17/12/2024

Bridging the Terahertz Gap:
High-Speed Photodiodes on Silicon Nitride

Public PhD Defense Dennis Maes

imec iemn Université de Lille

5G auction: radio spectrum is a precious good

Nieuwkomers in telecomland mogen borst natmaken

Het belangrijkste deel van de 5G-veiling zit erop. Het Roemeense **Digi Communications** verraste met een samenwerking met de West-Vlaamse telecomspeler Citymesh. Wat zijn hun plannen en wat betekenen die voor de Bel

Het hoofdkwartier van Digi Communications in Boekarest. Het bedrijf is geen groentje. Het is actief sinds 1992.

Wie is de winnaar van de 5G-veiling?

Zullen de prijzen voor mobiel internet dalen?

€ 1,42 MILJARD
VOOR SNELLE 5G-VERBINDINGEN

De veiling van frequenties voor snelle 5G-verbindingen heeft de Belgische schatkist uiteindelijk 1,42 miljard euro opgebracht. Proximus, Telenet en Orange Belgium kochten onlangs nog voor 216,5 miljoen euro aan bijkomende gebruiksrechten. Eerder kocht ook Citymesh/Digi al spectrumruimte. *(JVG)*

Regering hoopt bij 5G-veiling markt open te breken

Met vierde telecomspeler dalen prijzen

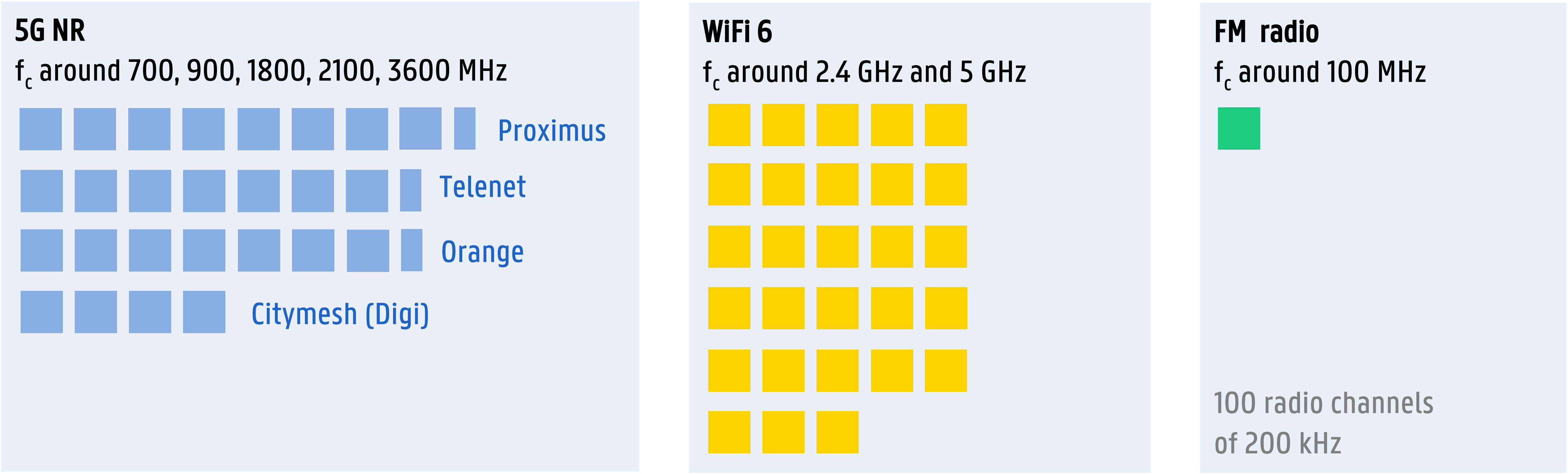
De komst van een vierde telecomspeler - naast Telenet, Proximus en Orange - zou de prijzen voor internet, televisie en gsm met 13 procent doen dalen. Dat blijkt uit een studie in opdracht van het Overlegcomité.

belden tegen. Zo is Vlaanderen bezorgd over een mogelijke verstoring van de concurrentie. Langs Franstalige kant weerklinkt er vooral bezorgdheid over de effecten op milieu en gezondheid, onder andere

Tegelijk zijn de bezorgdheden niet onterecht. Zo zullen de winsten van de operatoren op mobiele diensten zowat 40 procent dalen. "Het disproportioneel voortrekken van een vierde speler zet de markt serieus onder druk", reageert technologiefederatie Agoria

Wireless communication: higher speeds require more bandwidth

Channel capacity is a linear function of channel bandwidth



5G NR

f_c around 700, 900, 1800, 2100, 3600 MHz

Proximus

Telenet

Orange

Citymesh (Digi)

WiFi 6

f_c around 2.4 GHz and 5 GHz

FM radio

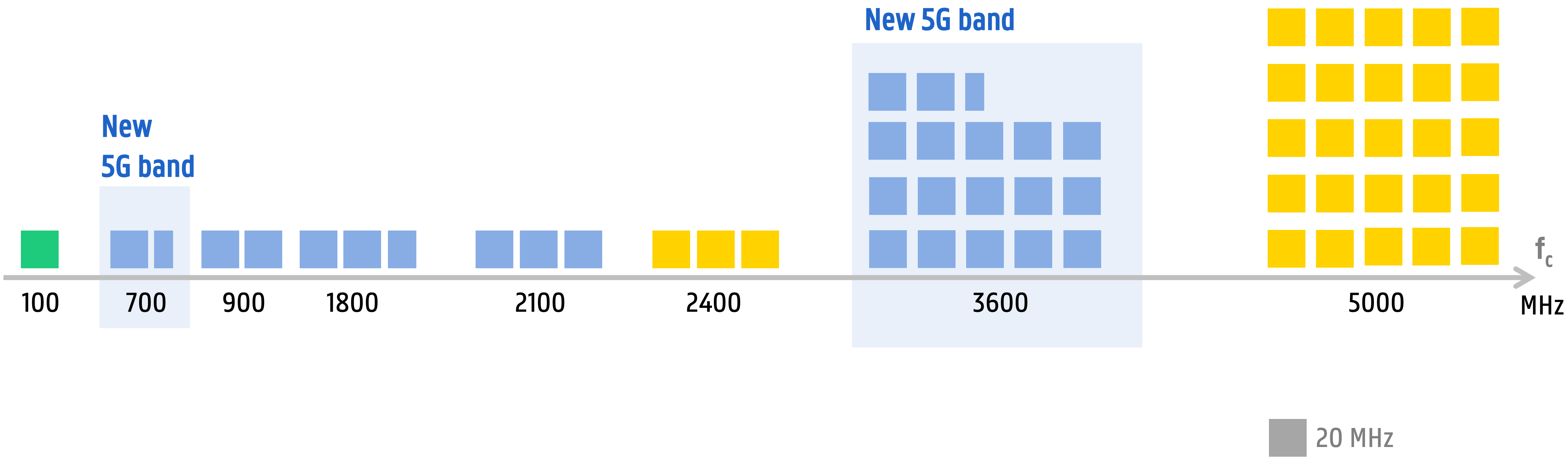
f_c around 100 MHz

100 radio channels
of 200 kHz

◼ 20 MHz

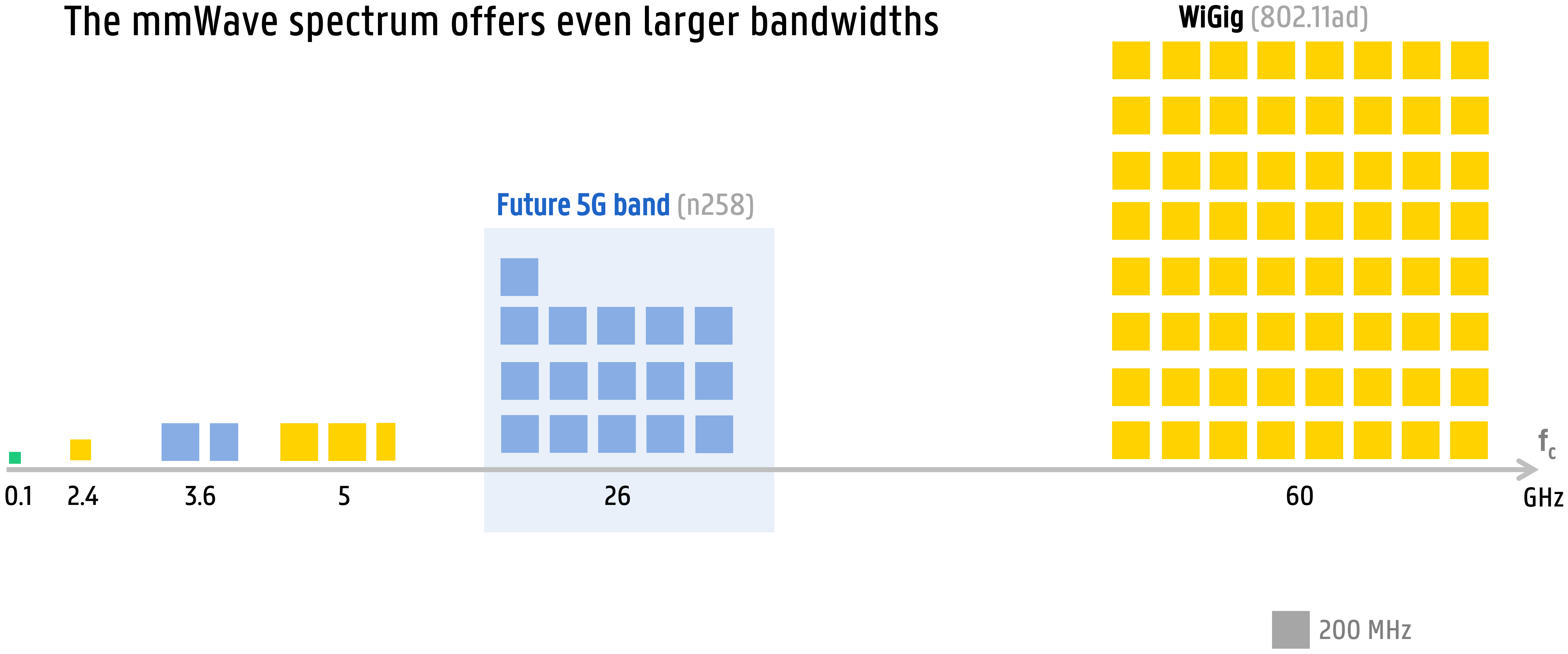
Wireless communication: higher speeds require more bandwidth

Radio waves: central frequency $\mathbf{f_c}$ and channel bandwidth **B**



Wireless communication: higher speeds require more bandwidth

The mmWave spectrum offers even larger bandwidths



Wireless communication: higher speeds require more bandwidth

For next generation communications we are looking beyond mmWave

Electromagnetic waves come in all sizes

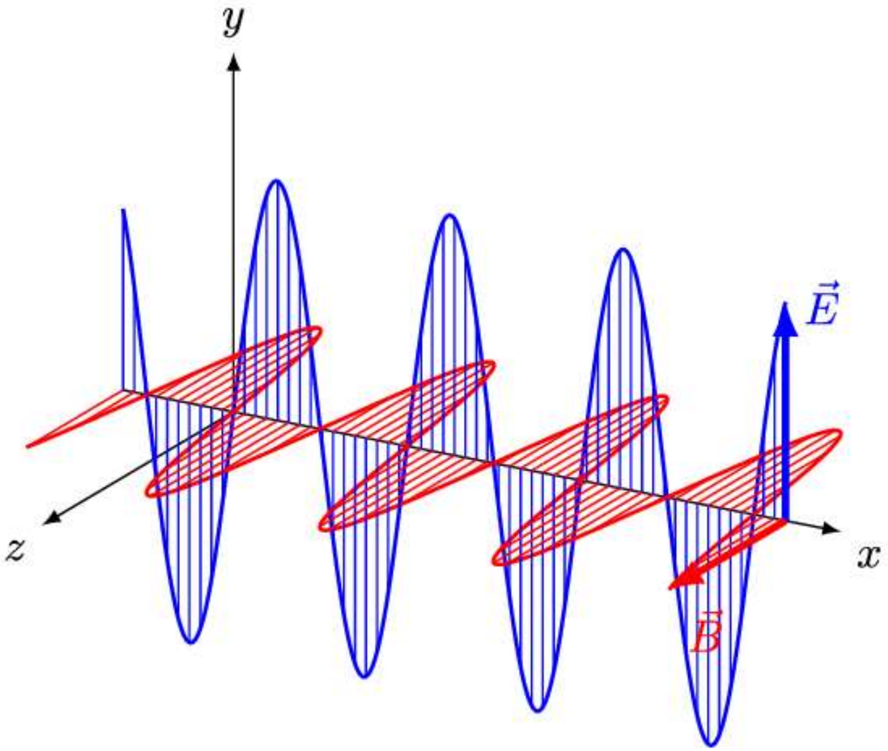
Energy waves with two parts:
an **electric field** and a **magnetic field**

Speed of light

300 000 000 m/s

Frequency $$f = \frac{c}{\lambda}$$

Wavelength



Electromagnetic waves come in all sizes

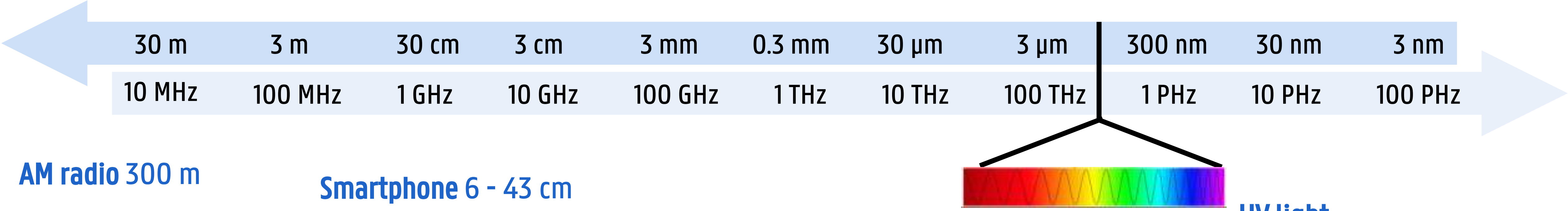
MRI 1 - 100 m

Microwave oven 12 cm

Weather radar 2 cm

Remote control 1 µm

X-rays 10 nm



30 m	3 m	30 cm	3 cm	3 mm	0.3 mm	30 µm	3 µm	300 nm	30 nm	3 nm
10 MHz	100 MHz	1 GHz	10 GHz	100 GHz	1 THz	10 THz	100 THz	1 PHz	10 PHz	100 PHz

