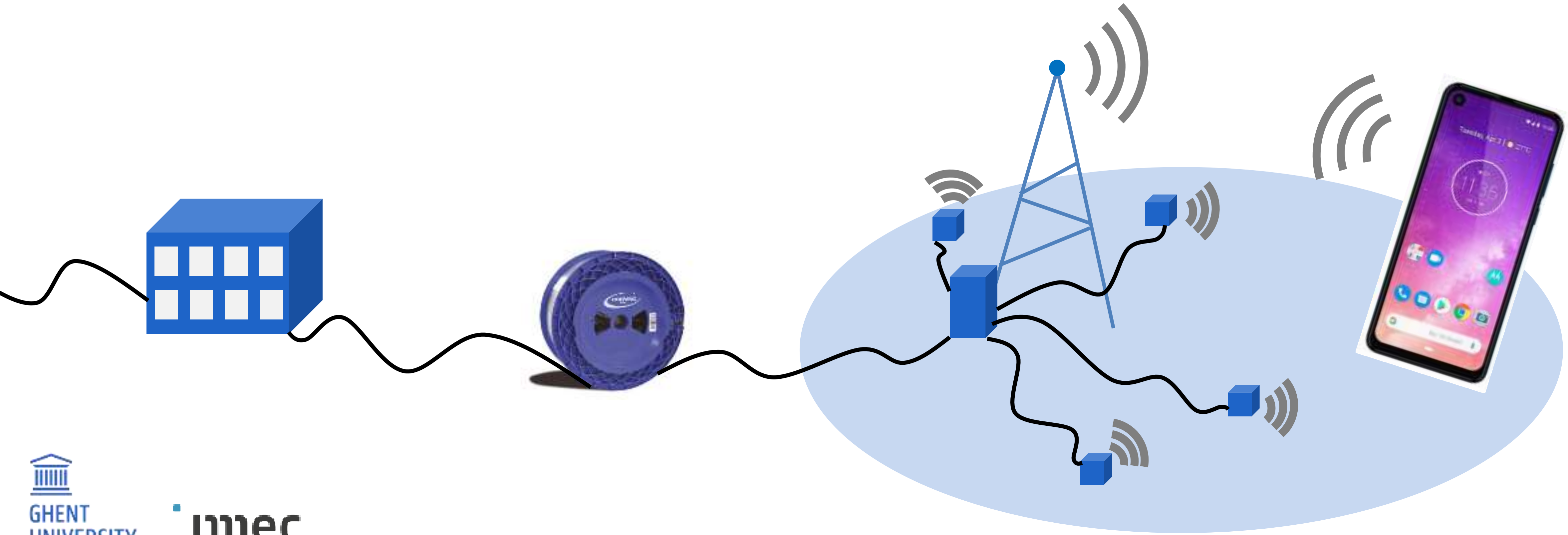
Heterogeneous silicon photonic devices and subsystems for microwave photonics

Optical systems used for the transmission or processing of microwave and wireless signals



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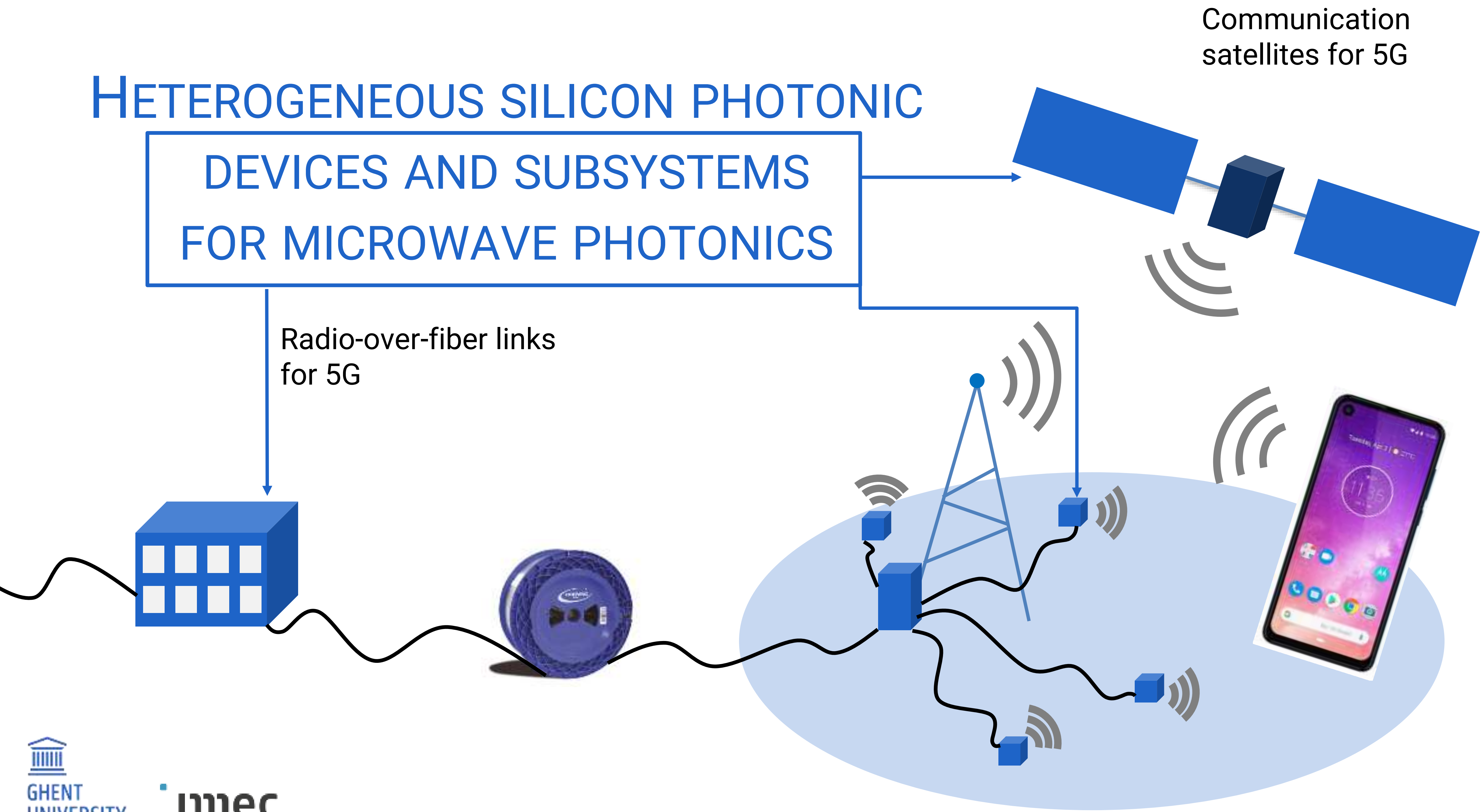

Overview

- Electromagnetic waves and waveguides
- Integrated silicon photonics technology
- Radio-over-fiber for 5G networks
    - Silicon photonic radio-over-fiber demonstration
    - Silicon photonic optical amplifier
    - Silicon photonic EAM-based mixer-transmitter
- Communication satellites in 5G radio networks
    - Communications satellites
    - Pulsed lasers
    - Electro-Photonic Frequency Converter
- Summary and conclusion

OVERVIEW

- **Electromagnetic waves and waveguides**
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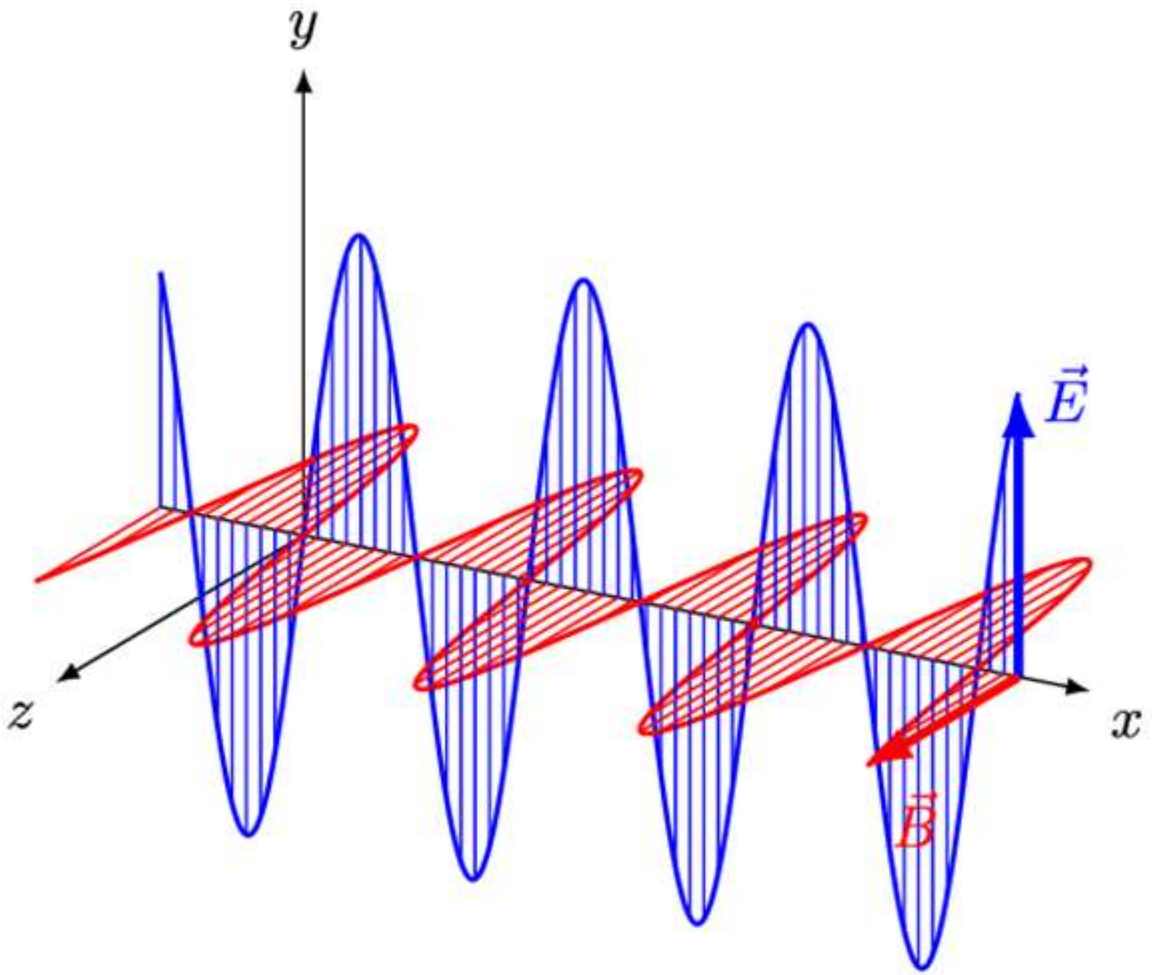
ELECTROMAGNETIC WAVES

- Both radio waves and light are electromagnetic waves
- Wave of the electric field E (and magnetic field B)
- Propagates at the speed of light 0.3 m/ns (in vacuum)
- Oscillation frequency f and wavelength λ such that:
    - $f \cdot \lambda = 0.3$ m/ns

- Radiowaves and light = electromagentic waves with different frequency:
    - Light = 500 THz = 100000x5 GHz
    - Microwaves = 5 GHz



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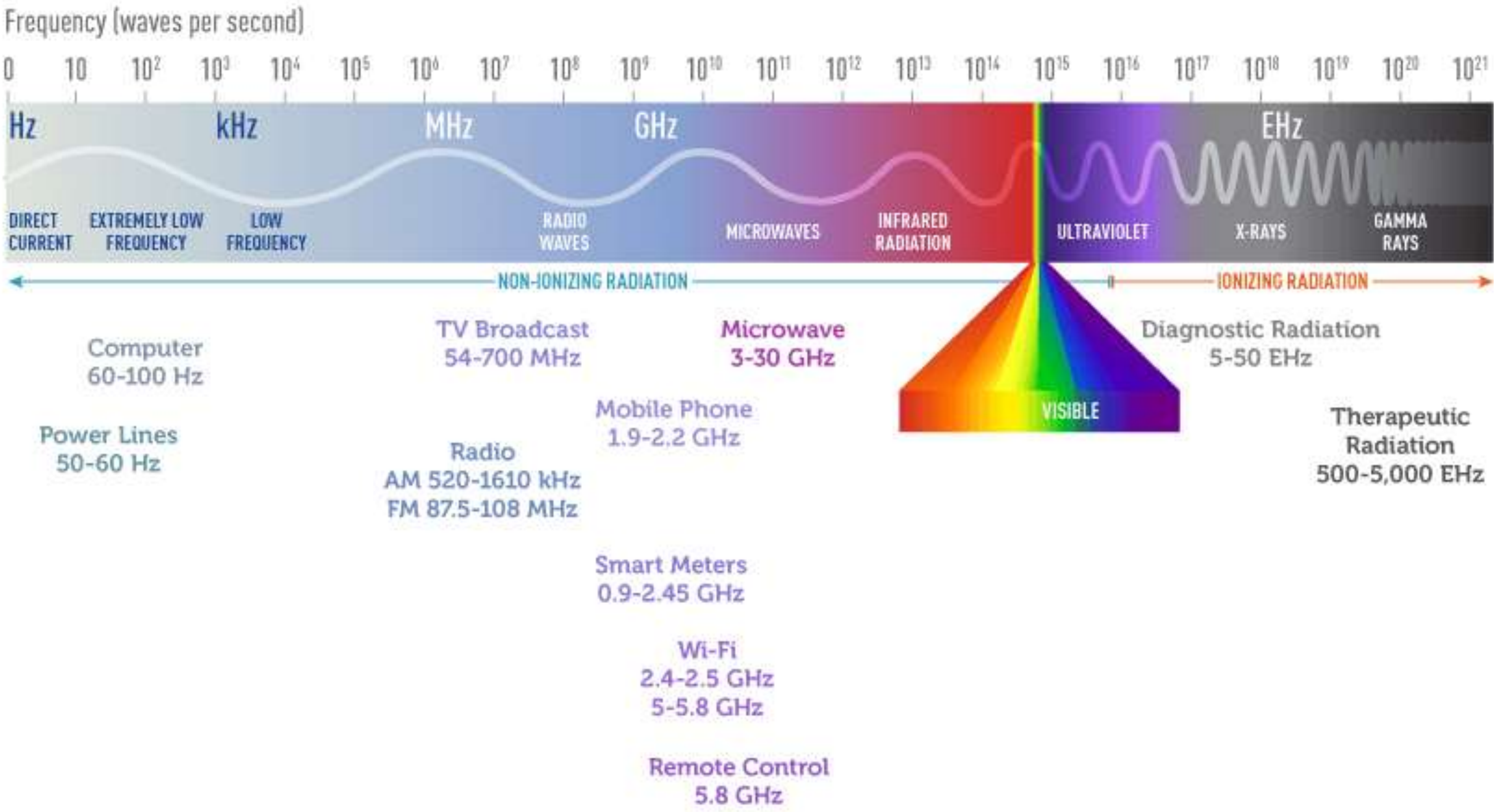
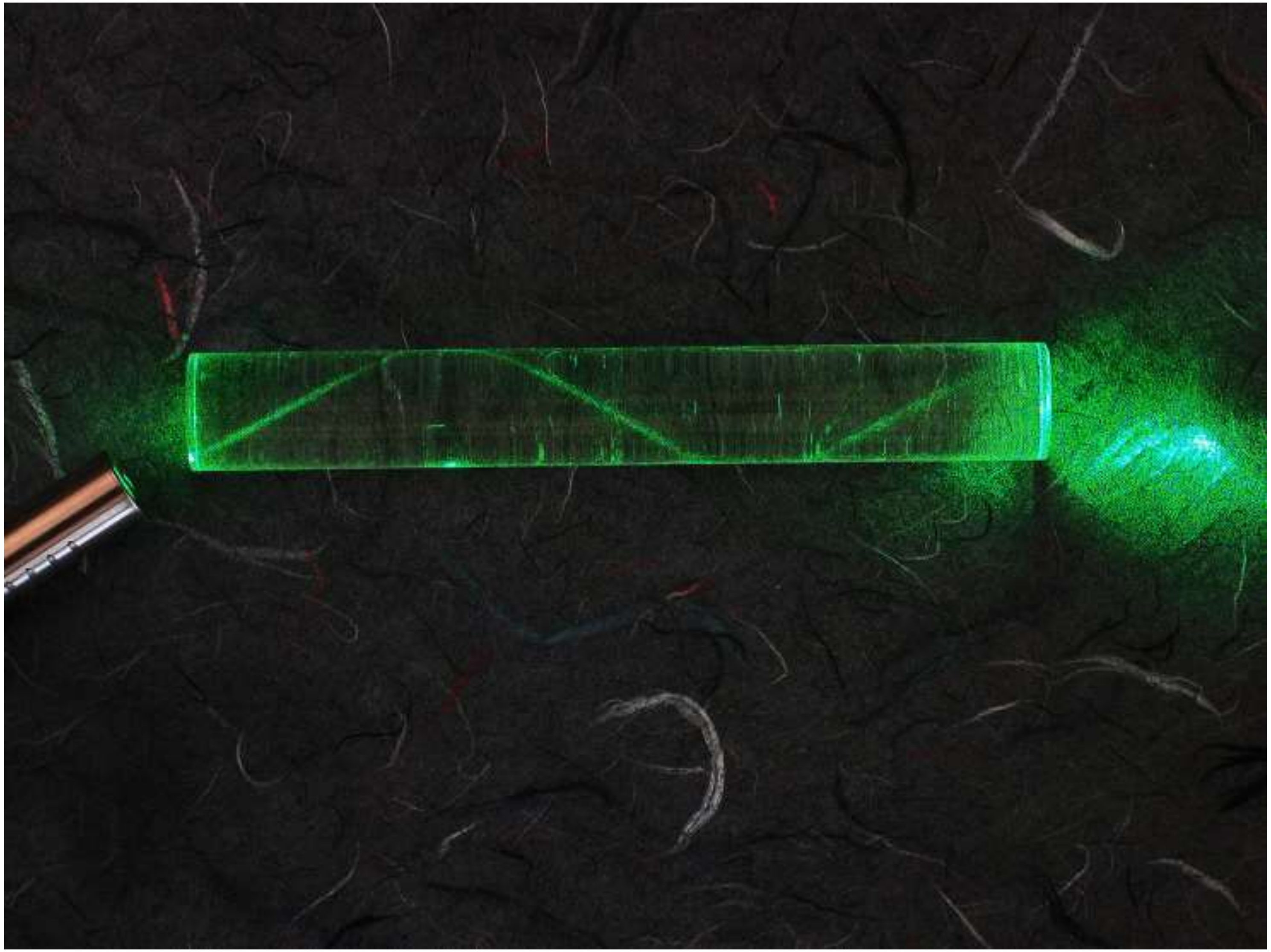
Spectrum of electromagnetic radiation



LIGHT CAN BE GUIDED - WAVEGUIDES

- Light can be guided in glass cylinders
- Basic principle behind optical fiber
- Light can be guided over 15 km before losing 50 % of intensity in modern optical fiber
- Development of low-loss optical fiber was a major scientific and technological breakthrough

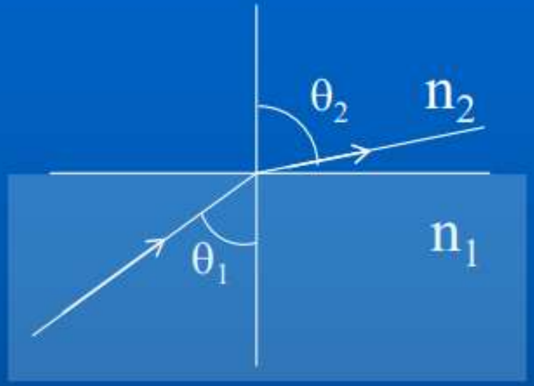


The Nobel Prize in Physics 2009

Charles Kuen Kao

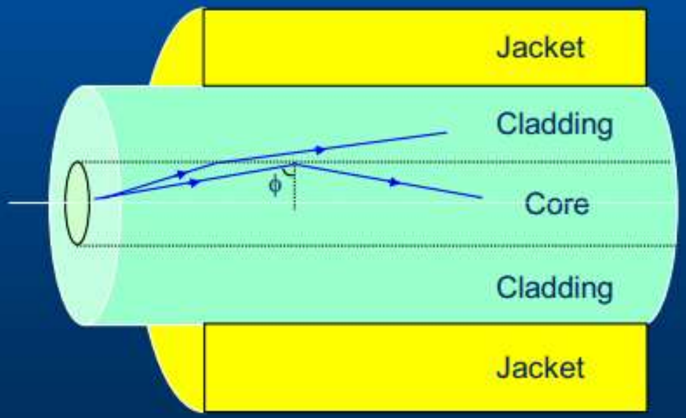
"for groundbreaking achievements concerning the transmission of light in fibers for optical communication",

