PHOTONICS RESEARCH GROUP

Heterogeneous Integration of III-V Semiconductor Light Sources on Low-Refractive-Index Platforms

Camiel Op de Beeck

Promotors: prof. dr. ir. Bart Kuyken, prof. dr. ir. Gunther Roelkens

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HETEROGENE INTEGRATIE VAN III-V-HALFGELEIDERLICHTBRONNEN OP PLATFORMEN MET LAGE BREKINGSINDEX

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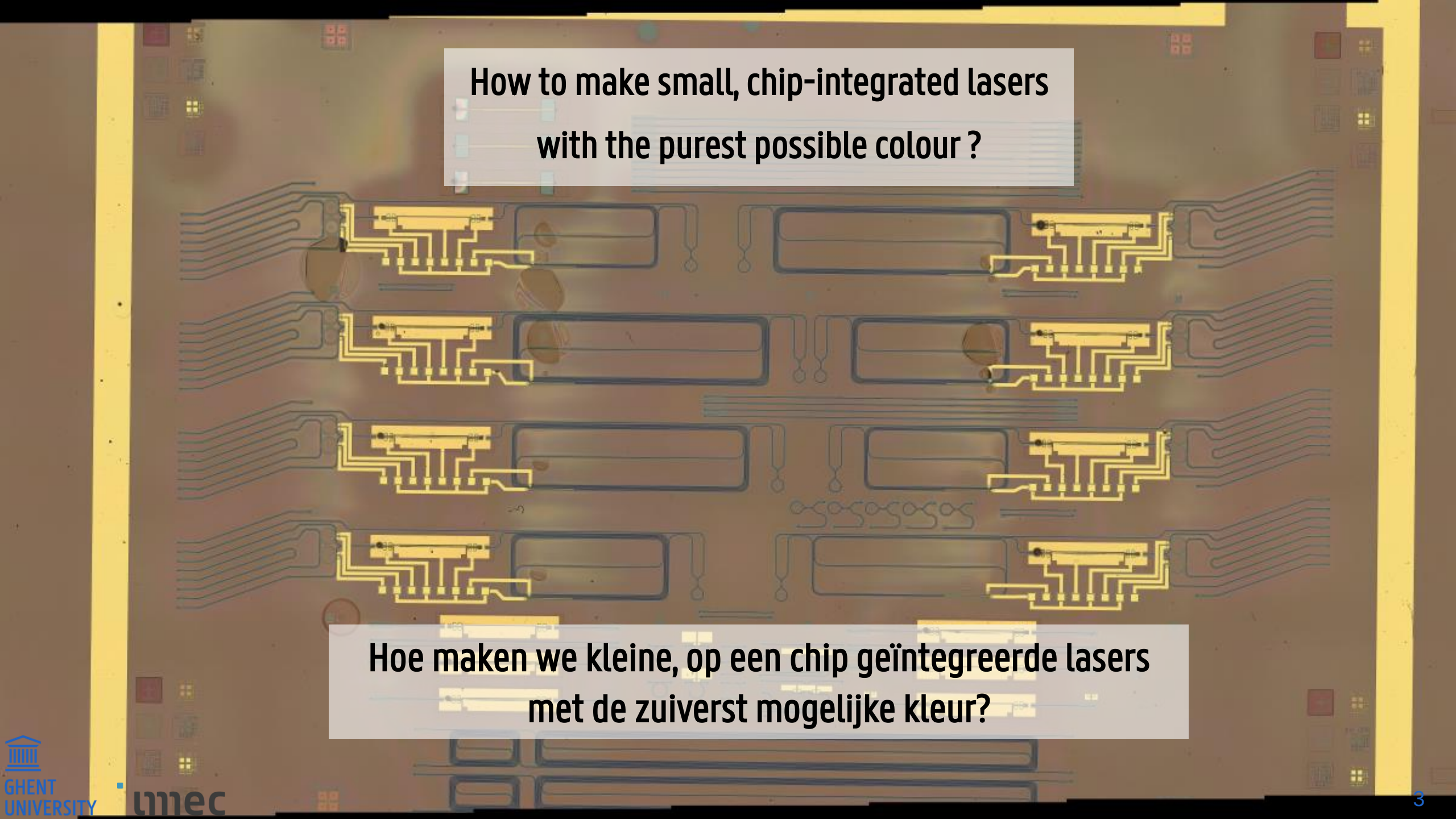
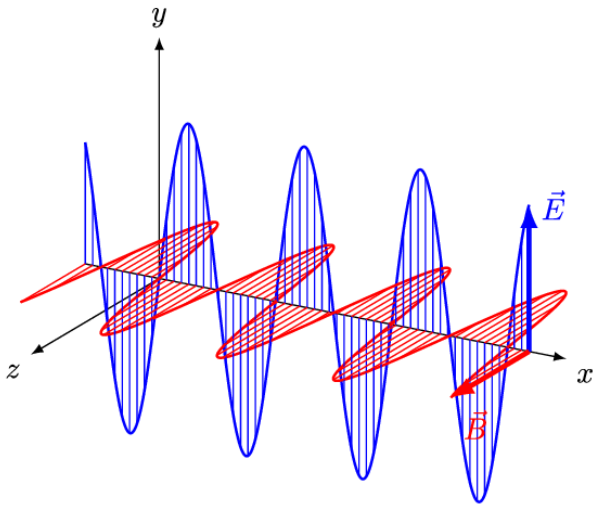

How to make small, chip-integrated lasers
with the purest possible colour ?
Hoe maken we kleine, op een chip geïntegreerde lasers
met de zuiverst mogelijke kleur?

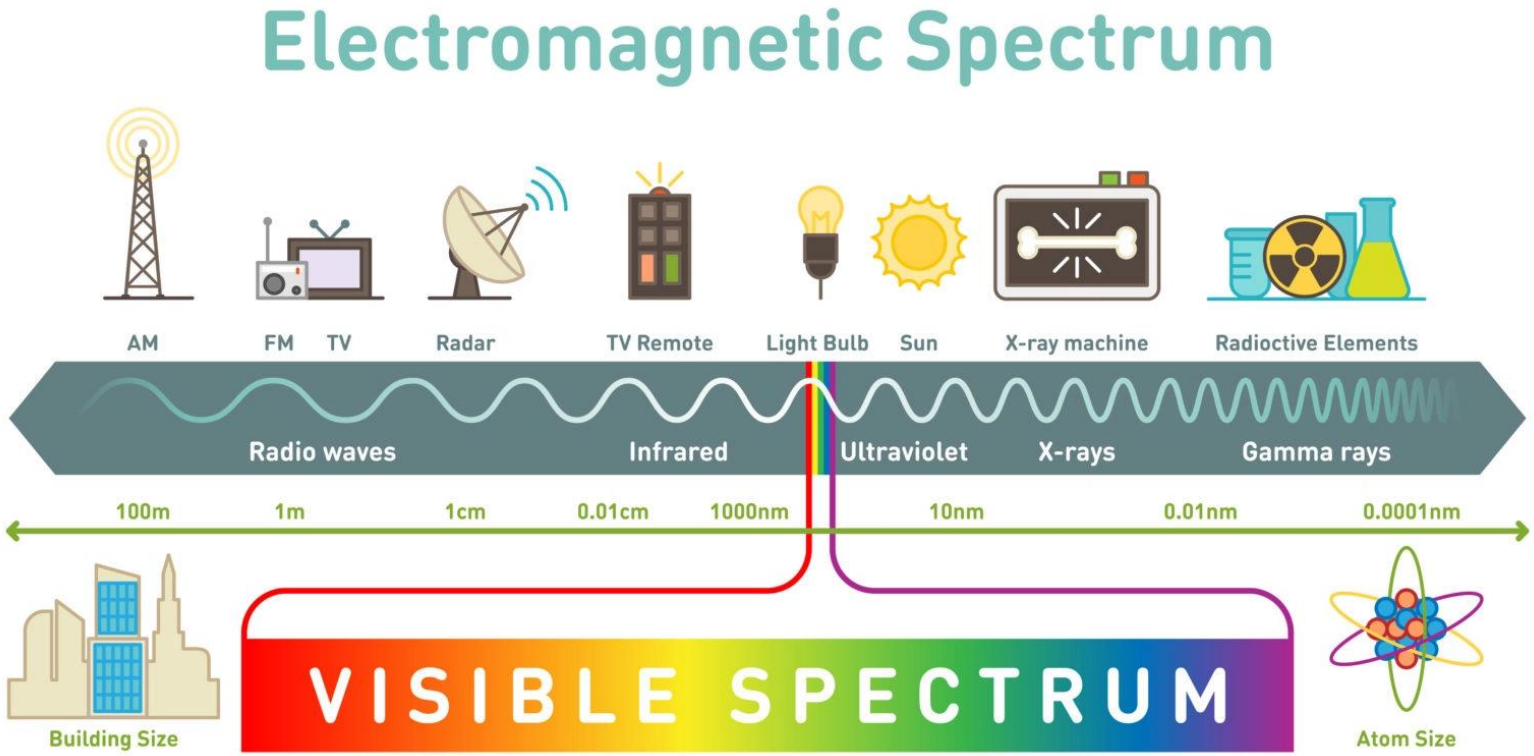
Overview

- Light – a general introduction
- History of the laser
- Integrated photonics
- External cavity lasers on Si_3N_4
- Heterogeneous integration
- Results

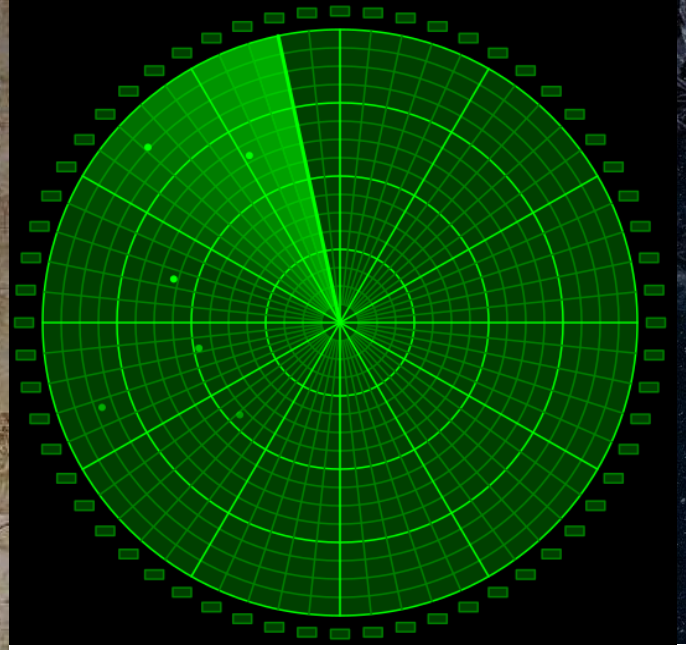
THE ELECTROMAGNETIC SPECTRUM

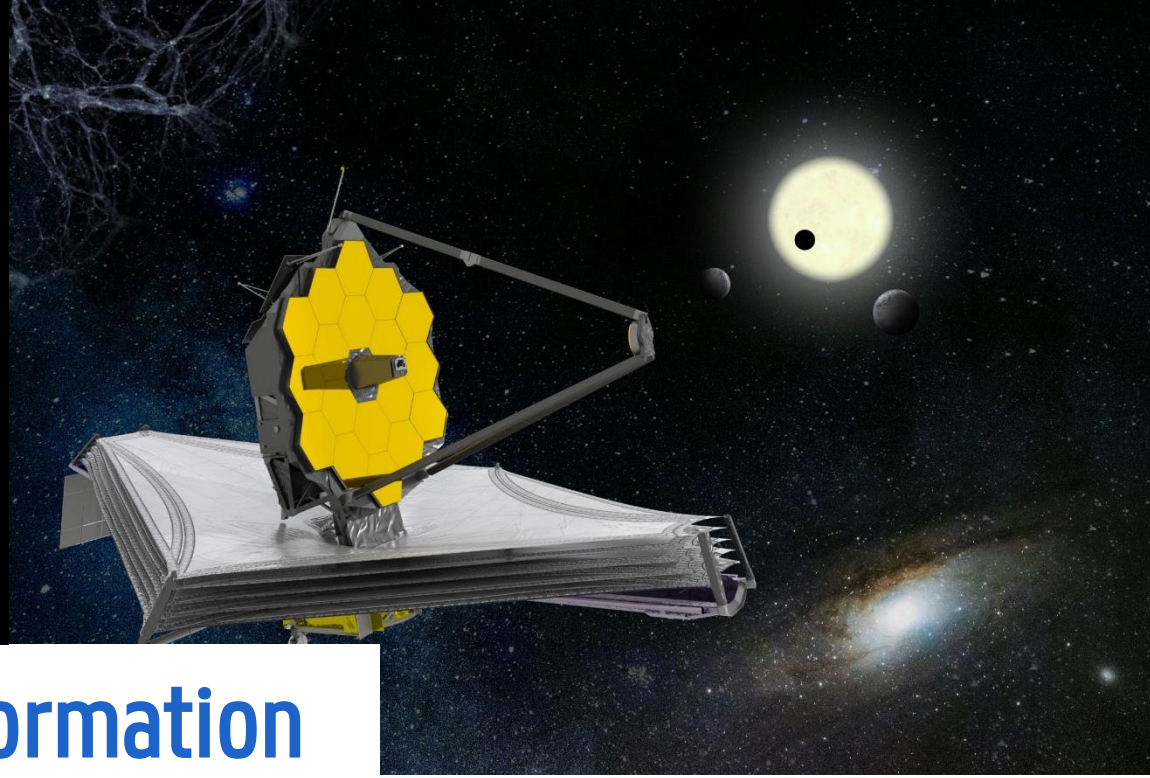
- Light is an electromagnetic wave ⟶ oscillating electric and magnetic fields
- Spans from below microwaves to beyond UV light and X-rays
- Travels 30 cm/ns in vacuum





Light carries energy

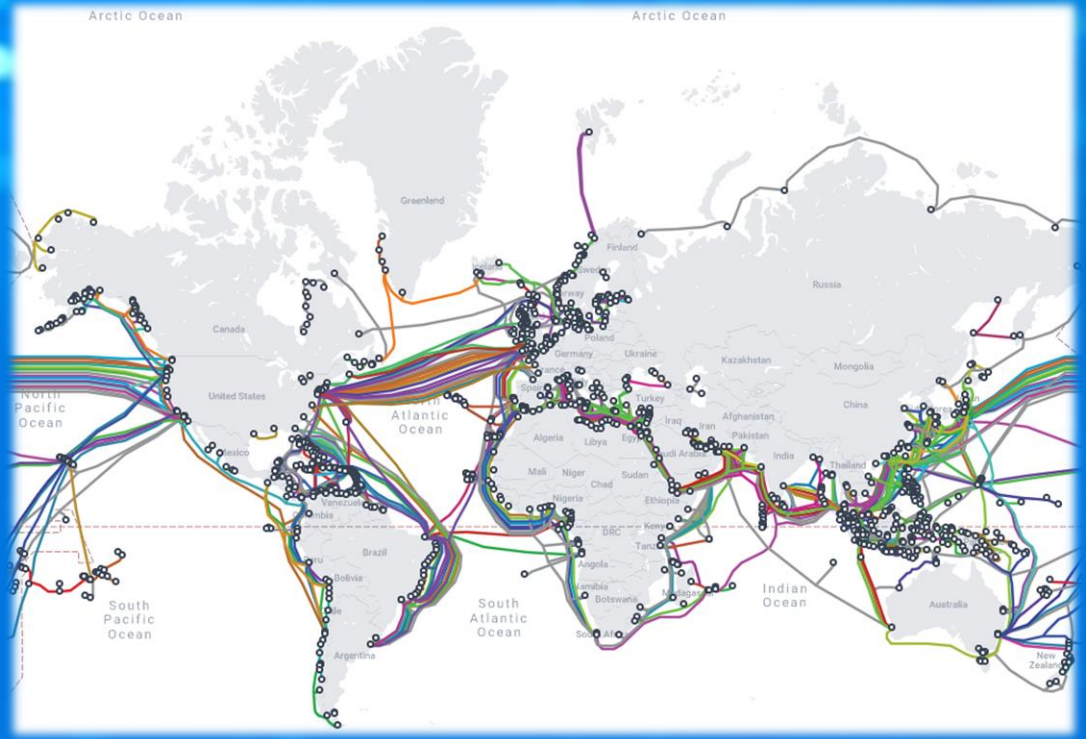




Light carries information

Light carries information

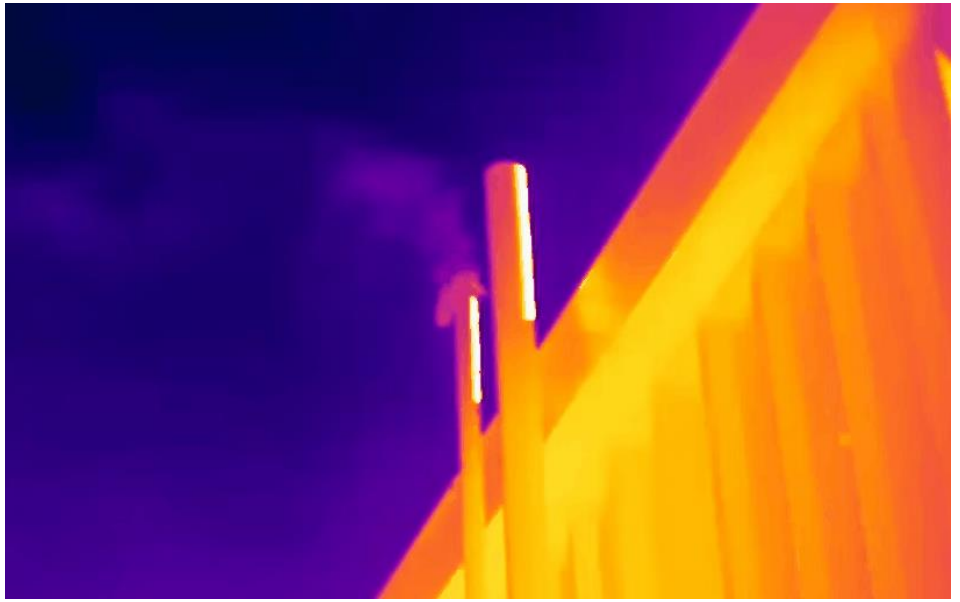
The world wide web is interconnected by submarine optical fiber cables.