AM radio 300 m

Smartphone 6 - 43 cm

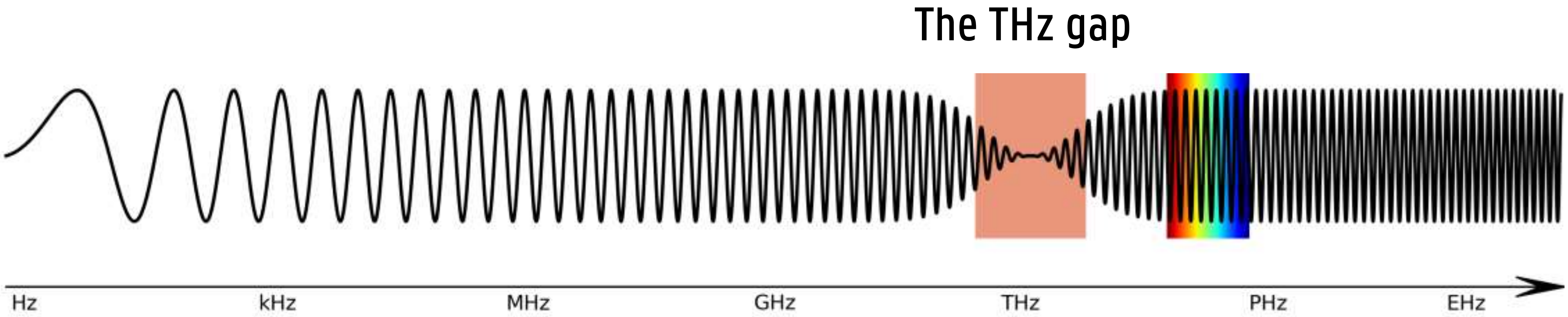
FM radio 3 m

Visible light

400 - 700 nm

UV light

Generating THz waves is difficult

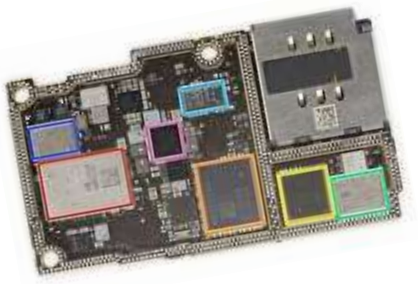


Electronic oscillators

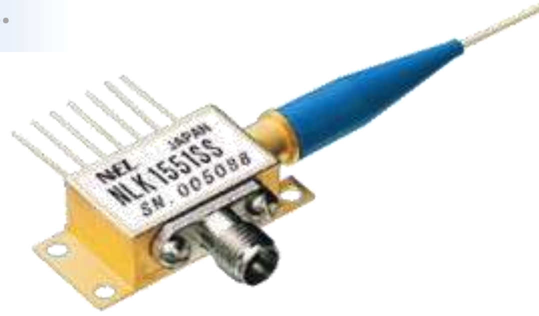
Crystal oscillator + frequency synthesizer (PLL)

Light sources

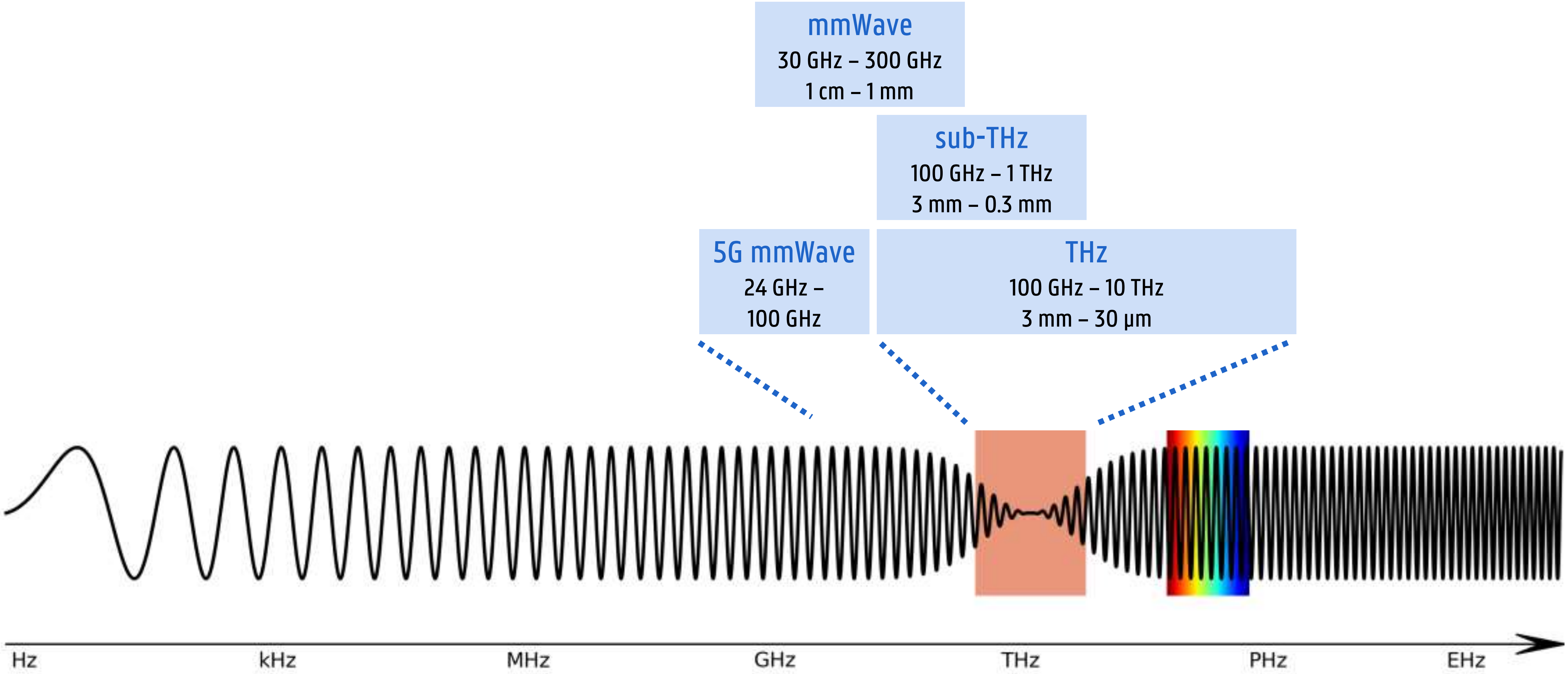
Lasers, LEDs...



Photonic technology
for THz generation?