Light guiding inside fiber



Snell's Law : $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Note: if we increase θ_1 to θ_c such that θ_2=90°



$$\rightarrow \quad \sin\theta_c = \frac{n_2}{n_1}, \quad n_2 < n_1$$

If $\theta_1 > \theta_c$

→ **Total Internal Reflection**

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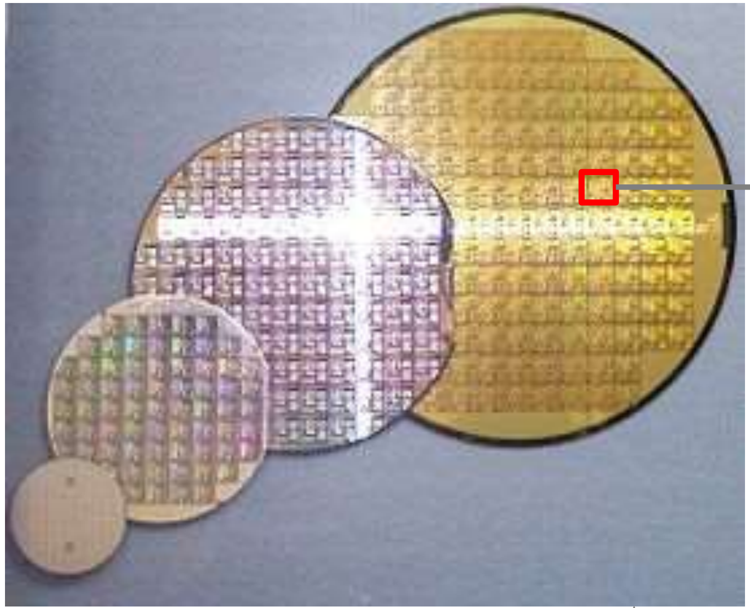
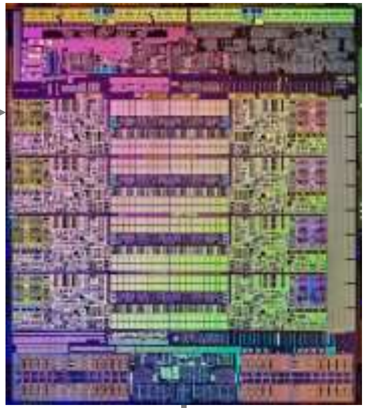
SILICON ELECTRONIC INTEGRATED CIRCUITS – "CHIPS"

Silicon ingot is made into wafers



Cut wafer into chips



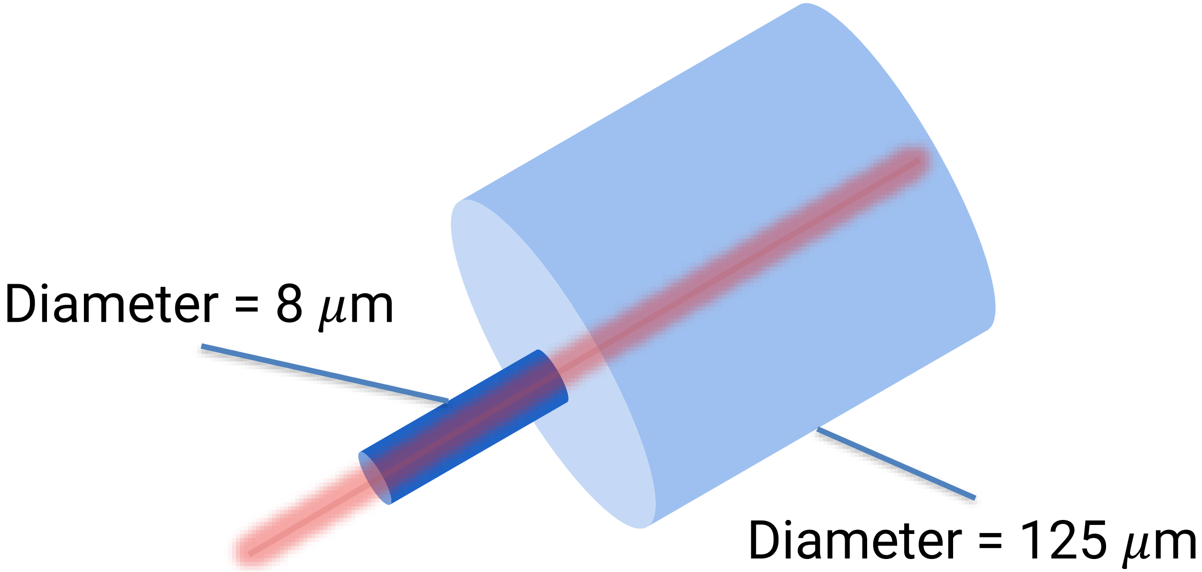
Put chip into package

Integrated circuit fabrication plant: Intel, IBM, TSMC...

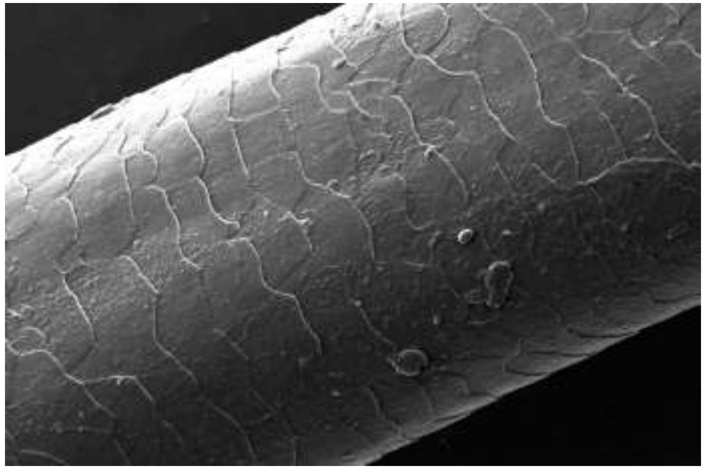
Integrated circuits are fabricated on silicon wafers

Optical integrated circuit?

Optical fiber



Human hair

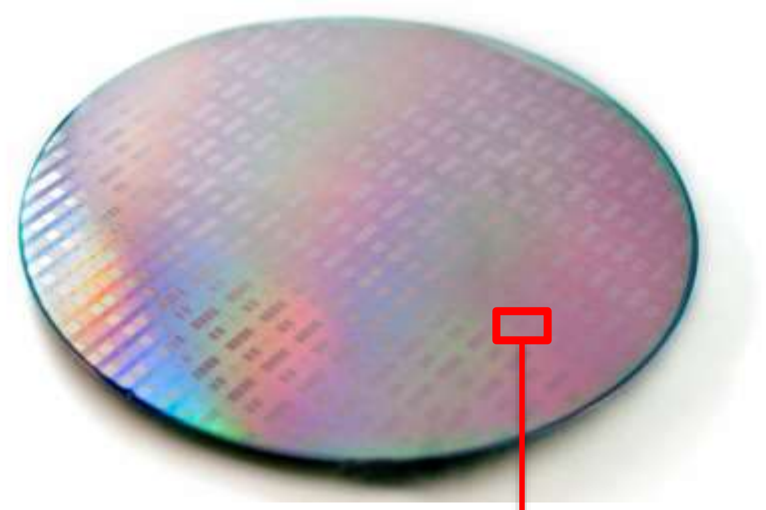


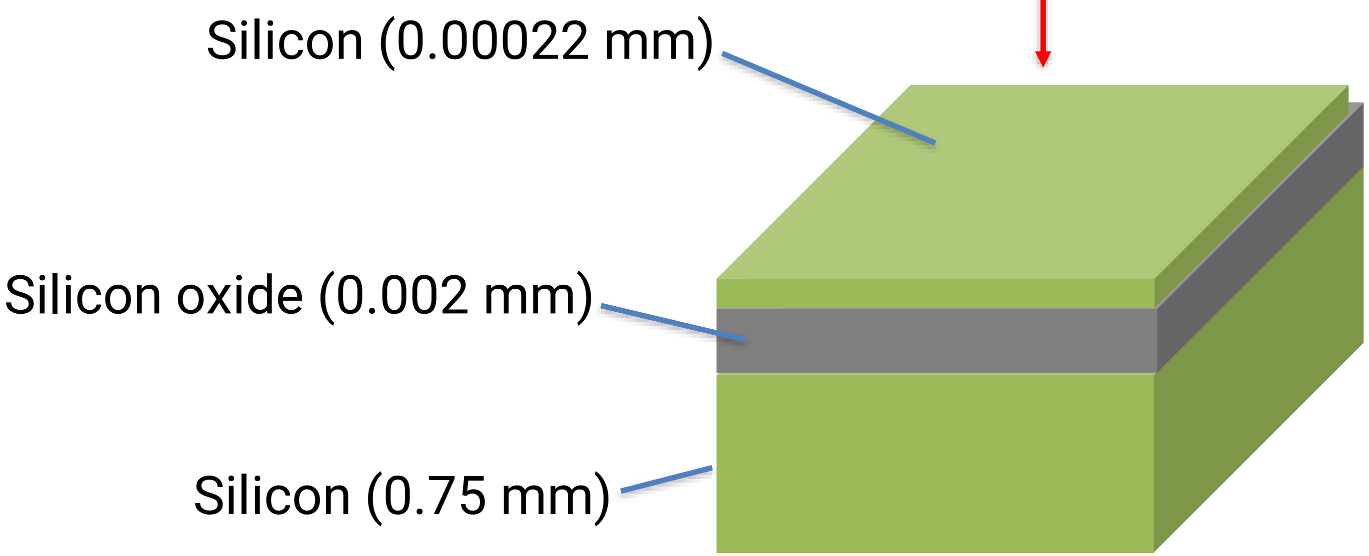
Diameter = 100 μm

Waveguides for light can be the size of micrometers

SILICON PHOTONIC INTEGRATED CIRCUITS – PICs

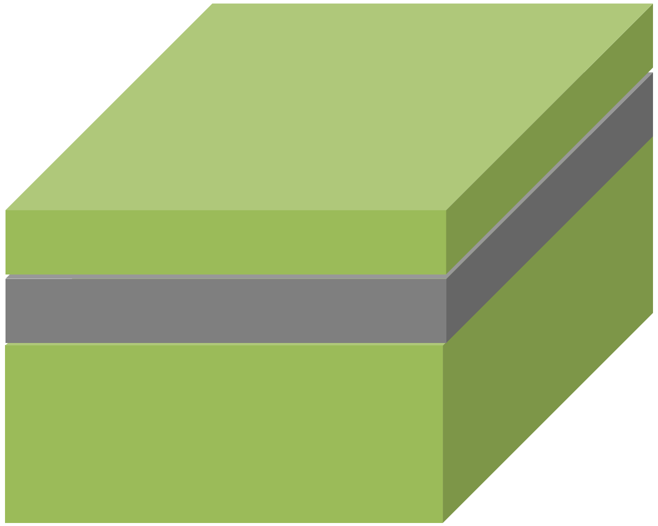
- Integrated optical or photonic circuits can be realized using silicon-on-insulator wafers
- Using 220 nm thick silicon optical waveguide layer
- Silicon has much higher refractive index than SiO2
- Silicon electronics fabrication compatible





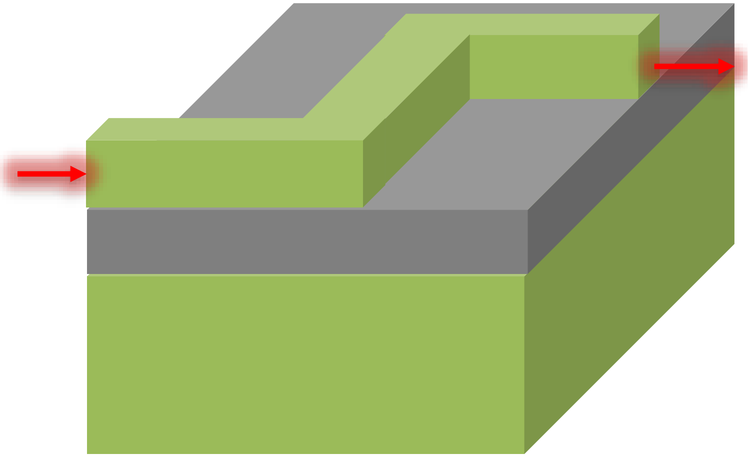
SILICON PHOTONIC INTEGRATED CIRCUITS – PICs

Start with silicon-on-insulator wafer



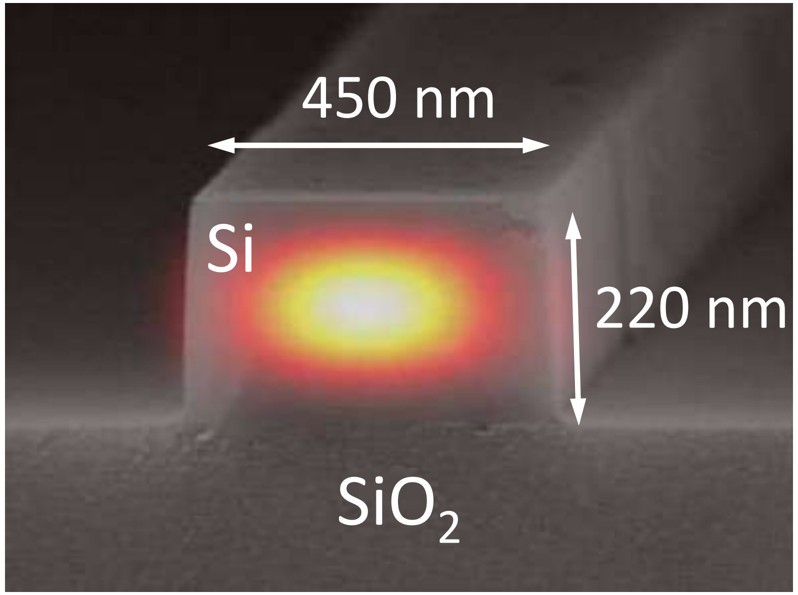
Use etching and photolithography methods designed for electronics

Circuit that can guide light

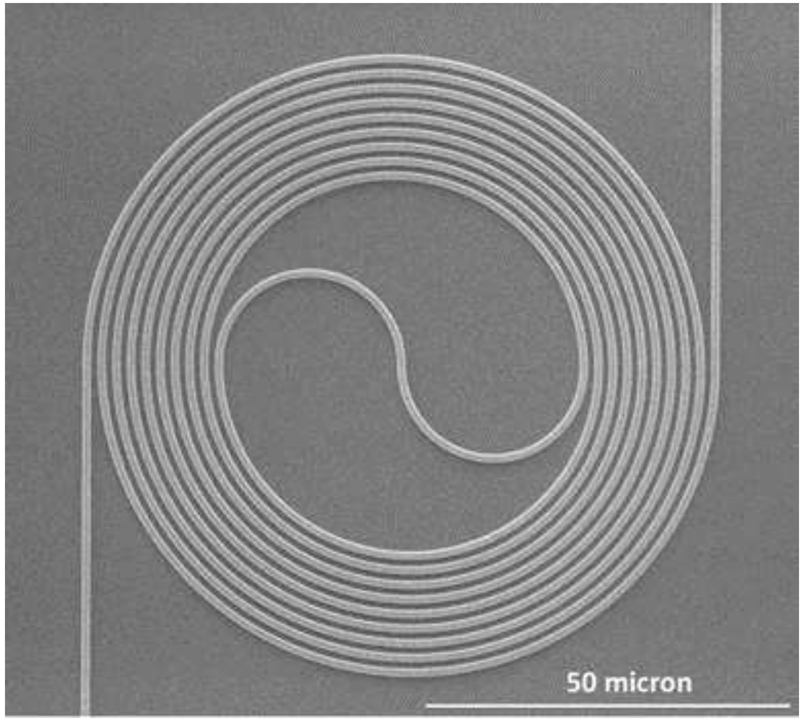


Using silicon fabrication technologies enables low-cost and high-volume manufacturing

Silicon photonic integrated circuits – PIC examples

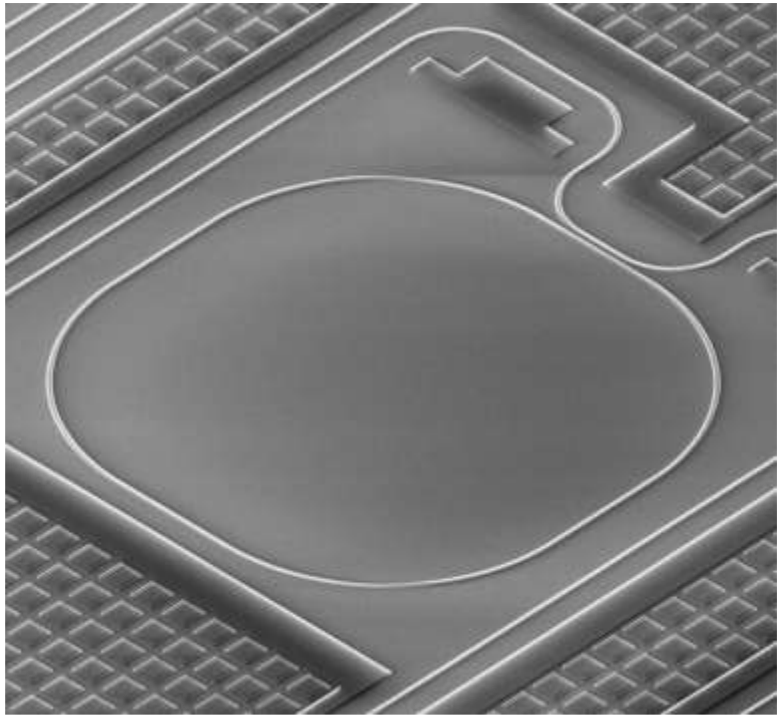


Long spiral waveguide



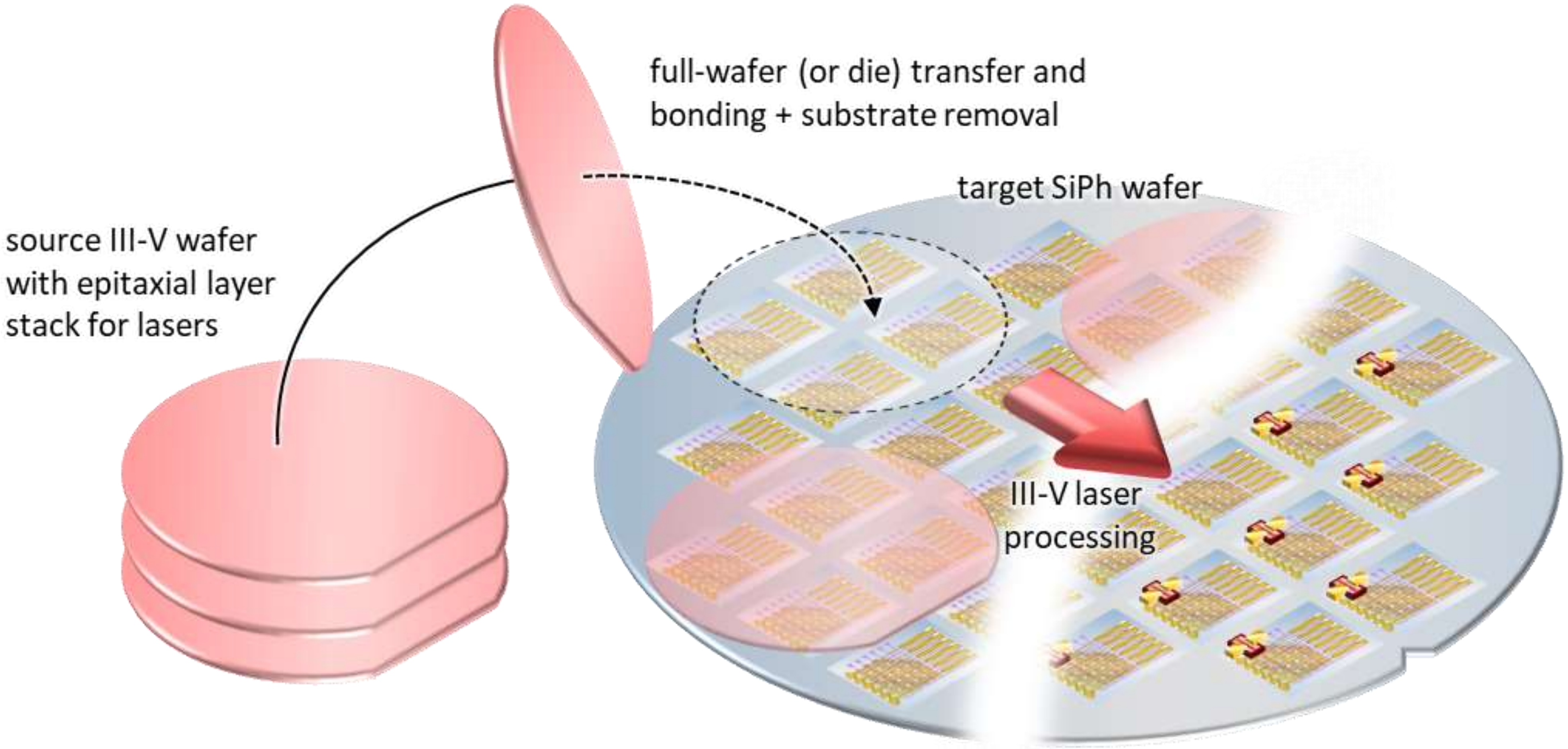
0.05 mm

Ring waveguide



HETEROGENEOUS SILICON PHOTONICS: III-V-ON-SILICON

How to integrate lasers on silicon PICs?