Optical sensing – looking at different colours

VIS

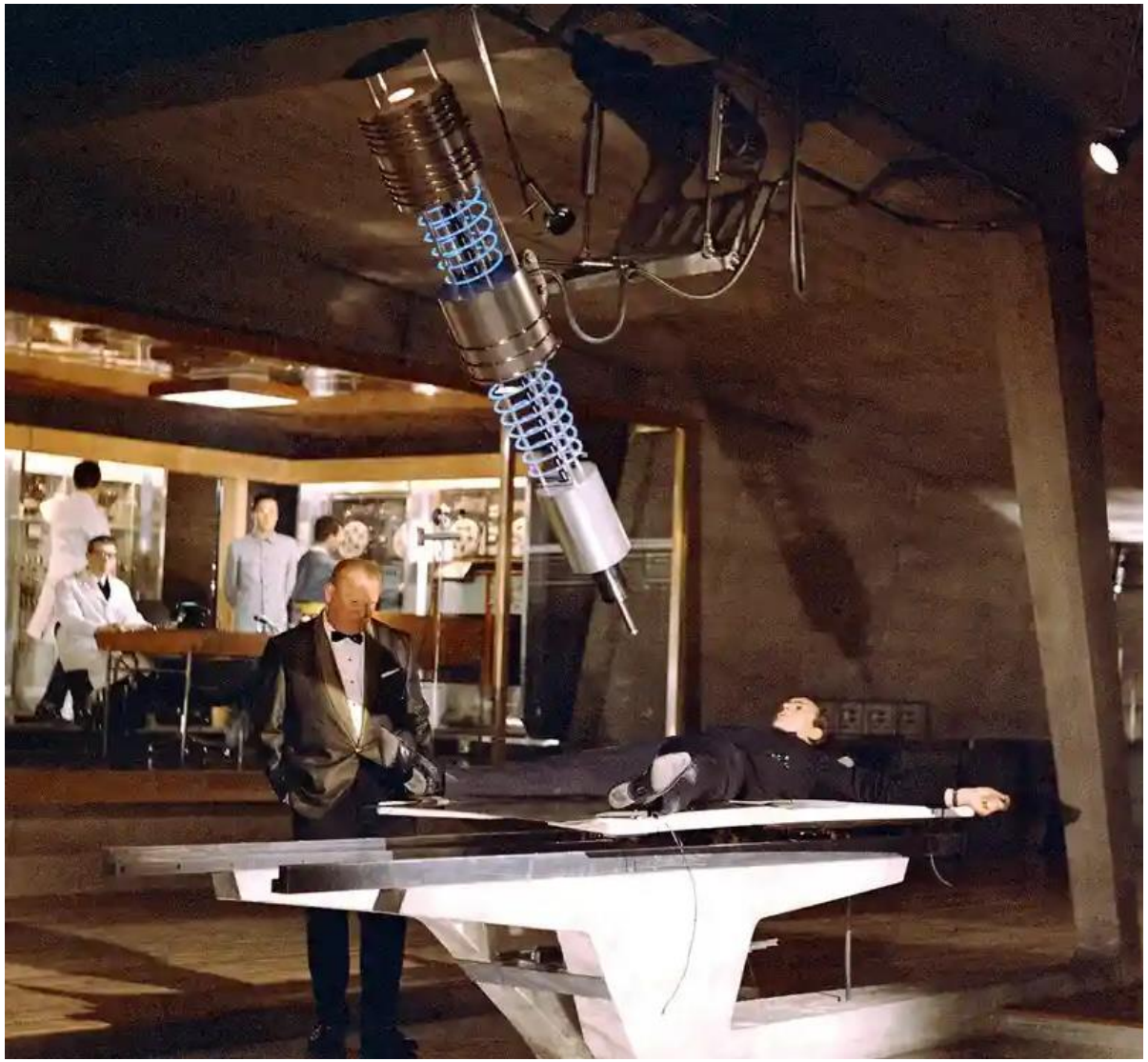
IR



Source: Teledyne FLIR YouTube channel

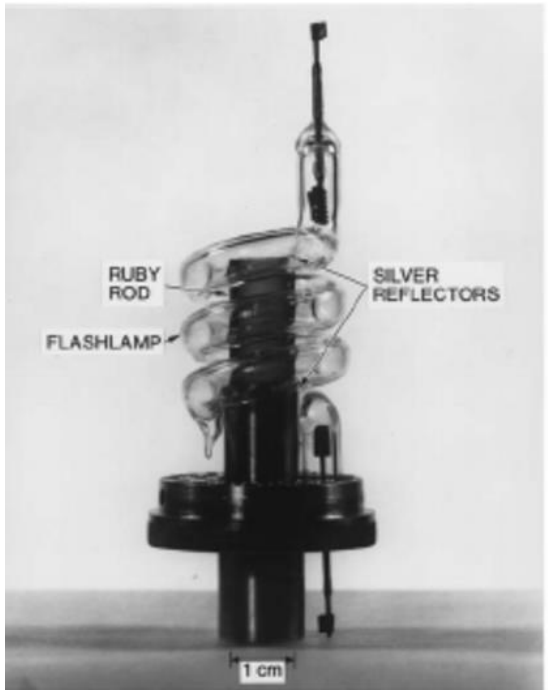
LASERS, OR DEATH RAYS

"Industrial laser cutter"
threatening James Bond, 1964 →

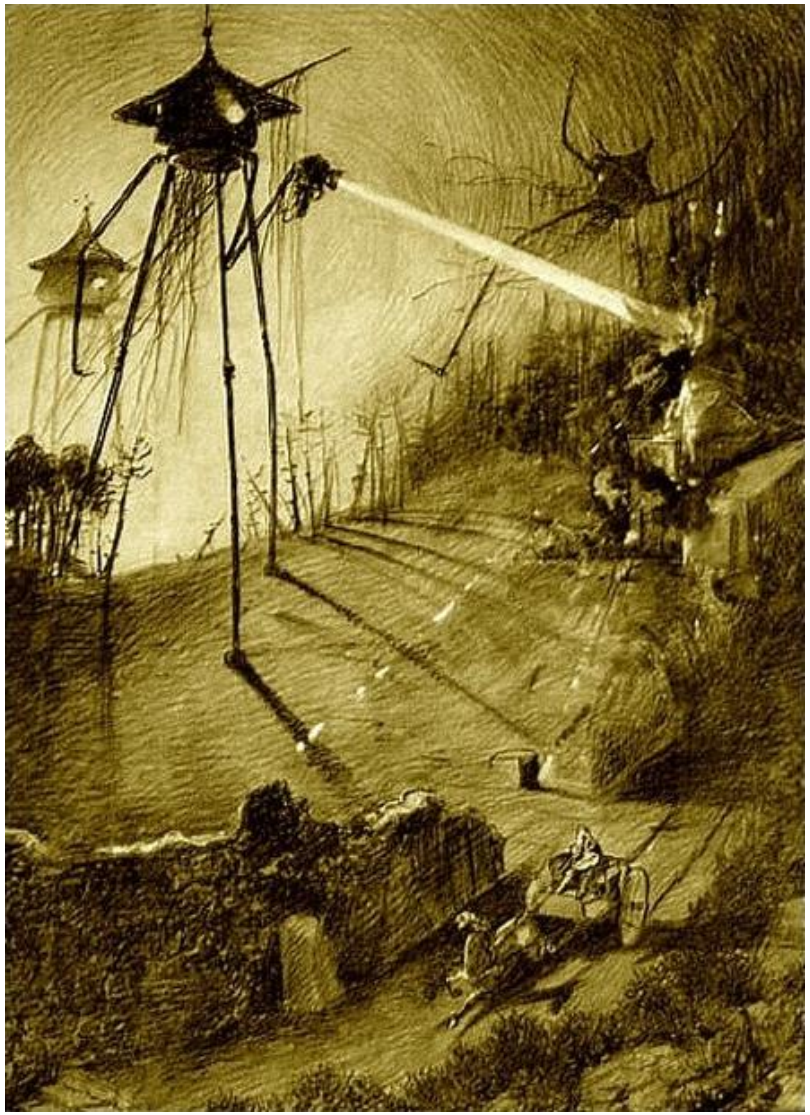


The original first laser, 1960

↓



LASERS, OR DEATH RAYS



← 1906 illustration of the novel
"*The war of the worlds*" by H.G. Wells

JUST LIKE SCIENCE FICTION

Death Ray Possibilities Probed by Scientists

By RALPH DIGHTON

A GIANT magnifying glass orbiting the earth, setting cities ablaze with the focused rays of the sun.

The science-fiction super weapon is a toy compared

Satellite With Ray Could Control Earth

the way a butcher slices baloney.

Maiman says he is working only with microwaves and light rays.

He leaves to your imagination what would happen if

↑ Sensationalist headline in "*Independent Star-news*", October 2nd, 1960

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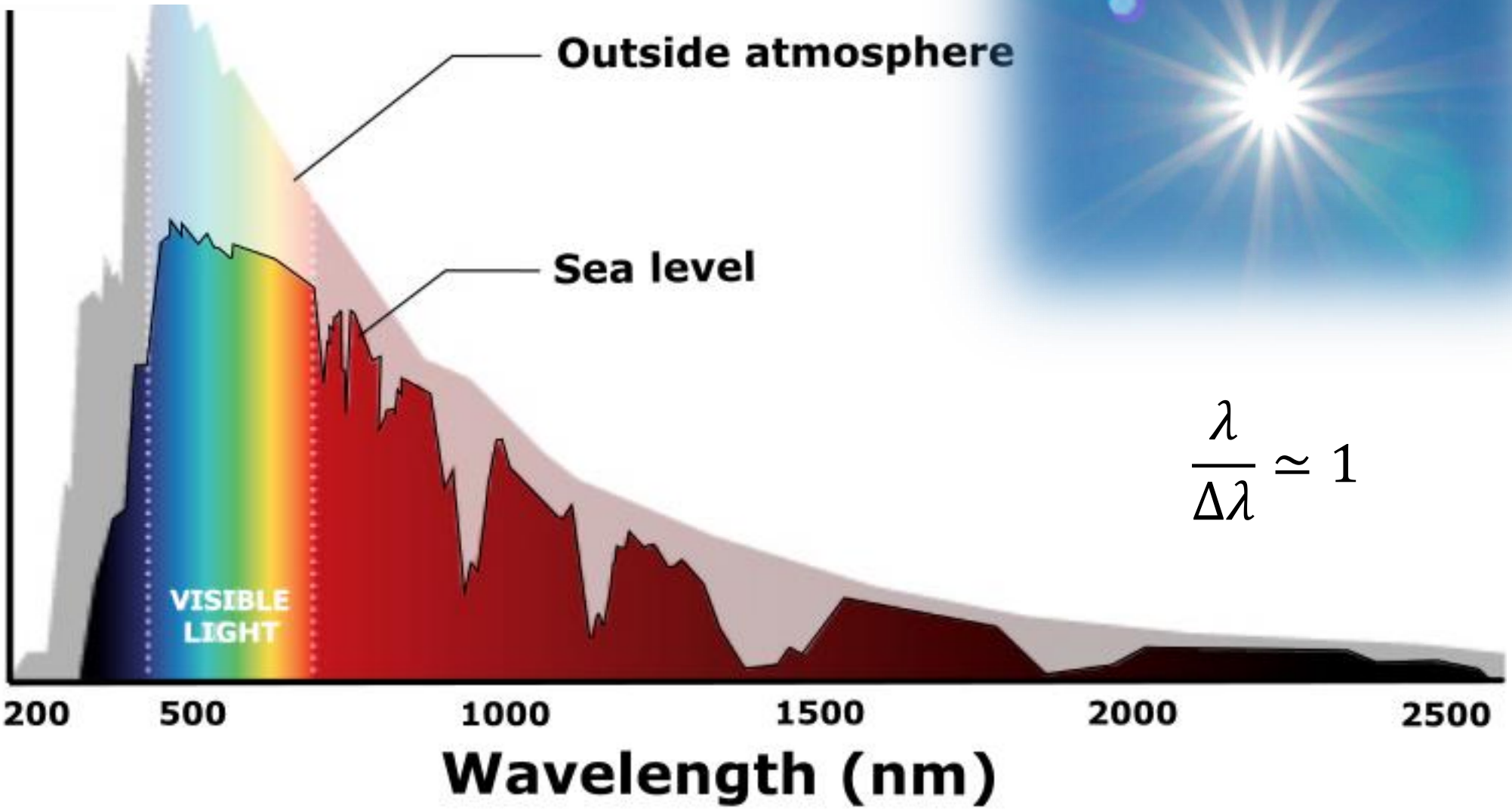
LASER LIGHT FUNDAMENTALS

Spectral distribution



$$\frac{\lambda}{\Delta\lambda} \simeq 1$$

LASER LIGHT FUNDAMENTALS

Spectral distribution

Incandescent lamp
(NL: gloeilamp)

$$\frac{\lambda}{\Delta\lambda} \simeq 1$$

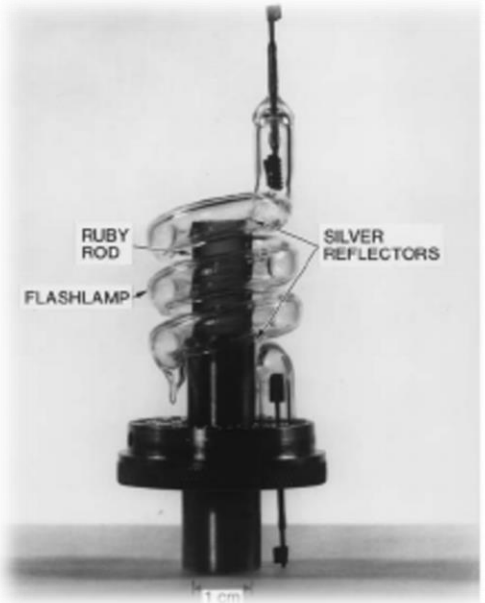
LASER LIGHT FUNDAMENTALS

Spectral distribution

$$\frac{\lambda}{\Delta\lambda} \simeq 20$$

LASER LIGHT FUNDAMENTALS

Spectral distribution

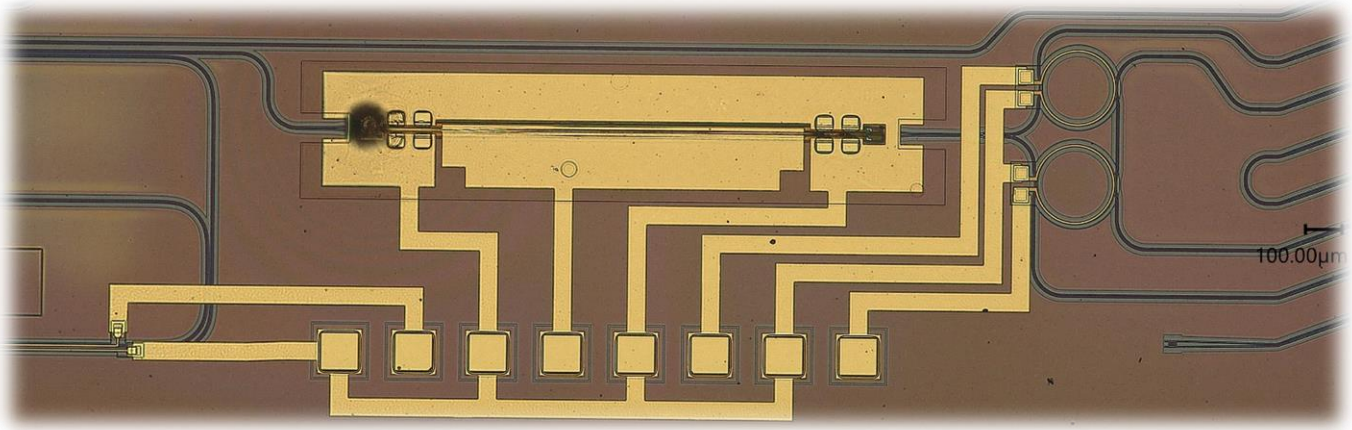


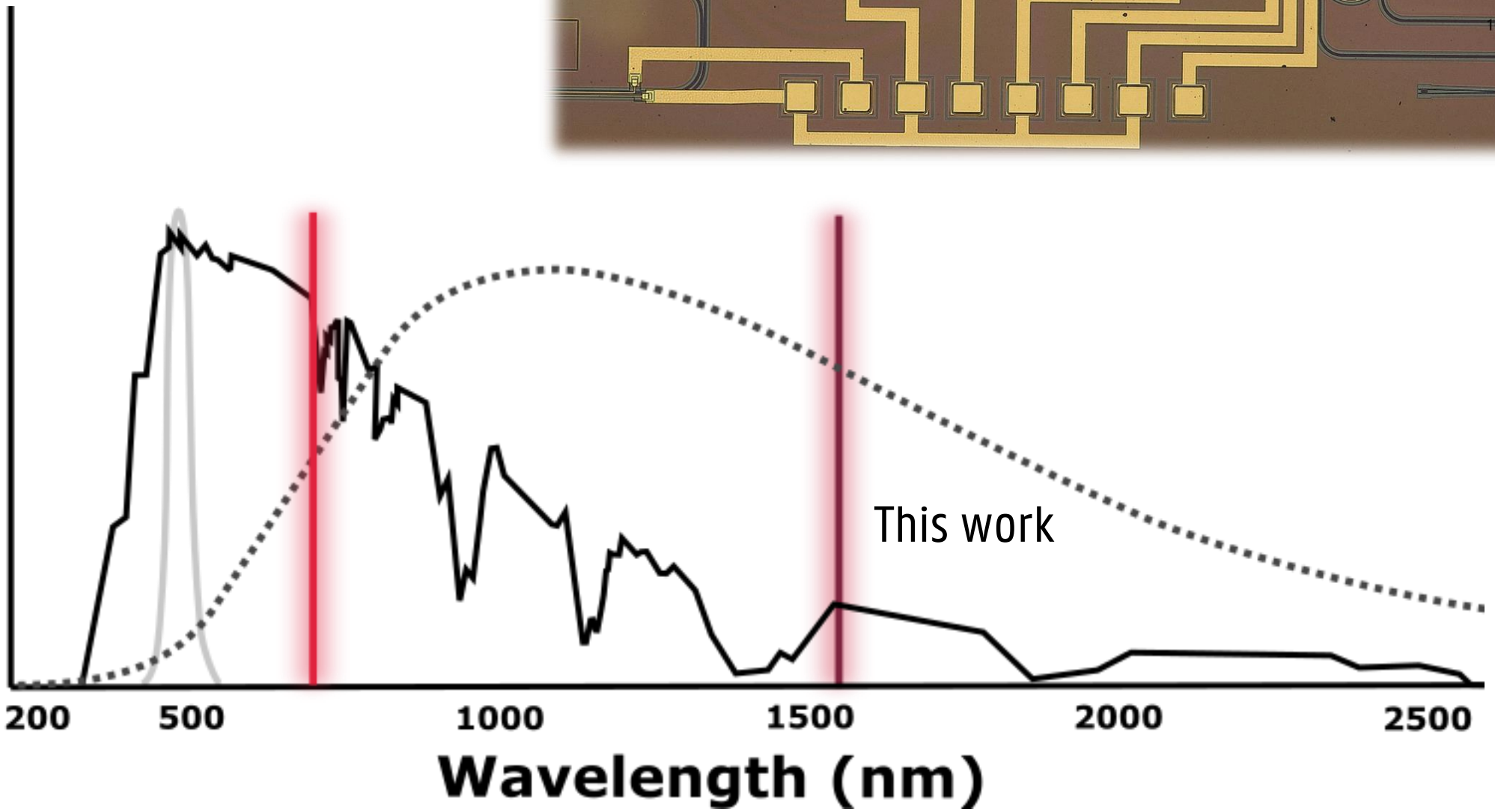
$$\frac{\lambda}{\Delta\lambda} \simeq 10^7 - 10^8$$

(LED x 1 million)

Laser light fundamentals

Spectral distribution





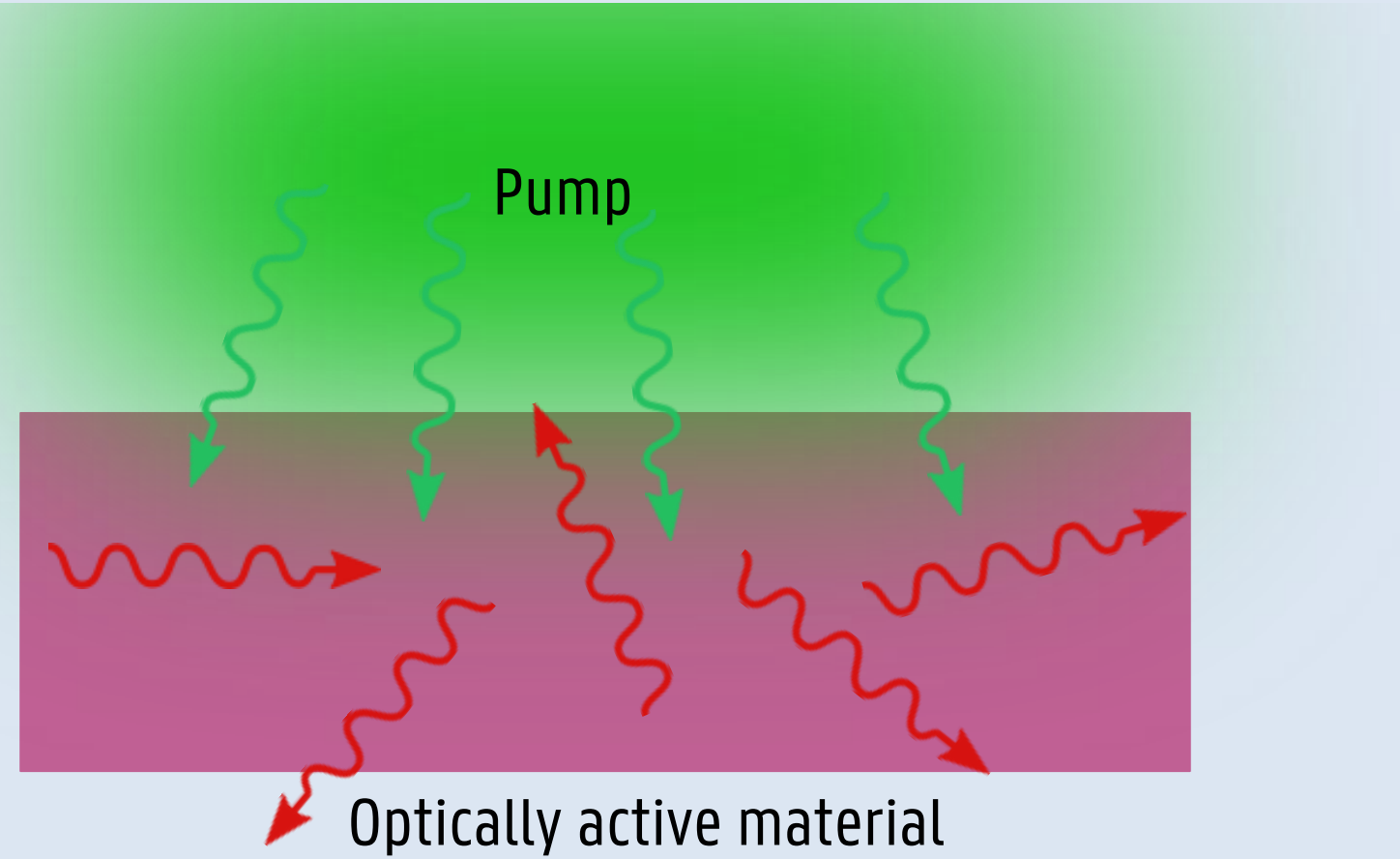
Lesson 1: how do lasers work

Fluorescent substances in our lives:

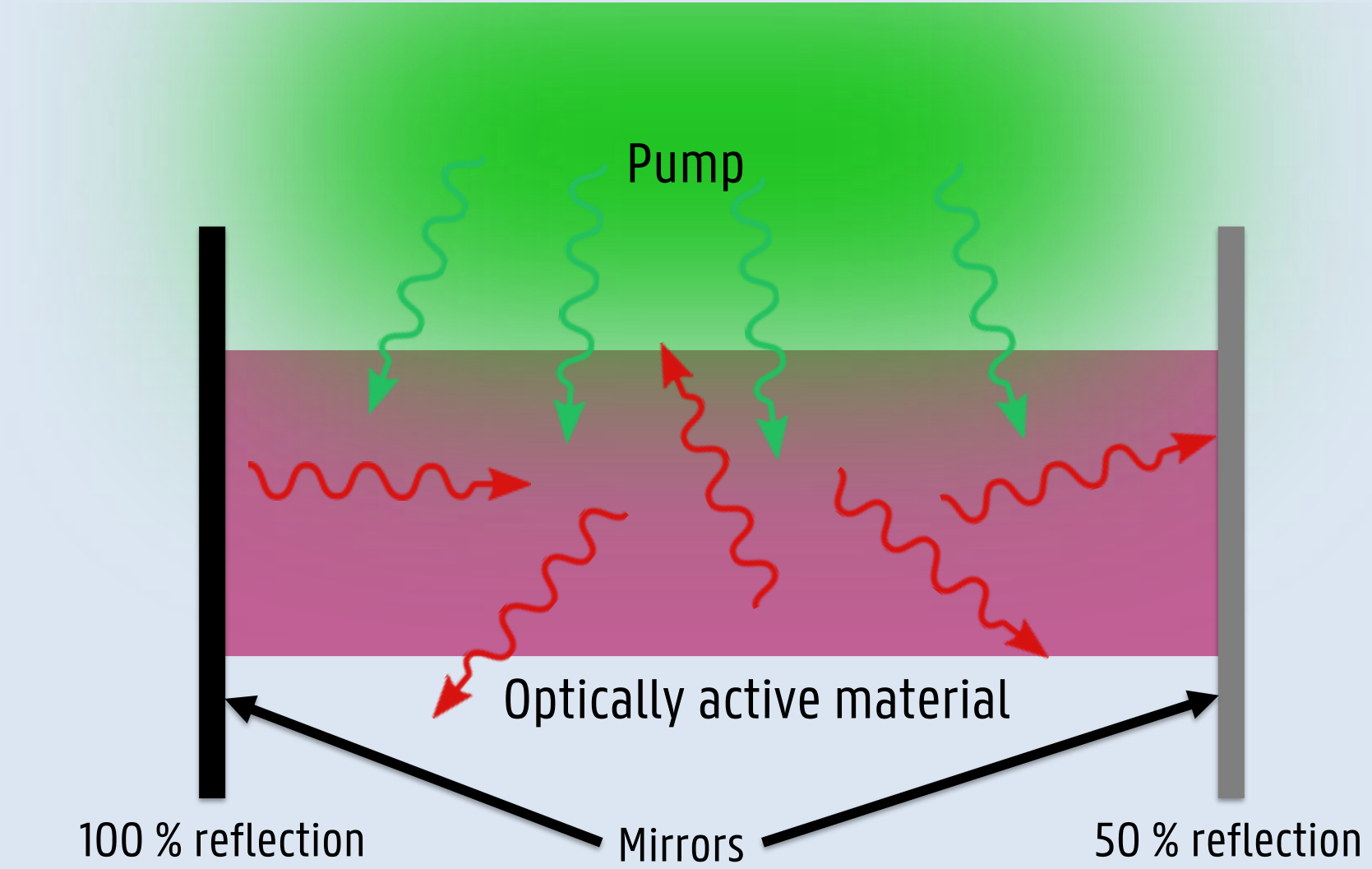
Tonic (under UV light)

Olive oil (under green light)

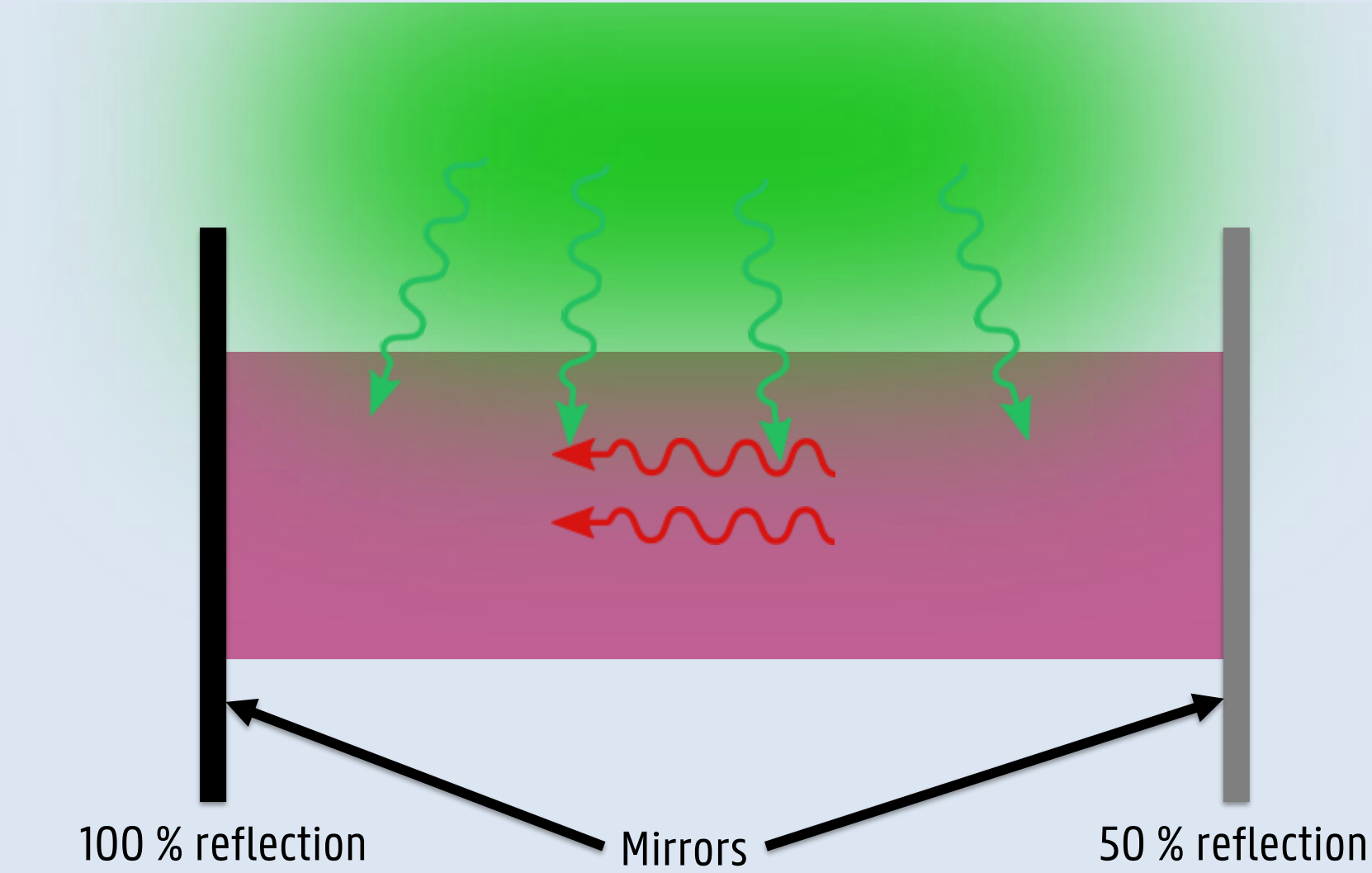
Lesson 1: how do lasers work



LESSON 1: HOW DO LASERS WORK

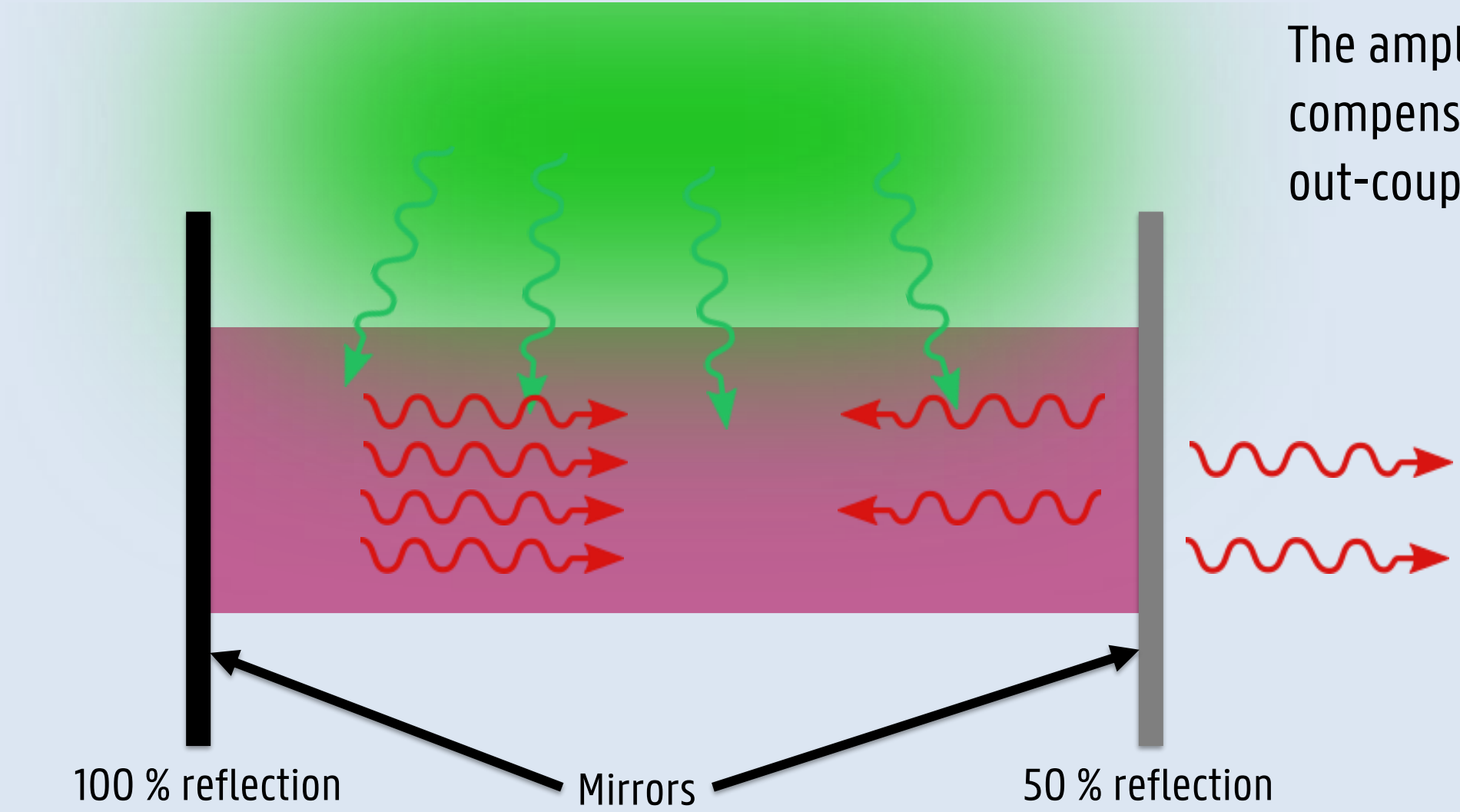


LESSON 1: HOW DO LASERS WORK



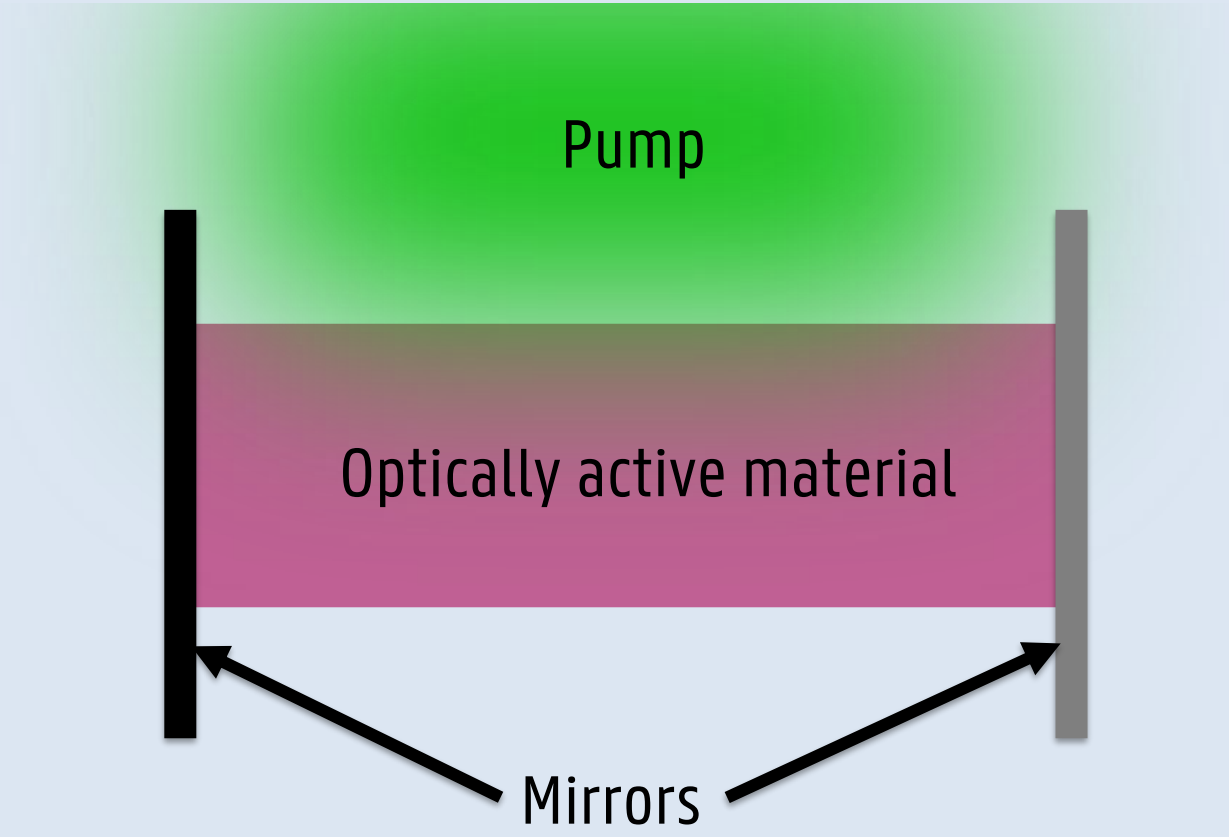
Red photons become **amplified** by the pump light.
= stimulated emission

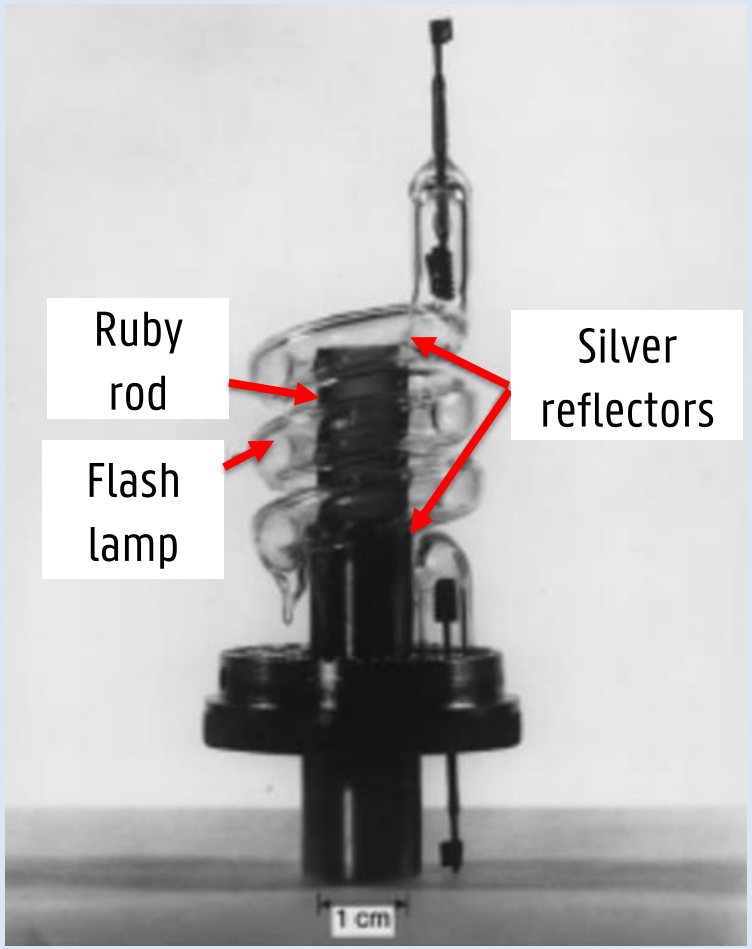
LESSON 1: HOW DO LASERS WORK



The amplification compensates for the out-coupled light.