Generating THz waves is difficult



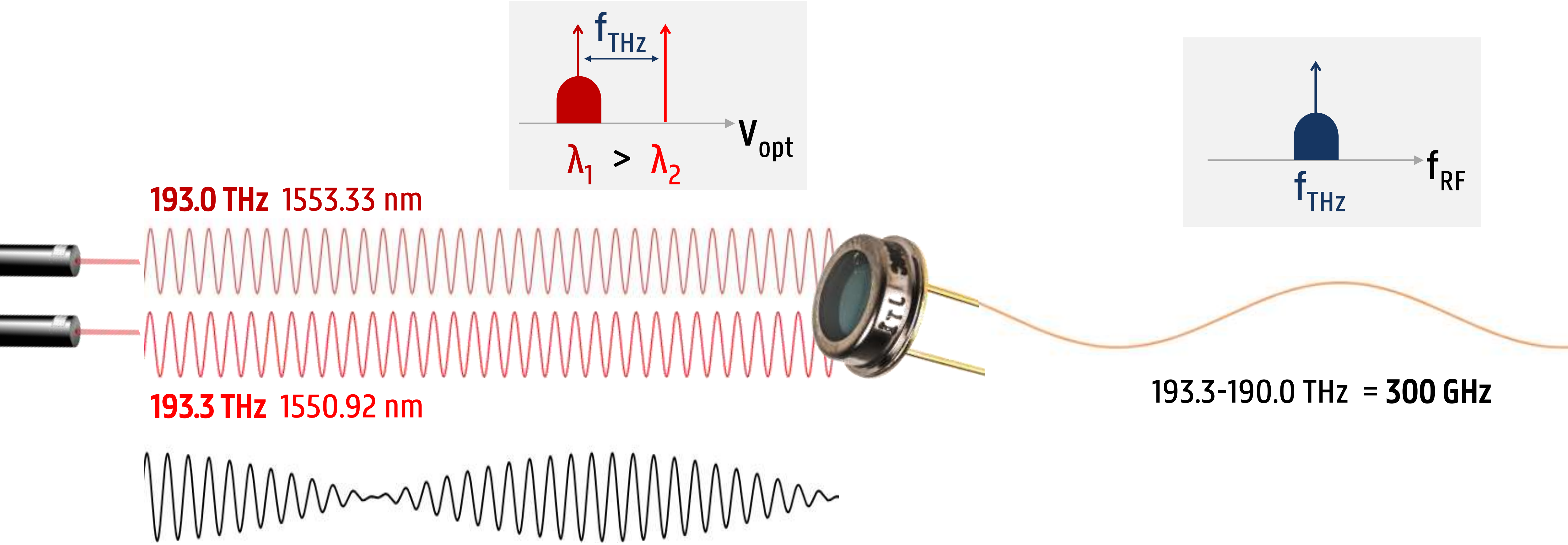
mmWave
30 GHz – 300 GHz
1 cm – 1 mm

sub-THz
100 GHz – 1 THz
3 mm – 0.3 mm

5G mmWave
24 GHz –
100 GHz

THz
100 GHz – 10 THz
3 mm – 30 µm

Photomixing: using light to generate THz waves



193.0 THz 1553.33 nm

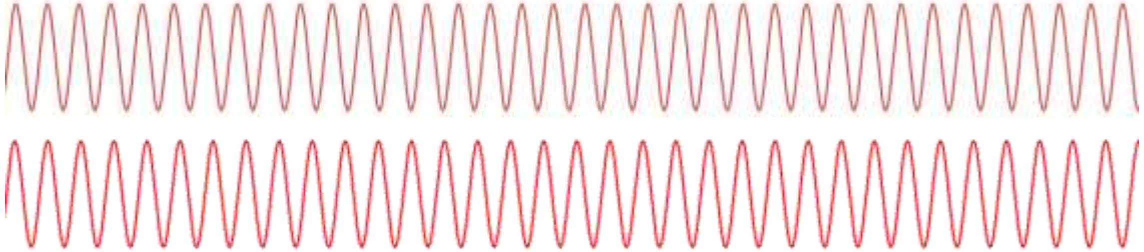
193.3 THz 1550.92 nm

193.3-190.0 THz = **300 GHz**

Photomixing: using light to generate THz waves

Analogy: sound v = 343 m/s

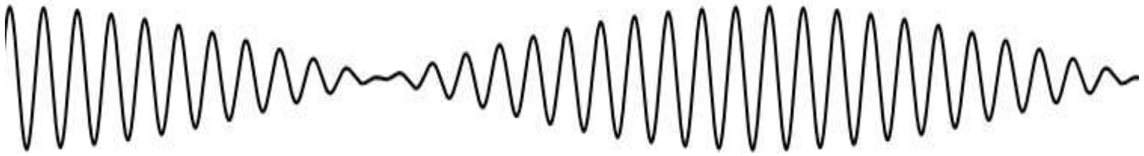
440 Hz 78cm



443 Hz 77.4cm

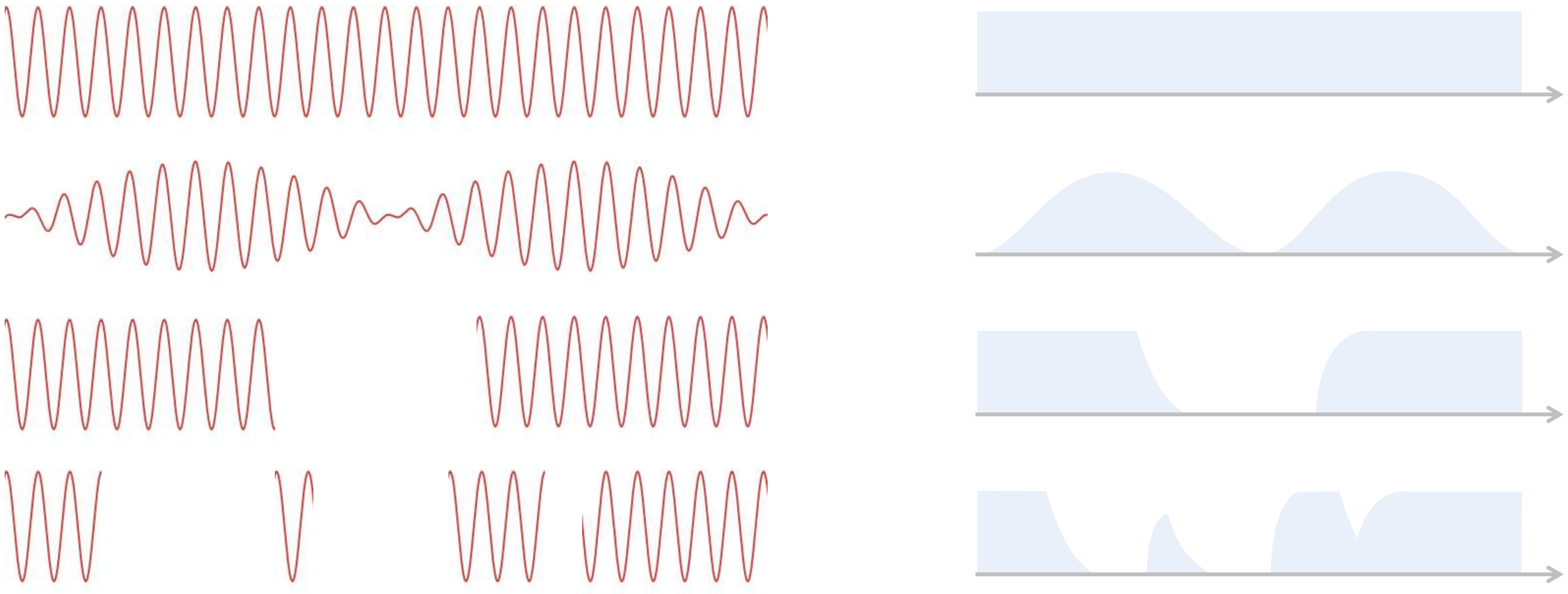
Beating of sound waves

443 – 440 Hz = 3 Hz = **3 s^{-1}**



When is a photodetector *fast?*

Follow the change in intensity equally fast

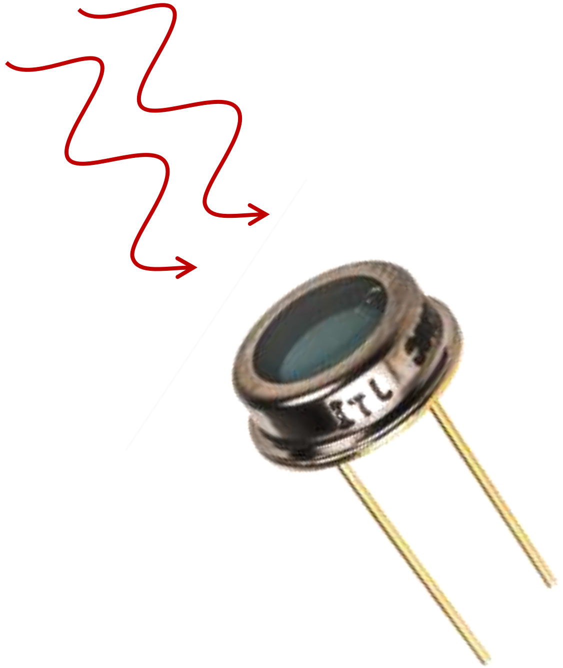


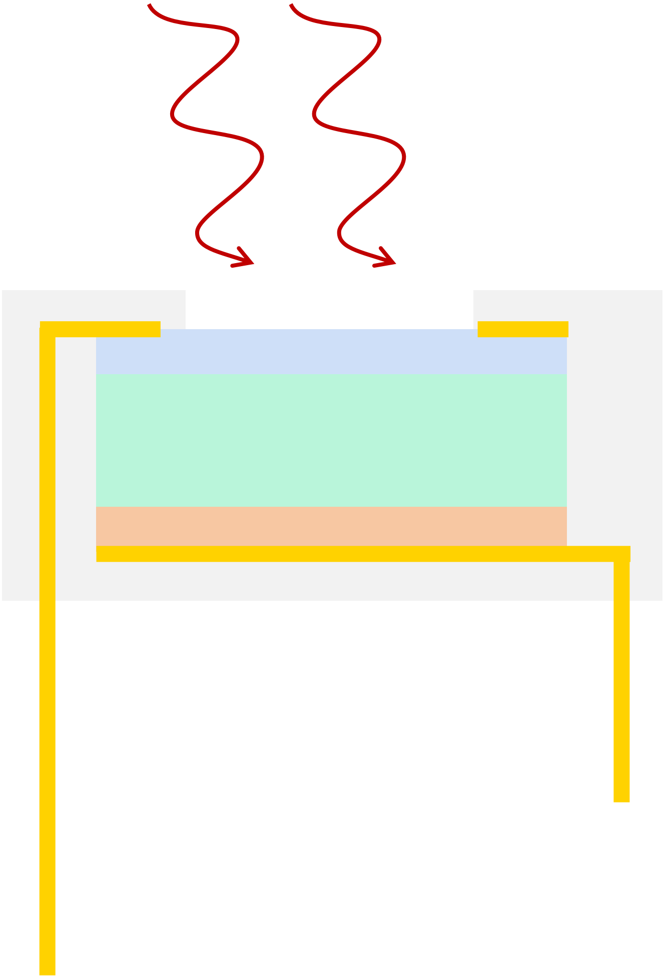
My PhD research questions

1. How can we make a fast photodetector to generate THz waves?

PIN photodiode: a semiconductor-based photodetector

A PIN diode is a *sandwich* of p-type, intrinsic, an n-type semiconductor layers.



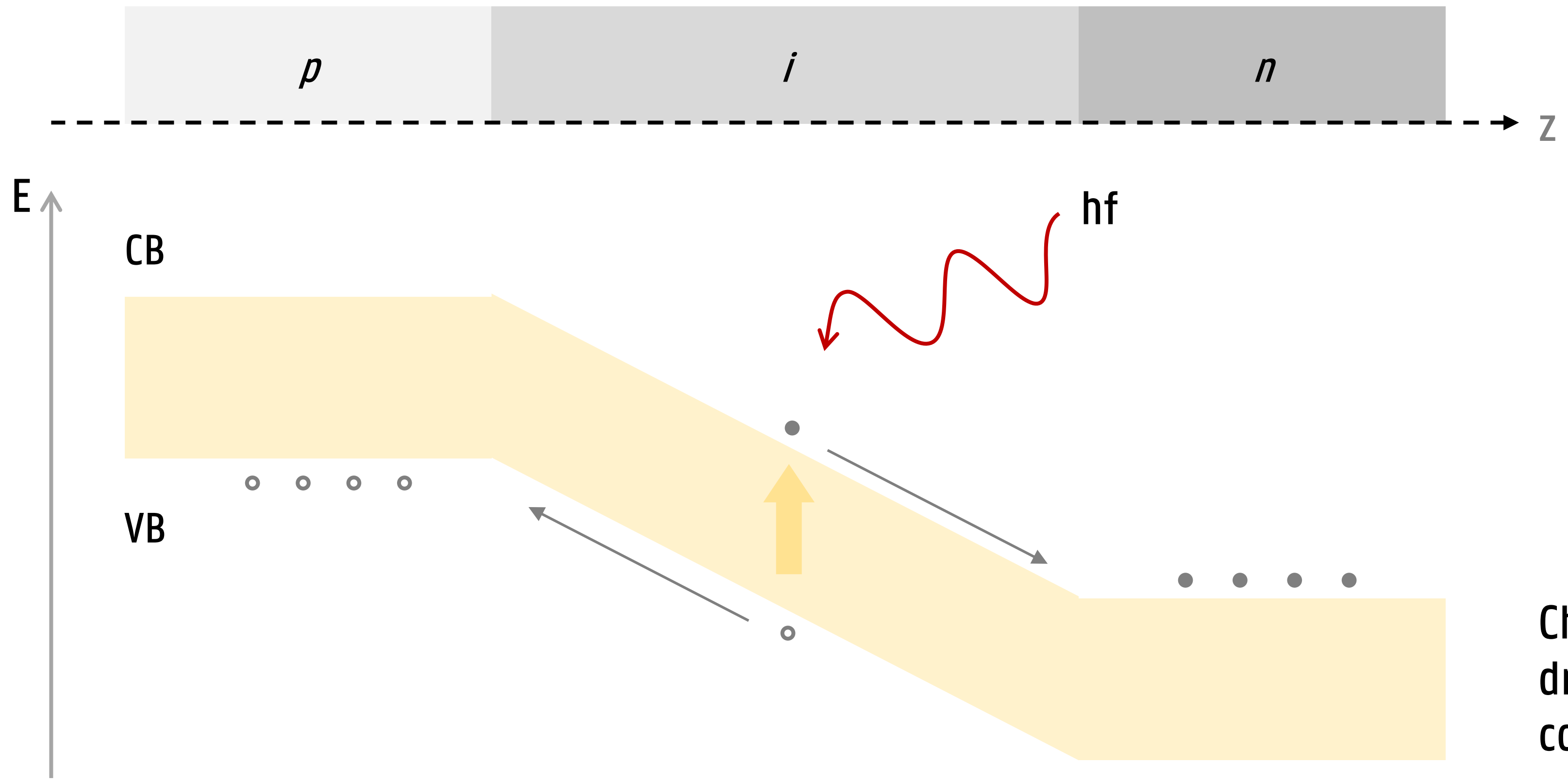


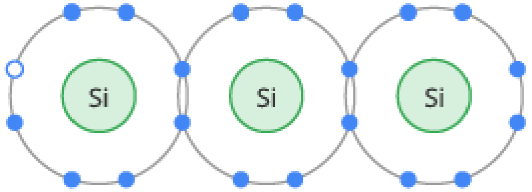
p-type	dopant: acceptor ion
Intrinsic type	no dopants
n-type	dopant: donor ion

Photoelectric effect causes a photon to create an electron-hole pair

Light is both a wave and a particle: a photon

$v_{electron} \sim 4 \times 10^7$ cm/s
$v_{hole} \sim 5 \times 10^6$ cm/s



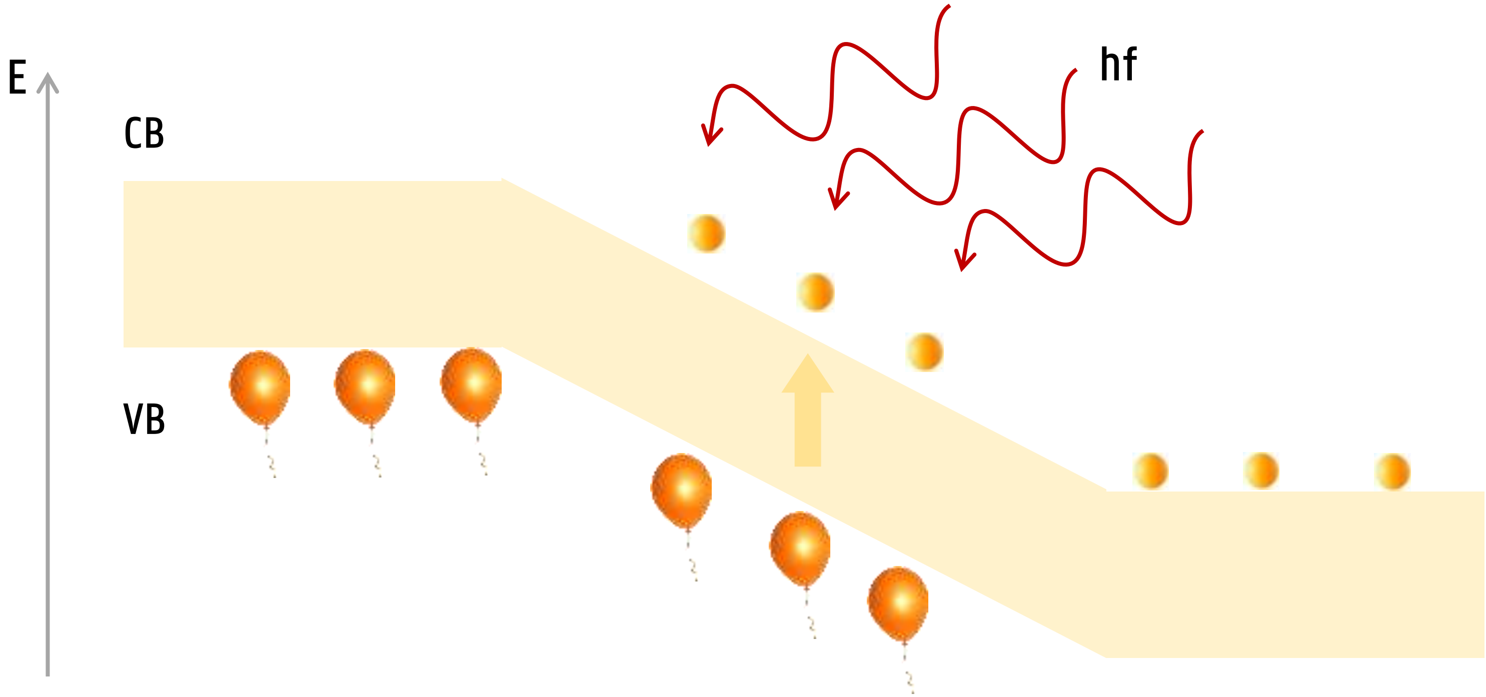


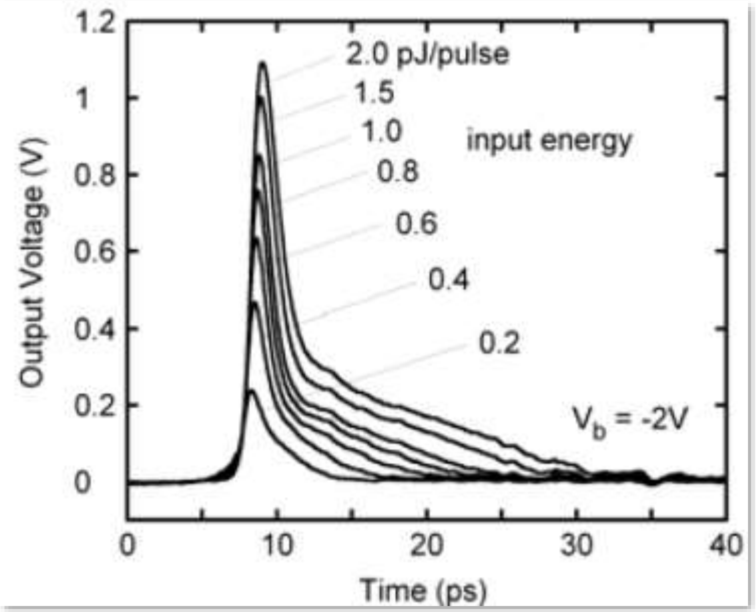
Charges are created and then drift/diffuse to the anode and cathode contact creating a (photo)current