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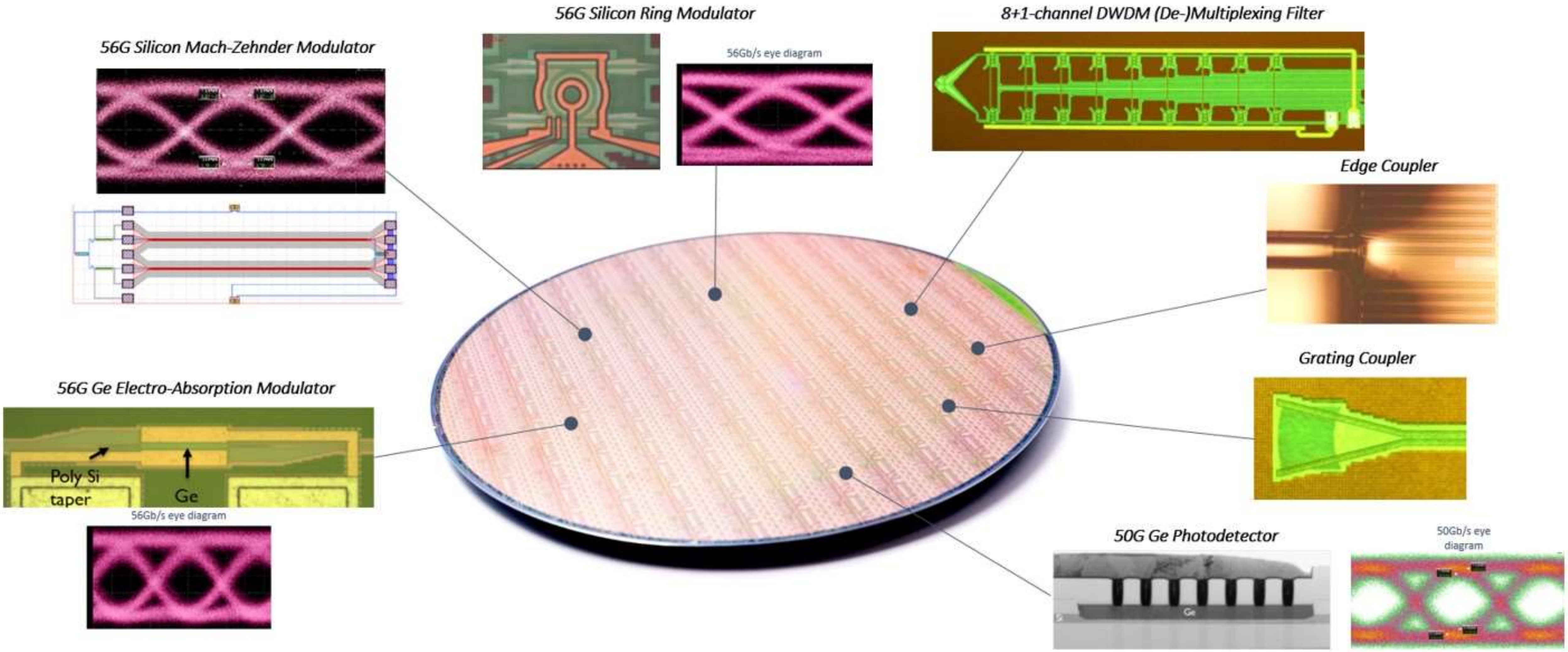
HETEROGENEOUS SILICON PHOTONICS: IMEC PLATFORM



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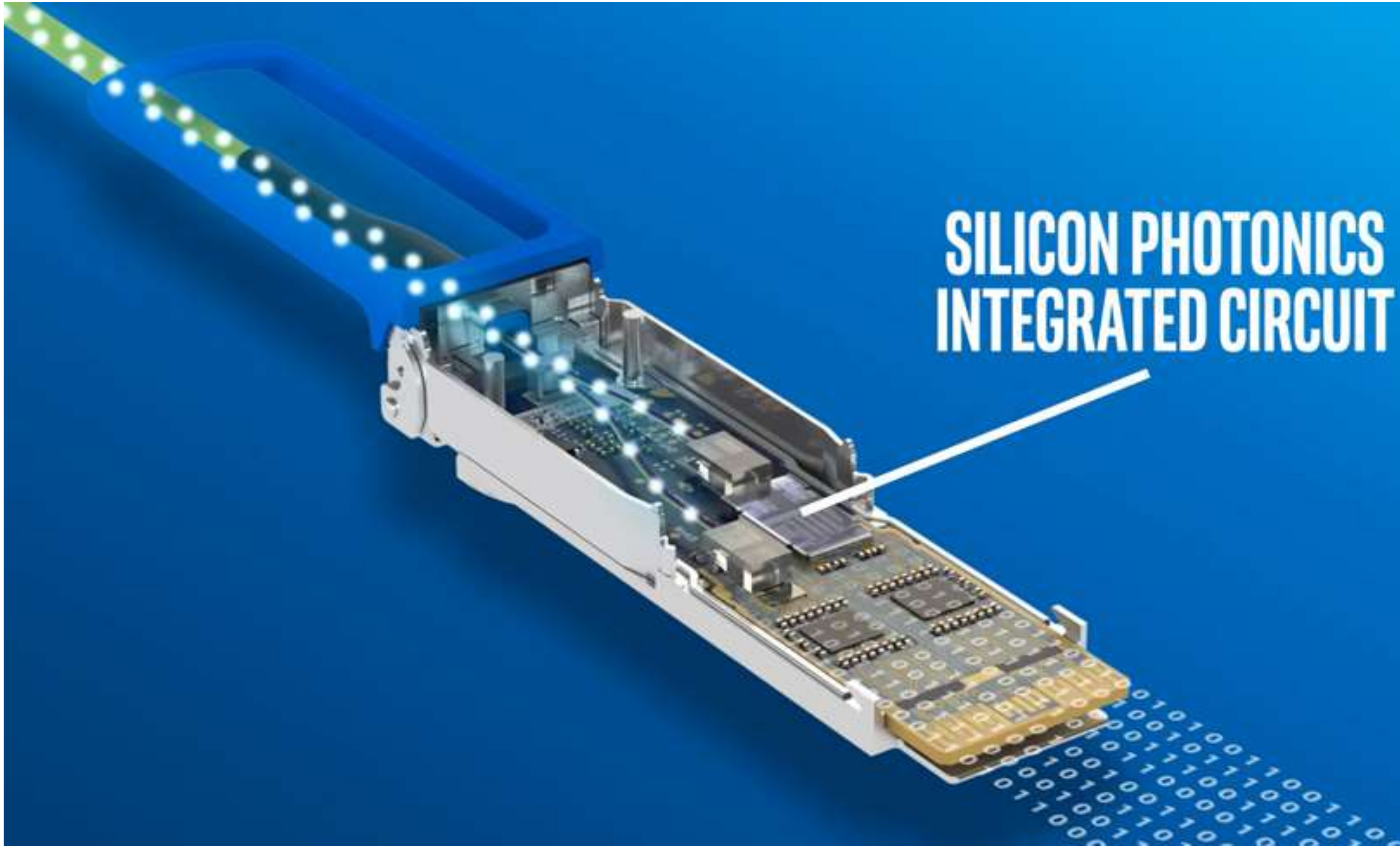
Not only in the lab - commercial products are avaiable



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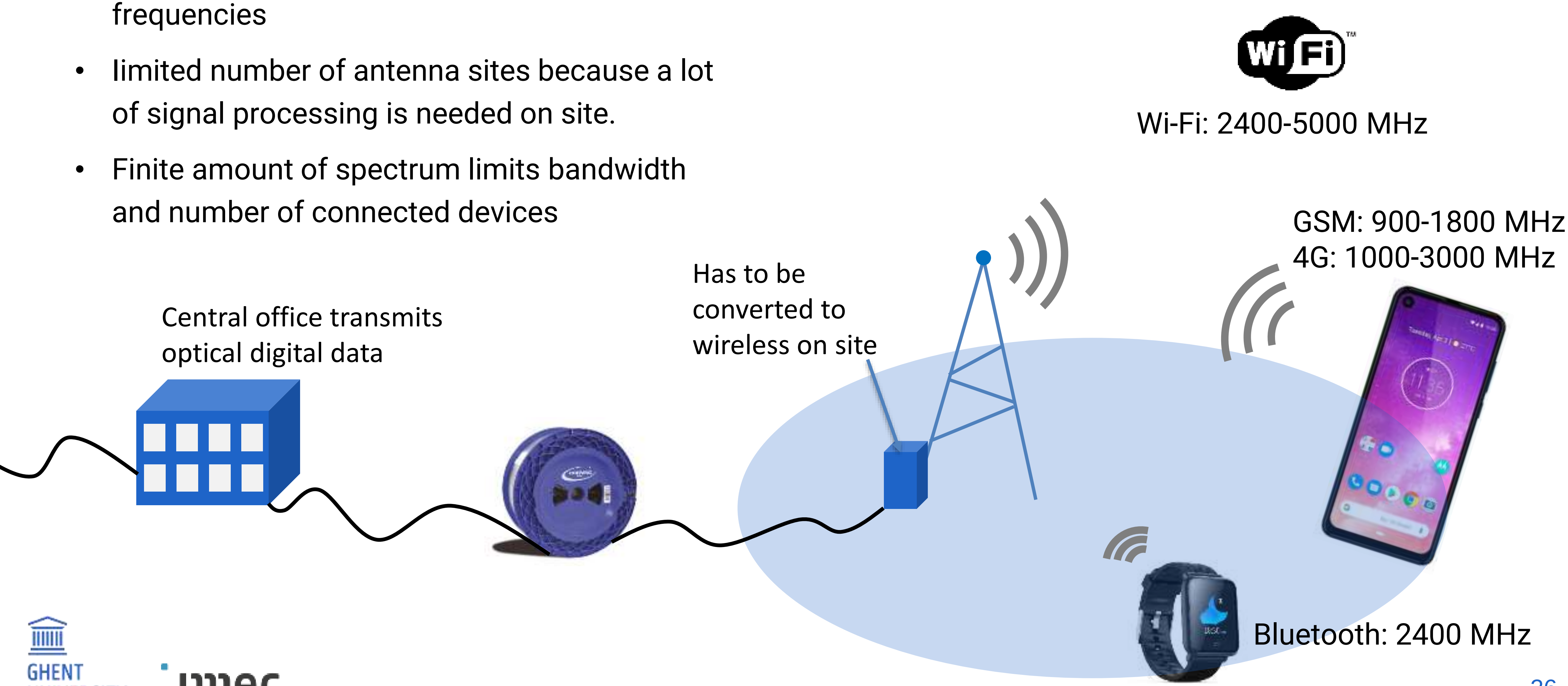
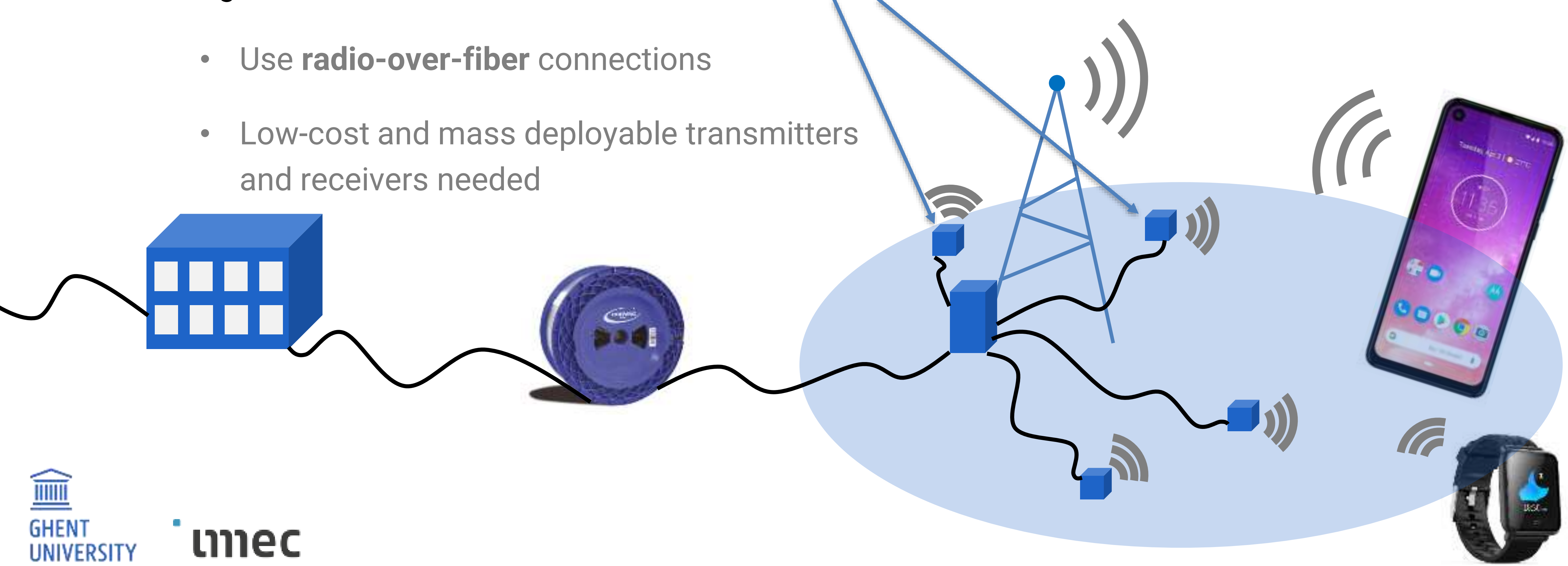
Limits of 4G

- Many devices and users have to share same frequencies
- limited number of antenna sites because a lot of signal processing is needed on site.
- Finite amount of spectrum limits bandwidth and number of connected devices

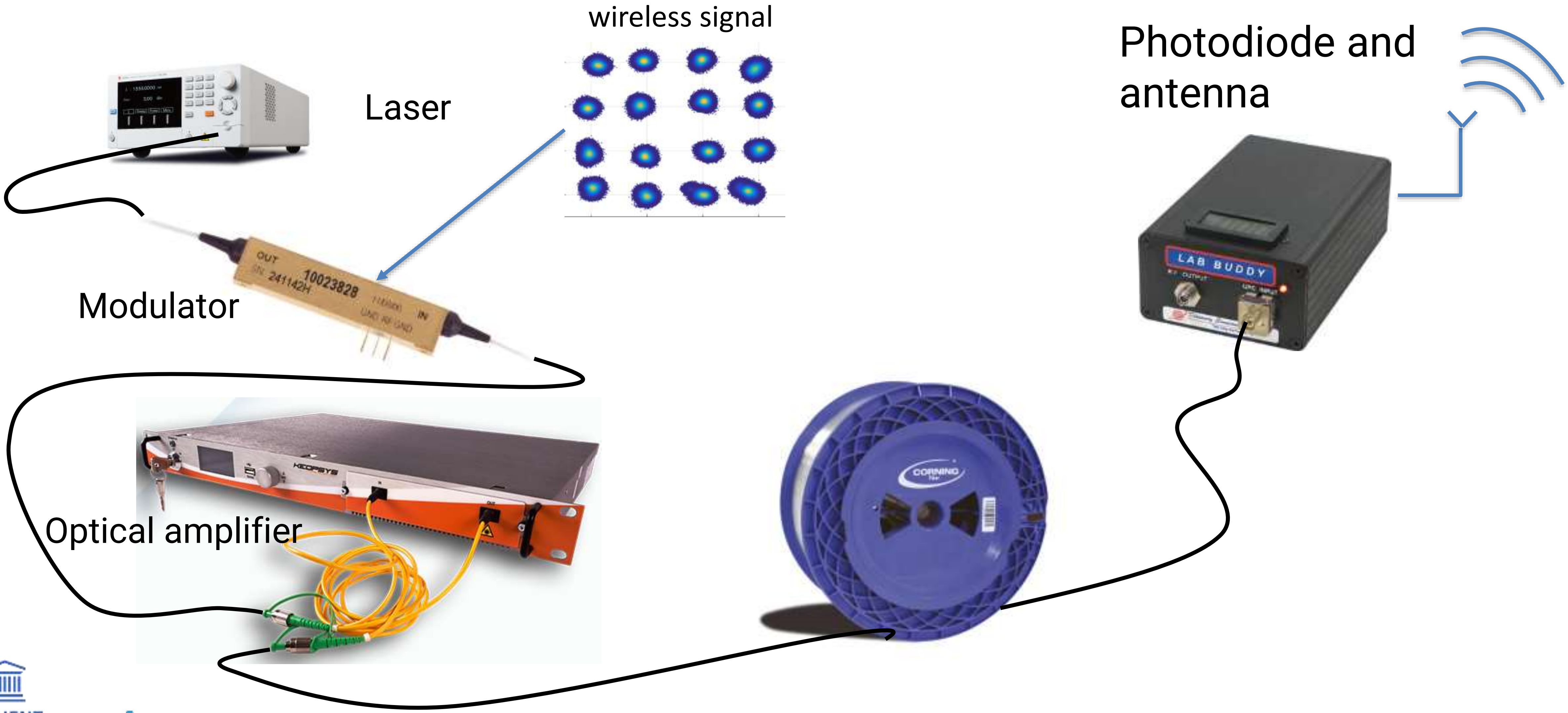


STRATEGIES ENABLING 5G

- Use new frequencies:
  - New bands at low frequencies: 3.5-5 GHz
  - Open up high frequency bands: 20-30 GHz
- Use large number of small low-cost remote antennas
  - Use **radio-over-fiber** connections
  - Low-cost and mass deployable transmitters and receivers needed