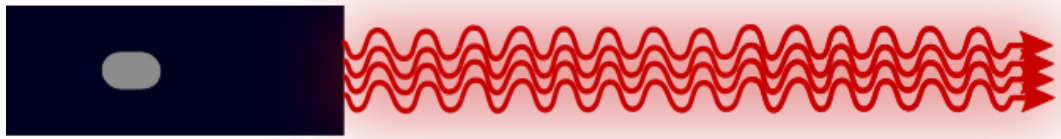
LESSON 1: HOW DO LASERS WORK





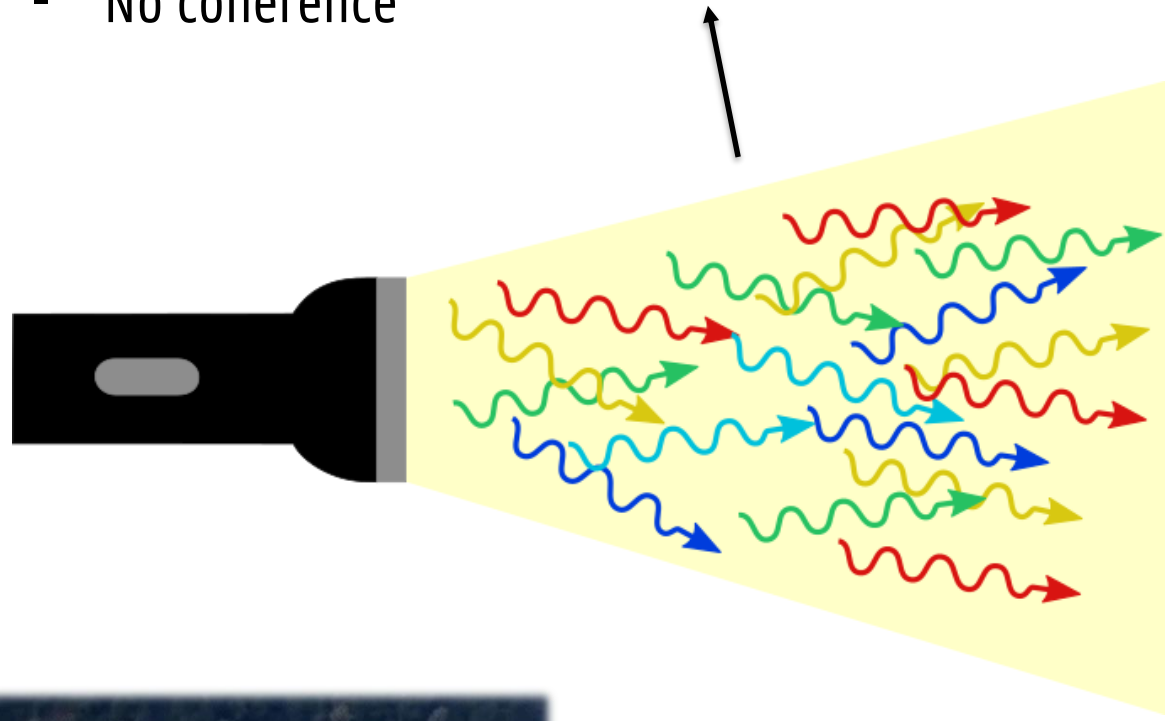
LASER LIGHT FUNDAMENTALS

- High directionality (narrow beam width)
- High intensity
- Coherence



Coherent laser light
- Nearly monochromatic (one colour)
- All waves in phase

Incoherent light source (light bulb, TL tube, LED)
- Broadband (multiple colours)
- No coherence

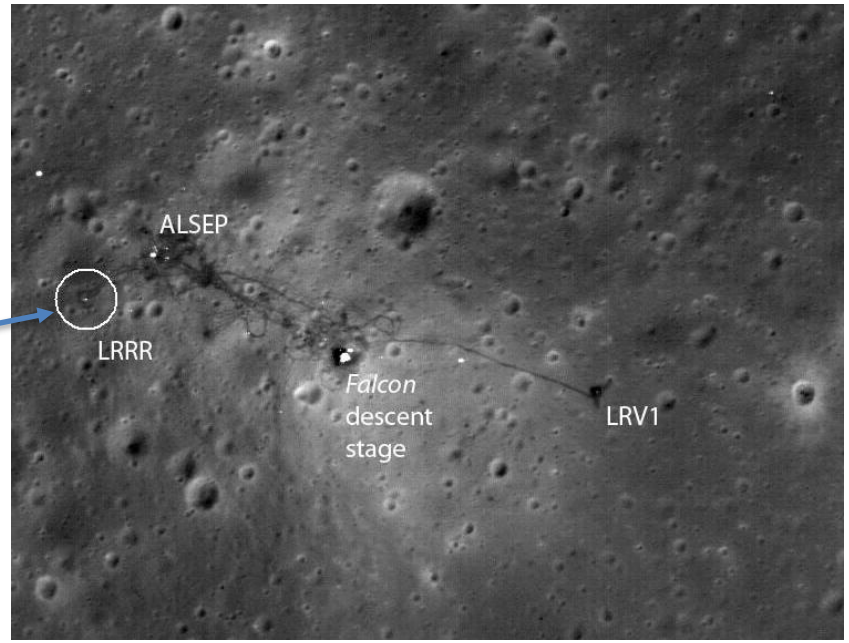


LASERS AT THE FOREFRONT OF PHYSICS

- Lunar ranging via reflectors on the moon

  "Lunar Laser Ranging RetroReflector"

- Already installed before 1970
- Ranging precision now better than 1 cm

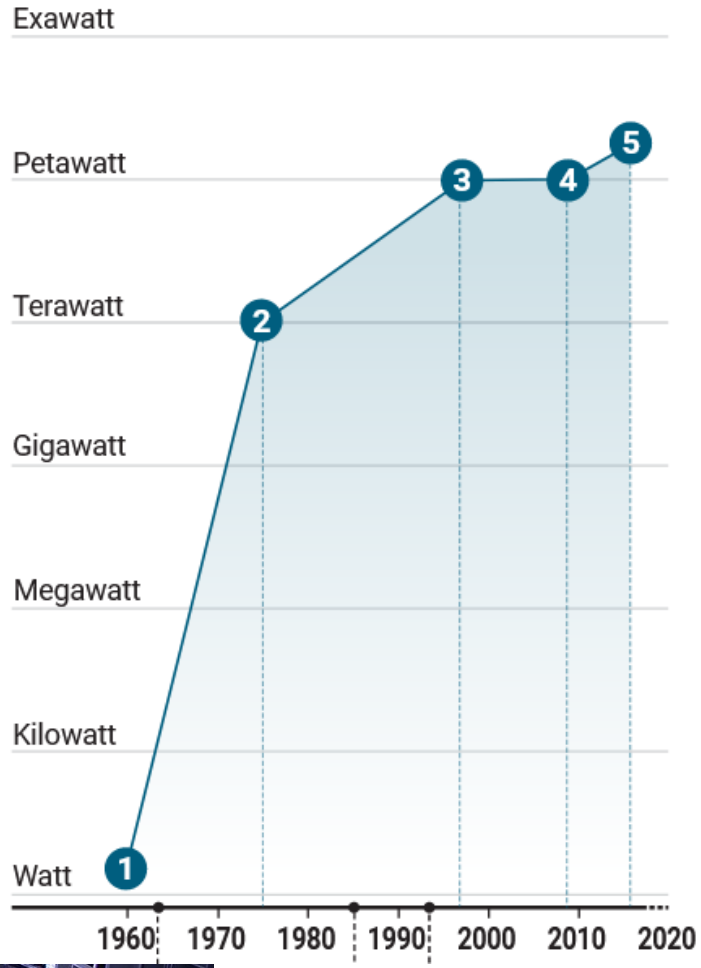


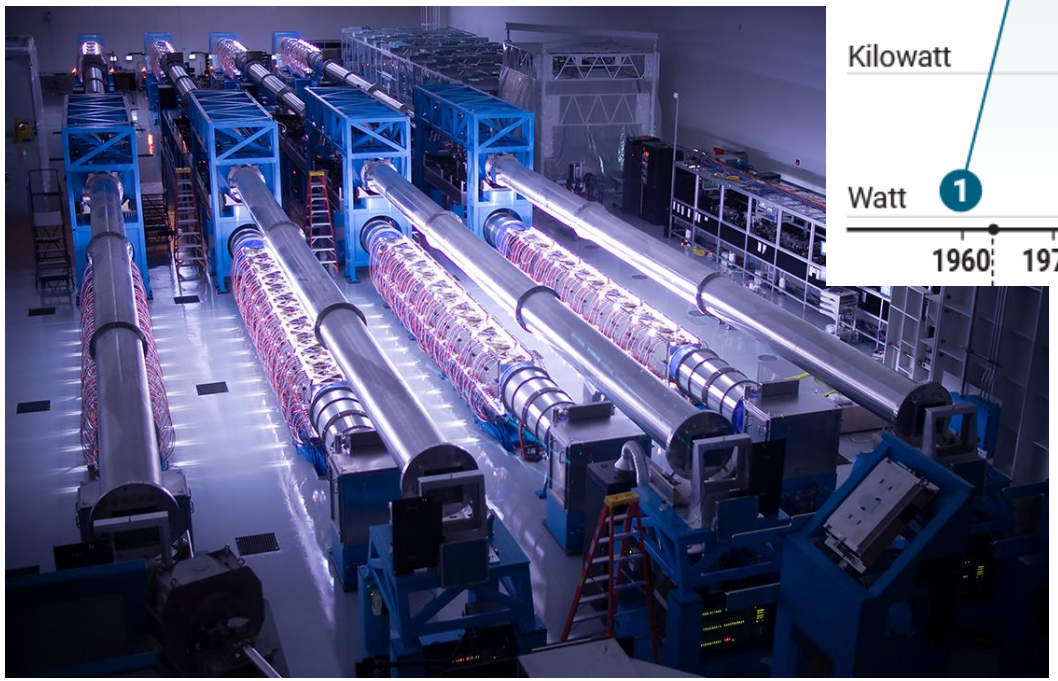
⟶ Gravitational measurements

⟶ Relativistic effects

LASERS AT THE FOREFRONT OF PHYSICS

- Ultra-high intensities (> 10 PW) may allow experimental validation of theoretical predictions from quantum mechanics
    - Electron-positron pair formation in vacuum
    - Photon-photon scattering
- Stimulating nuclear transmutation
  → reduce nuclear waste lifetimes

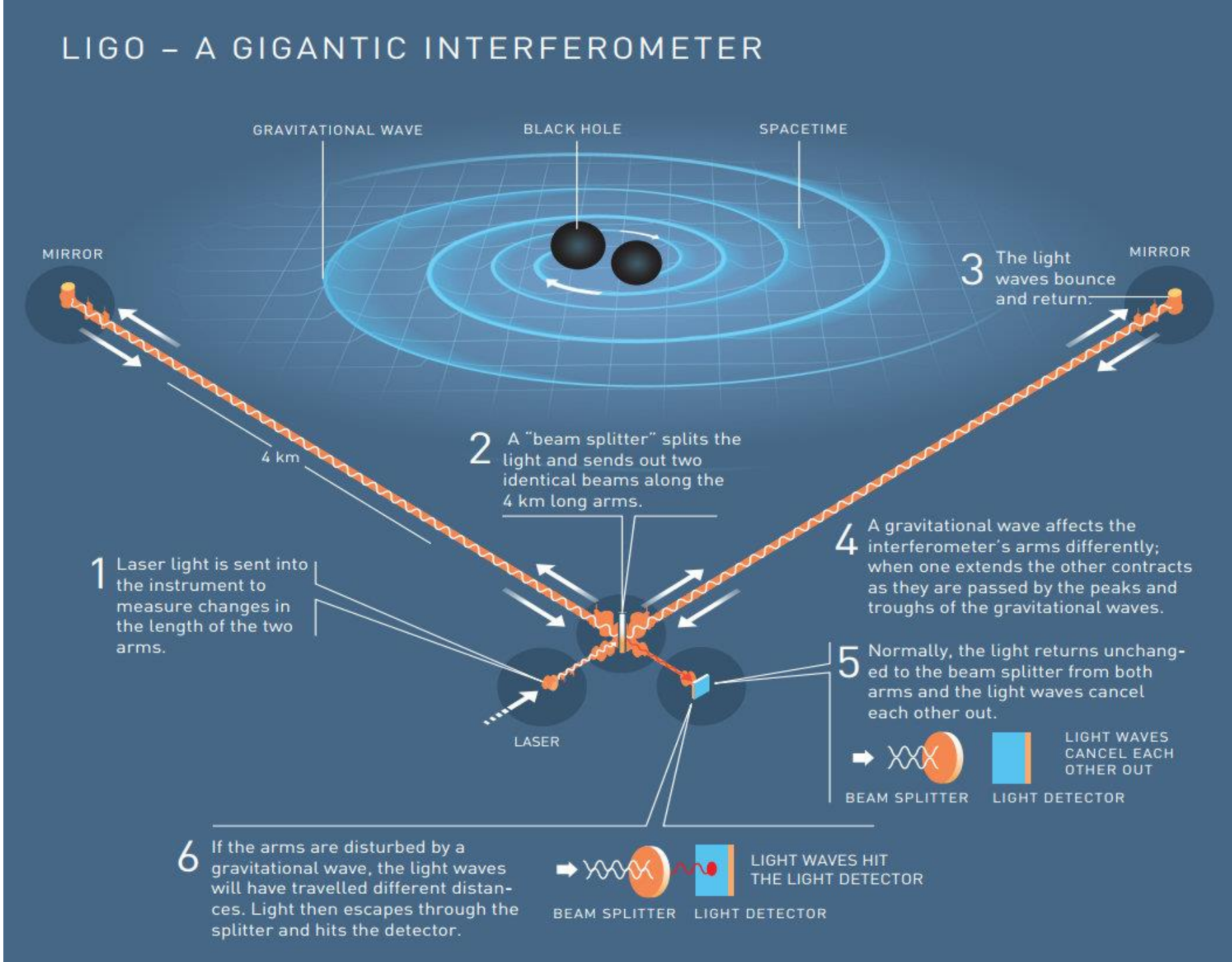




LASERS AT THE FOREFRONT OF PHYSICS

LIGO:

Interferometer for the detection of gravitational waves.



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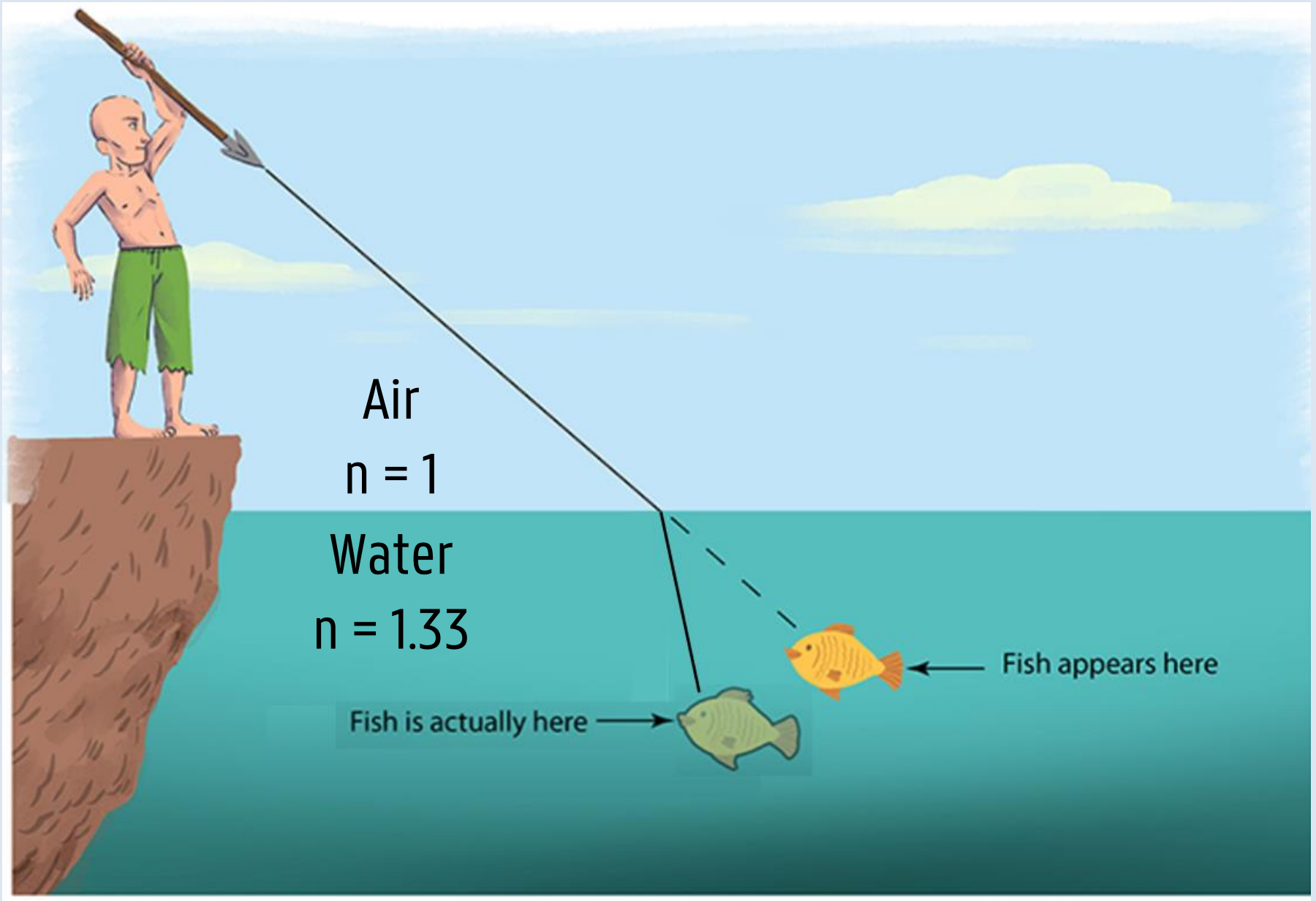
- External cavity lasers on Si_3N_4
- Heterogeneous integration
- Results