Charges travel at different speed

$v_{electron} \sim 4 \times 10^7$ cm/s
$v_{hole} \sim 5 \times 10^6$ cm/s

Electrons have a higher mobility than holes

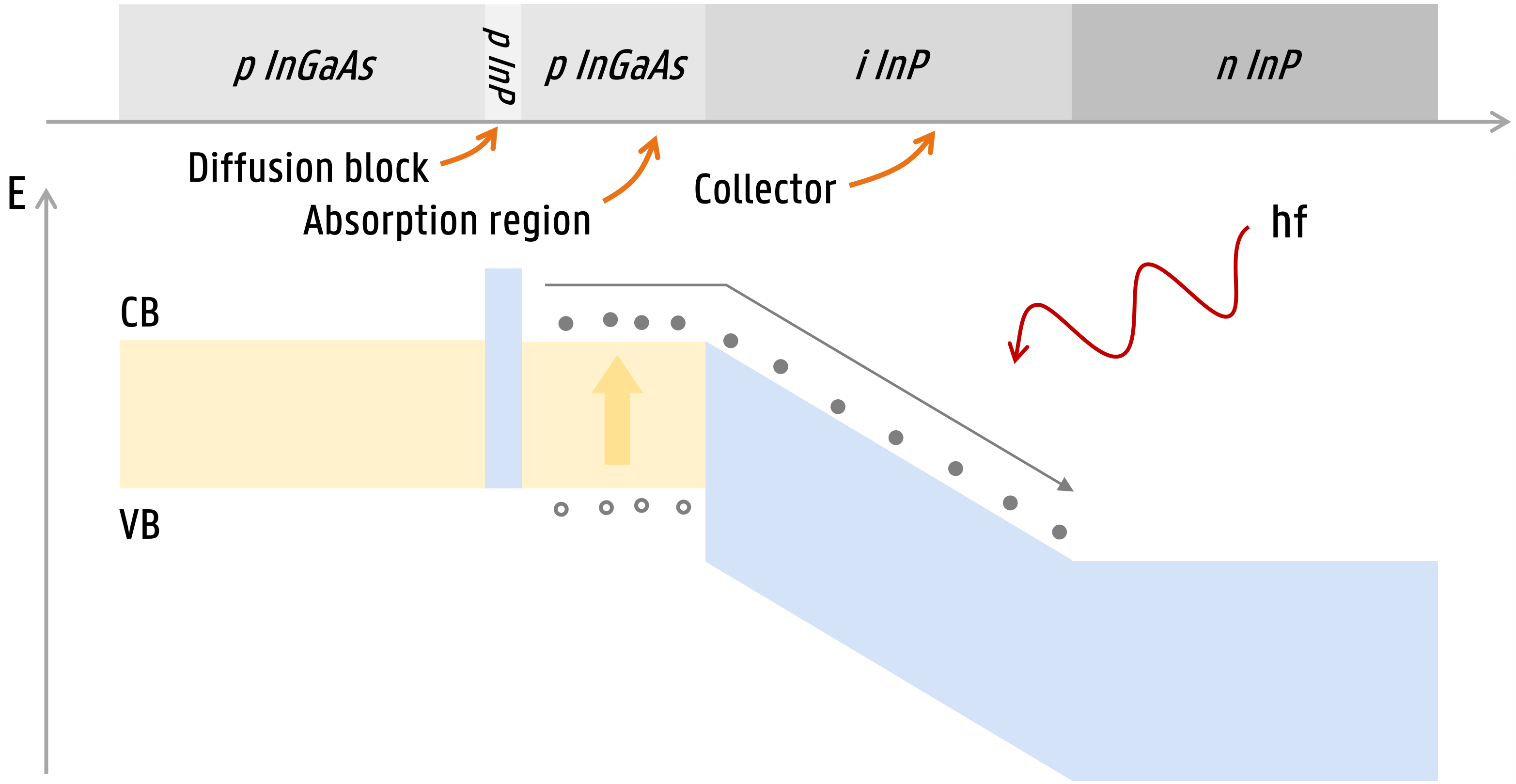




[T.Nagatsuma and H. Ito, 2010]

Uni-Traveling-Carrier (UTC) photodiodes: faster than PIN

Split the central part in two: an absorber and a collector



[Tadao Ishibashi, 1997]

Uni-Traveling-Carrier Photodiodes

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Abstract

A new ultrafast photodiode, uni-traveling-carrier photodiode (UTC-PD) is proposed, and its photoresponse characterization on fabricated devices is presented. The prime feature of this PD is much higher output saturation current than that in a conventional pin-PD. This is achieved by reducing the space charge effect by utilizing electron velocity overshoot in the carrier collecting layer. A 20 μm^2-area UTC-PD fabricated with MOVPE-grown InP/InGaAs heterostructure generated an output voltage as high as 2 V for a 25 Ω load while maintaining an f_{3dB} of 80 GHz. Proper device operations at high photocurrent densities up to 400 kA/cm^2 were observed.

Key Words
Detectors, Optoelectronics, Ultrafast Devices.

Introduction

It is very important to achieve high saturation power and broad bandwidth simultaneously in the photodetectors used in various fiber-optic communication systems and for ultrafast measurements. A high output voltage with no

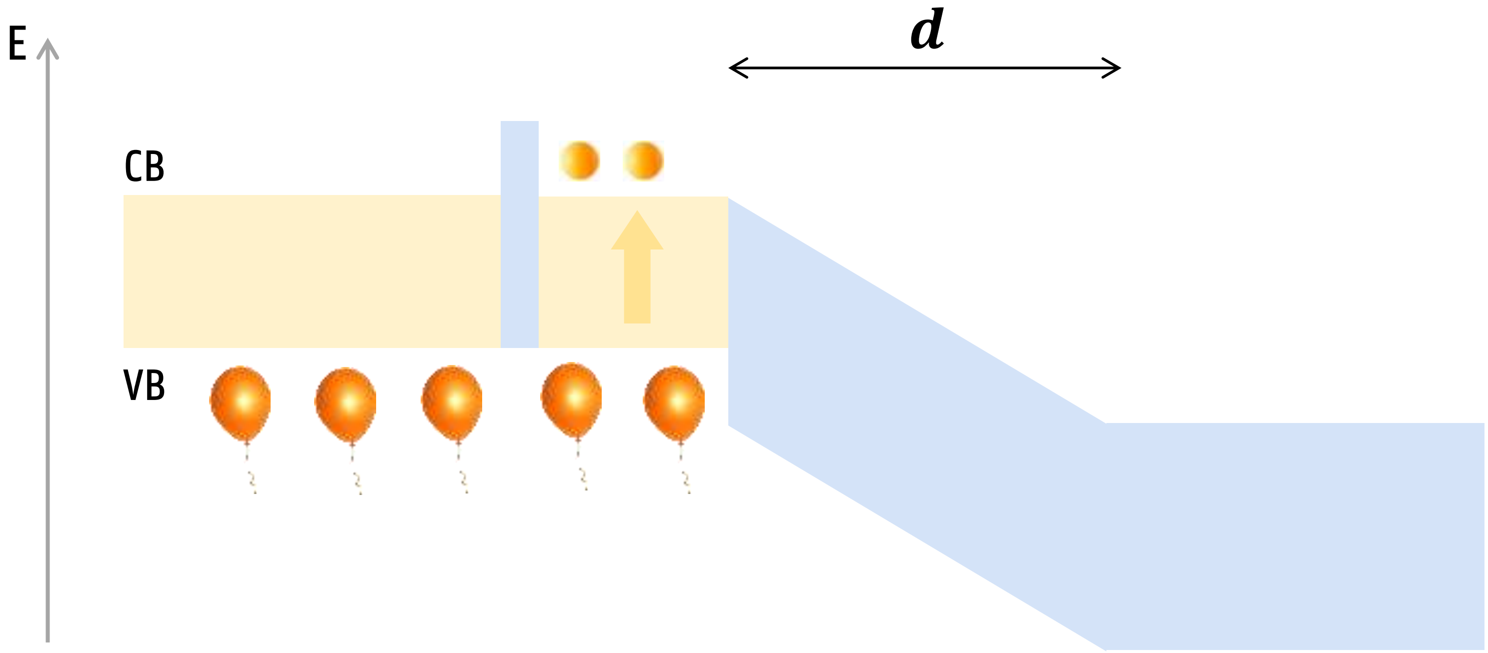
in possible current densities during high frequency operations. Because of the much lower drift velocity, holes are responsible for the dominant space charge, and induced field modulation can more easily decelerate low-mobility holes. Another important fact is that photoresponse speed is mostly determined by hole transport due to the same reasons. However, when only high-velocity electrons are used, it is possible to delay the onset of the space charge effect, which can lead to much easier high current operations.

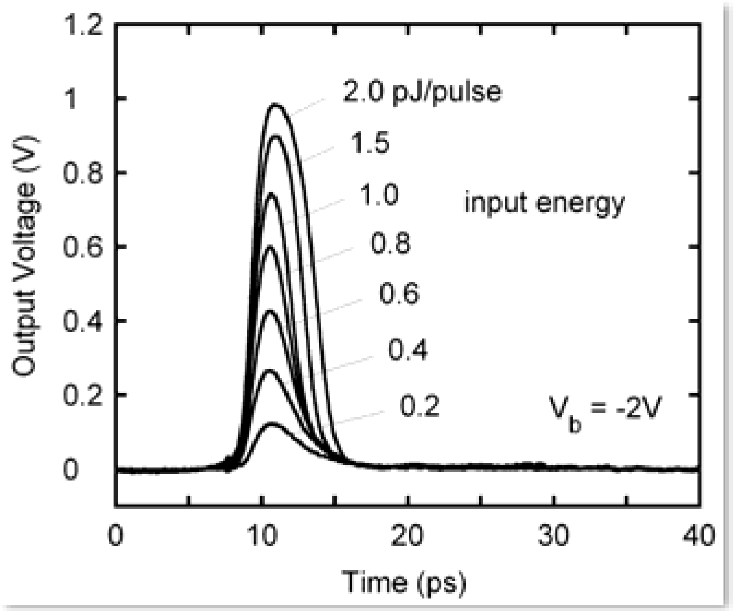
This paper proposes a uni-traveling-carrier photodiode (UTC-PD) in which only electrons are used as active carriers for enhancing saturation output current. The key to the higher output is superior high-field electron transport properties to those for hole in InP/InGaAs materials. We also study photoresponse speed of the UTC-PDs by small signal analysis. The analysis predicts the response to be sufficiently fast. A preliminary experiment on InP/InGaAs PDs showed that a photocurrent density in the mid 10^5 A/cm^2 range permitted an output voltage as high as 2 V for a 25 Ω load as well as a 3-dB bandwidth of 80 GHz.

Design Considerations

Uni-Traveling-Carrier (UTC) photodiodes: faster than PIN

Only fast electrons contribute to photocurrent





[T. Nagatsuma and H. Ito, 2010]

Transit time (delay)

$$\tau_{TT} = d\, v_{e^-}$$

A second constraint: larger = slower

Resistance

Time constant (delay)

$$\tau = RC$$

Capacitance

A large photodiode has a large capacitance

Capacitance

Area

$$C = \varepsilon \frac{A}{d}$$

Thickness

Simple analogy: a bucket of water

Bucket with a capacity **C** and opening at the bottom (1/**R**)

A second constraint: larger = slower

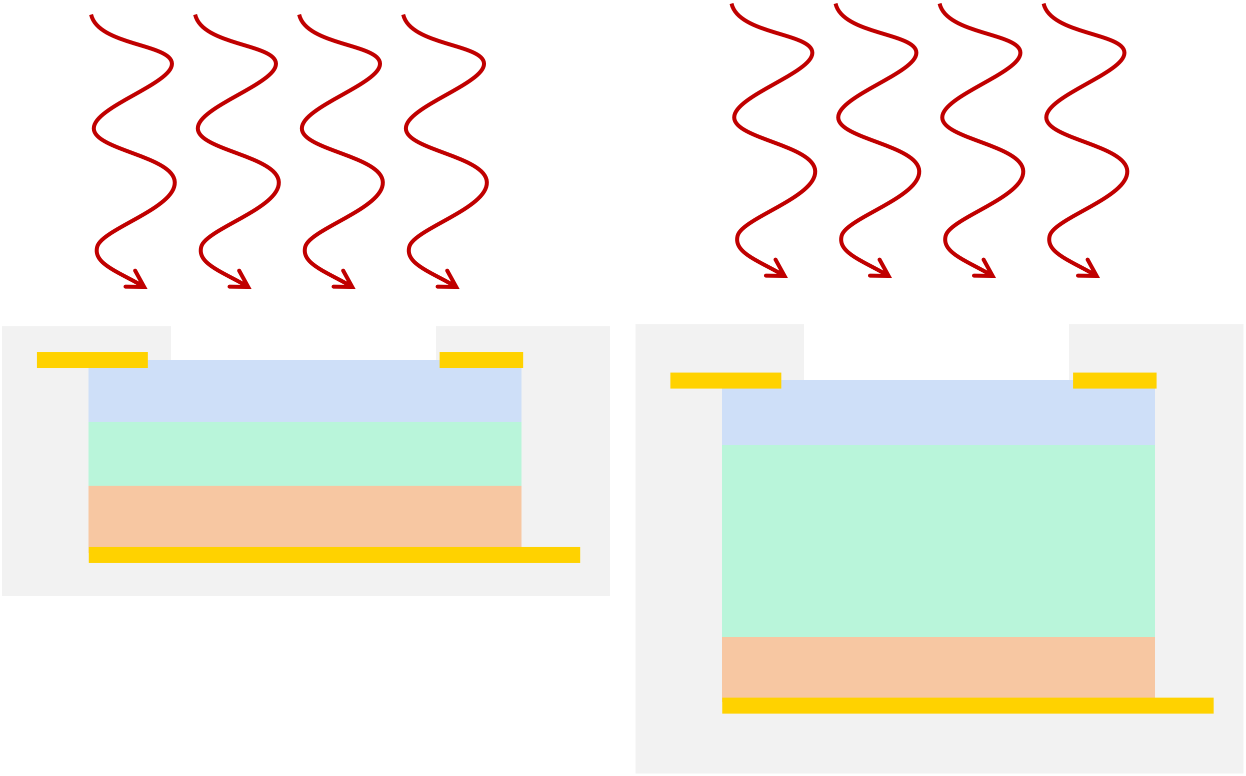
Capacitance

$$C = \varepsilon \frac{A}{d}$$

Area

Thickness

Increase thickness *d*?