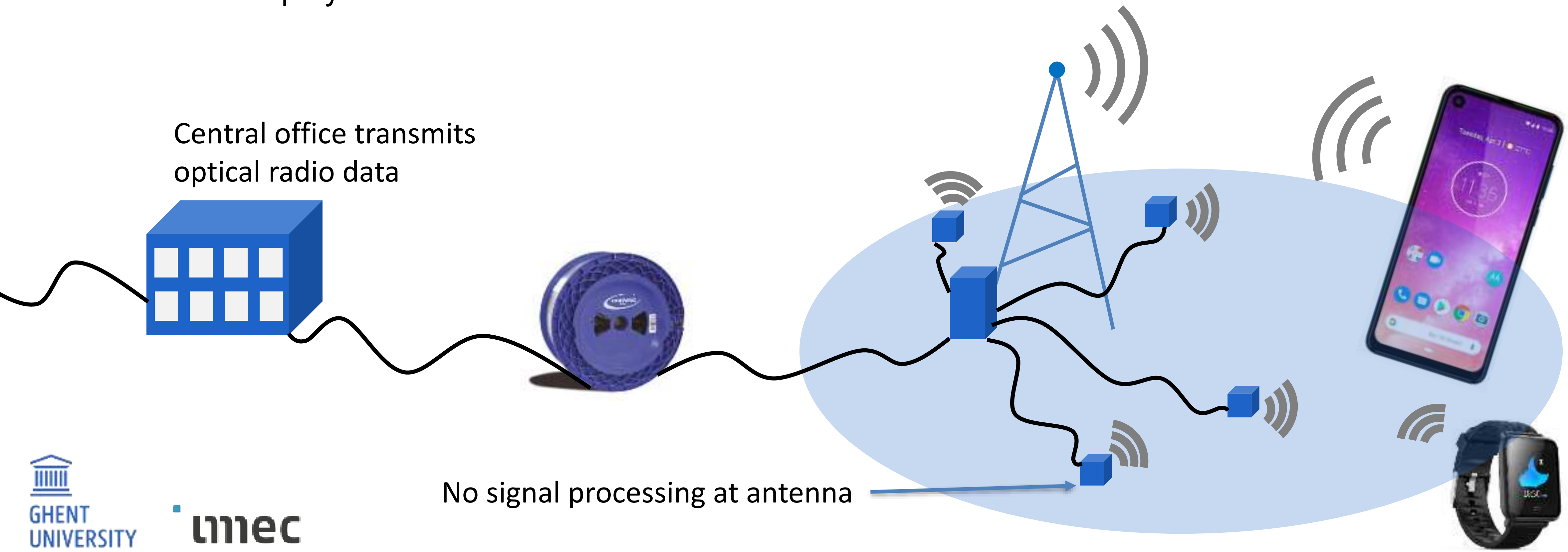


RADIO-OVER-FIBER LINK



TECHNOLGIES ENABLING 5G: RADIO-OVER-FIBER

- Directly modulate wireless signal on optical carrier
- Centralized antenna management
- Remote antenna units without signal processing
- Use silicon photonic devices to enable low-cost and scalable deployment



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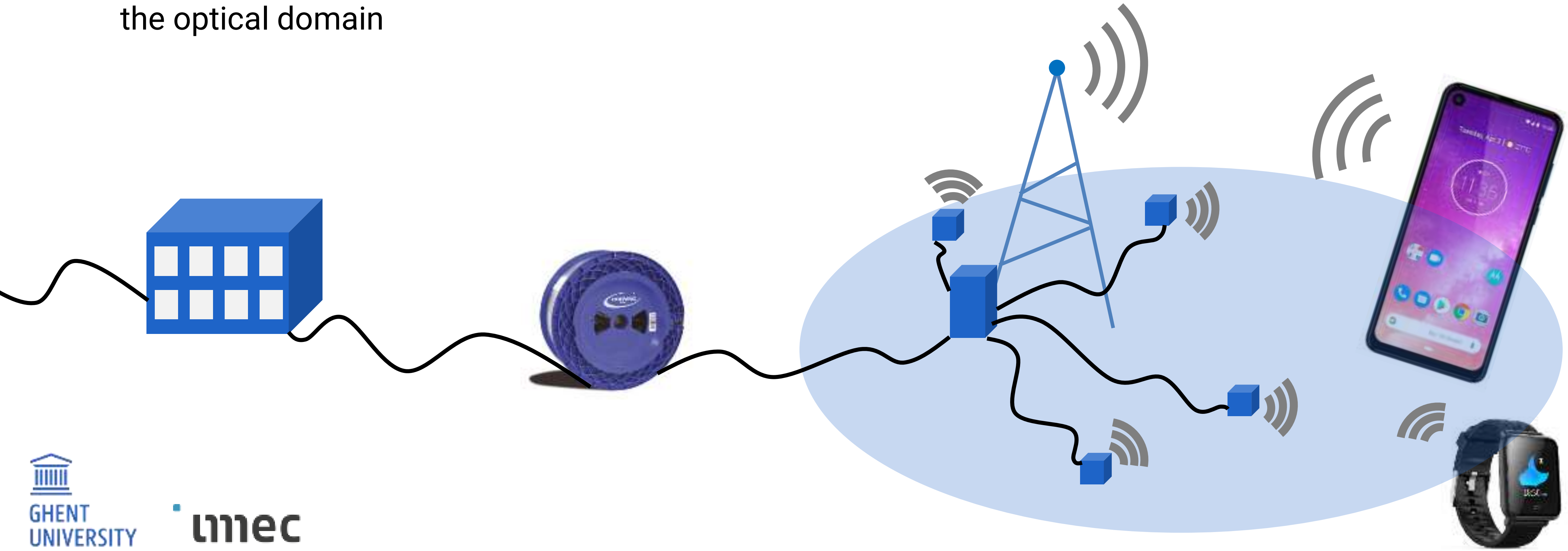
SILICON PHOTONIC RADIO-OVER-FIBER LINKS: THIS WORK

- Demonstrate radio-over-fiber link using existing heterogeneous silicon photonic devices
- Integrate optical amplification on-chip
- Improve links by developing microwave photonic subsystem that performs an electronic functionality in the optical domain



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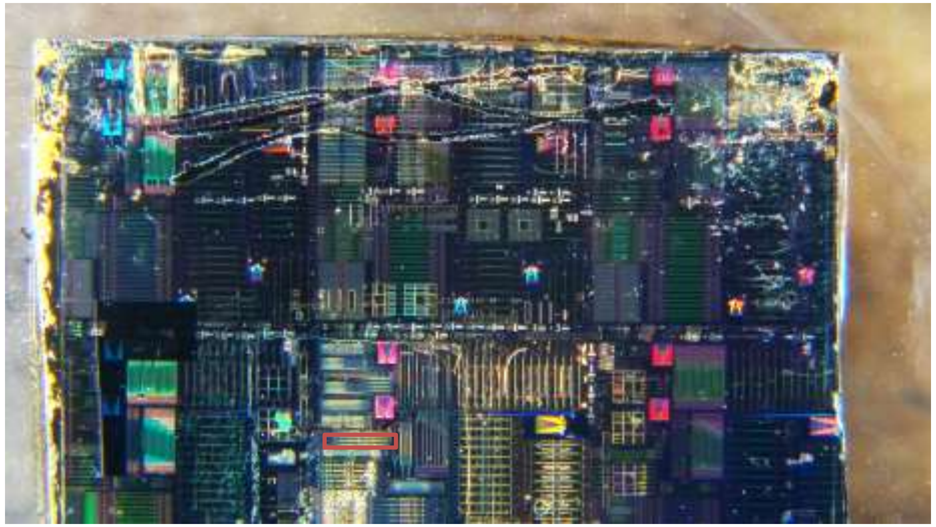
SILICON PHOTONIC RoF DEMONSTRATION: TRANSMITTER

- High speed directly modulated laser was developed in Photonics Research Group
- Analogue bandwidth beyond 30 GHz demonstrated making it suitable for 5G carrier frequencies
- Directly modulated lasers allows low-cost low-complexity architecture

Dr. Amin Abbasi

Prof. Geert Morthier



III-V-on-Si DFB laser

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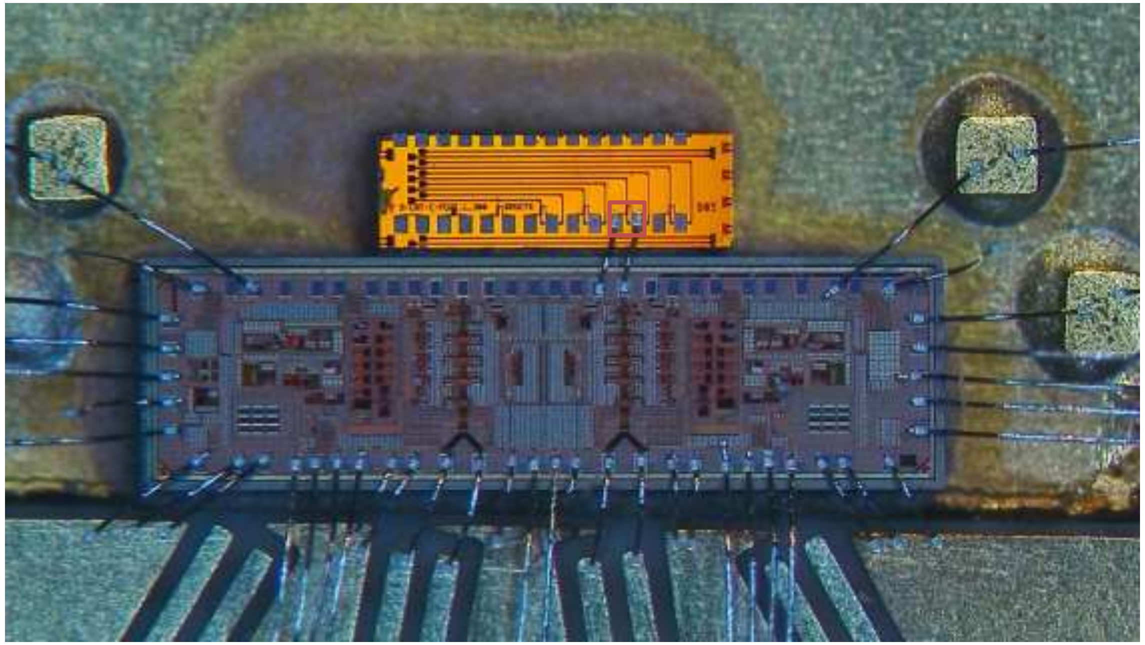
SILICON PHOTONIC RoF DEMONSTRATION: RECEIVER

- High performance silicon photonic receiver developed in our group
- Waveguide-coupled germanium photodiode and CMOS transimpedance amplfiier co-integrated on single PCB



Dr. Hongtao Chen

Jochem Verbist

Prof. Gunther Roelkens

Ge PD + TIA

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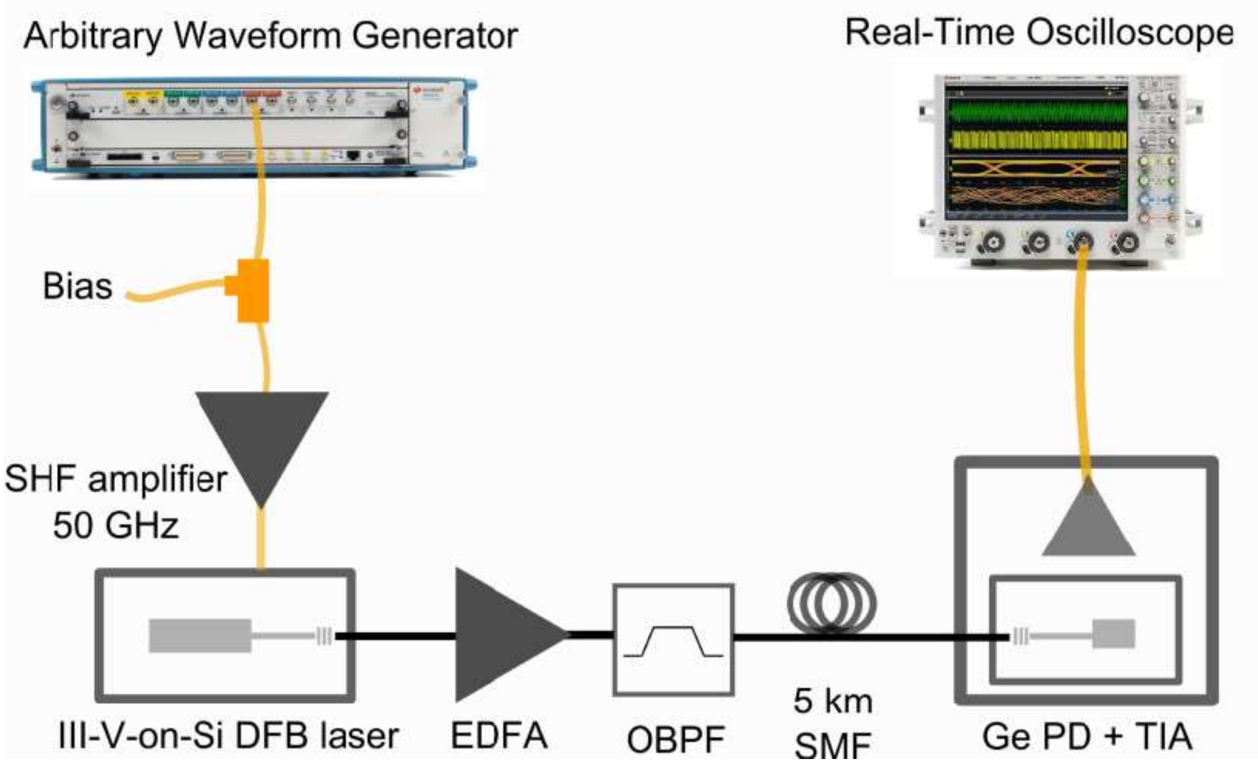
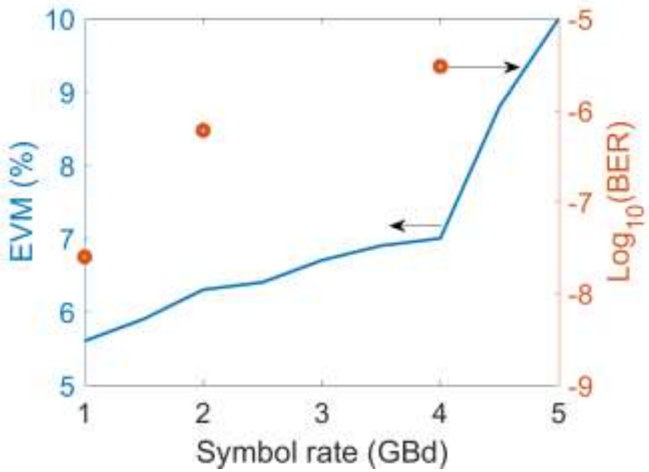
4438 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 36, NO. 19, OCTOBER 1, 2018

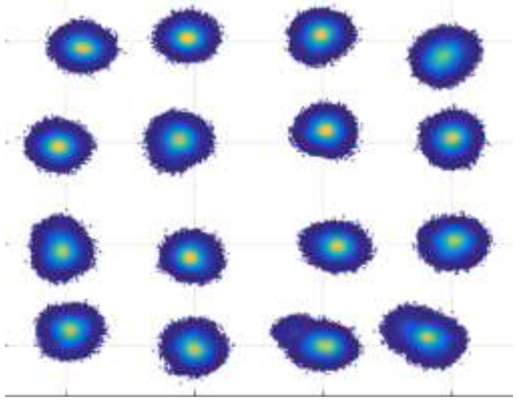
III-V-on-Silicon Photonic Transceivers for Radio-Over-Fiber Links

K. Van Gasse, J. Van Kerrebrouck, A. Abbasi, J. Verbist, G. Torfs, B. Moeneclaey, G. Morthier, X. Yin, J. Bauwelinck, and G. Roelkens



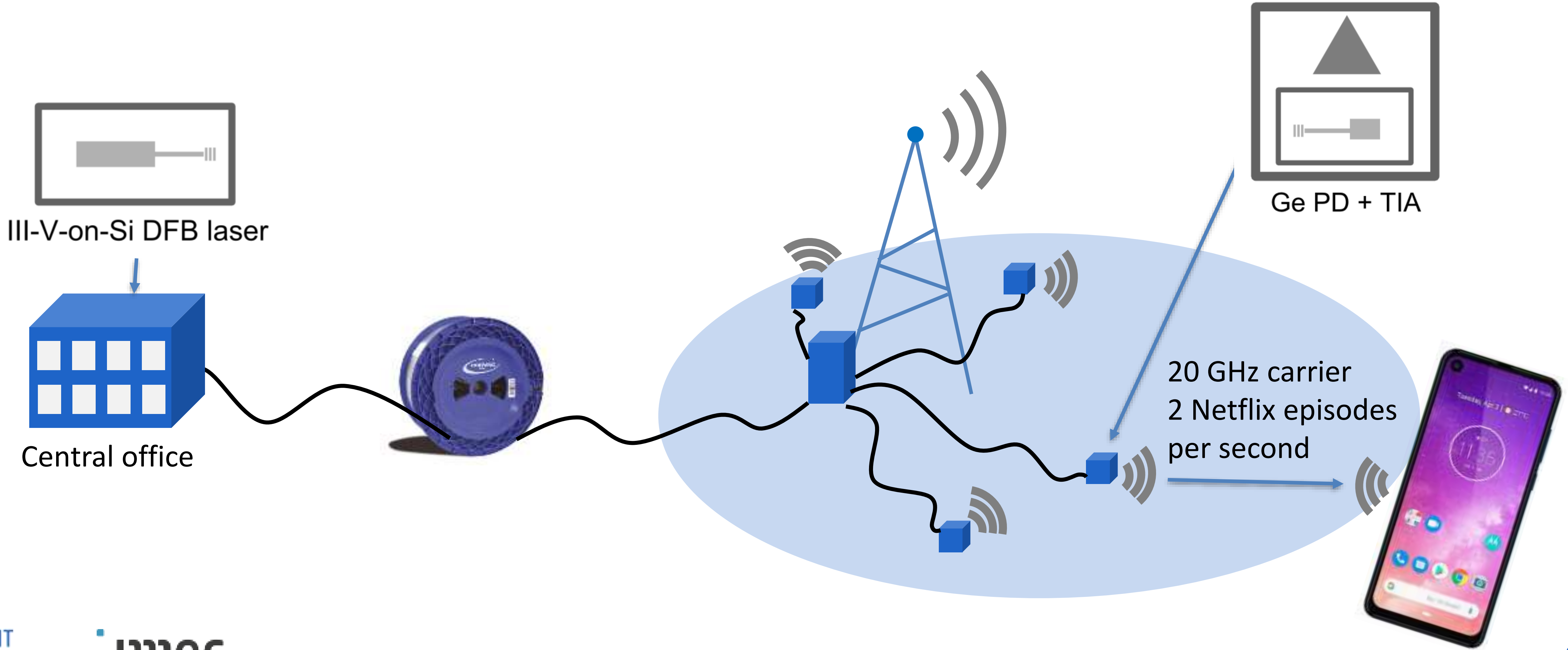
20 GHz carrier link (5G)
16 Gbit/s (16-QAM) transported over 5 km of fiber





SILICON PHOTONIC RADIO-OVER-FIBER LINK FOR 5G

This experiment shows that silicon photonics is a promising technology to realize low-cost scalable radio-over-fiber links.