Light refraction – Spearfishing for beginners



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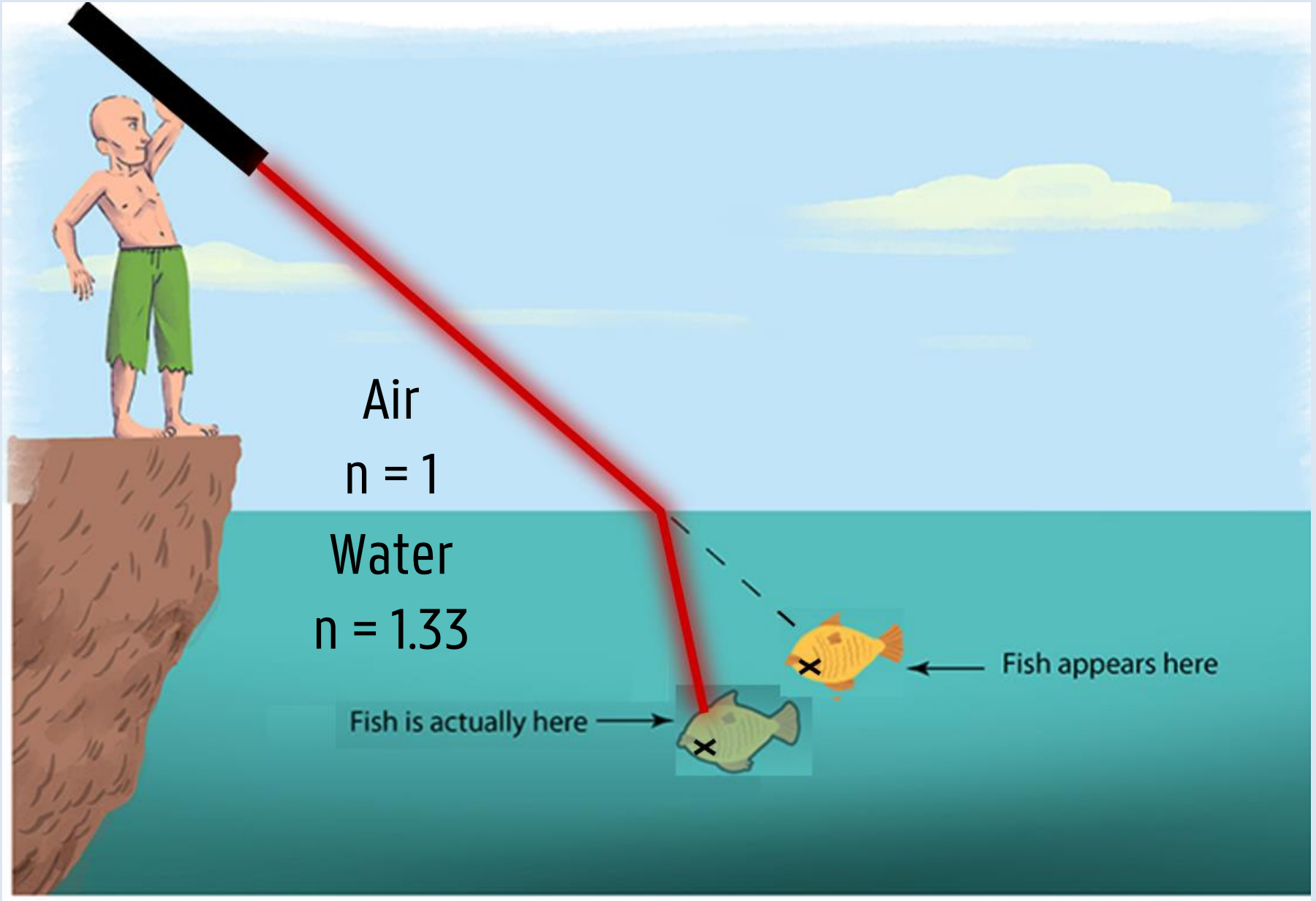
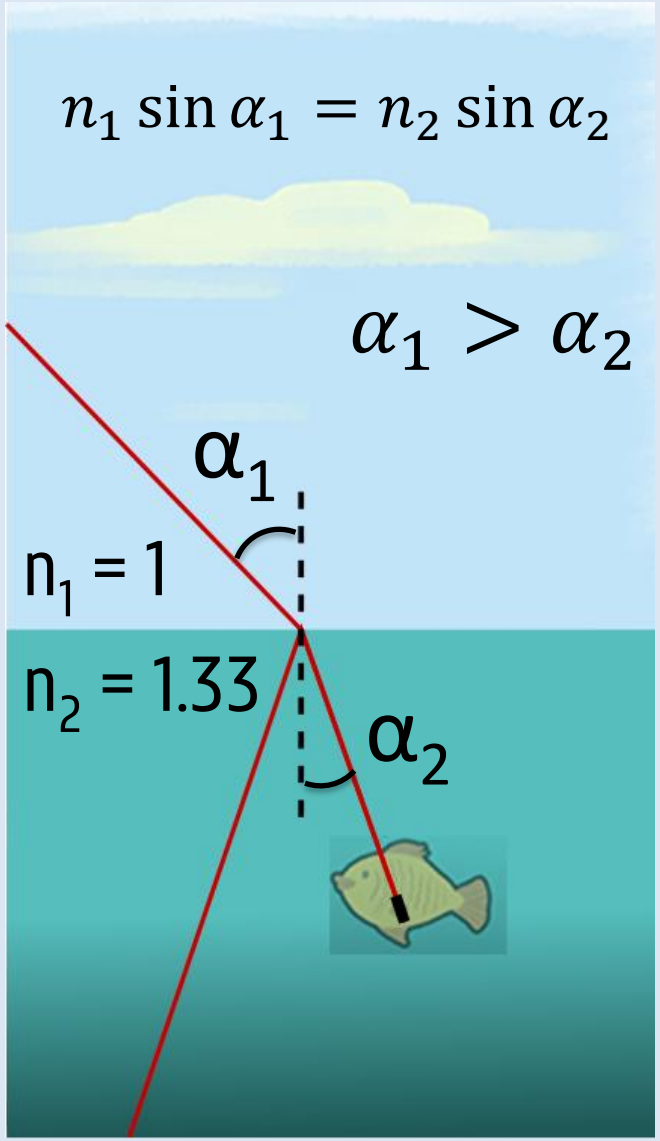
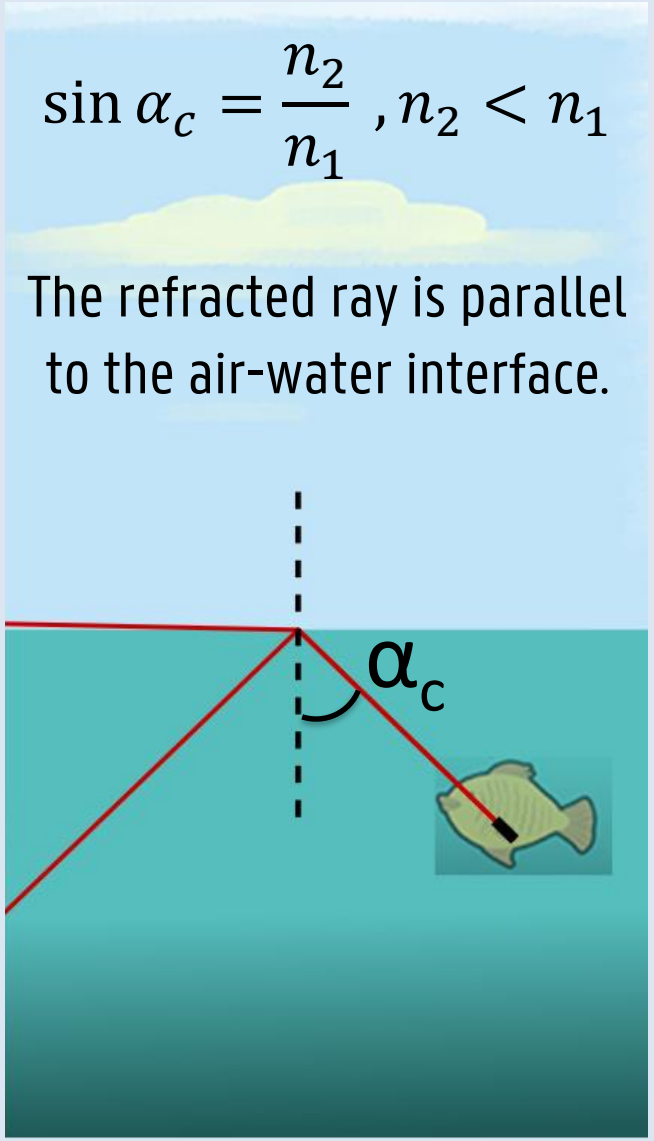
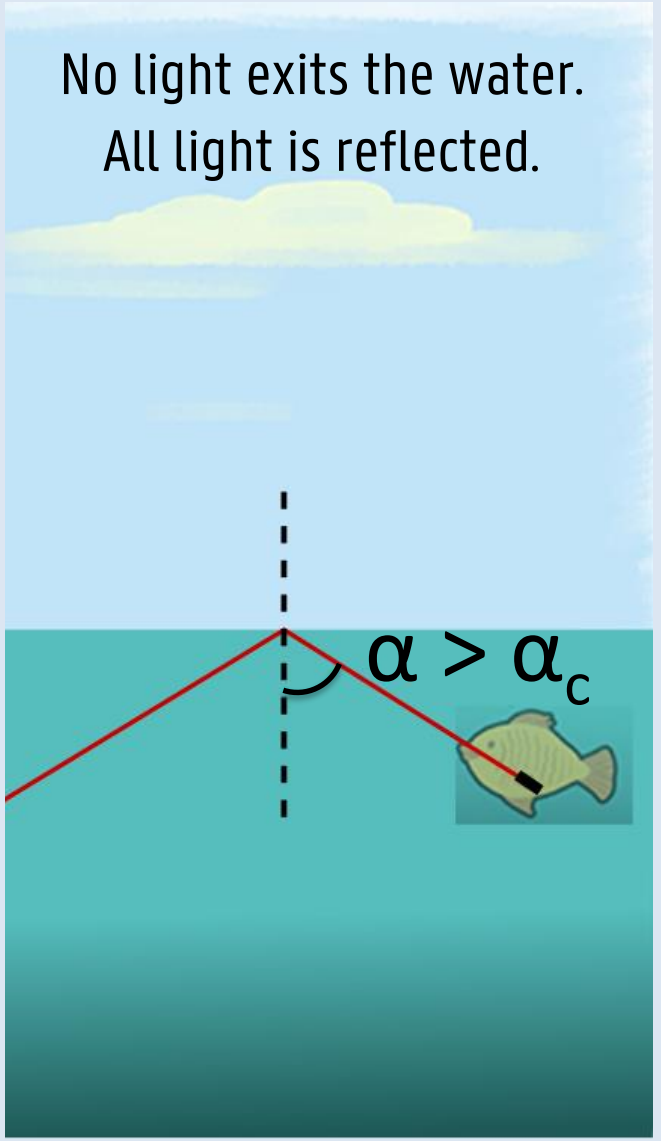


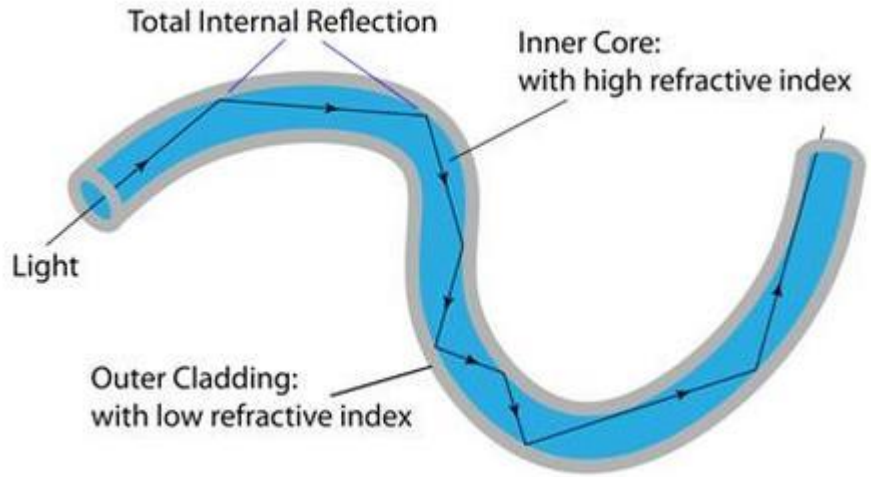
LIGHT REFRACTION – TOTAL INTERNAL REFLECTION



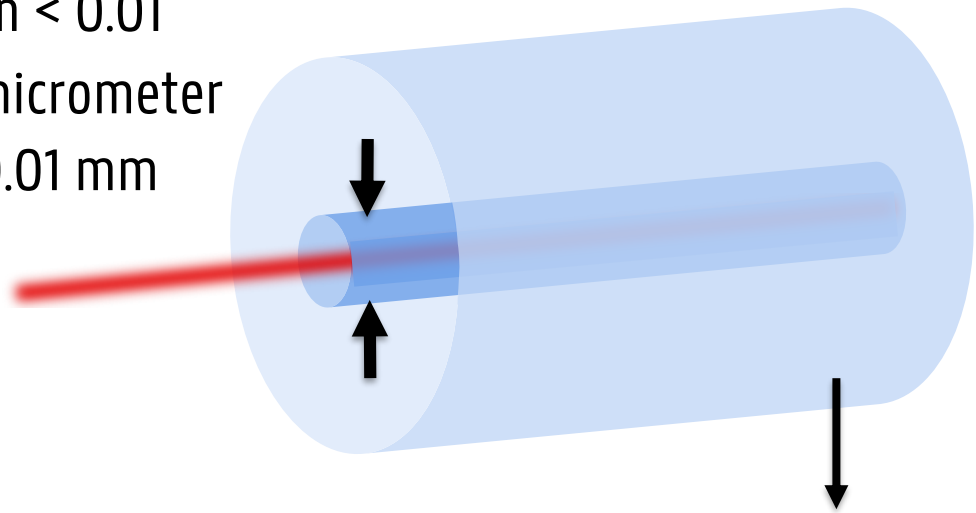




GUIDING LIGHT

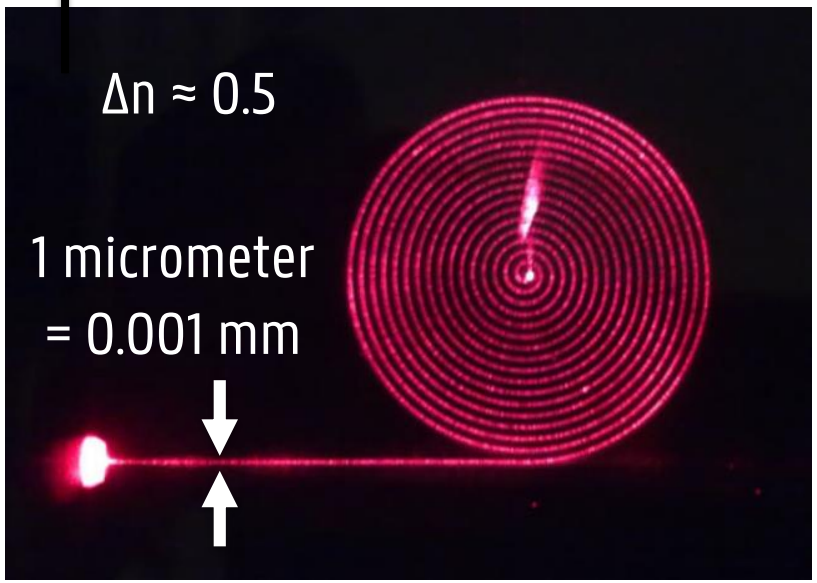


Δn < 0.01
± 10 micrometer
= 0.01 mm



Optical fiber

Photonic integrated circuit

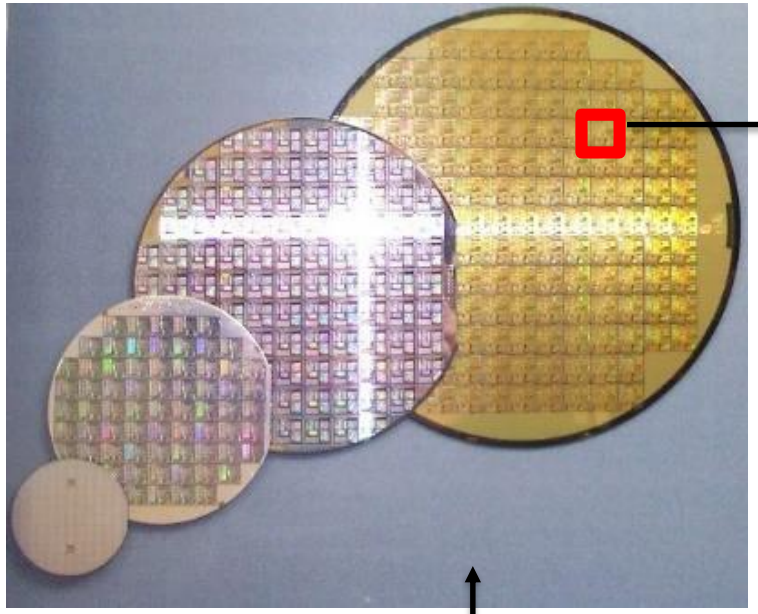


- Light can be guided/confined by materials with a higher refractive index than their surroundings
  → **waveguides (golfgeleiders)**

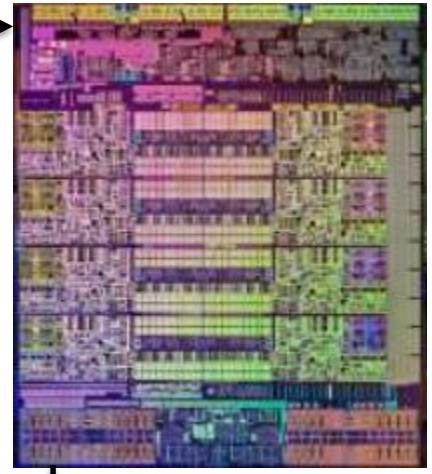
- Higher refractive index contrast
  = stronger confinement, more compact circuits

SEMICONDUCTOR INTEGRATED CIRCUITS - CHIPS

Silicon ingot is sliced into wafers



Chips are cut out of a wafer

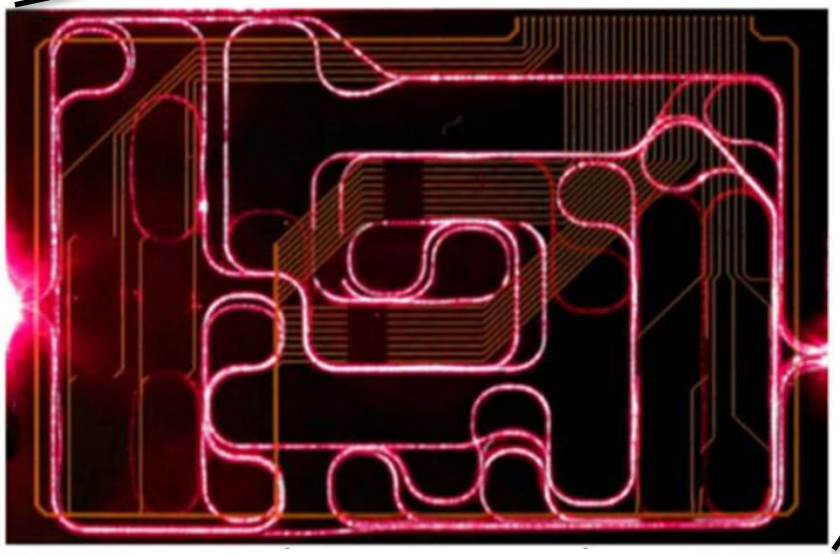


Integrated circuits are fabricated on wafers

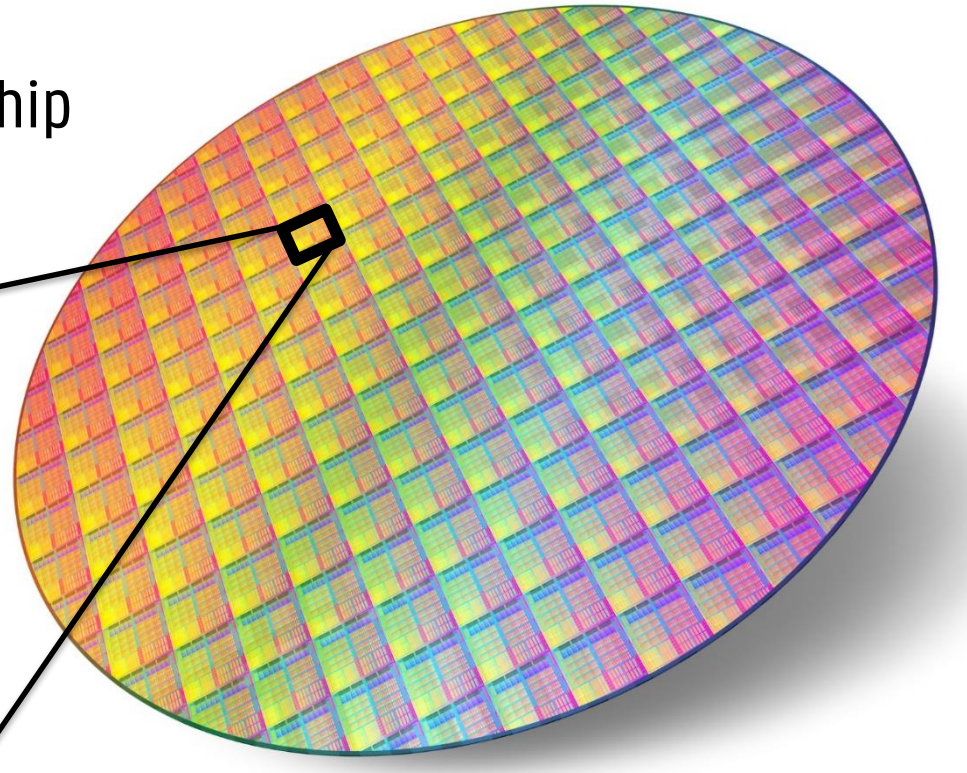
Chip packaging

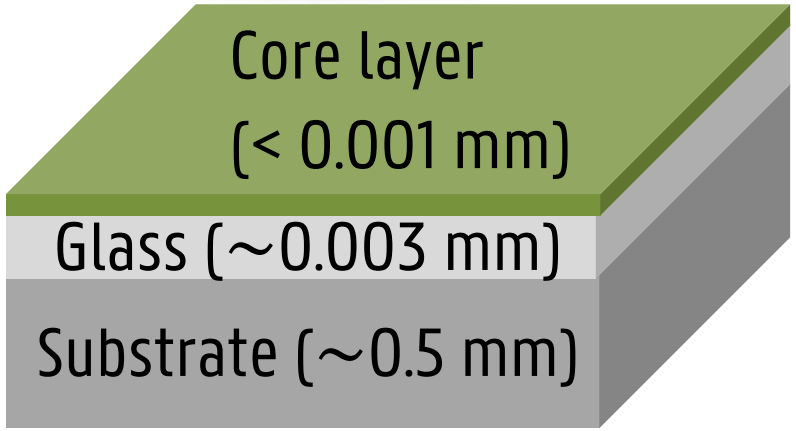
INTEGRATED PHOTONICS

- Light can be guided in integrated circuits on a chip
- Chips can be fabricated with tools from mature electronics fabs



$< 1\ mm^2$ – $> 15\ cm^2$





INTEGRATED PHOTONICS

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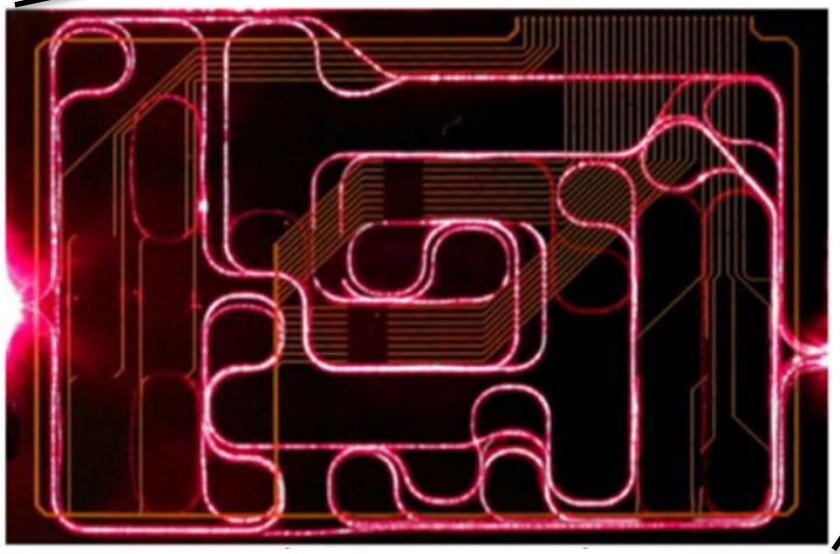