$$\tau = RC$$

$$\tau_{TT} = d\, v_{e^-}$$

In practice limited thickness
due to transit time (delay)

A second constraint: larger = slower

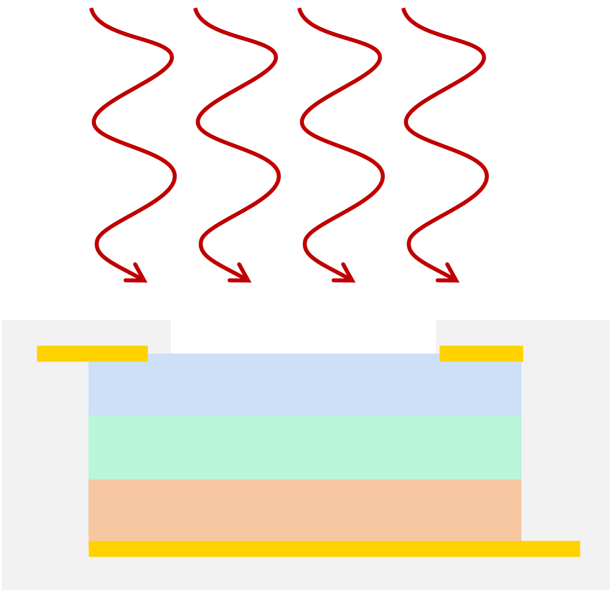
Capacitance

Area

$$C = \varepsilon \frac{A}{d}$$

Thickness

Reduce area *A*?



Responsivity **R** is the ratio of electrical current to incident light

Efficiency **η** is 100% if every photon is converted into electron-hole pair

My PhD research questions

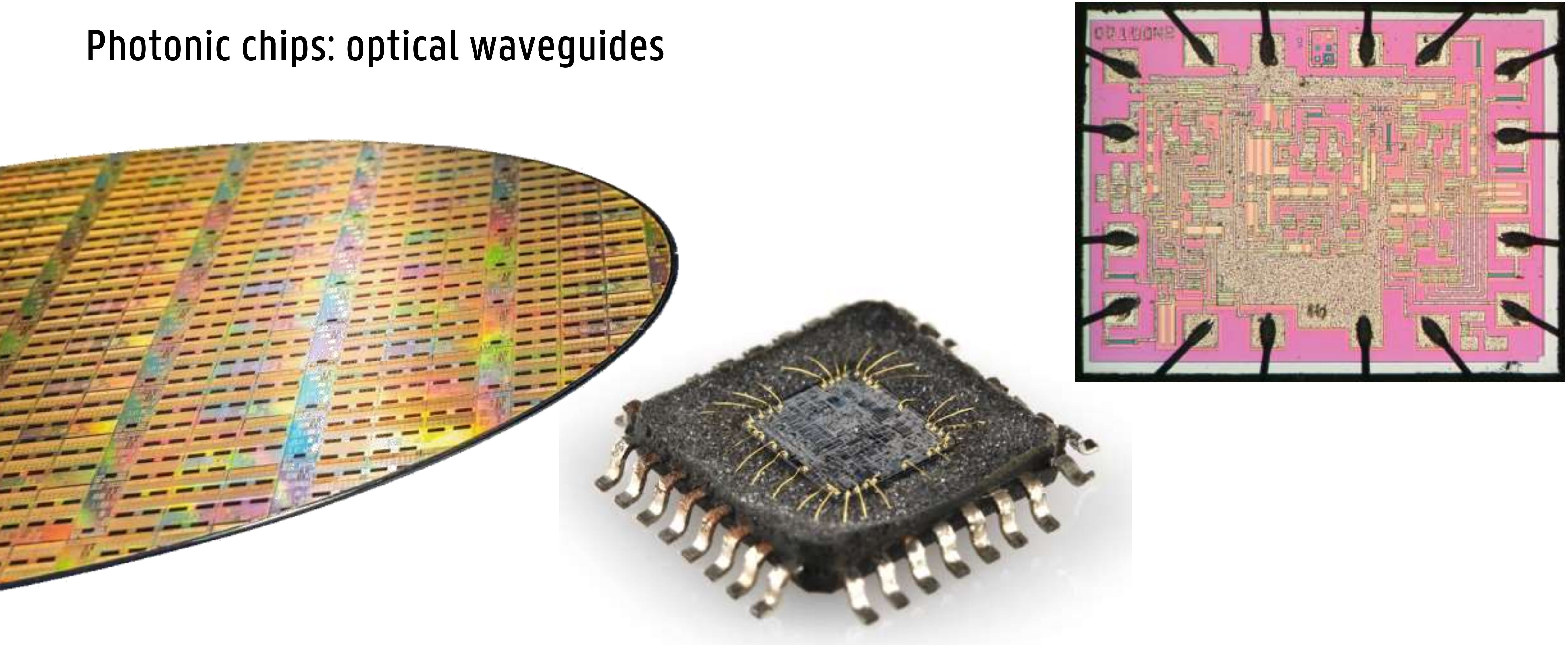
1. How can we make a fast photodiode to generate THz waves?
   A UTC photodiode
2. How do we make it small without sacrificing responsivity?

Bridging the Terahertz Gap:
High-Speed Photodiodes on Silicon Nitride Photonic Chips

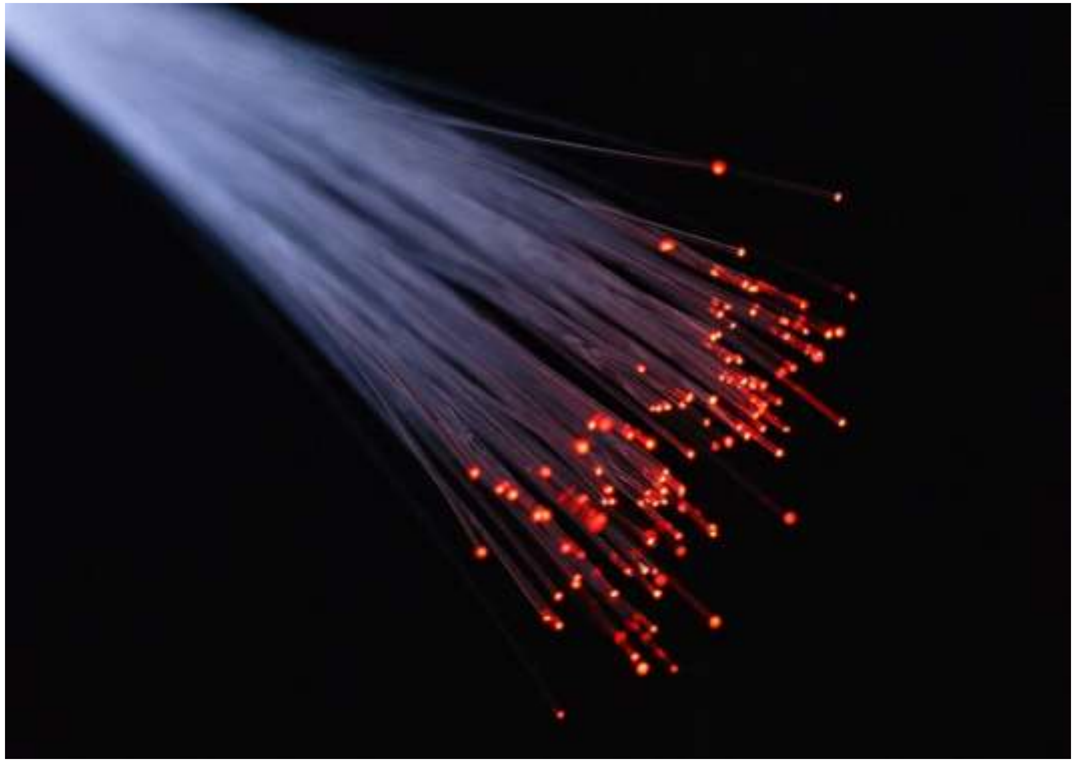
Scaling down optical components to microchip sizes