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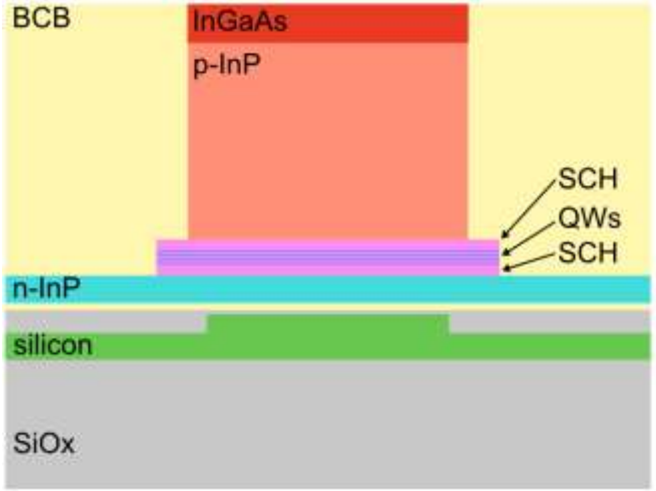
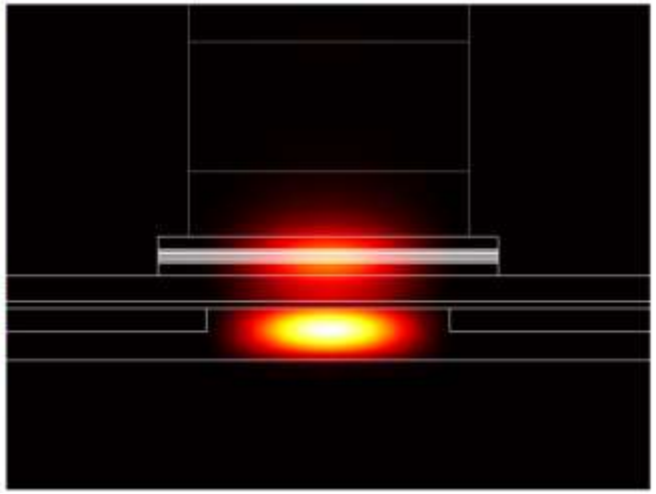
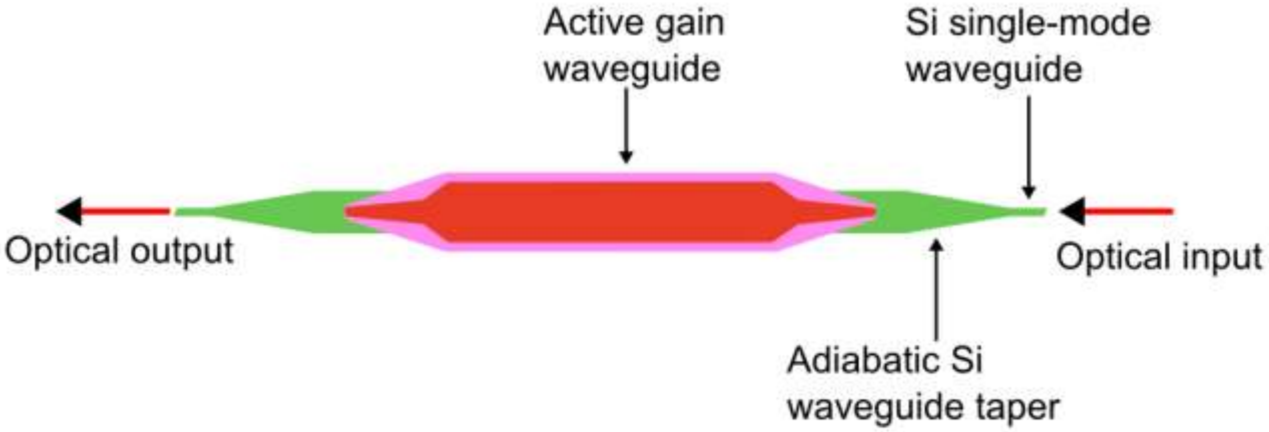
SILICON PHOTONIC SEMICONDUCTOR OPTICAL AMPLIFIER

- Integrated optical amplifier with high output power is needed for an efficient and scalable radio-over-fiber link
- No silicon photonic optical amplifier was available with more than 50 mW output power
- We designed a III-V-on-silicon optical amplifier specifically to achieve high output power
- Design using passive silicon waveguide underneath active material
- Silicon single mode input and output waveguide allow full integration in all silicon photonic PICs







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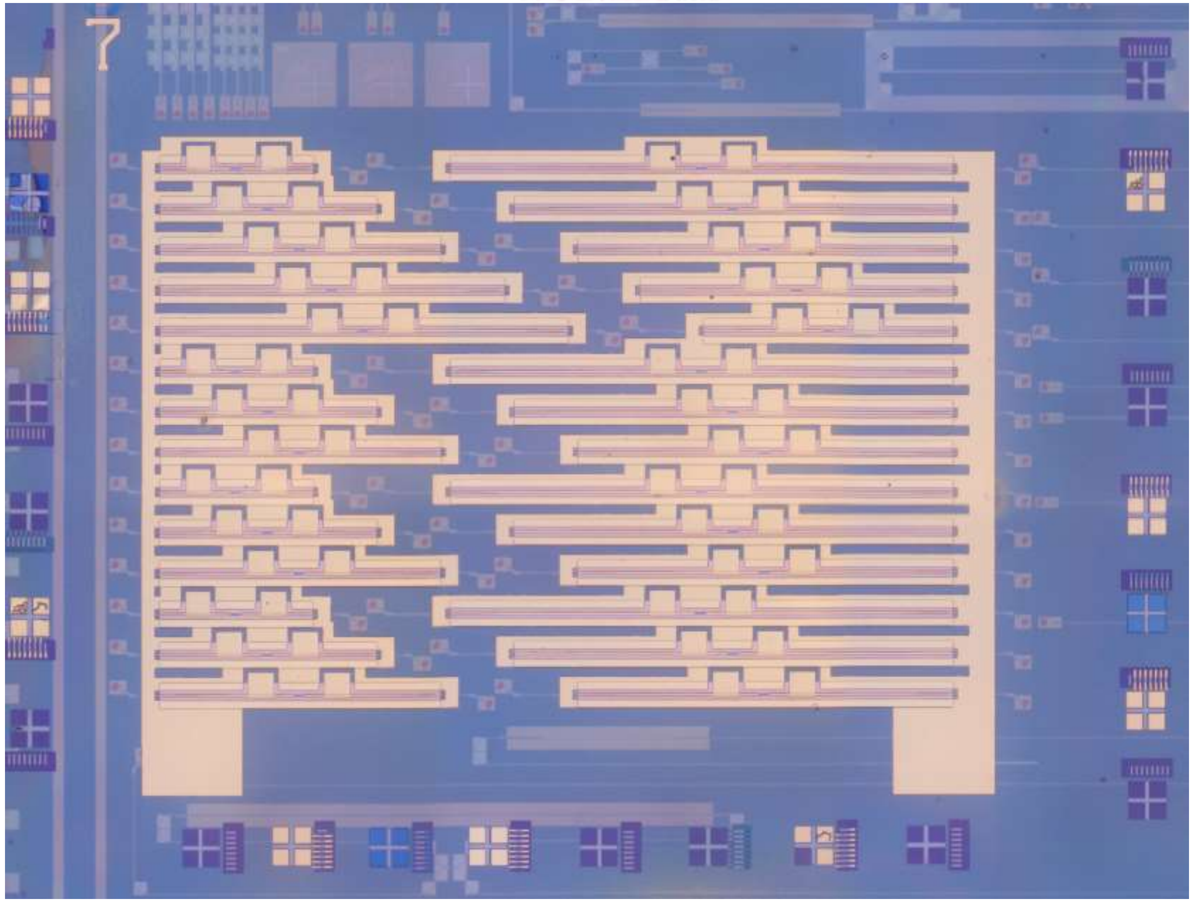
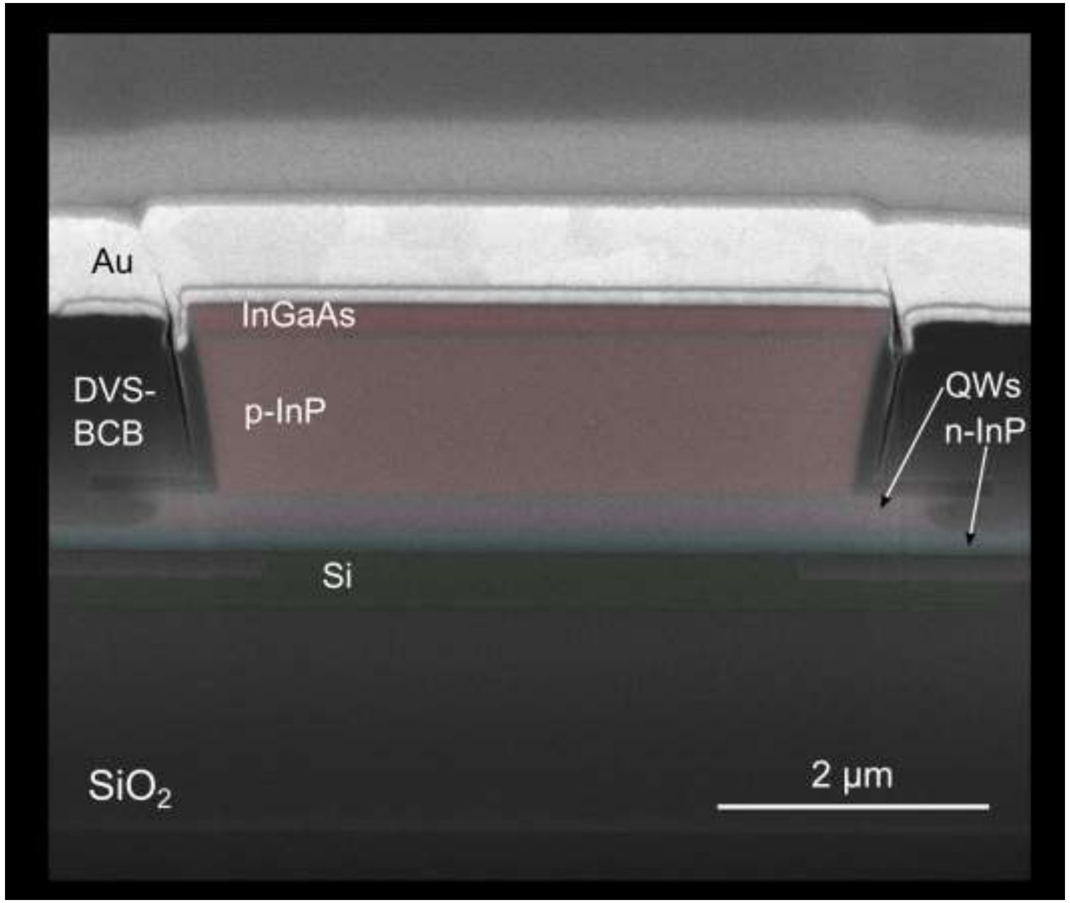
Research Article
Vol. 27, No. 1 | 7 Jan 2019 | OPTICS EXPRESS 293
Optics EXPRESS

27 dB gain III-V-on-silicon semiconductor optical amplifier with > 17 dBm output power

KASPER VAN GASSE,[1,2,3,*] RUIJUN WANG,[1,2,3] AND GUNTHER ROELKENS[1,2]





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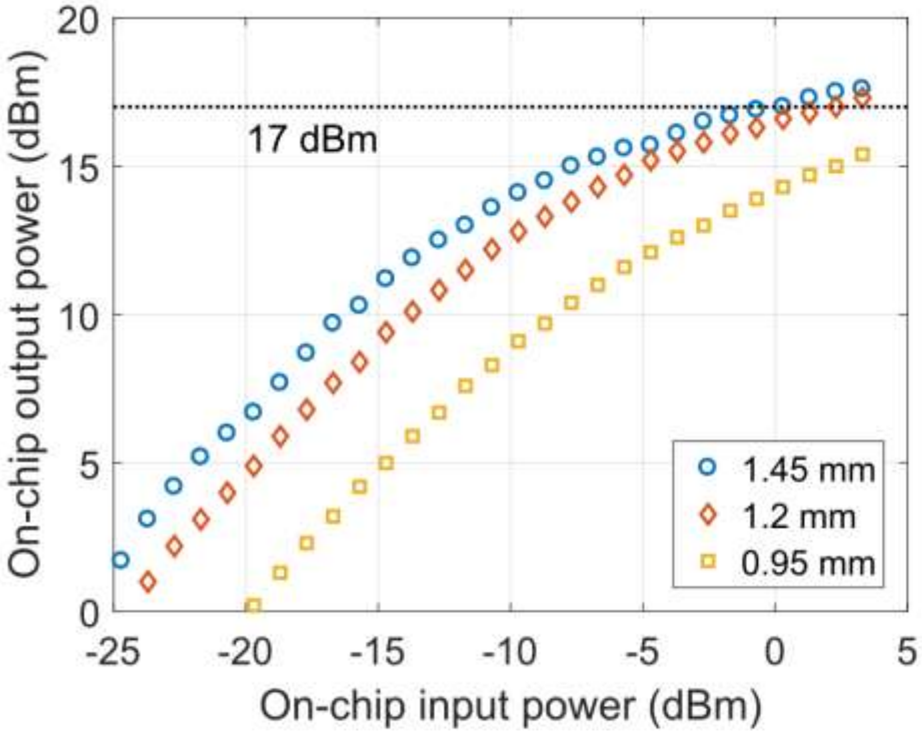
KASPER VAN GASSE,[1,2,3,*] RUIJUN WANG,[1,2,3] AND GUNTHER ROELKENS[1,2]

- We demonstrated amplifiers that can achieve output powers exceeding 50 mW
- Even at high output power the gain exceeds 10 dB
- Small-signal gain up to 27 dB (G = 500)
- Can enable radio-over-fiber links with fully integrated optical amplification



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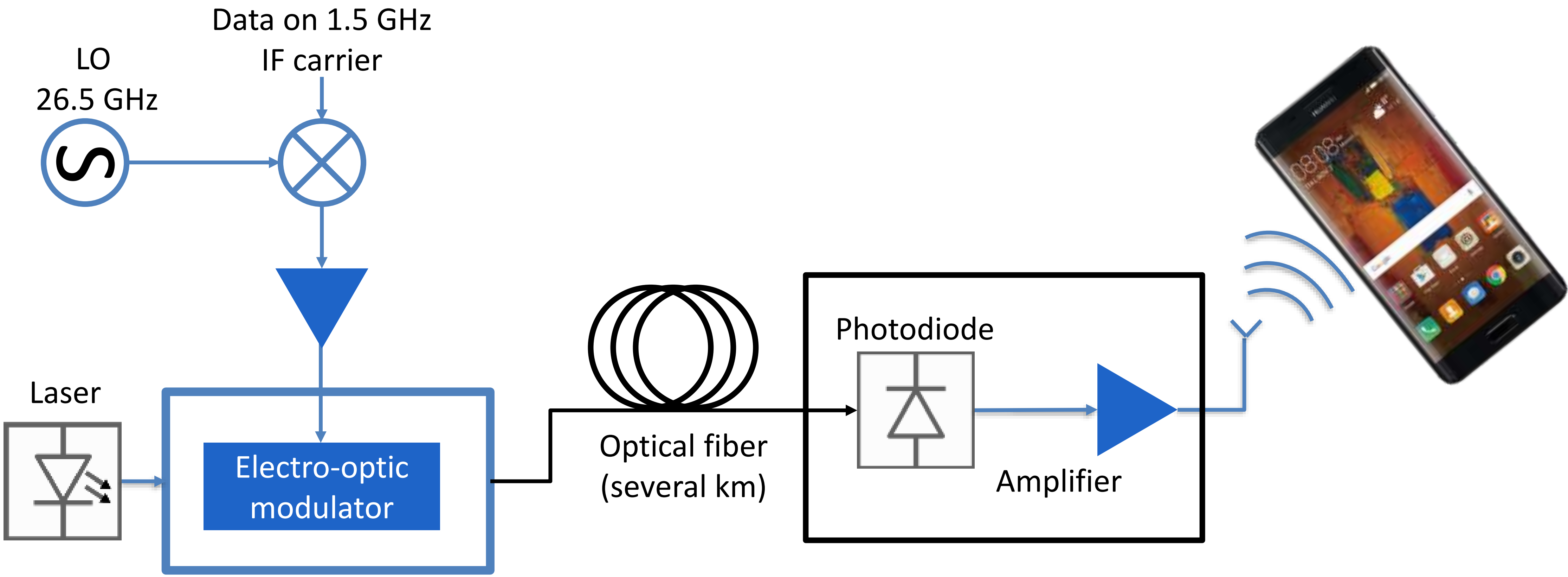
ARCHITECTURE RADIO-OVER-FIBER LINK 28 GHz

- Can we improve efficiency of link by performing microwave mixing in optical domain?



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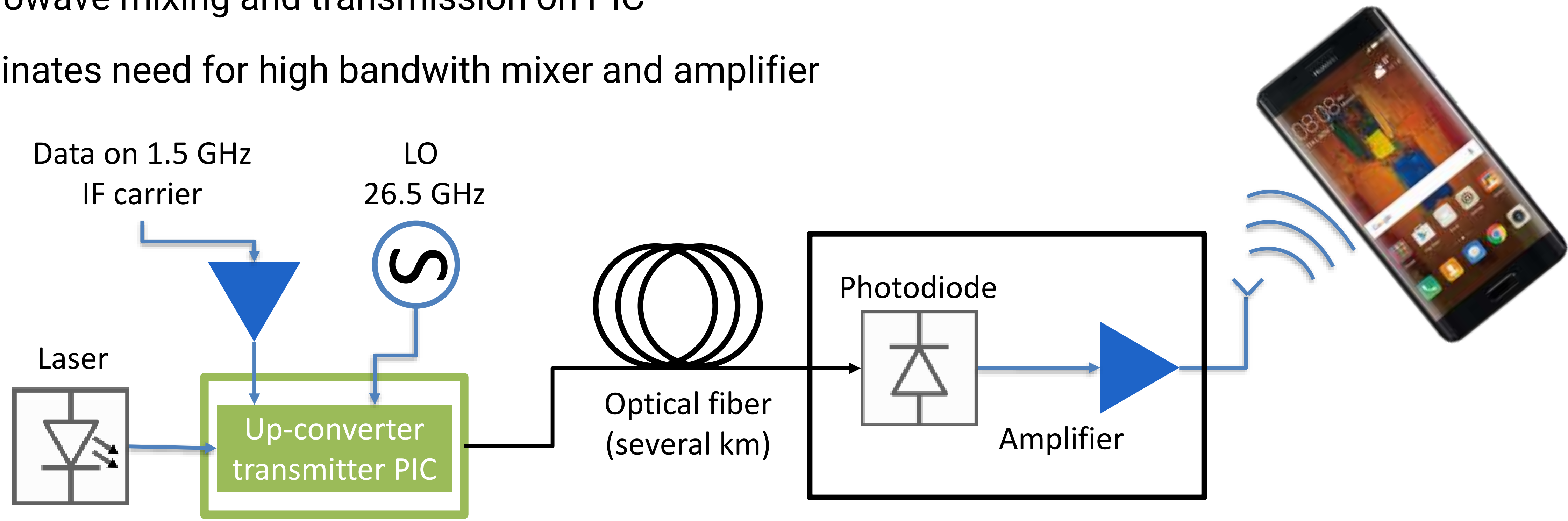
ARCHITECTURE RADIO-OVER-FIBER LINK 28 GHz

- Implementing microwave frequency mixing with LiNbO3 MZMs in optical domain is well-known technique
- Using high-speed Ge EAMs allows to implement both microwave mixing and transmission on PIC
- Eliminates need for high bandwith mixer and amplifier