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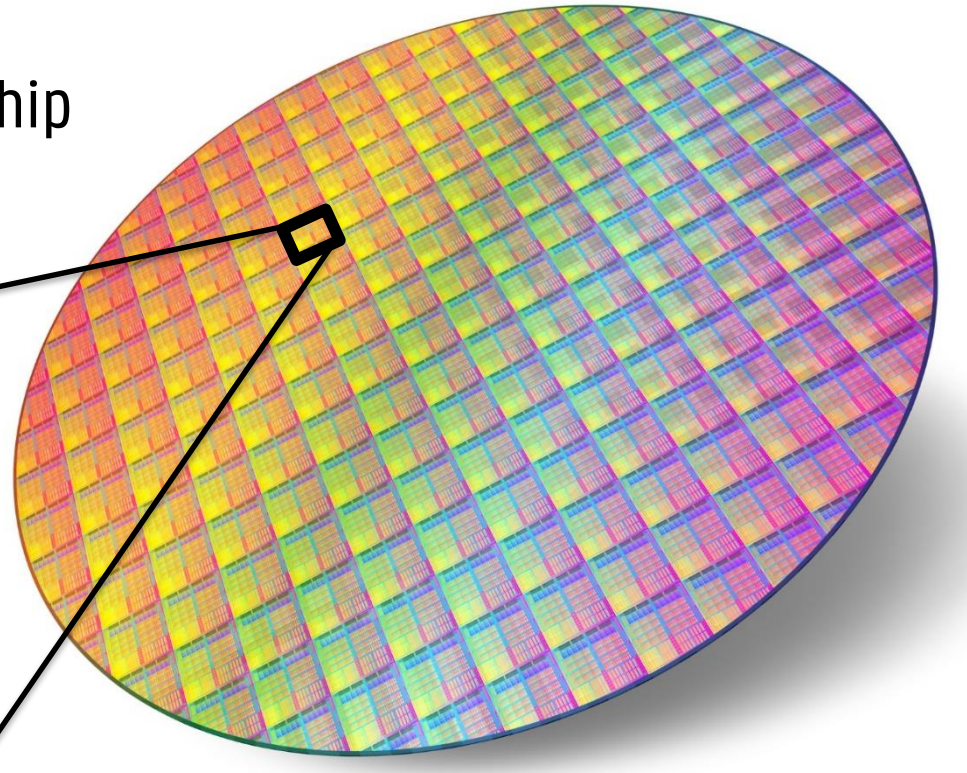
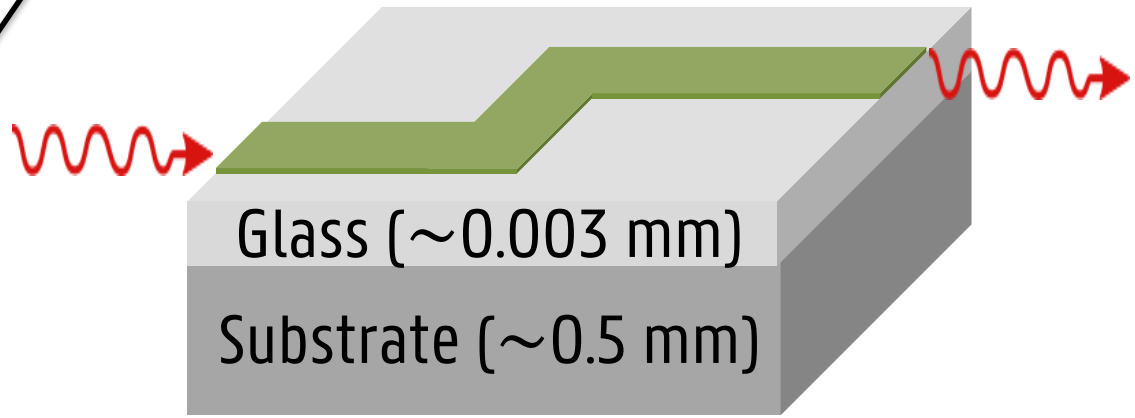
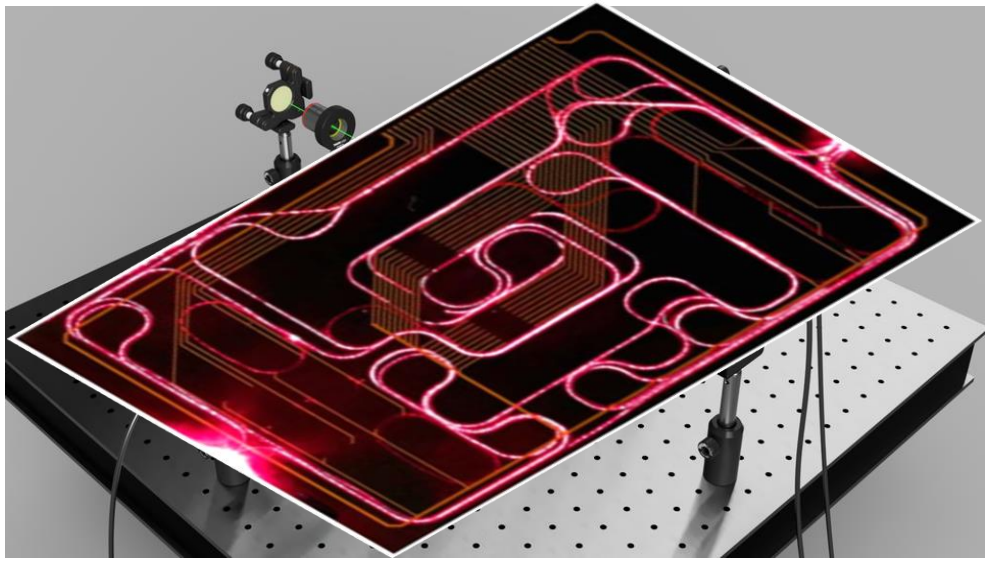
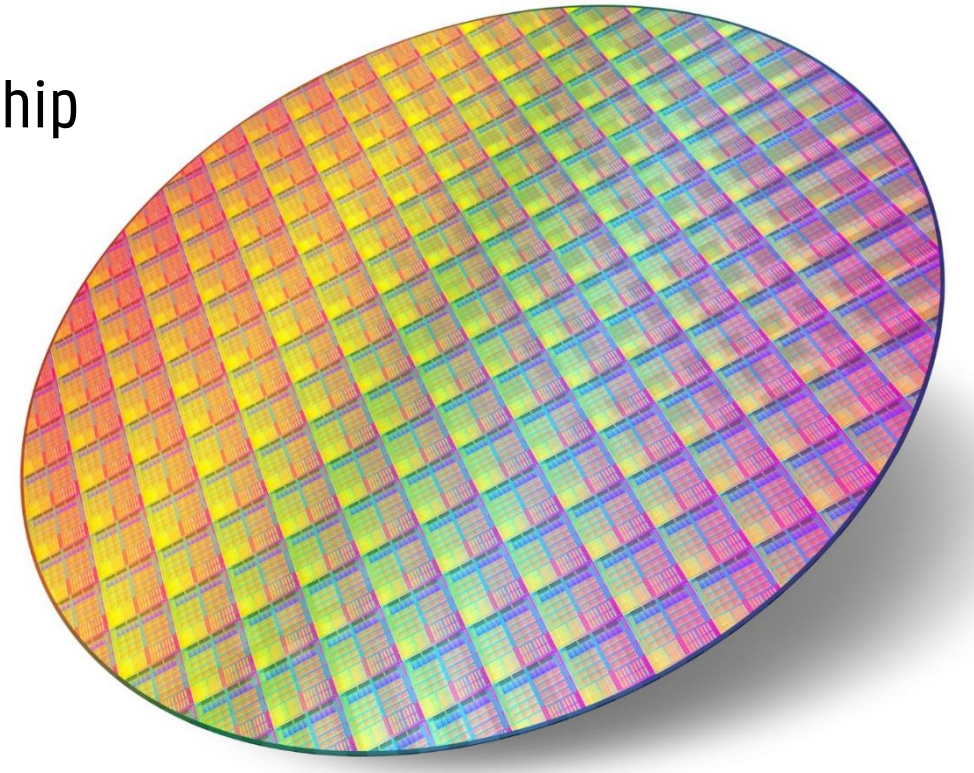


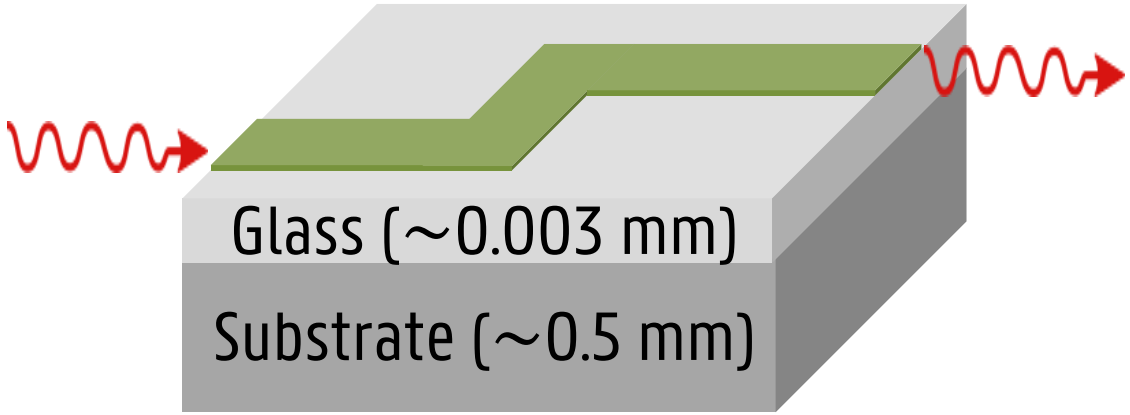


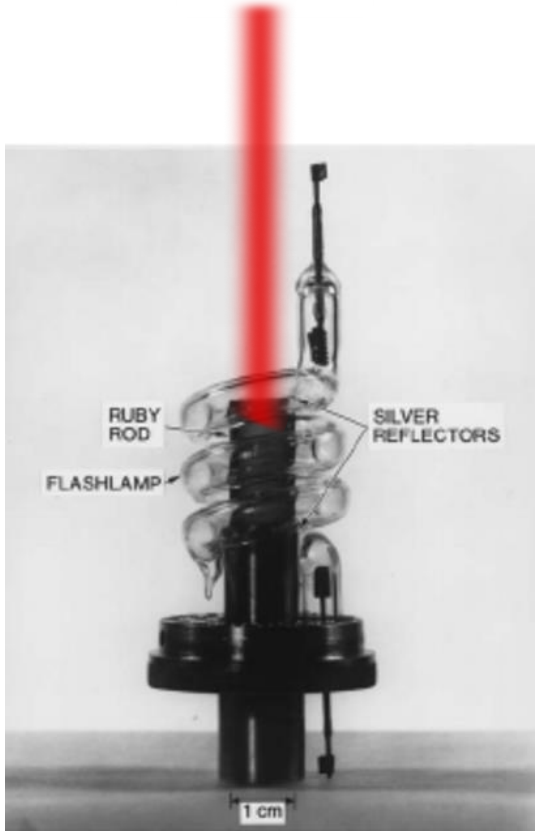
Integrated photonics

- Light can be guided in integrated circuits on a chip
- Chips can be fabricated with tools from mature electronics fabs









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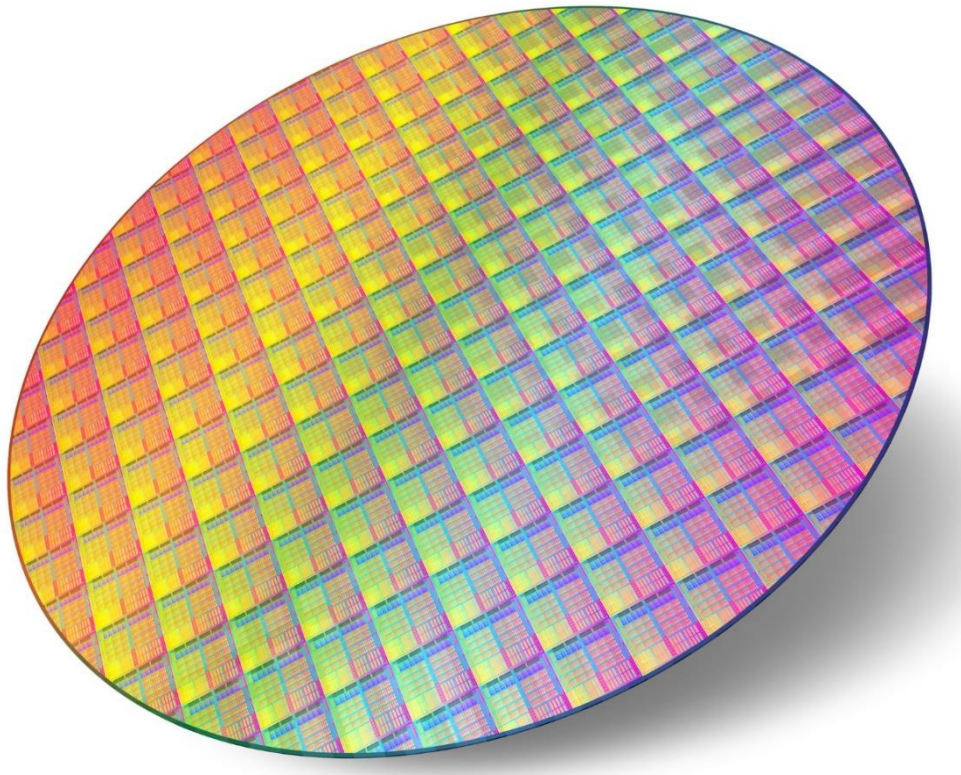

Lasers

Integrated photonics

Integrated lasers?

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LASERS WITH DIFFERENT GAIN MEDIA

Many materials/substances can be used for lasers, with varying colours and efficiencies.

- Gas lasers (e.g. CO_2 laser, He-Ne laser)
- Dye lasers (NL: kleurstof; organic molecules emitting mostly visible light)
- Solid state lasers (e.g. ruby laser)
- Semiconductor lasers (III-V semiconductor compounds; InP, GaAs, GaN, GaSb)

→ **Which laser is more suitable for integrated circuits?**

LASERS WITH DIFFERENT GAIN MEDIA

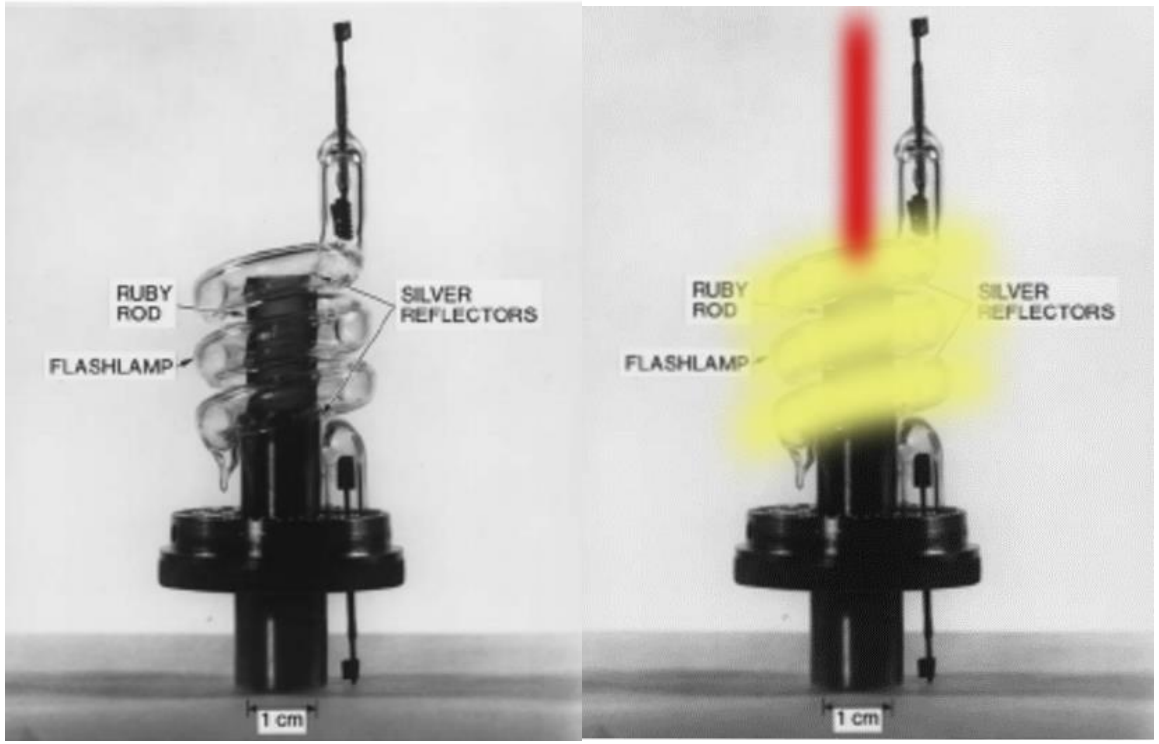
Many materials/substances can be used for lasers, with varying colours and efficiencies.

- Gas lasers (e.g. CO_2 laser, He-Ne laser)
- Dye lasers (NL: kleurstof; organic molecules emitting mostly visible light)
- Solid state lasers (e.g. ruby laser)
- **Semiconductor lasers → Electrical pumping**

Optical versus electrical pumping

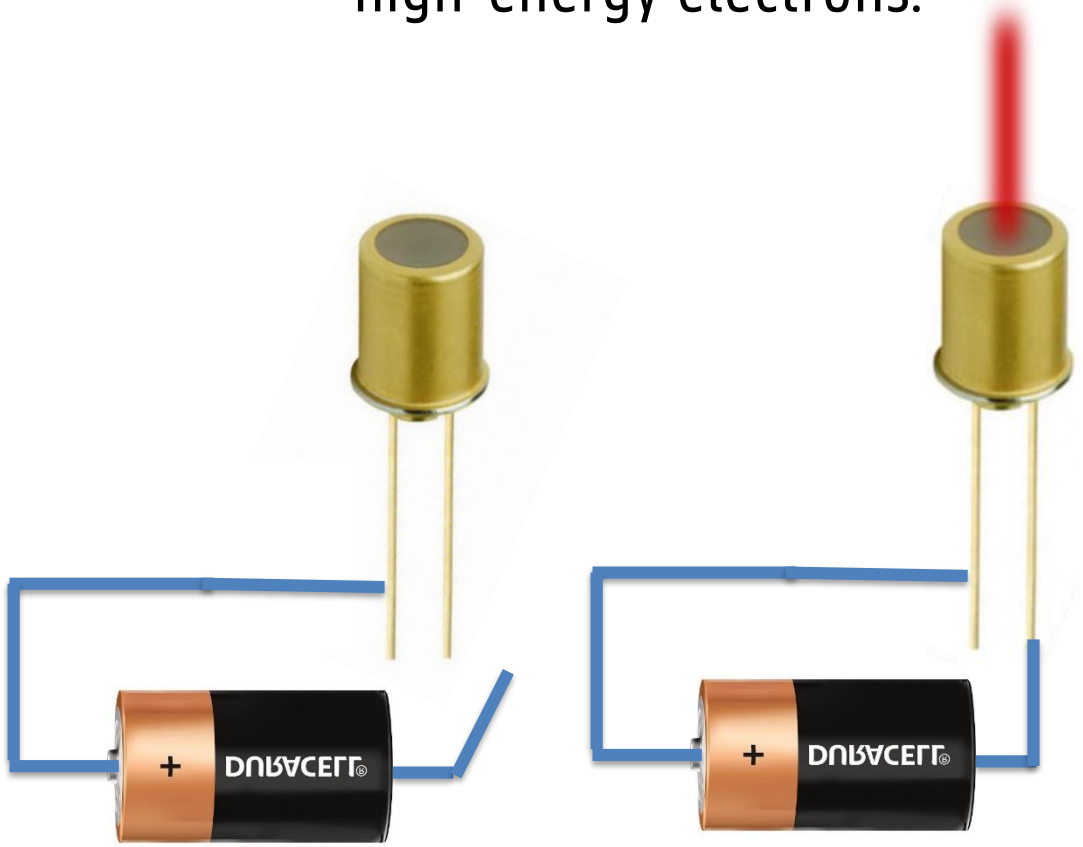
Optical pumping

Energy of high-energy pump photon is converted to lasing photon.



Electrical pumping in semiconductors

Photons are generated by injected high-energy electrons.