Electronic microchips: transistors and microscopic wires

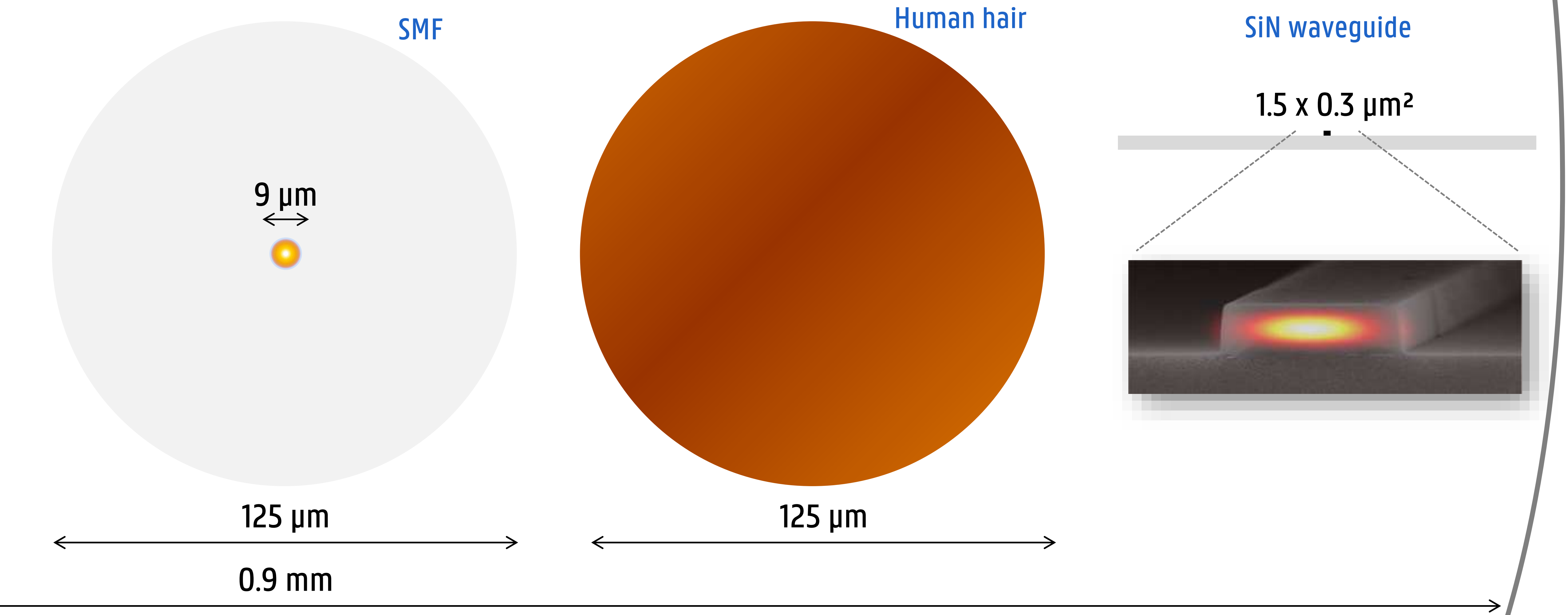
Photonic chips: optical waveguides



Waveguides are a microscopic version of the optical fiber



Silicon Nitride waveguides guide the light around the chip



SMF

9 µm

125 µm

0.9 mm

Human hair

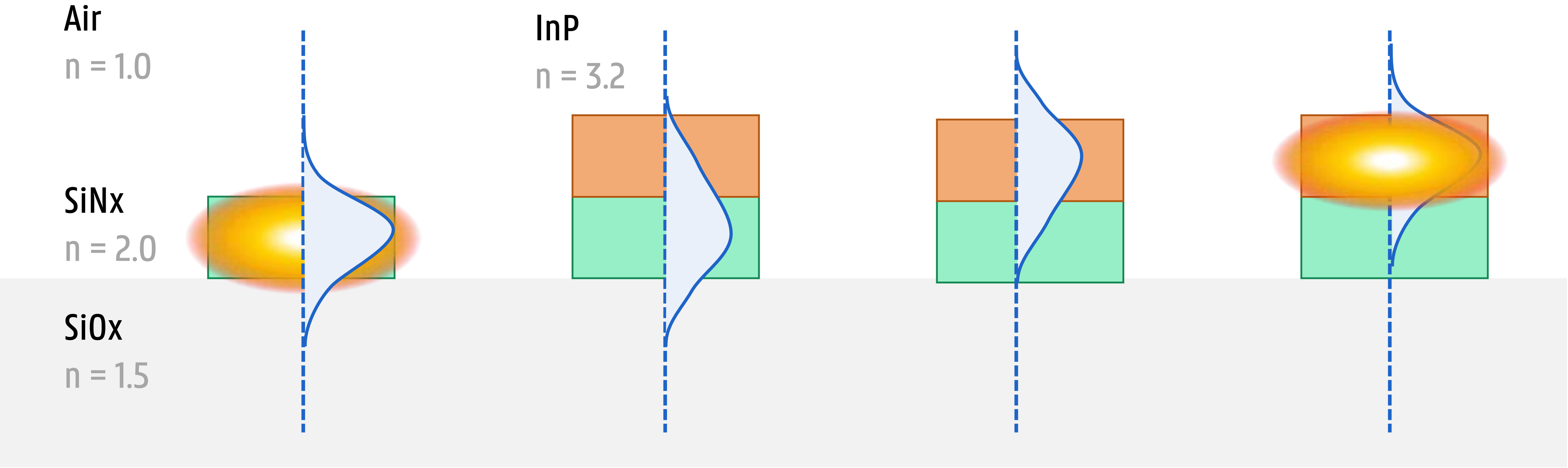
125 µm

SiN waveguide

1.5 x 0.3 µm²

Light couples evanescently to a different material

Light is confined to the material with the highest optical index ***n***



Air
n = 1.0

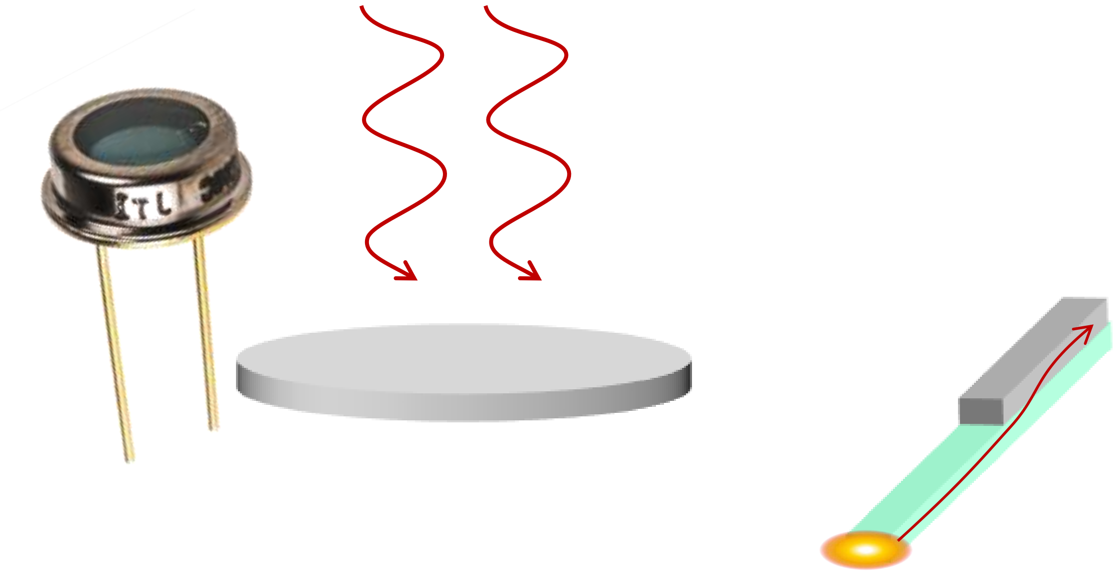
InP
n = 3.2

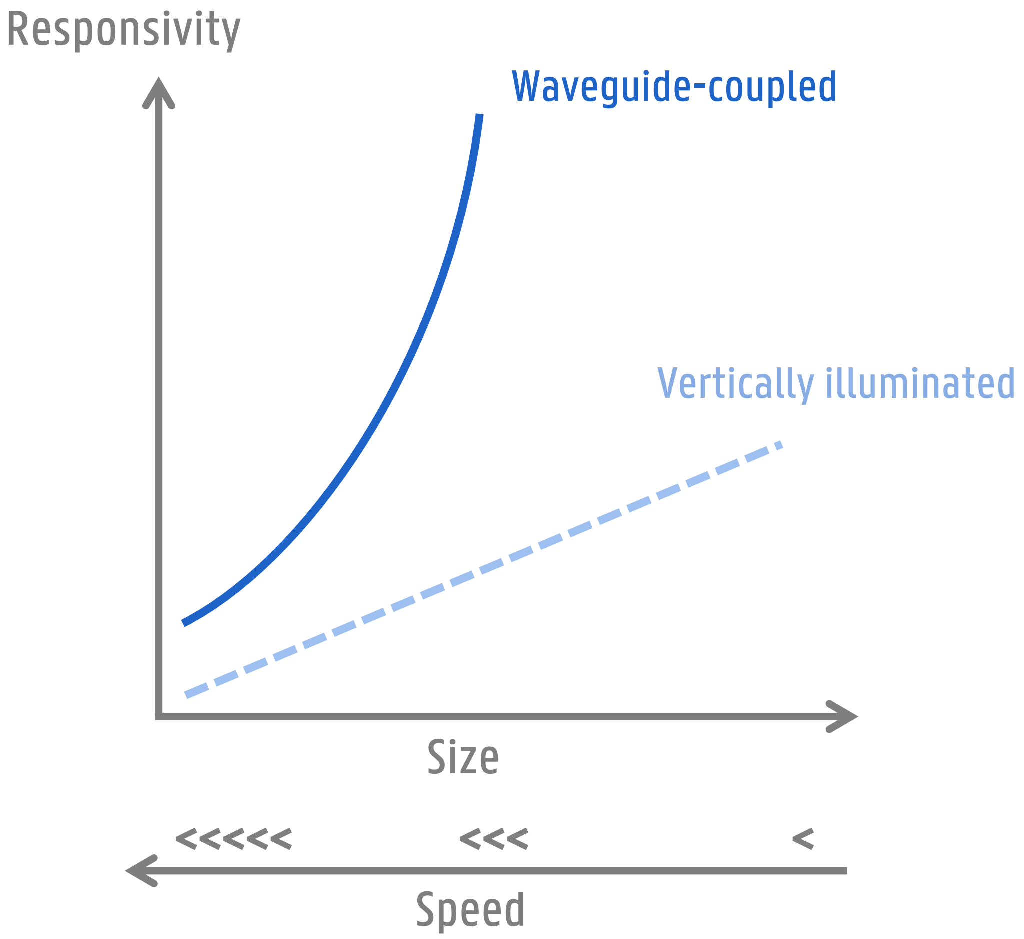
SiNx
n = 2.0

SiOx
n = 1.5

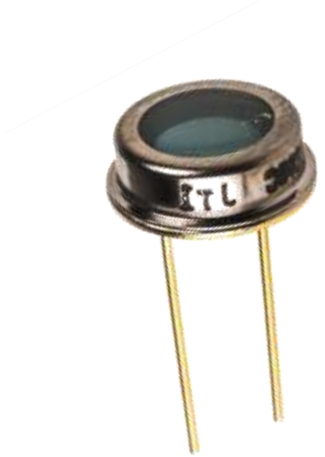
Achieving a high responsivity for a small device

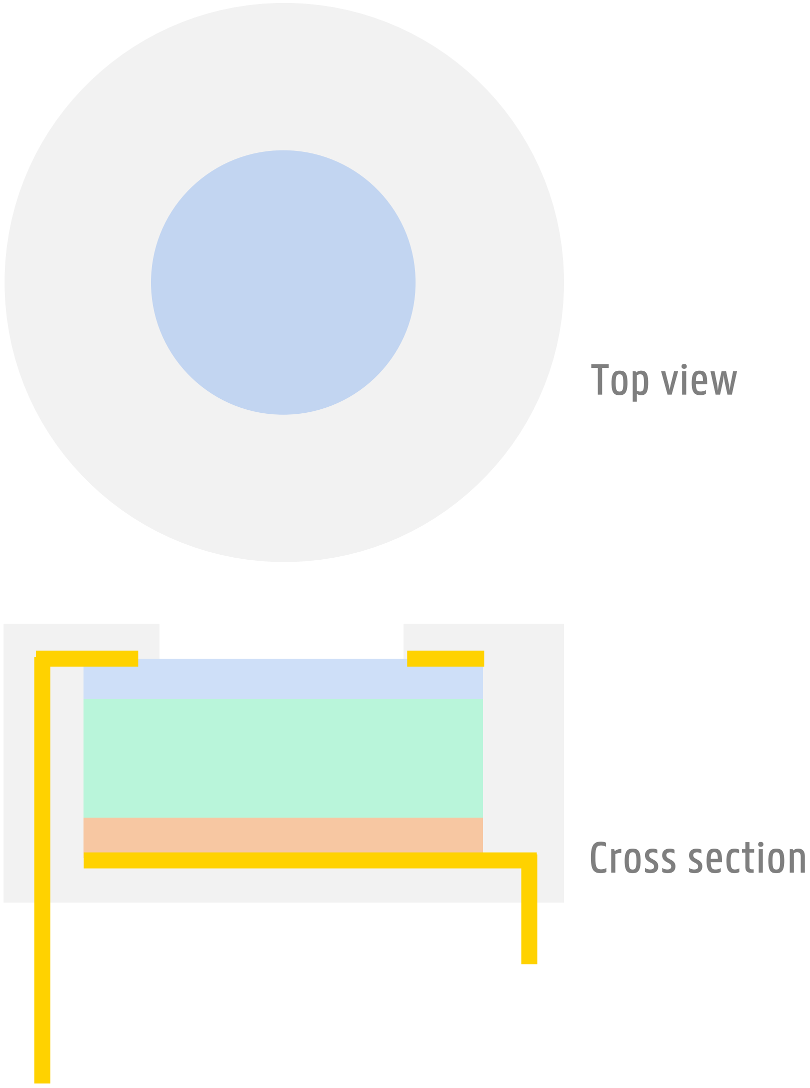
From a vertically-illuminated PD to a waveguide-coupled chiplet

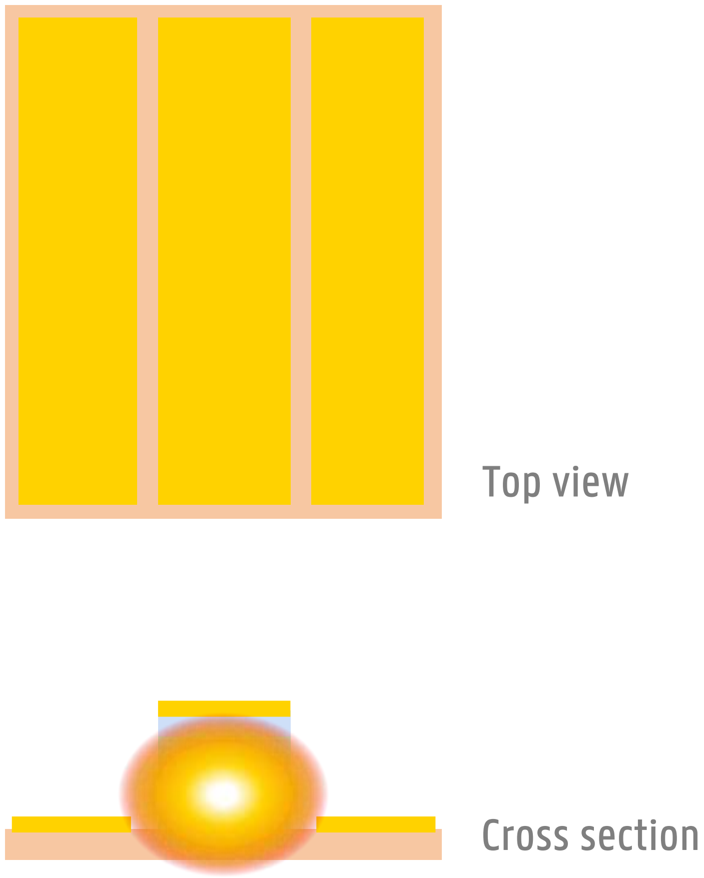




Achieving a high responsivity for a small device



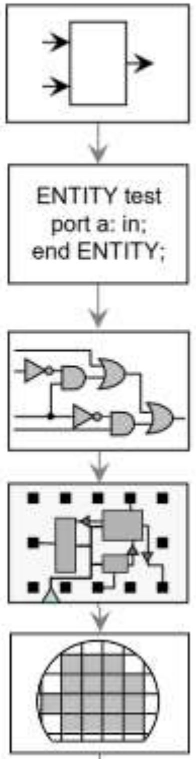




My PhD research questions

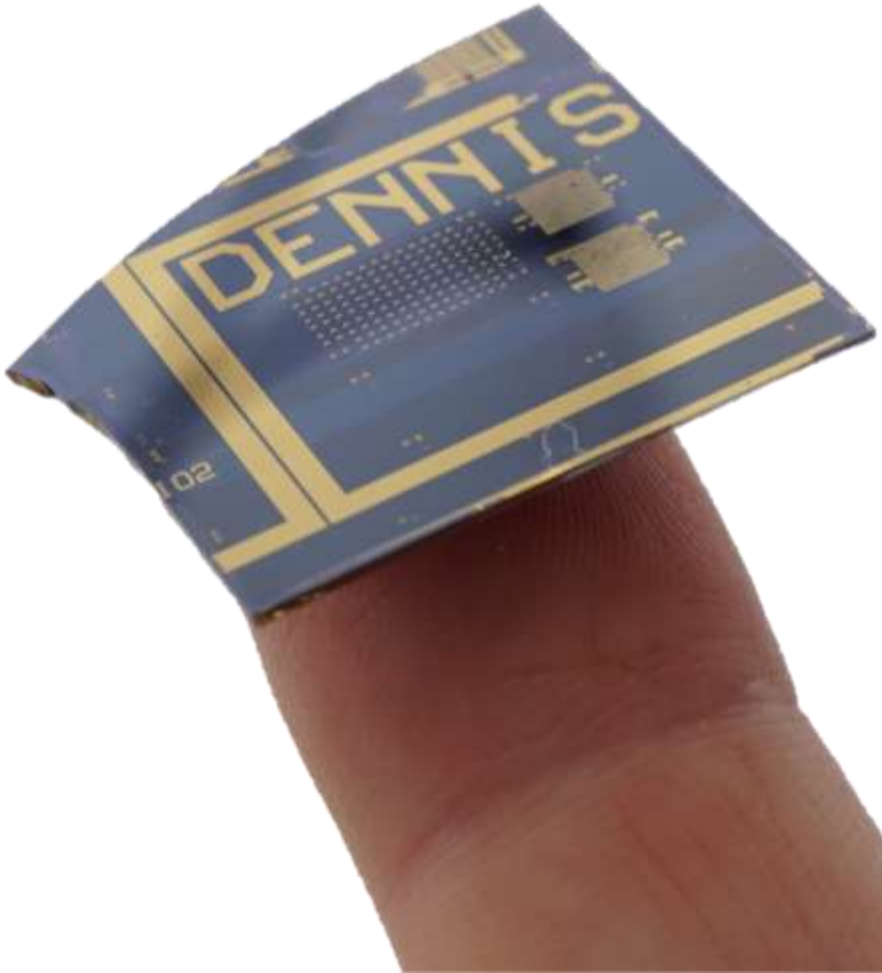
1. How can we make a fast photodetector to generate THz waves?
   A UTC photodiode
2. How do we make it small without sacrificing responsivity?
   Design a waveguide-coupled device
3. How do we make such a small waveguide-coupled device on chip?