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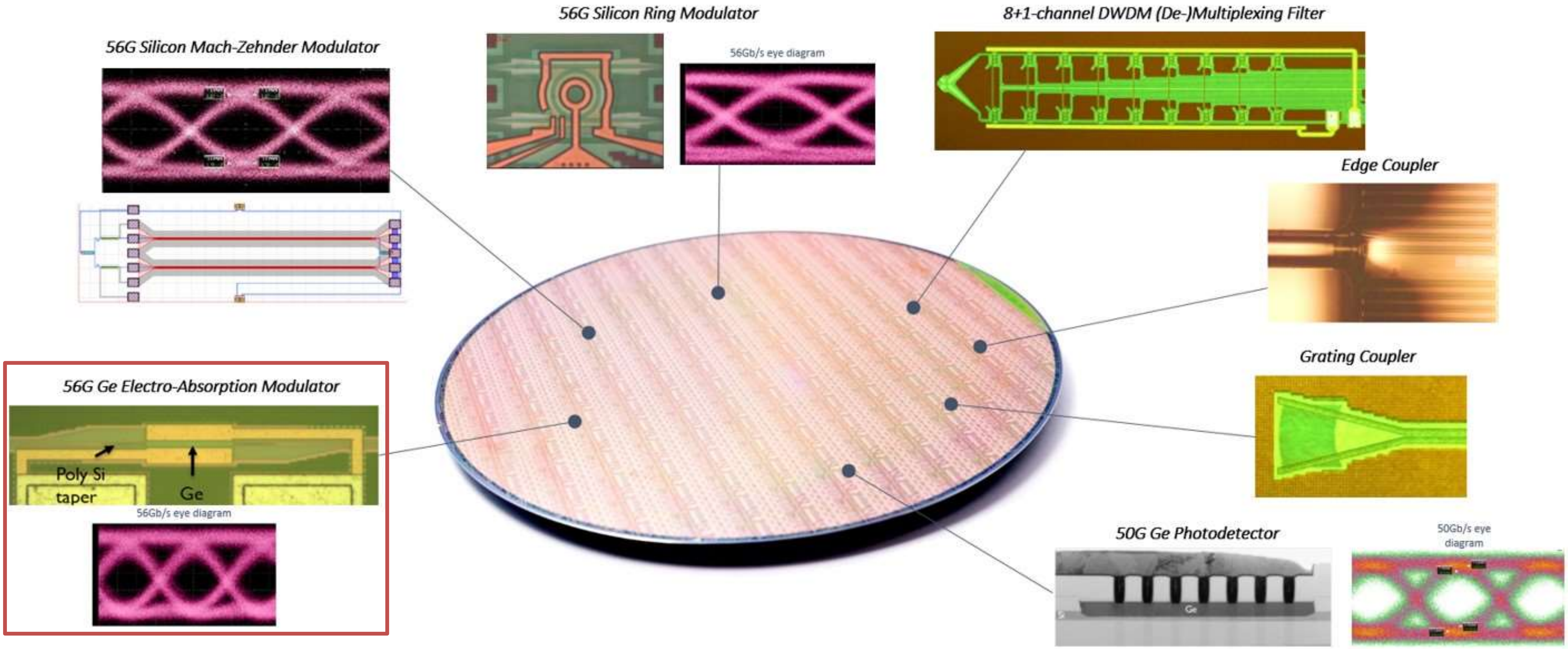
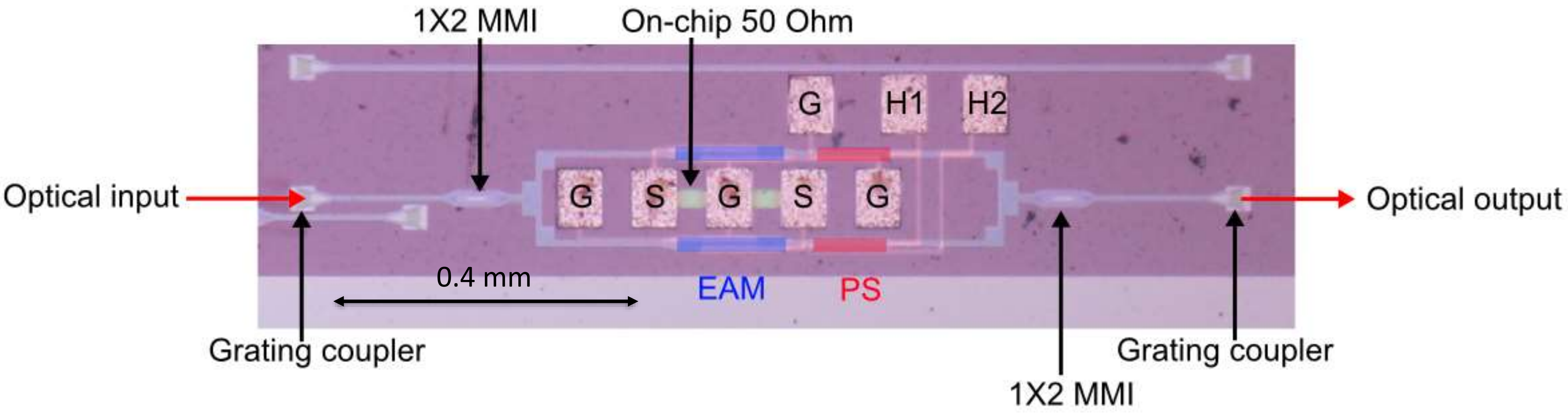
HETEROGENEOUS SILICON PHOTONICS: IMEC PLATFORM



EAM-BASED UP-CONVERTER TRANSMITTER

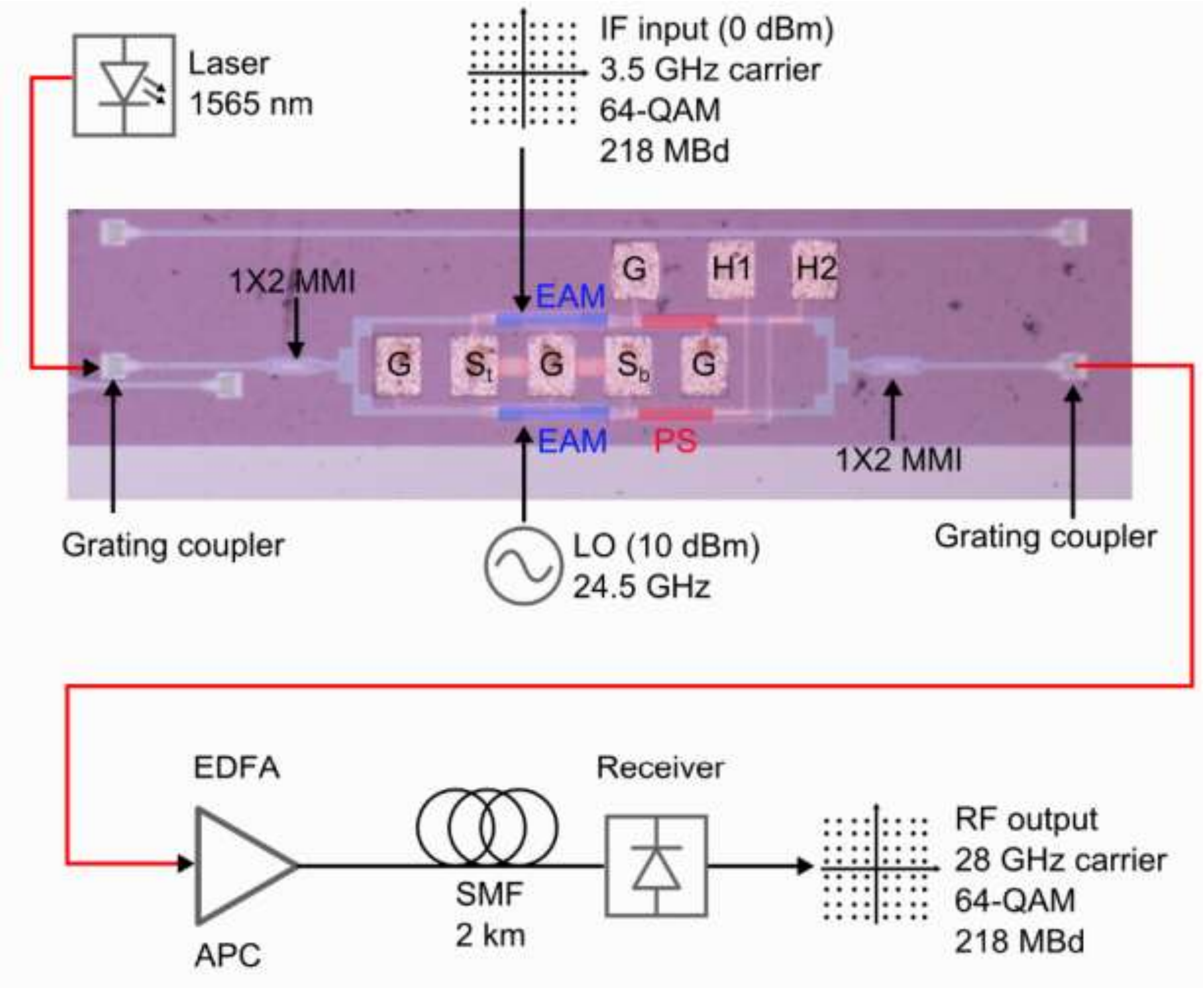
- We designed and fabricated a microwave photonic up-converter transmitter using two EAMs in a MZI structure
- Germanium EAMs have analogue bandwidth beyond 67 GHz allowing high-frequency (5G) carrier operation



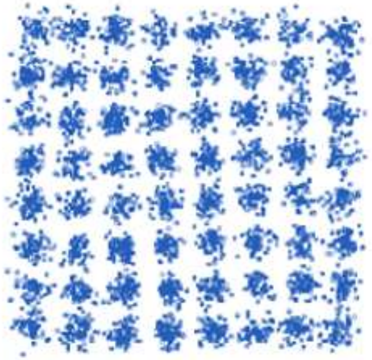
IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 31, NO. 2, JANUARY 15, 2019 181

Silicon Photonics Radio-Over-Fiber Transmitter Using GeSi EAMs for Frequency Up-Conversion

K. Van Gasse, J. Verbist, H. Li, G. Torfs, J. Bauwelinck, and G. Roelkens



1.3 Gbit/s on a 28 GHz carrier
218 MBd (64-QAM)
rms EVM 5.4 %



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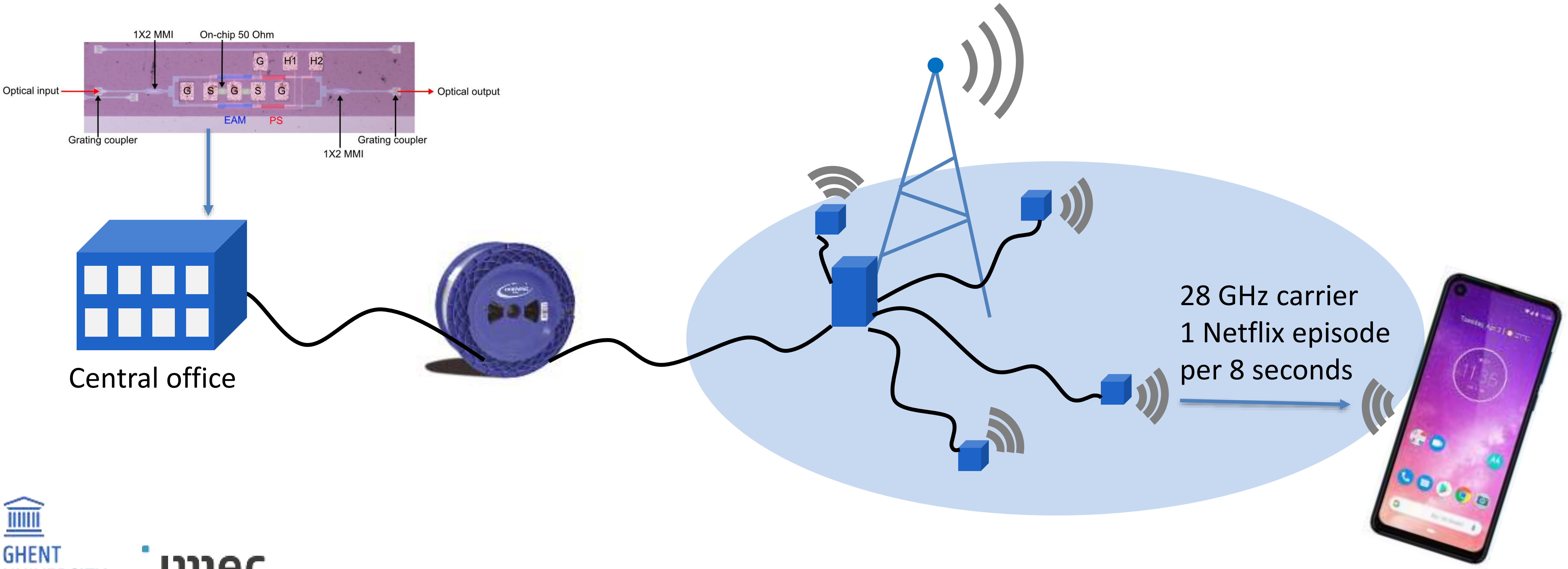
EAM-BASED UP-CONVERTER TRANSMITTER

Silicon photonics is a promising technology for 5G networks



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Overview

- Electromagnetic waves and waveguides
- Integrated silicon photonics technology
- Radio-over-fiber for 5G networks
    - Silicon photonic radio-over-fiber demonstration
    - Silicon photonic optical amplifier
    - Silicon photonic EAM-based mixer-transmitter
- **Communication satellites in 5G radio networks**
    - Communications satellites
    - Pulsed lasers
    - Electro-Photonic Frequency Converter
- Summary and conclusion

COMMUNICATION SATELLITES IN 5G NETWORKS

- Communication satellites can play important role in 5G networks:
  - Provide connectivity in remote locations
  - Internet connection on planes
  - Communication channel in emergency situations
- SpaceX wants to develop broadband satellite network (Starlink)
- European Space Agency pushes for satellite network

OVERVIEW

- Electromagnetic waves and waveguides
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    - **Communications satellites**
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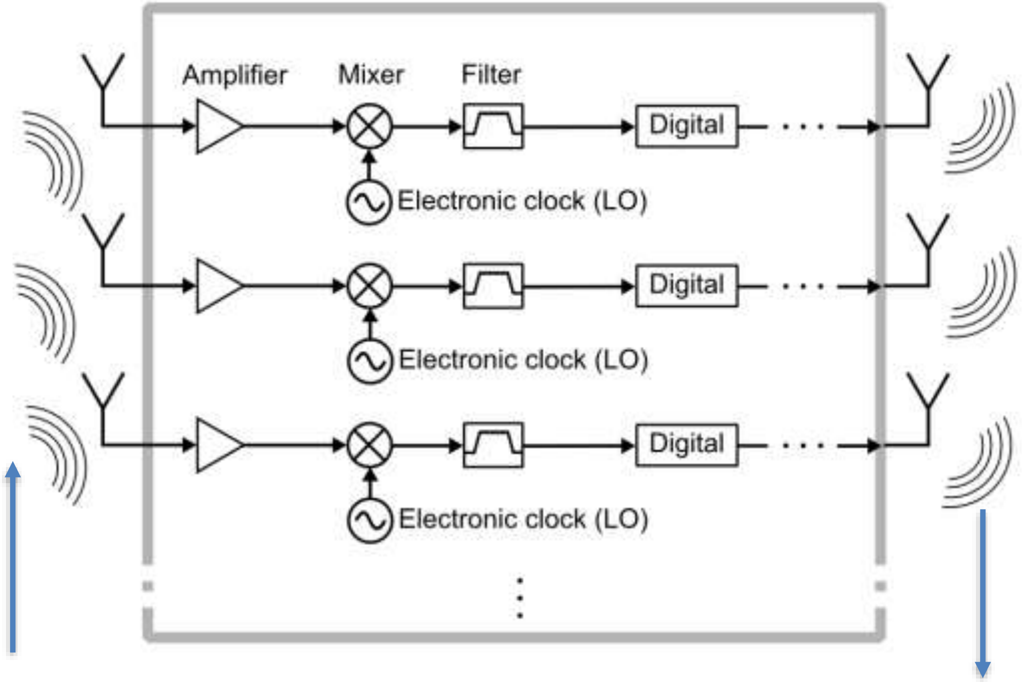
- Summary and conclusion

COMMUNICATION SATELLITES

Communication satellite



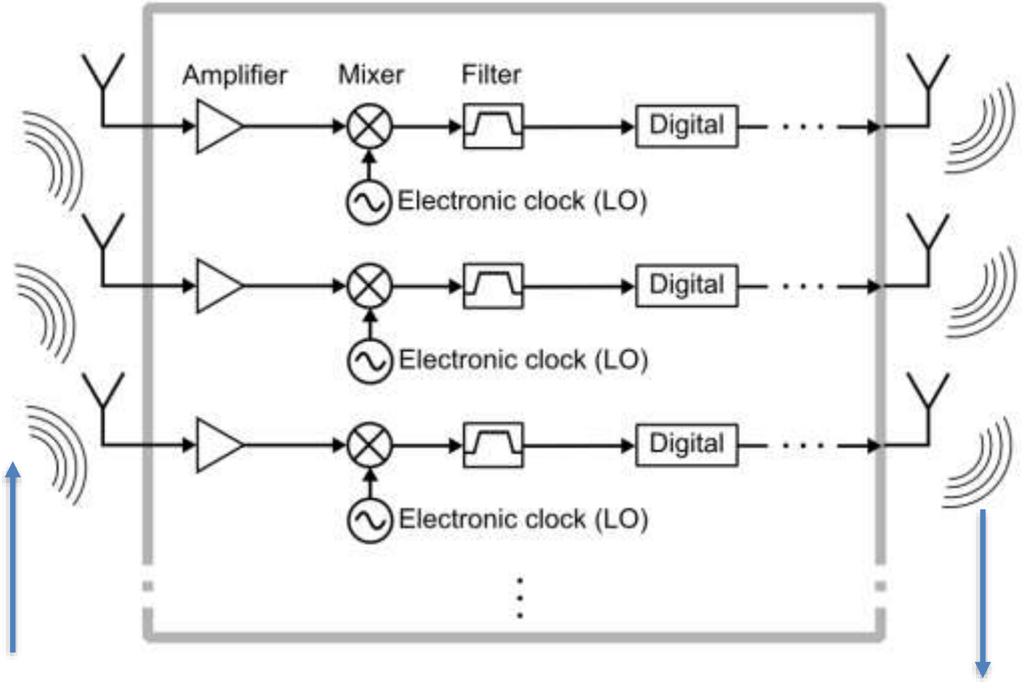
30 GHz channel from Earth to satellite

15 GHz channel from satellite to Earth

COMMUNICATION SATELLITES

- High number of channels have to be frequency converted in parallel
- Each channel requires high performance electronic clock
- Push for photonic payloads in communication satellites from industry and European Space Agency
- Using optical fiber and components can dramatically reduce weight, cost and sensitivity to electromagnetic interference

Communication satellite



30 GHz channels
from Earth to satellite

15 GHz channels
from satellite to Earth

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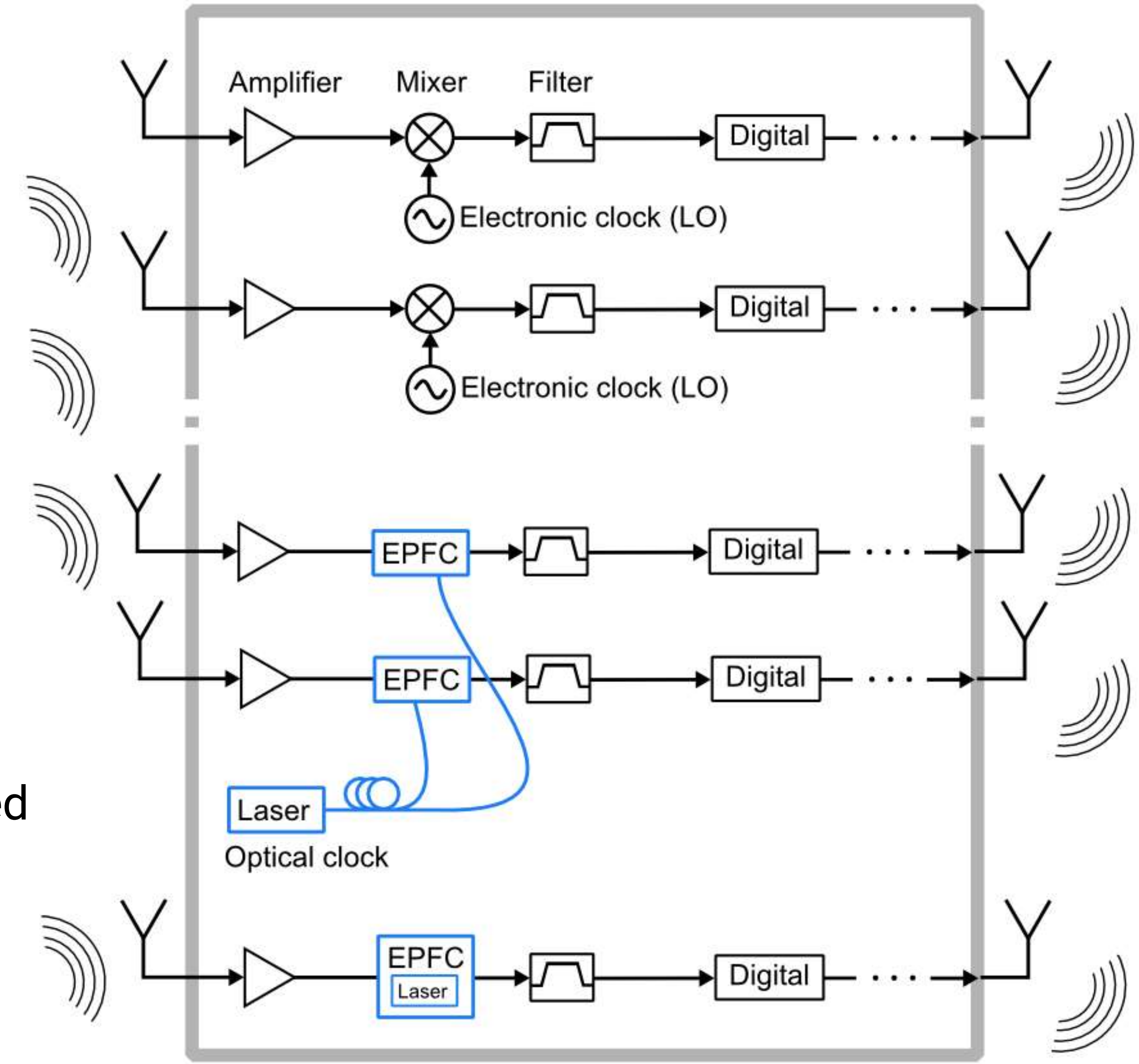
ELECTRO-PHOTONIC FREQUENCY CONVERTER (EPFC)