3 main integrated photonics platforms

- Indium phosphide
- Silicon-on-insulator
- Silicon nitride

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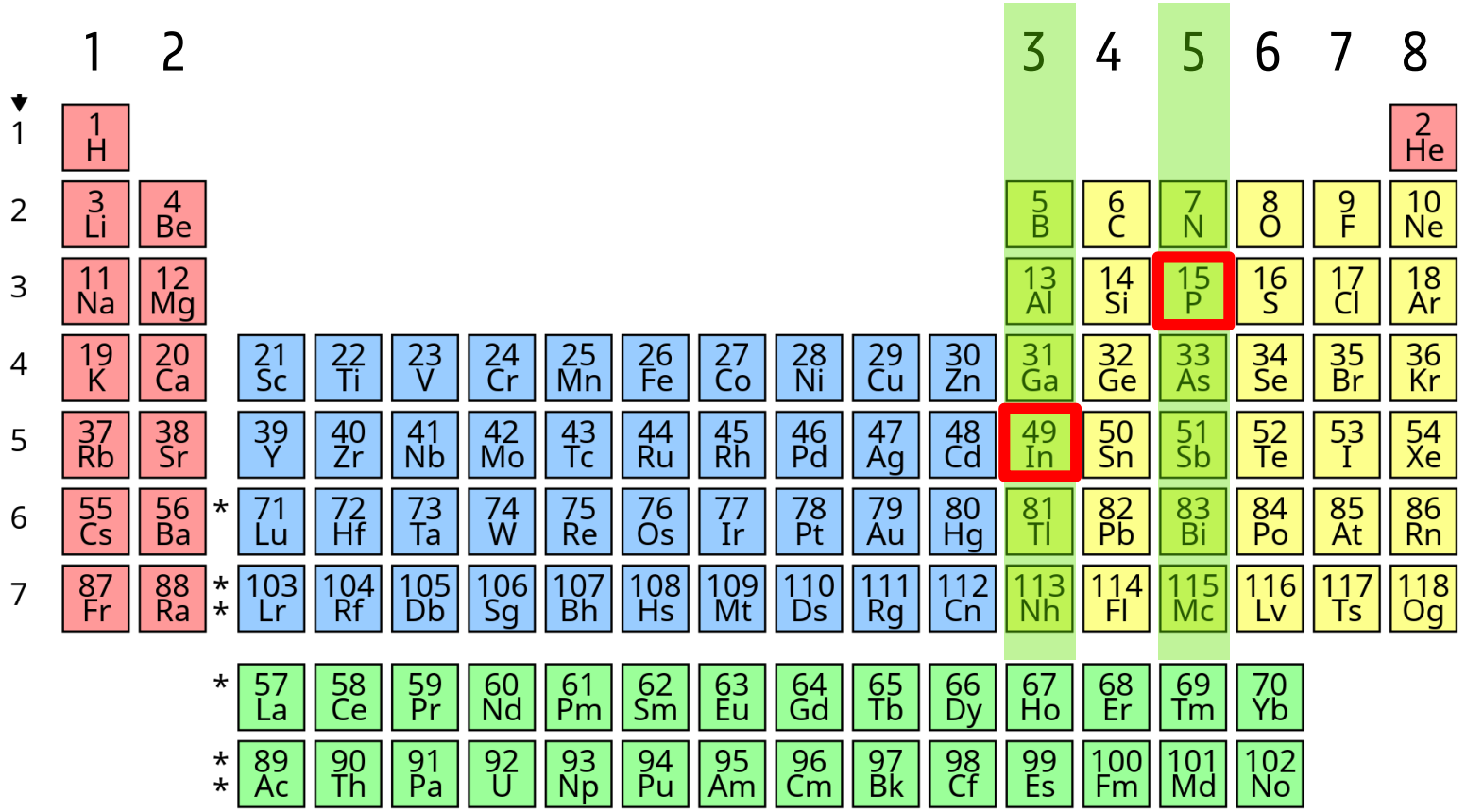
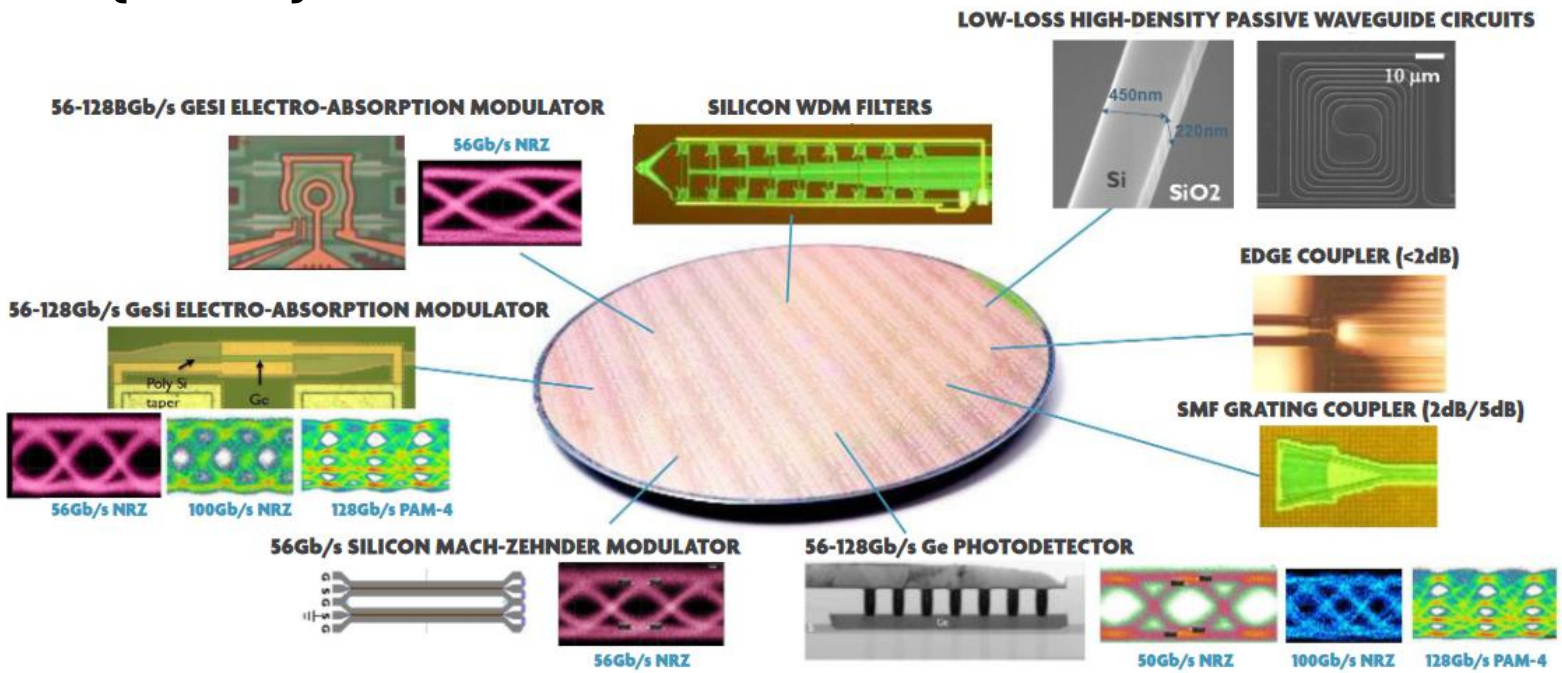
Integrated photonic platforms – Indium Phosphide

- **III-V materials** group: InP, GaAs, GaN, GaSb
- **Light generation, modulation, detection**
- Higher losses in passive components.
- (Currently) limited to smaller wafers
- First “complete” PIC in 1987



Integrated photonic platforms – Silicon-on-insulator

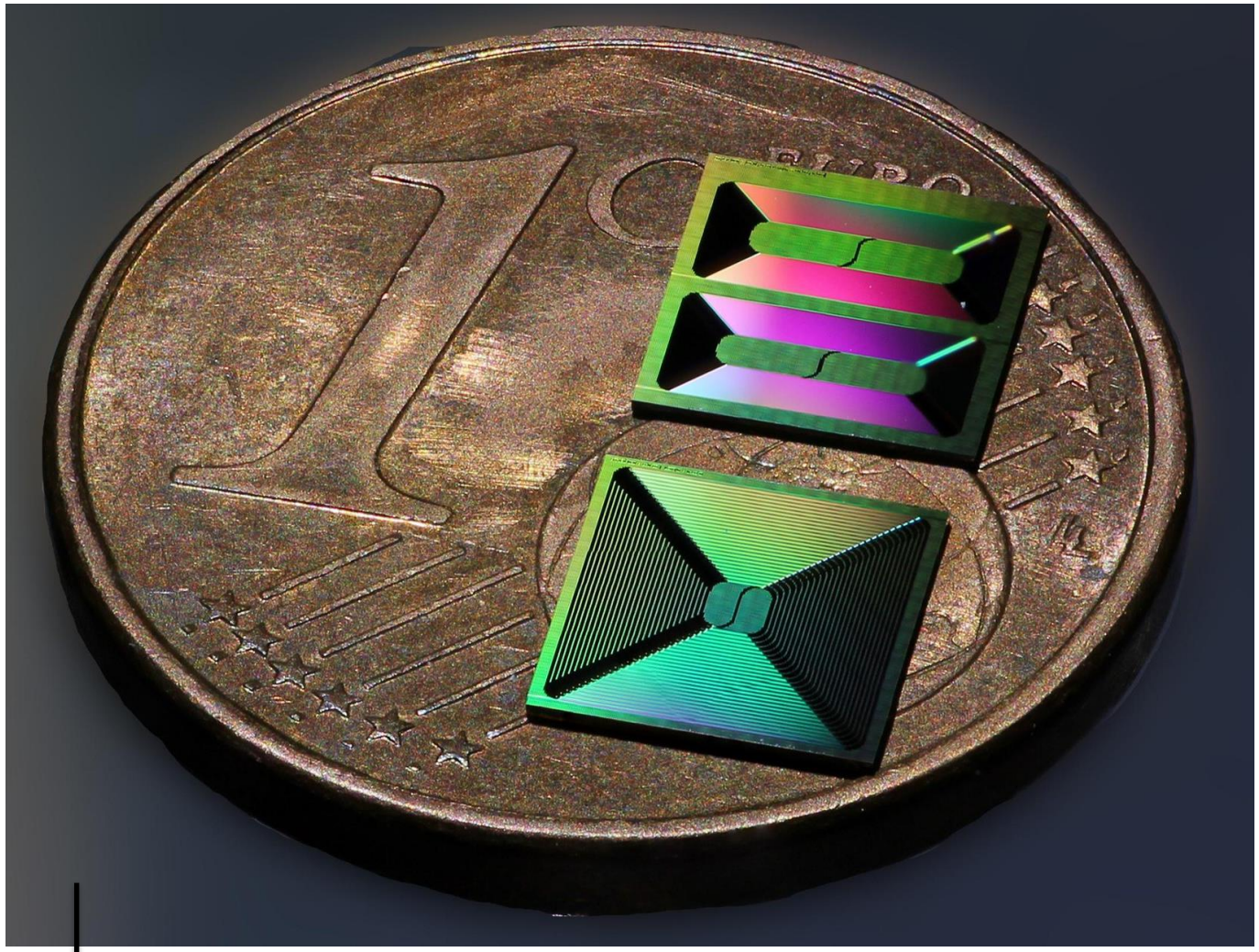
- Leverages from CMOS foundries for **high-volume** fabrication
- Cheaper raw materials
- Better performant passive devices (vs. InP)
- **Light modulation, detection**
- Common on 200mm wafers, possible up to 300mm
- **No native light source**



Imec's versatile 50G+ silicon photonics platform

Integrated photonic platforms – Silicon Nitride

- Can be processed in CMOS fabs
- **Ultra-low losses** possible
- Best for passive filters
- **Lower refractive index**
- **Transparent at visible wavelengths**
- Common on 100mm wafers, possible on 200mm
- **No native active functionality**



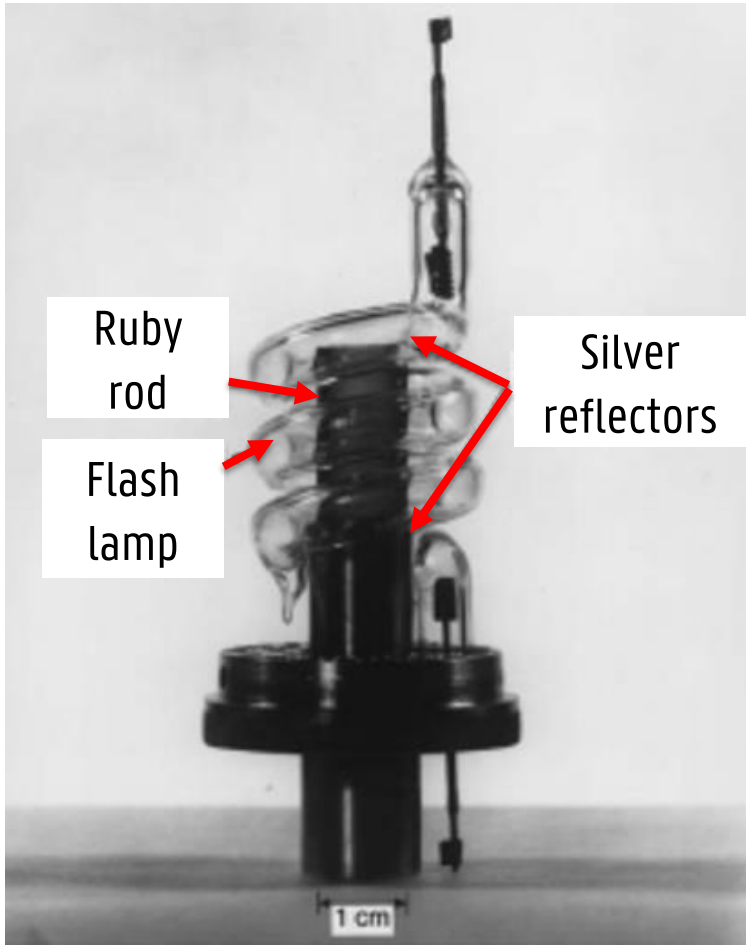
1 meter long waveguides on small Si_3N_4 chips

Overview

- Light – a general introduction
- History of the laser
- Integrated photonics
- External cavity lasers on Si_3N_4
- Heterogeneous integration
- Results

External cavity lasers

A **simple** laser needs 3 elements:



1. An optically active material (ruby)
2. A pump (flash lamp)
3. Mirrors (silver reflectors)

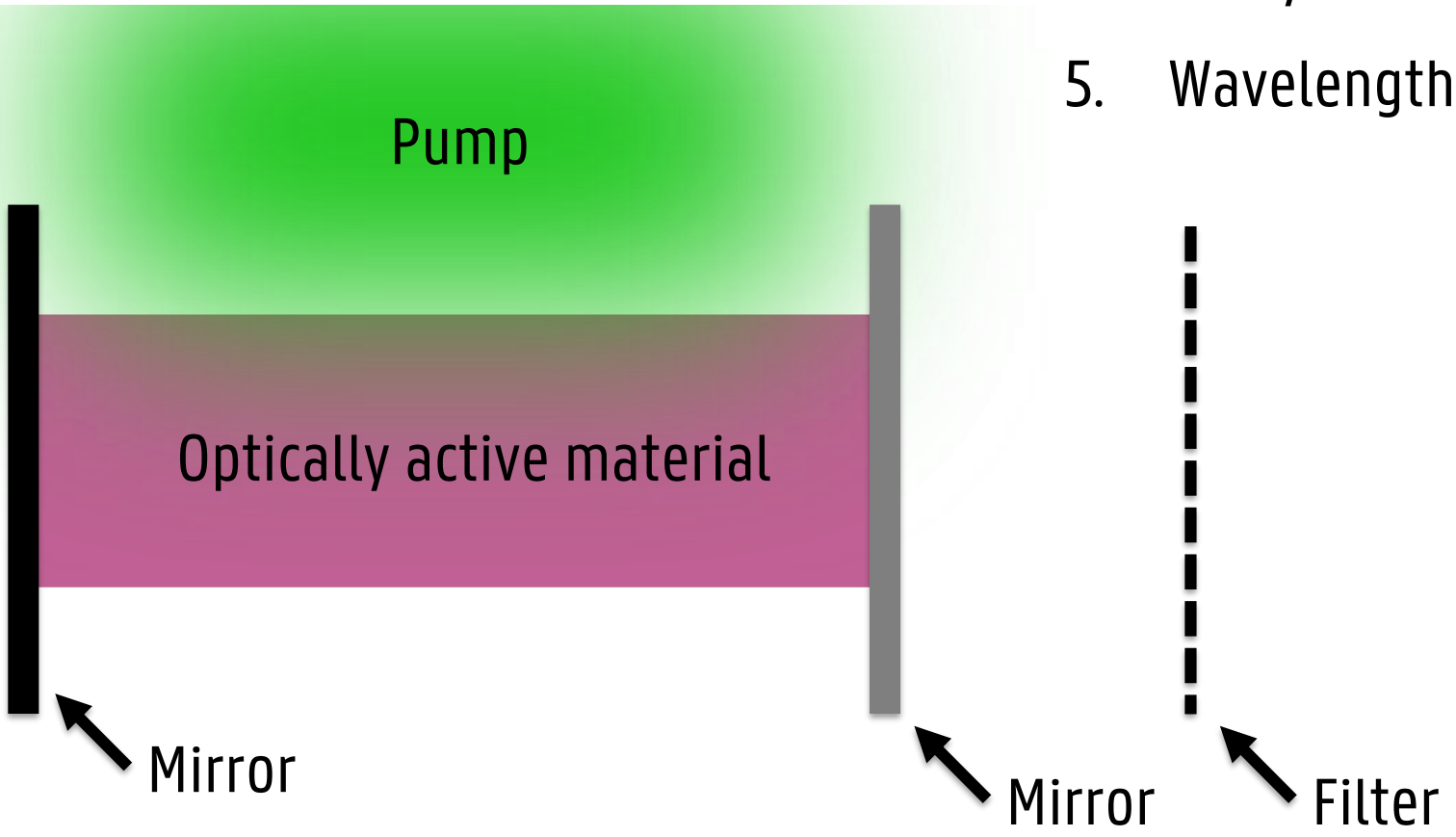
→ Still not perfectly monochromatic

Remember: $\frac{\lambda}{\Delta\lambda} \simeq 10^7 - 10^8$ (LED x 1 million)

External cavity lasers

A **more pure** laser needs more elements:

1. An optically active material (ruby)
2. A pump (flash lamp)
3. Mirrors (silver reflectors)
4. Delayed feedback
5. Wavelength (colour) filter



External cavity lasers on Si_3N_4

How do we combine all elements for a pure laser on an integrated chip?

1. An optically active material → Indium phosphide (III-V)
2. A pump → Electrical pumping
3. Mirrors → Si_3N_4, SOI, InP …
4. Delayed feedback → Silicon nitride (low waveguide losses)
5. Wavelength (colour) filter → Silicon nitride (superior filters)

Best published results with this combination:
→ line widths < 100 Hz @ f = 192 THz

$$\frac{\lambda}{\Delta\lambda} \simeq 10^{12}$$ ('normal laser' x 10 000)

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How to make small, chip-integrated lasers

with the purest possible colour ?

Heterogeneous Integration of III-V Semiconductor Light Sources
on Low-Refractive-Index Platforms

Indium phosphide

Silicon nitride

Hoe maken we kleine, op een chip geïntegreerde lasers
met de zuiverst mogelijke kleur?