The process of creating a (photonic) chip



```
ENTITY test
port a: in;
end ENTITY;
```

1. System specifications
2. Architectural design
3. Circuit design + simulation
4. Layout
5. **Fabrication**
6. Testing
7. Packaging



Cleanroom for dust-free fabrication

A large set of tools for nano- and microfabrication

Add layers

Growing thin layers of semiconductors
molecular beam epitaxy (MBE)

Depositing layers of insulators or metal
plasma-enhanced chemical vapor deposition (PECVD), sputtering, evaporation

Coating layers of photoresist or polymers
spin coater, spray coater

Remove layers

Dry/wet etching of thin layers
Reactive Ion Etching (RIE), Inductively Coupled Plasma (ICP) etching, acids and bases

Lift-off with solvents
of metal layers on top of photoresist

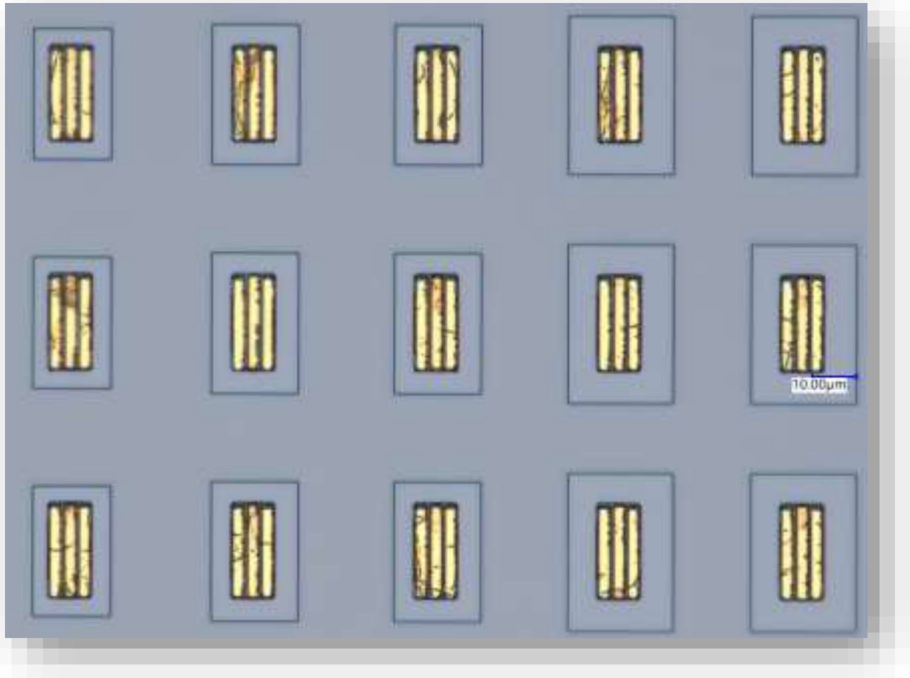
Make shapes

Patterning layers
lithography (UV light) or **e-beam** lithography (electron beams)

The *hammer* and *chisel* for chips

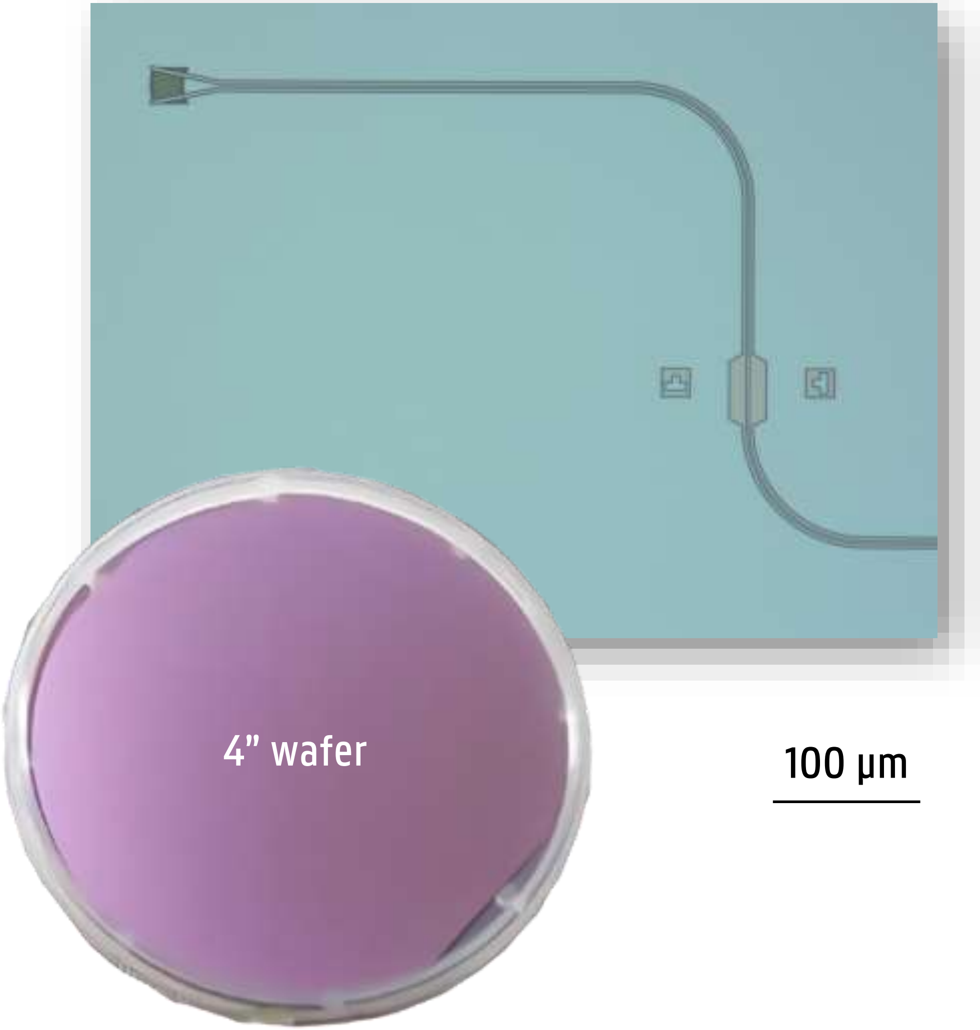
How do we get the InP photodiode on top of a SiN waveguide?

Sample 1: InP chip with >1000 photodiodes



50 µm

Sample 2: SiN chip with a photonic circuit

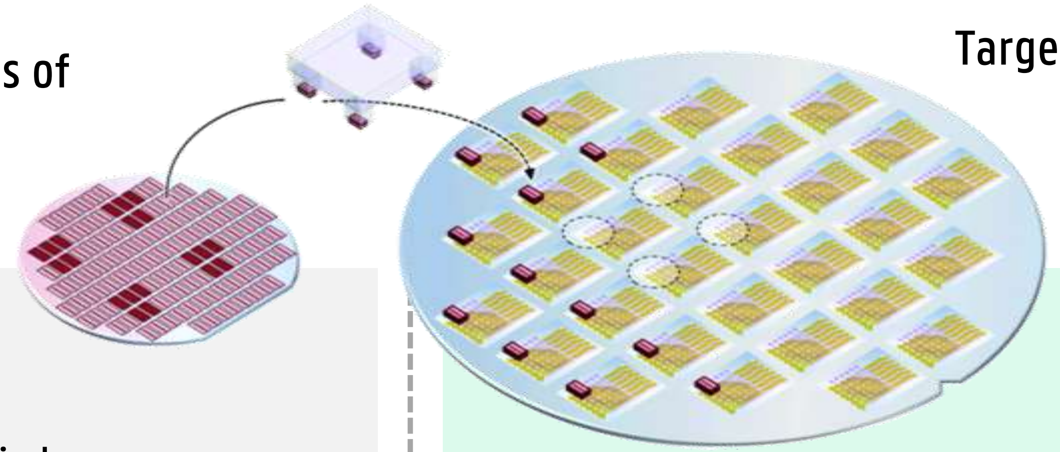


100 µm

Heterogeneous integration to combine the best of both material platforms

Micro transfer-printing

Source wafer with 100’s of
processed chiplets



Target wafer with SiN circuits

InP photonic chips

Great photodiodes

Expensive
semiconductor

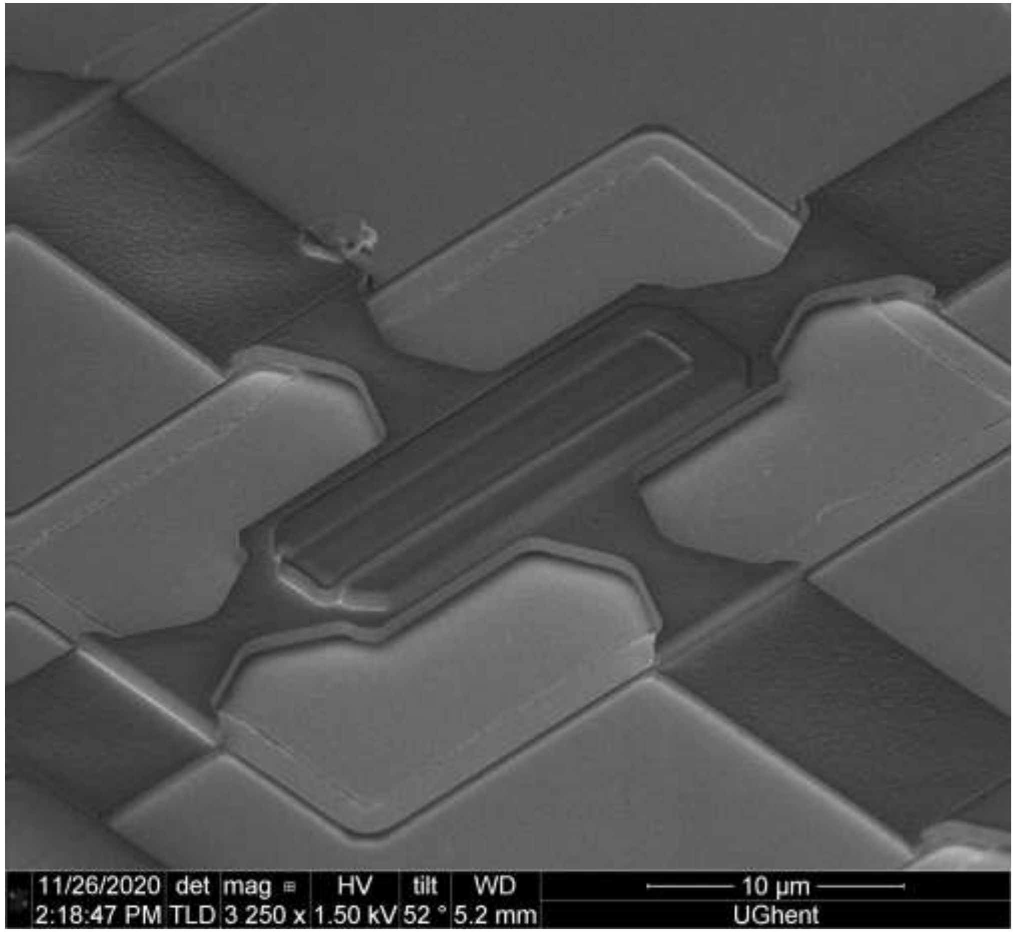
SiN photonic chips

Cost-effective
(CMOS compatible)