- Use silicon microwave photonic PIC to achieve frequency conversion
- Use optical clock
  - Can be distributed using lightweight optical fiber
  - Can be integrated on the same chip
- Pulsed lasers can operate as extremely precise optical clocks
- We developed both an **E**lectro-**P**hotonic **F**requency **C**onverter circuit and integrated pulsed laser



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OVERVIEW

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  - Communications satellites
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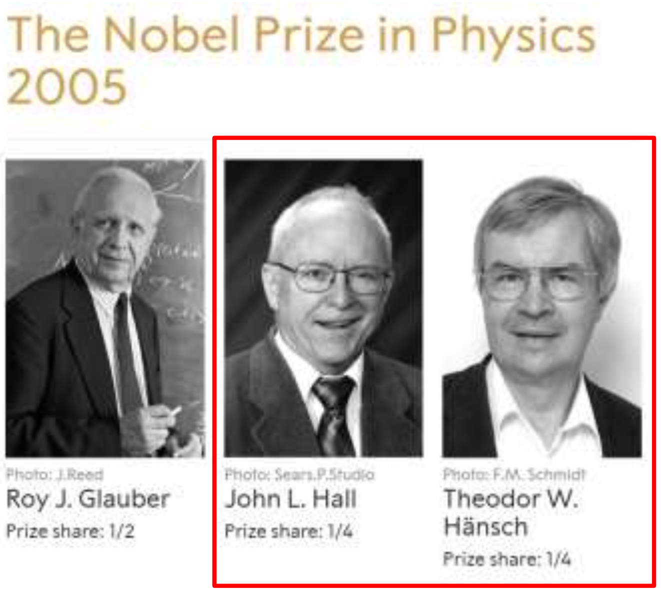
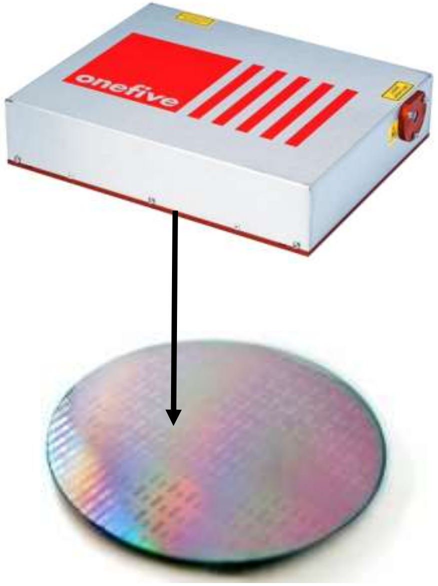
PULSED (MODE-LOCKED) LASERS

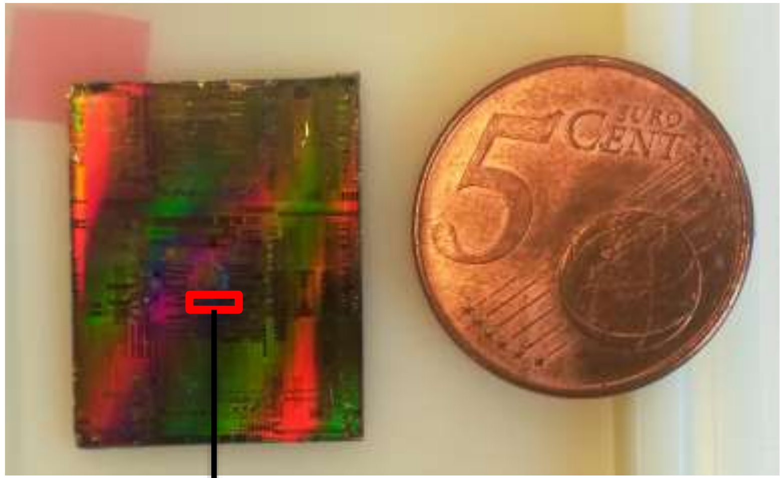
- Pulsed lasers have seen dramatic development in the past decades
- Pulsed lasers have been key to research leading to several Nobel prizes
- Very high performance pulsed lasers commercially available (tabletop)
- Development high-performance integrated pulsed lasers ongoing

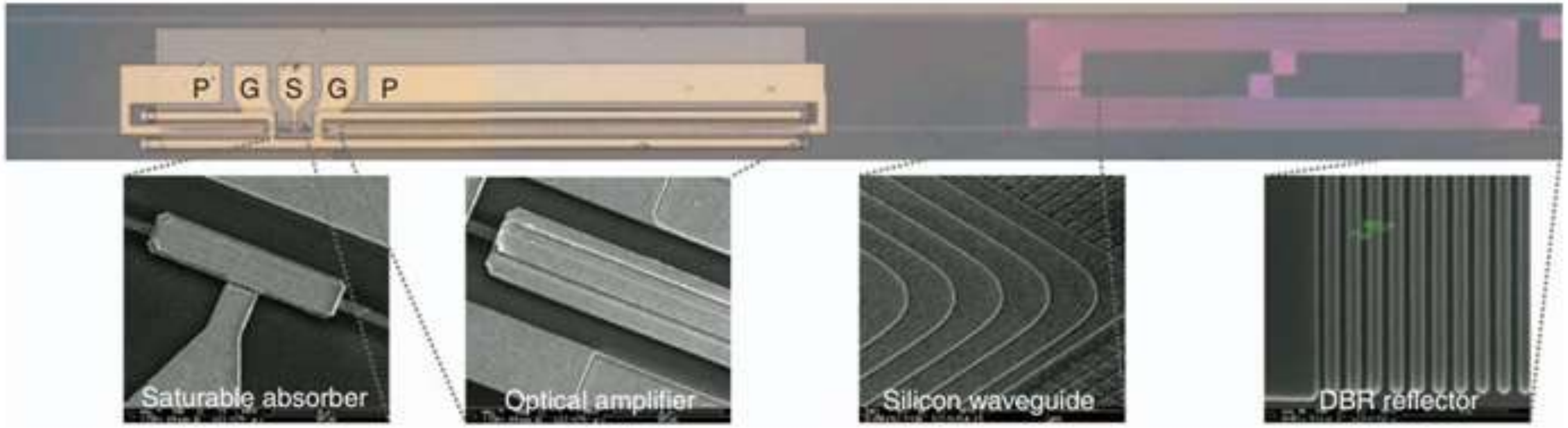


III-V-ON-SILICON PULSED (MODE-LOCKED) LASER

- We developed an on-chip pulsed laser using III-V-on-silicon technology
- Very compact (< 1 mm^2)
- Semiconductor based mode-locked lasers have seen great development in the last decades
- Combining III-V gain material with low-loss silicon waveguide enables beyond state-of-the-art performance







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Light | Science & Applications

A III-V-on-Si ultra-dense comb laser

Zhechao Wang[1,2,*], Kasper Van Gasse[1,2,*], Valentina Moskalenko[3], Sylwester Latkowski[3], Erwin Bente[3], Bart Kuyken[1,2] and Gunther Roelkens[1,2]

nature photonics

Research Highlights | Published: 30 June 2017

Integrated optics

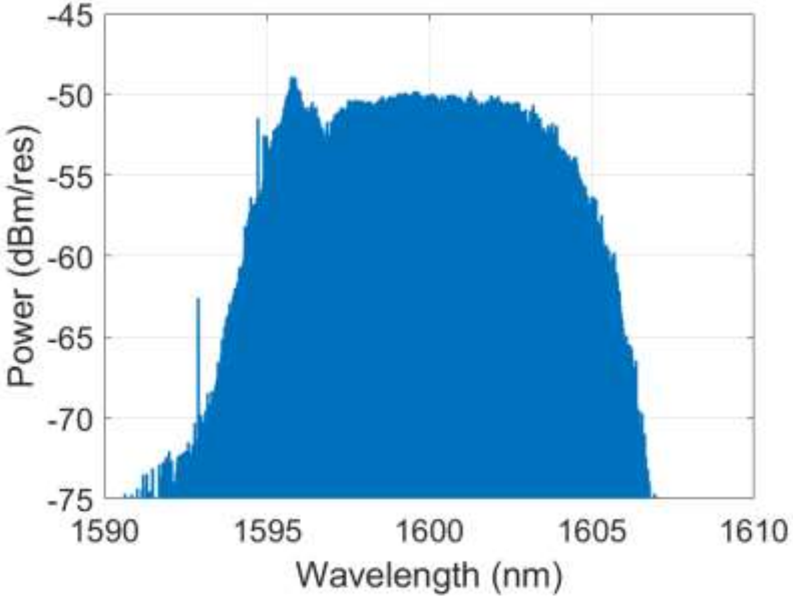
Dense comb on a chip

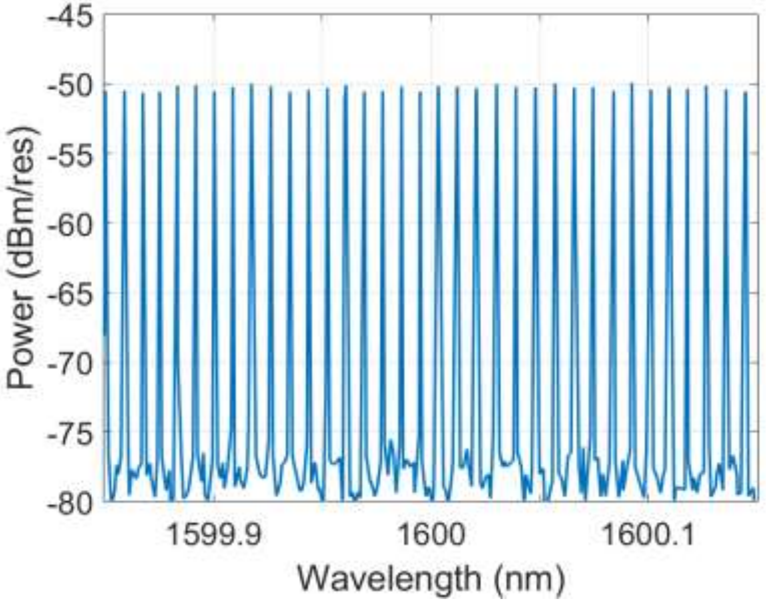
Rachel Won

Nature Photonics **11**, 402 (2017) | Download Citation

Demonstration beyond state of the art III-V-on-silicon (passively mode-locked) pulsed laser:

- 10 nm optical bandwidth
- 1400 optical modes
- Record on-chip repetition rate
- RF linewidth < 1 kHz
- Optical linewidth < 400 kHz





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OVERVIEW

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- Communication satellites in 5G radio networks
    - Communications satellites
    - Pulsed lasers
    - **Electro-Photonic Frequency Converter**
- Summary and conclusion

ELECTRO-PHOTONIC FREQUENCY CONVERTER

esa

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Prof. Gunther Roelkens

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Dr. Valentina Moskalenko

Prof. Erwin Bente

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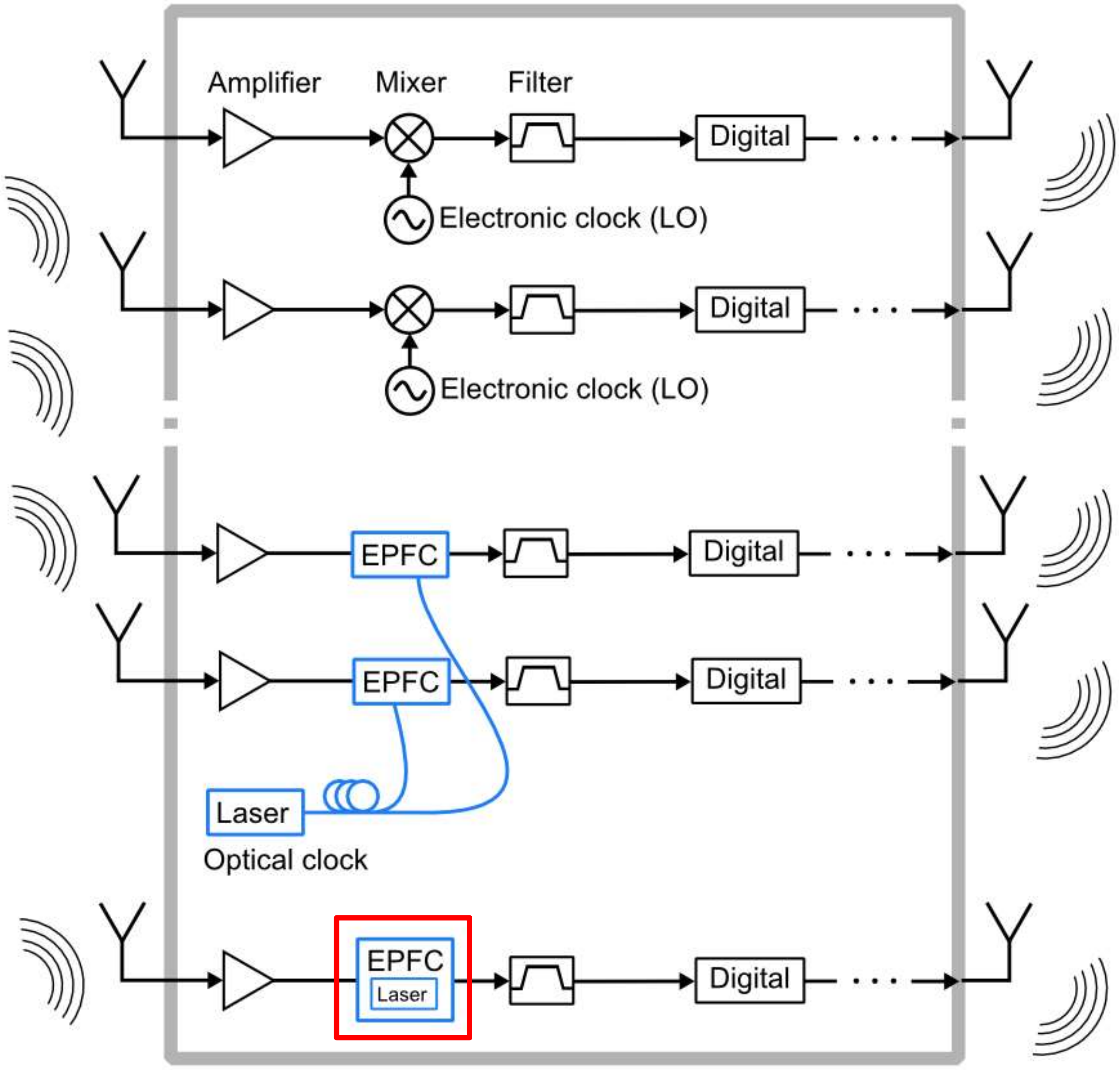
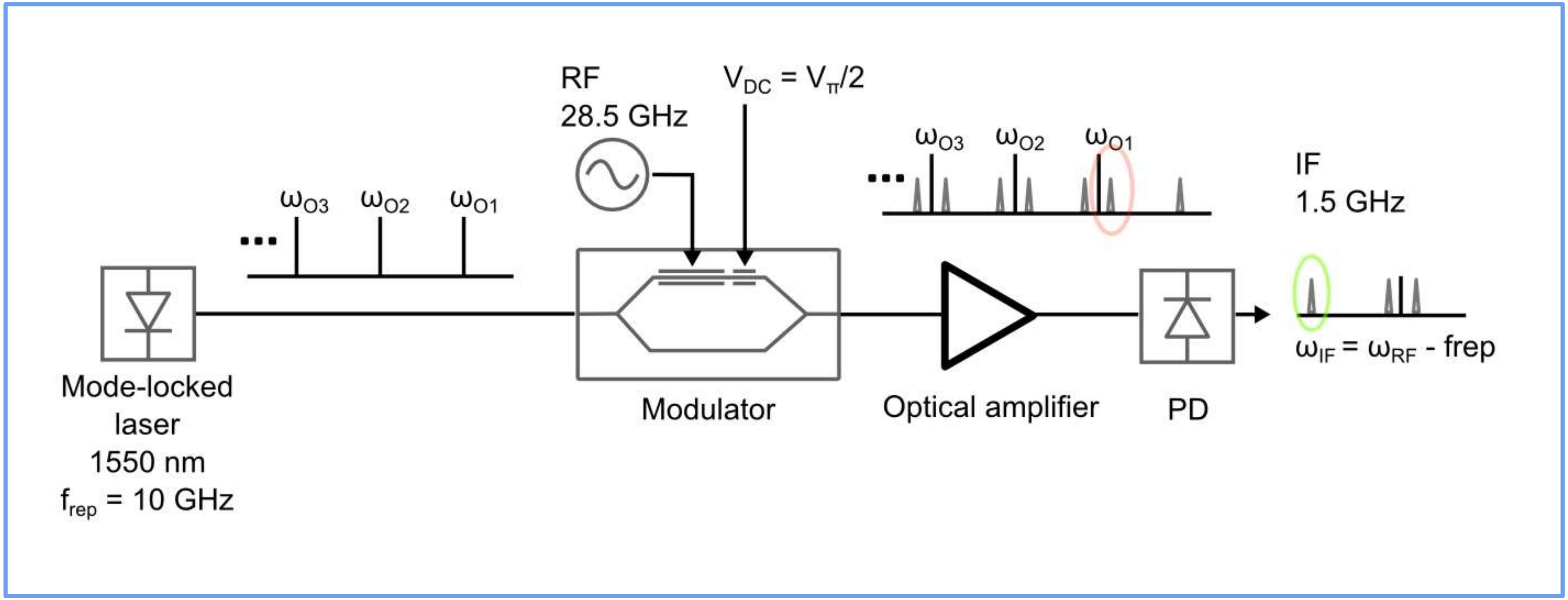
Electro-Photonic Frequency Converter (EPFC)