Heterogene integratie van III-V-halfgeleiderlichtbronnen
op platformen met lage brekingsindex

Indiumfosfide

Siliciumnitride

Overview

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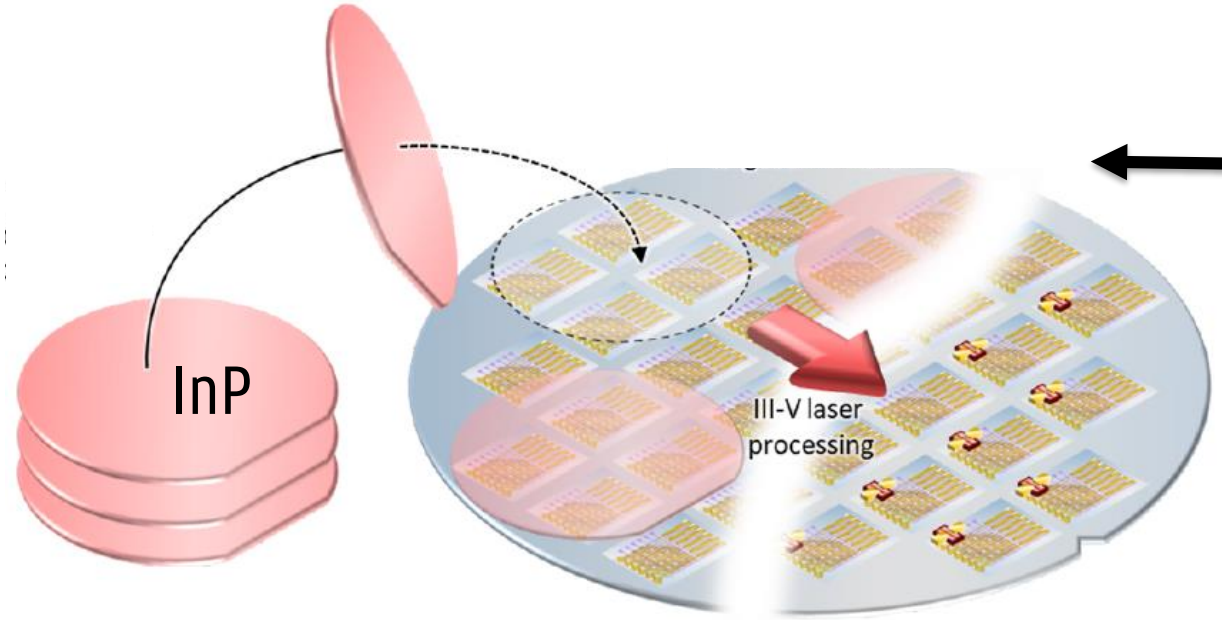
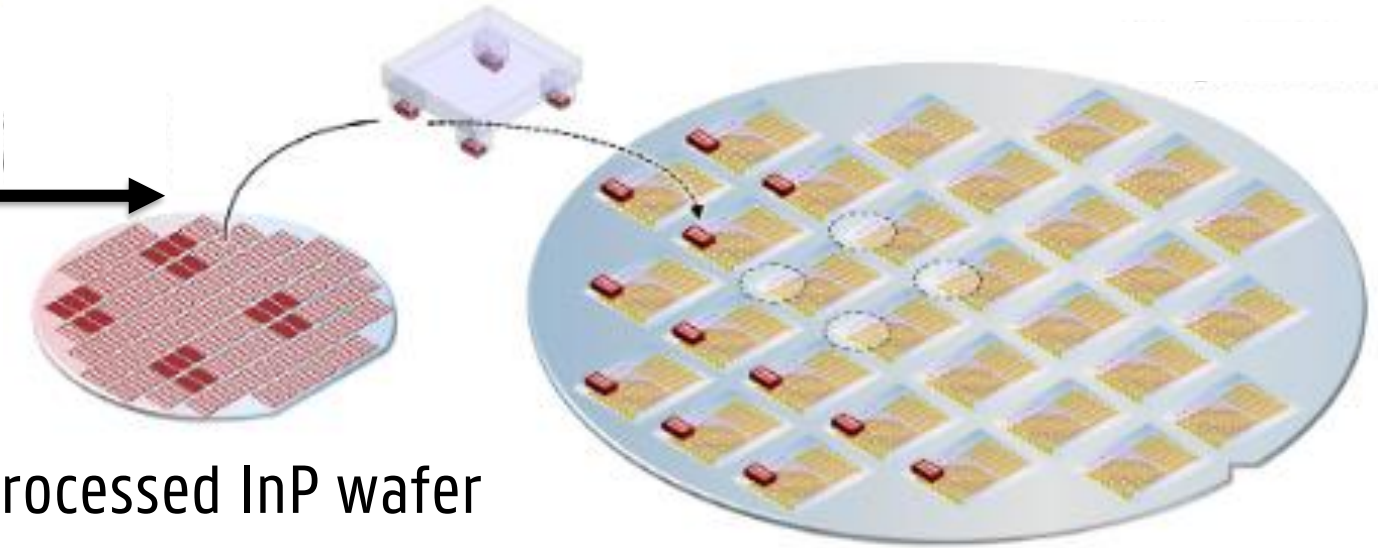
HETEROGENEOUS INTEGRATION

Problem: how to integrate two different material classes on the same chip?



"Bonding": attaching unprocessed InP wafers using Van der Waals forces.
Create covalent bonds upon heating.

"Micro-transfer printing": pick-and-place small InP 'coupons' on desired locations.



Processed InP wafer

Integration of InP on silicon nitride

Silicon nitride

Main circuit

Filters

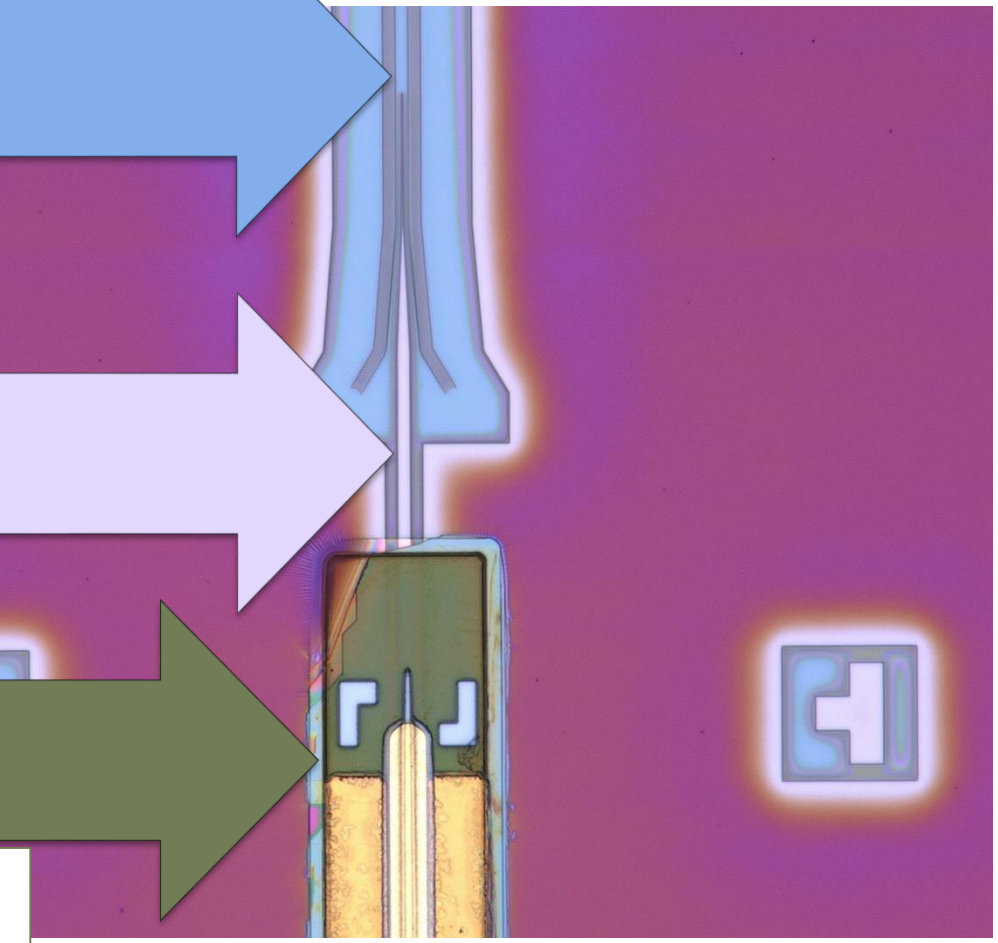
Mirrors

Silicon

Transition layer between SiN and InP

Indium phosphide

Optical amplifier



Overview

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RESULT 1: AMPLIFICATION AND LASING ON SILICON NITRIDE

386 Vol. 7, No. 5 / May 2020 / Optica Research Article

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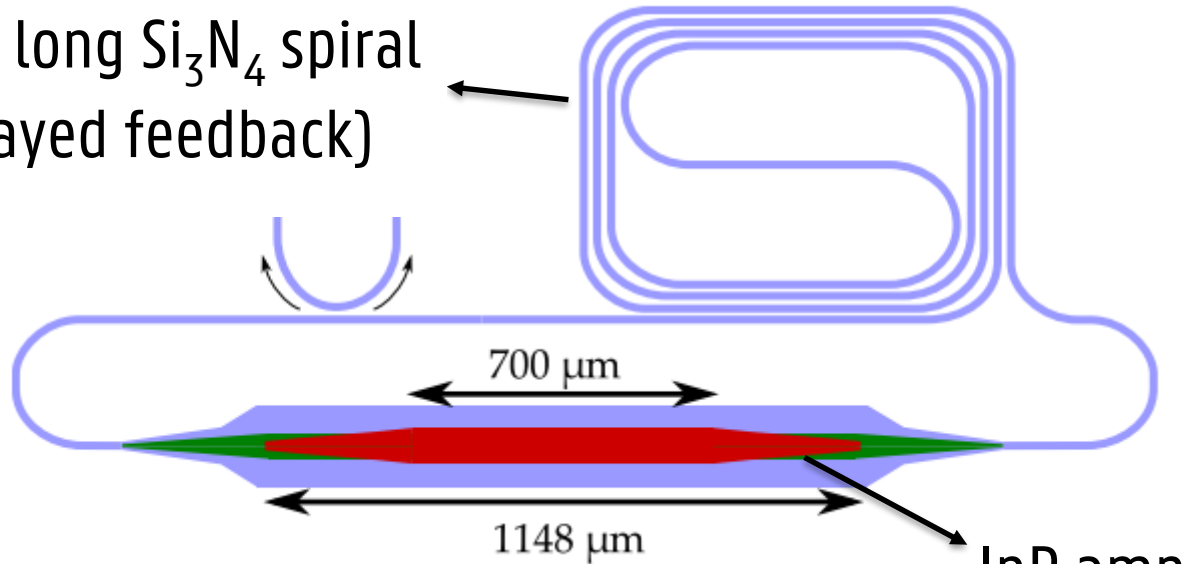
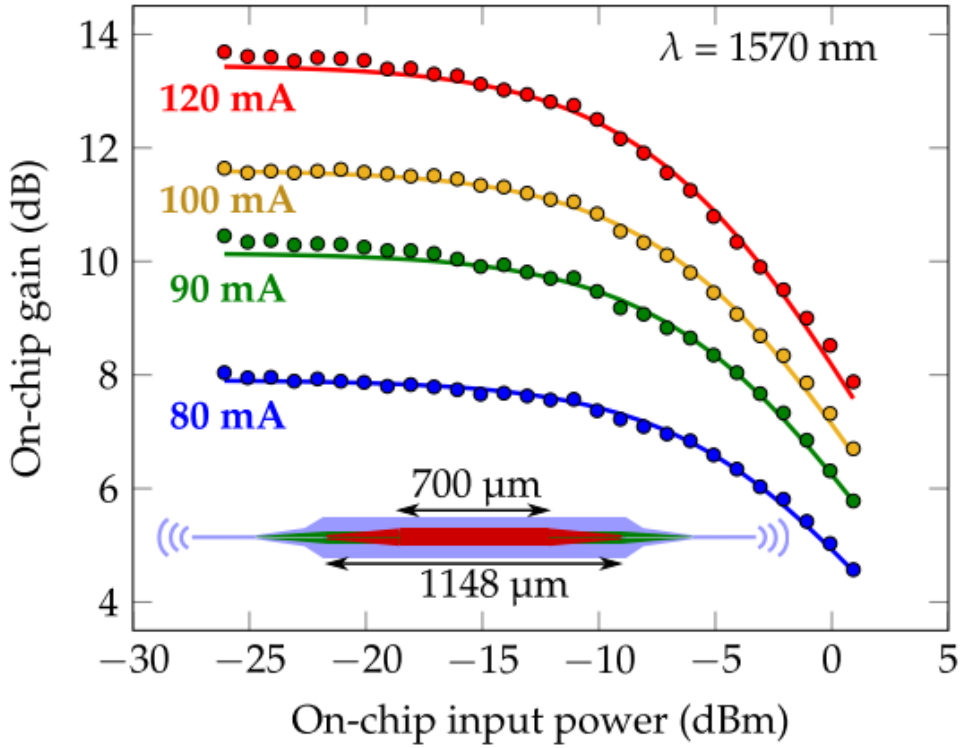
Heterogeneous III-V on silicon nitride amplifiers and lasers via microtransfer printing

CAMIEL OP DE BEECK,[1,2,*] BAHAWAL HAQ,[1,2] LUKAS ELSINGER,[1,2] AGNIESZKA GOCALINSKA,[3] EMANUELE PELUCCHI,[3] BRIAN CORBETT,[3] GÜNTHER ROELKENS,[1,2] AND BART KUYKEN[1,2]

1 cm long Si_3N_4 spiral (delayed feedback)



InP amplifier



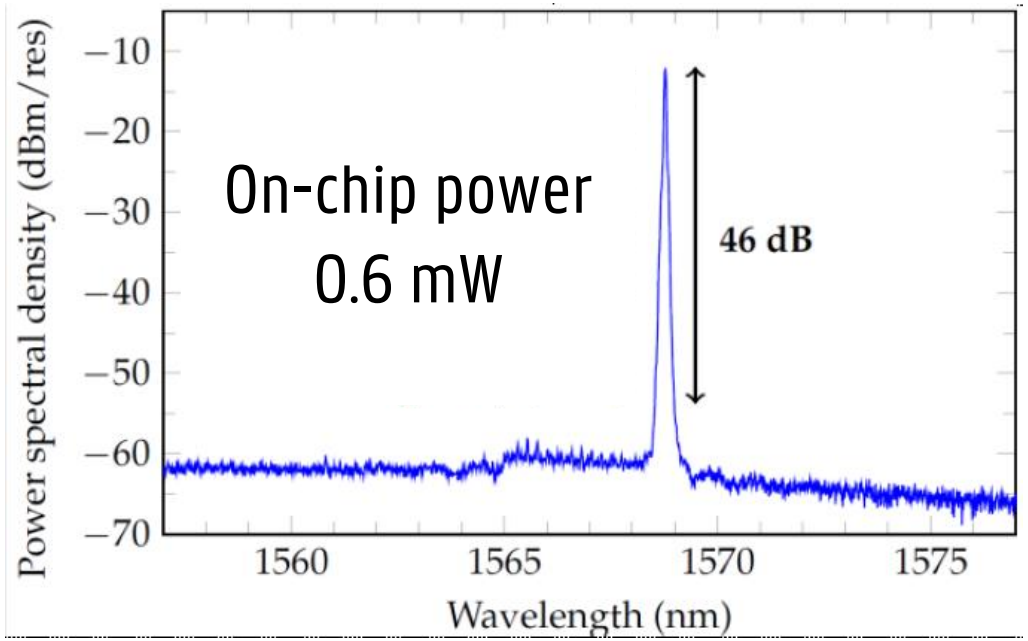
Amplification up to x 23 of the input signal.

RESULT 2: SINGLE-COLOUR LASING ON SILICON NITRIDE

Single-mode heterogeneous III-V/Si_3N_4 laser

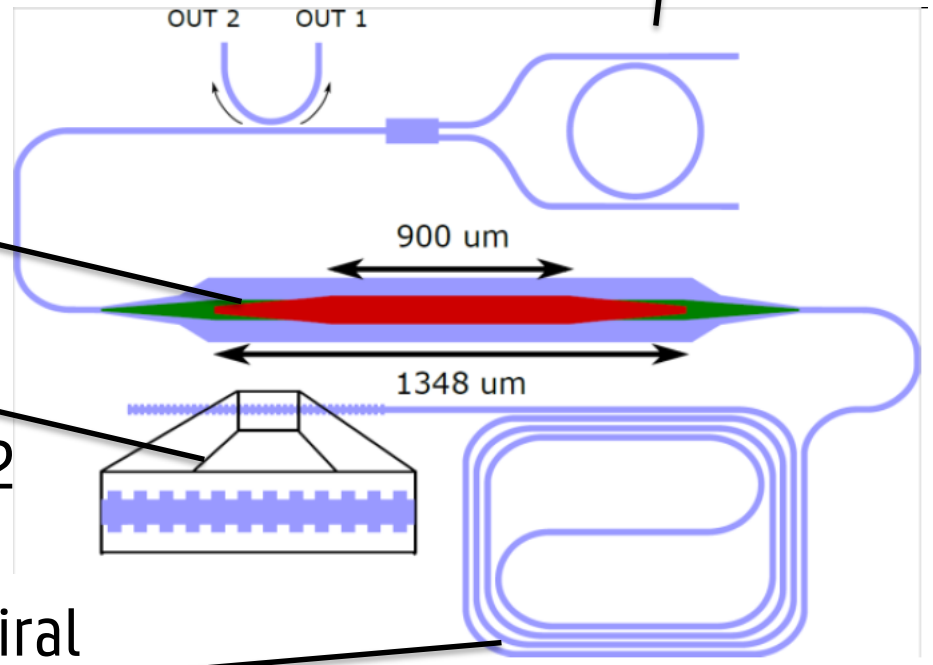
C. Op de Beeck[1,2]*, G. Roelkens[1,2], B. Kuyken[1,2]

[1]Photonics Research Group, Department of Information Technology, Ghent University - imec, Belgium
[2]Center for Nano- and Biophotonics, Ghent University, Belgium
*Camiel.OpdeBeeck@UGent.be



On-chip power
0.6 mW

Mirror +
(narrowband) filter 1



InP amplifier

Mirror +
(broadband) filter 2

1 cm long Si_3N_4 spiral
(delayed feedback)

Result 3: Adjustable-colour lasing on lithium niobate

1288 Vol. 8, No. 10 / October 2021 / Optica Memorandum

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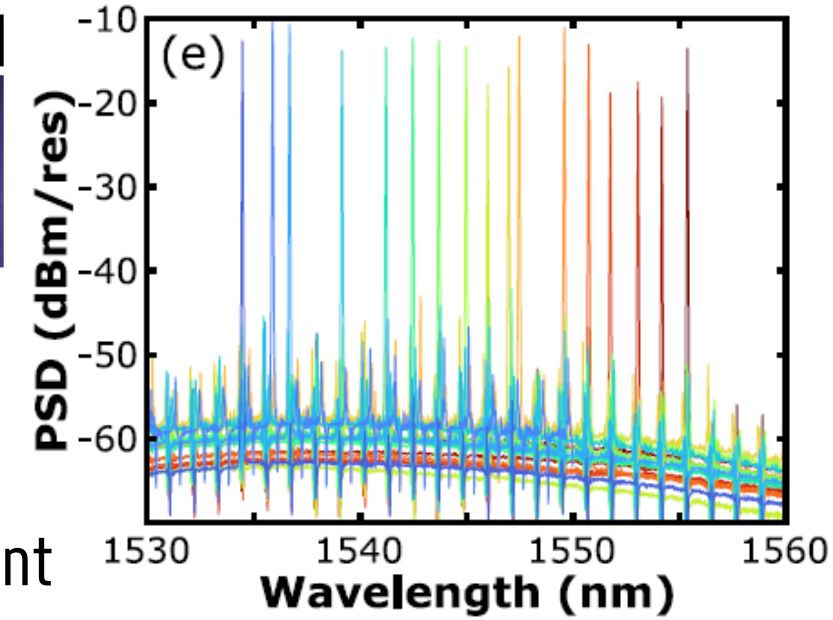
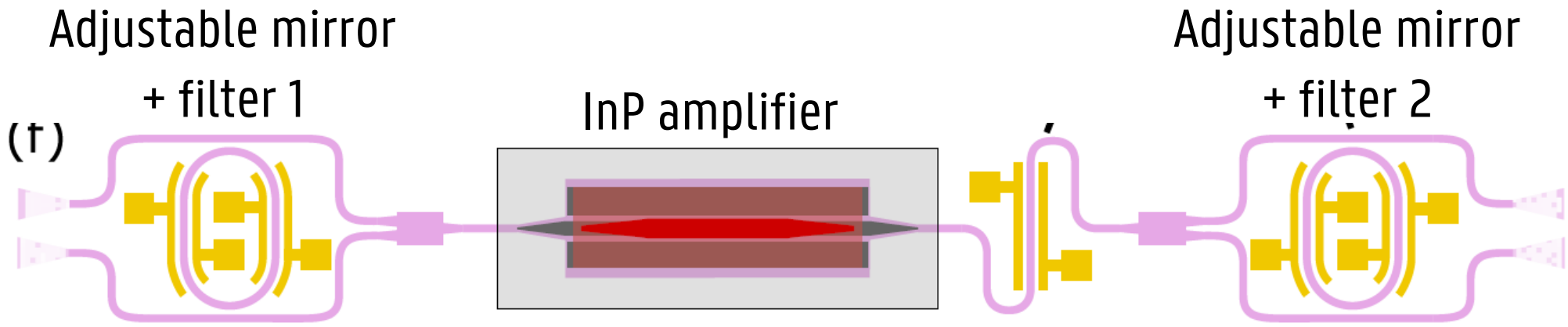
III/V-on-lithium niobate amplifiers and lasers

Camiel Op de Beeck,[1,†] Felix M. Mayor,[2,†] Stijn Cuyvers,[1] Stijn Poelman,[1] Jason F. Herrmann,[2] Okan Atalar,[2] Timothy P. McKenna,[2] Bahawal Haq,[1] Wentao Jiang,[2] Jeremy D. Witmer,[2] Gunther Roelkens,[1] Amir H. Safavi-Naeini,[2] Raphaël Van Laer,[1,2,3] and Bart Kuyken[1,*]



Lasing colour adjustment achieved over a 21 nm span.



Q&A