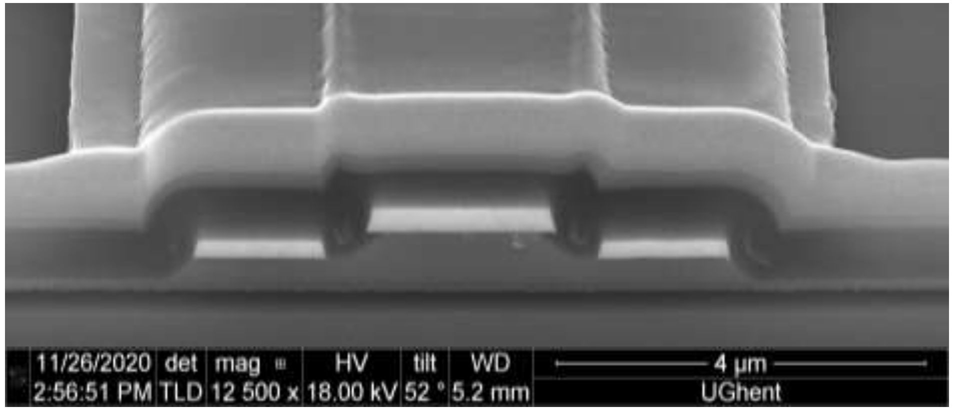
Scalable
for complex circuits

Low-loss waveguides

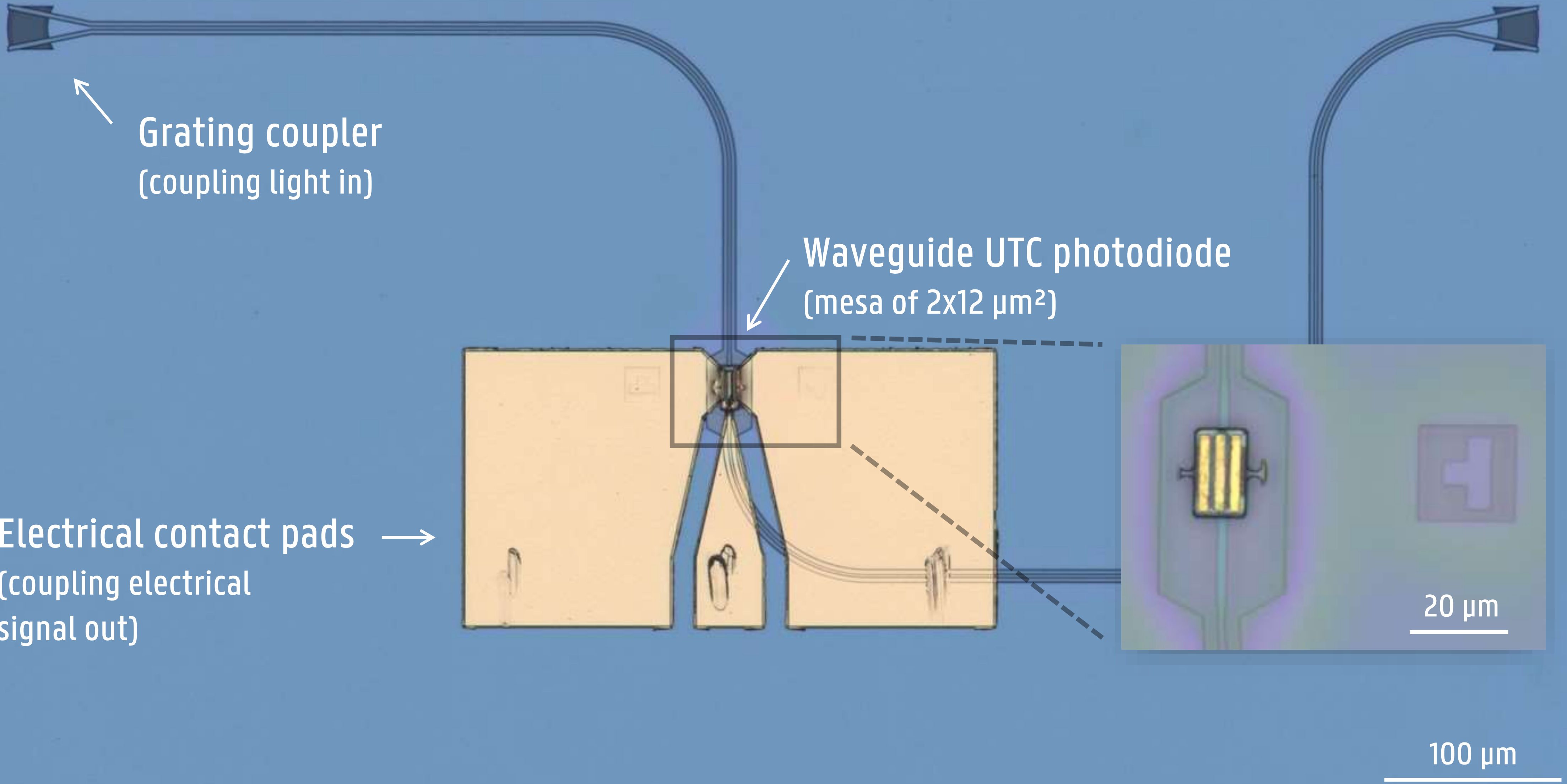
Micro-transfer printing as flexible tool for heterogeneous integration



Convert the photodiode into a tethered coupon



A minimalistic photonic circuit to test our idea



Grating coupler
(coupling light in)

Waveguide UTC photodiode
(mesa of 2x12 μm^2)

Electrical contact pads
(coupling electrical
signal out)

My PhD research questions

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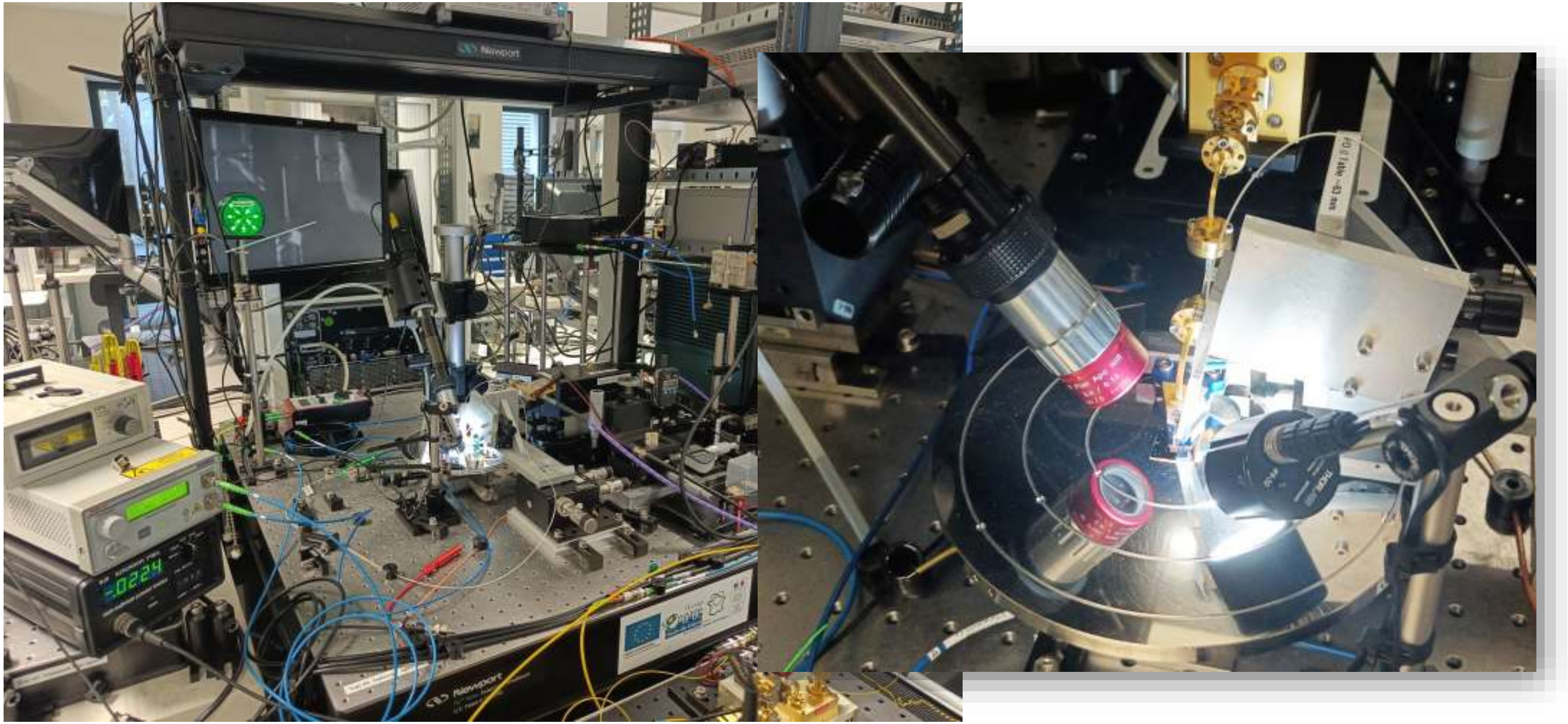
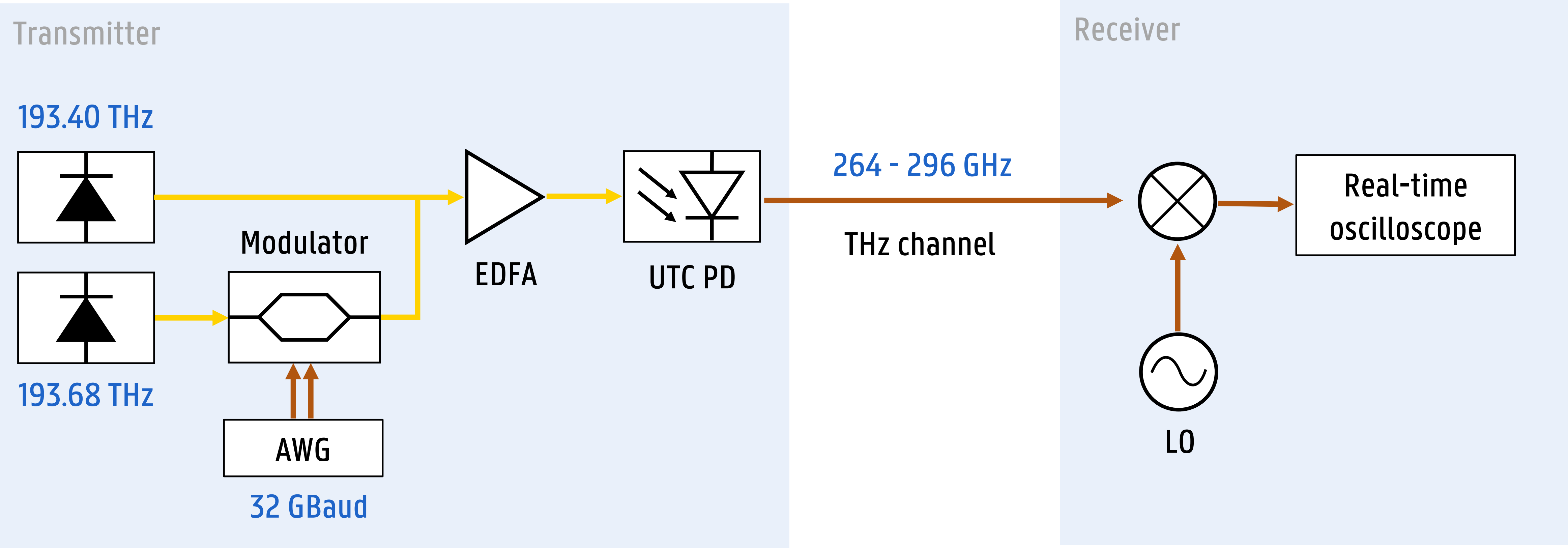
   A UTC photodiode
2. How do we make it small without sacrificing responsivity?
   Make a waveguide-coupled device
3. How do we make such a small waveguide-coupled devices on chip?
   Using microchip technology & micro-transfer printing
4. Can we generate THz signals and transmit data?

Putting the component to the test: generating THz signals



Putting the component to the test: photomixing

The setup for a photomixing experiment at THz frequencies



Putting the component to the test: a data link

How much data can we transmit over this link?

Bitrate = symbol rate x bits/symbol

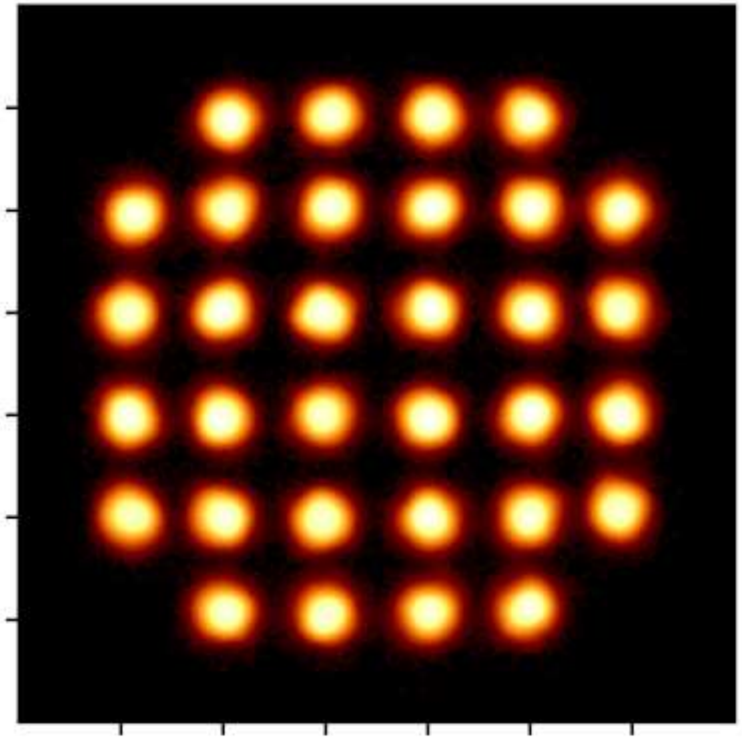
= 32 symbols/s x 5 bits/symbol

= **160 Gbit/s**

= 10 000 4K Netflix streams (16 Mbit/s)

NETFLIX

32 symbol points = 2^5 bits



My PhD research questions

1. How can we make a fast photodetector to generate THz waves?
   A UTC photodiode
2. How do we make it small without sacrificing responsivity?
   Make a waveguide-coupled device
3. How do we make such a small waveguide-coupled devices on chip?
   Using microchip technology & micro-transfer printing
4. Can we generate THz signals? (and transmit data over it)
   Yes!

What’s next?

Future research questions

1. Can we improve these photodiode chiplets even further?
   Smaller? Faster? More efficient?

2. How do we efficiently radiate these THz signals off chip?
   Co-integration with electronics and antennas?

3. How can we scale this technology to 100-1000s of chiplets?
   High-speeds UTC PDs as a standard building block?

17/12/2024

Bridging the Terahertz Gap:
High-Speed Photodiodes on Silicon Nitride

Public PhD Defense Dennis Maes