Electro Photonic Frequency Converter - PIC



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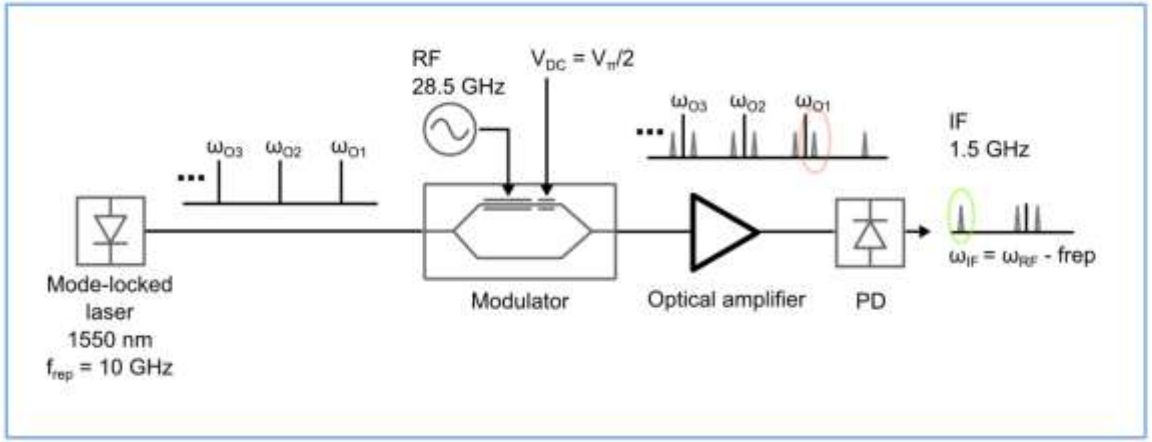
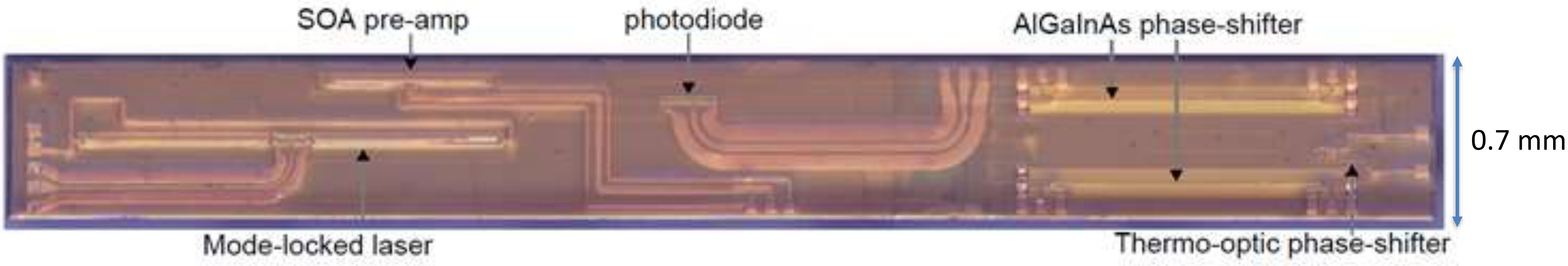
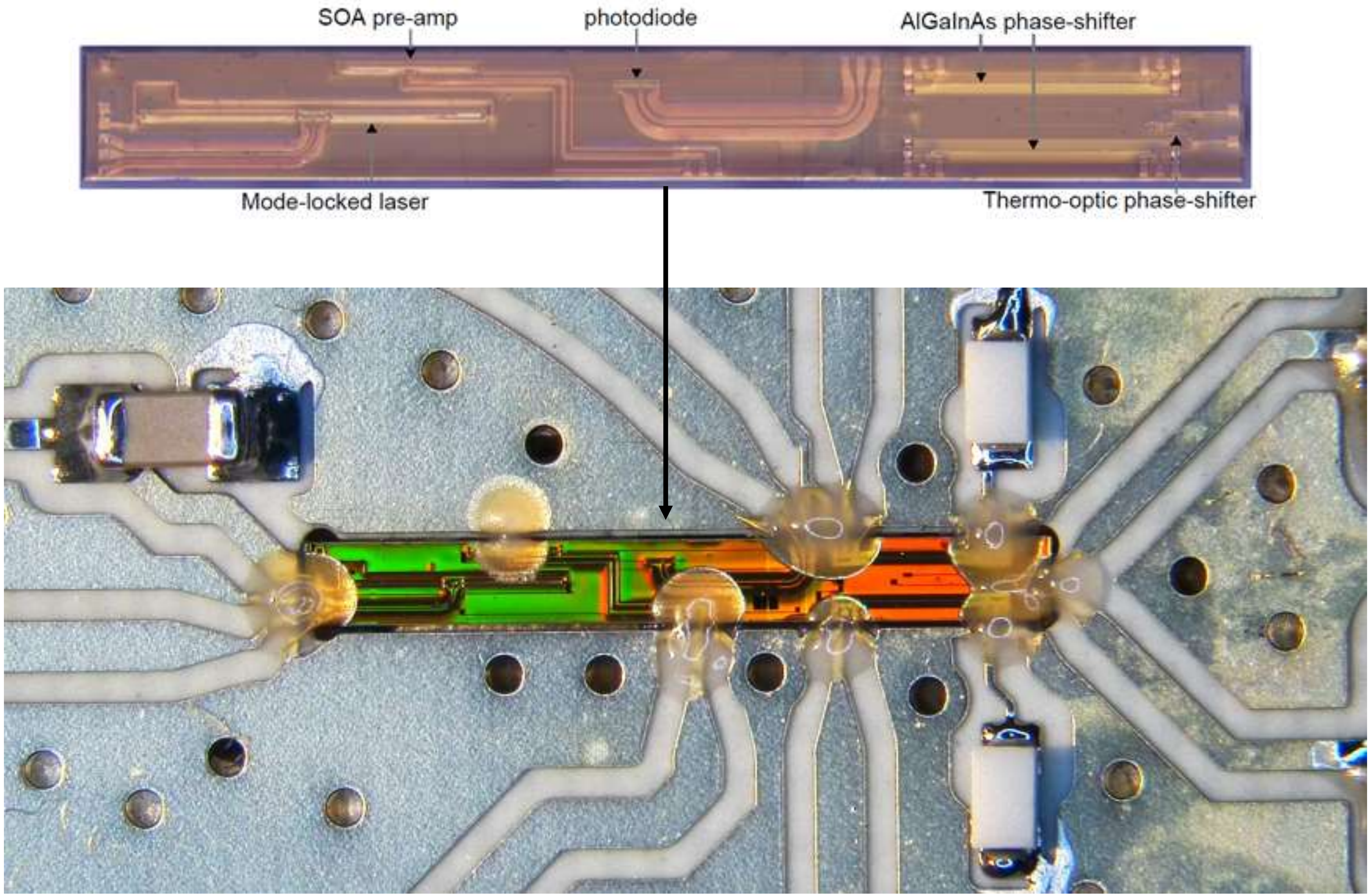
ELECTRO PHOTONIC FREQUENCY CONVERTER - PIC

- We designed, fabricated and characterized a fully integrated III-V-on-silicon electro-photonic frequency converter PIC

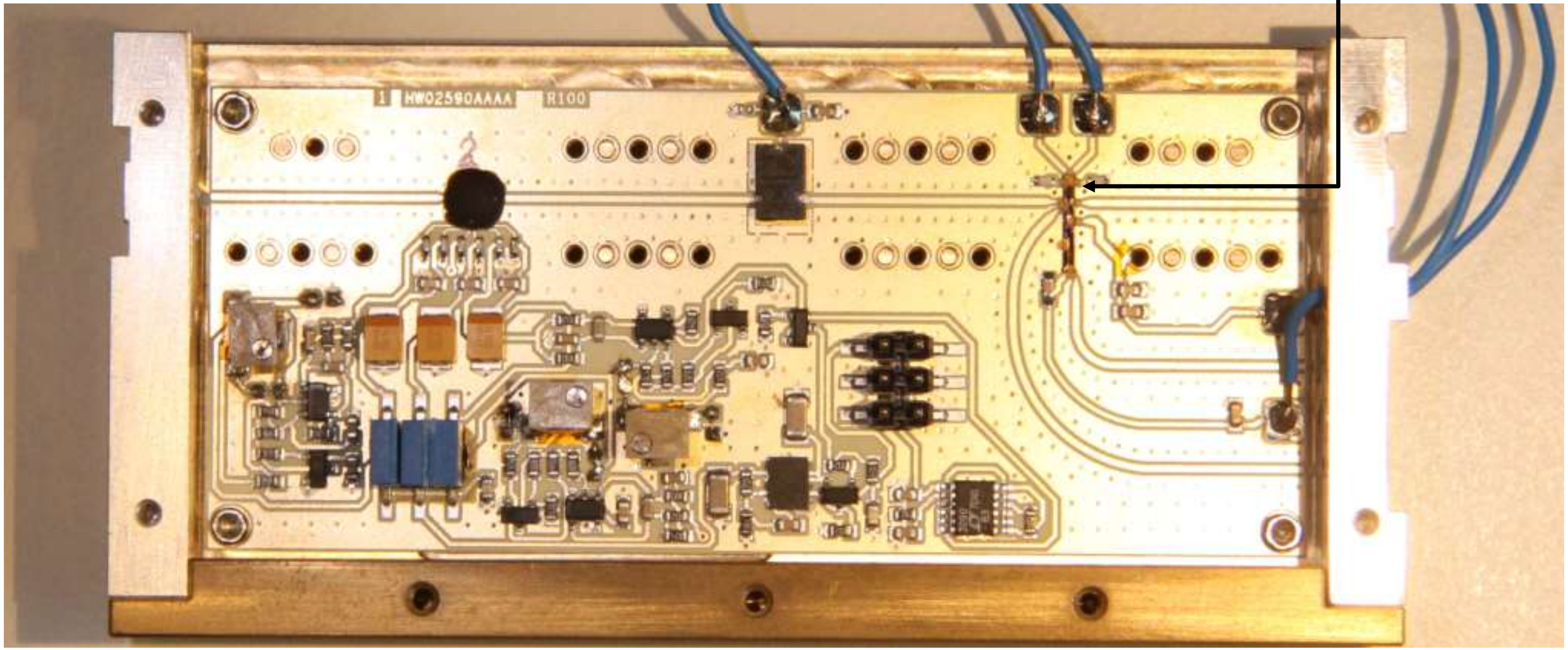


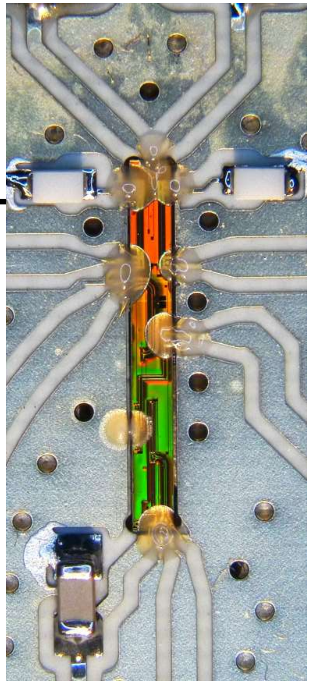


ELECTRO PHOTONIC FREQUENCY CONVERTER - ASSEMBLY



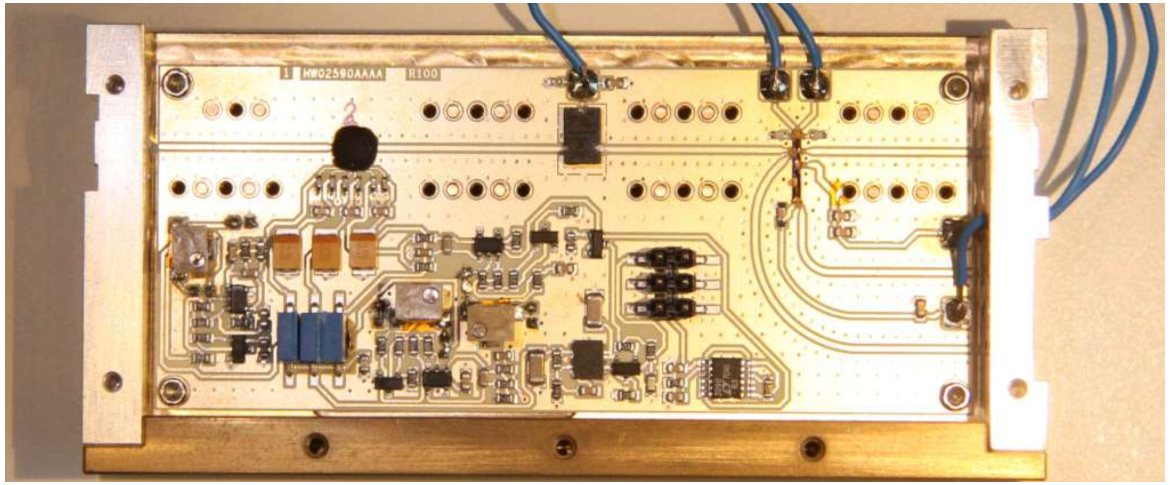
Electro Photonic Frequency Converter - PIC





Electro Photonic Frequency Converter - PIC

- Individual photonic devices were demonstrated to be functional
- Wire-bonding of PIC to PCB was challenging due to short high-speed wire-bonds
- Demonstration of fully operational assembly needs further development



OVERVIEW

- Electromagnetic waves and waveguides
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  - Communications satellites
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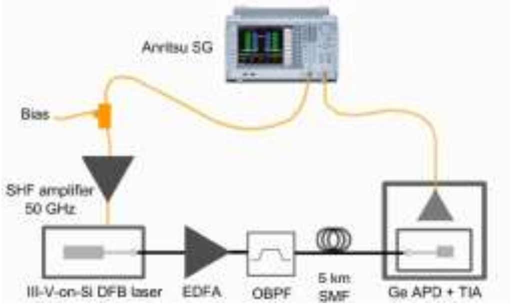
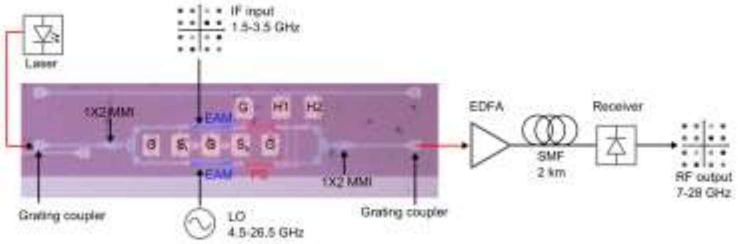
- **Summary and conclusion**

SUMMARY

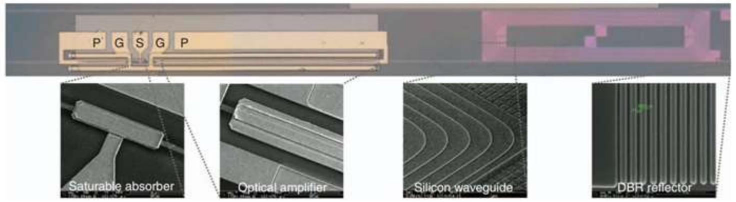
Demonstrated silicon photonic radio-over-fiber link



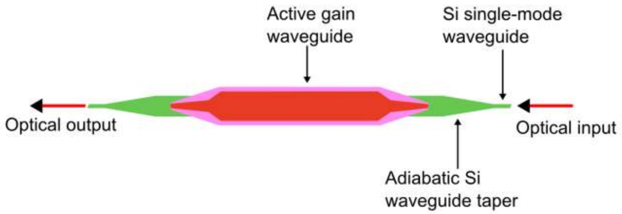
Demonstrated EAM-based up-converter-transmitter



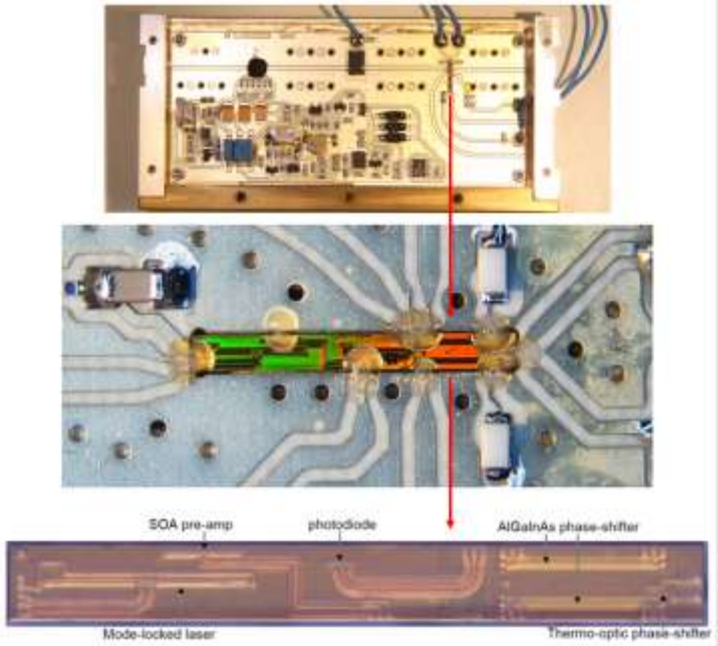
Demonstrated III-V-on-silicon pulsed laser for optical sub-sampling



III-V-on-silicon SOA for high-power photonic analogue links

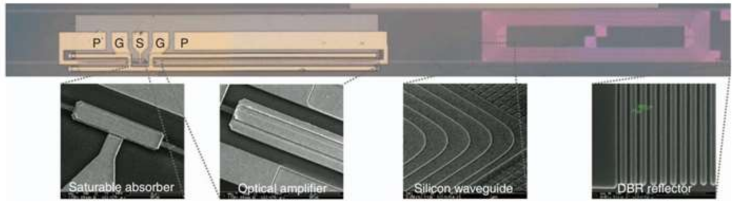


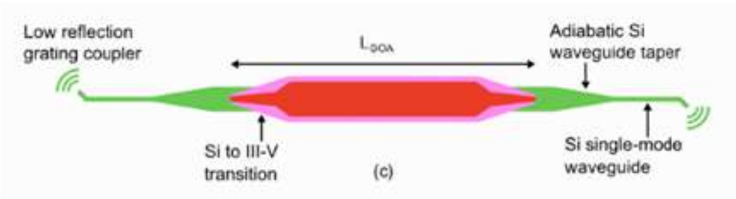
The development of III-V-on-silicon photonic sampler for commnication satelites



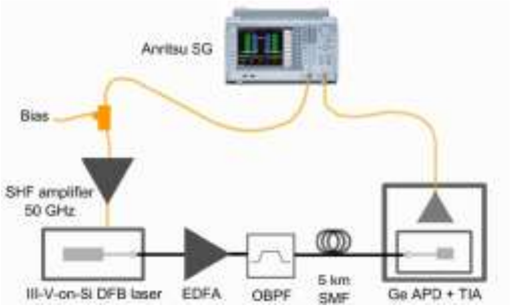
CONCLUSION

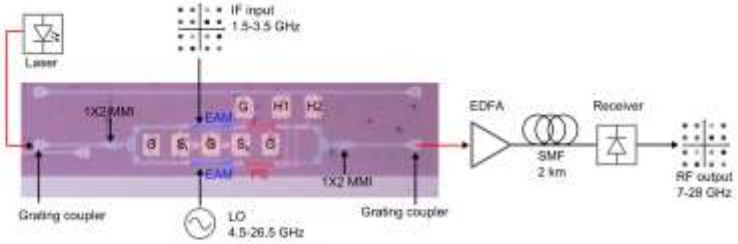
Using heterogeneous silicon photonic technology we were able to create devices with beyond state-of-the-art performance.

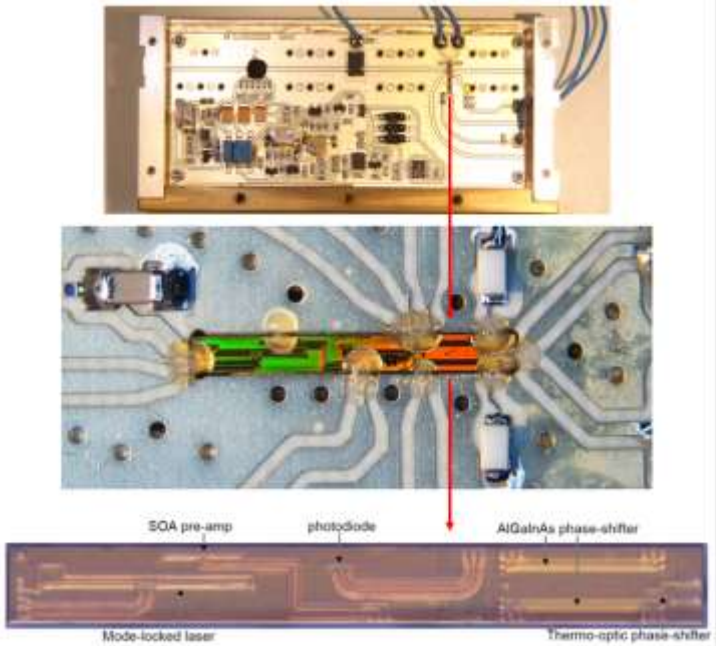




Using state-of-the-art heterogeneous silicon photonic devices we were able to demonstrate several novel subsystems.







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Thank you for your attention.
Are there any questions?

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