# QT/photonics devices;
# FET project EPIQUS with 3D integration for QT

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It-fab Italian Network for Micro and Nano Fabrication

# Outline

- Introduction
  - **Photonics**
  - **Integrated photonics**
  - **Integrated quantum photonics**
- The project EPIQUS
  - **Scope**
  - **Our approach**
- Conclusions/Perspectives

# Photonics – the practical application of optics

- Introduction
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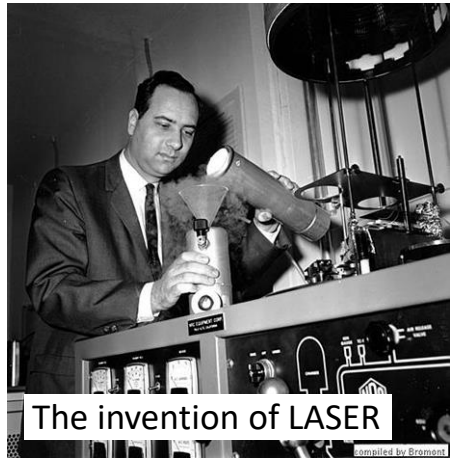
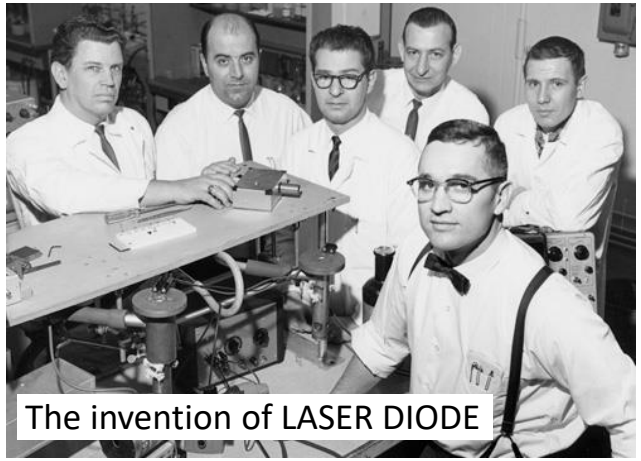
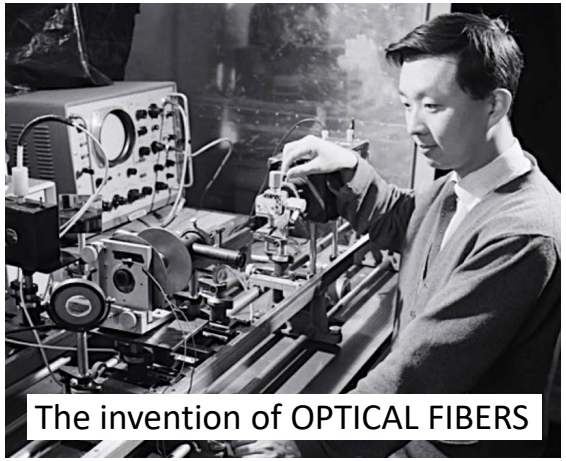
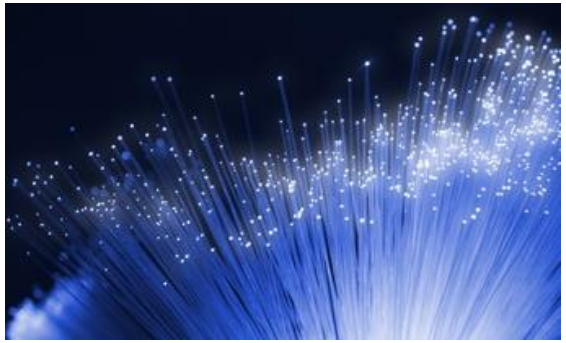
is the physical science of light (photon) **generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and sensing**


The invention of LASER


The invention of LASER DIODE

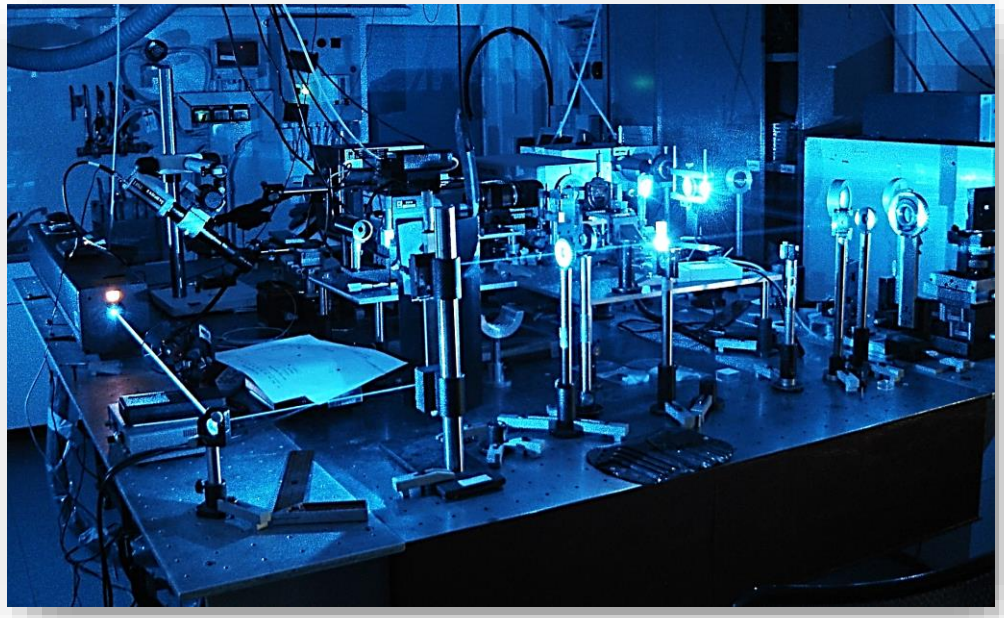

The invention of OPTICAL FIBERS

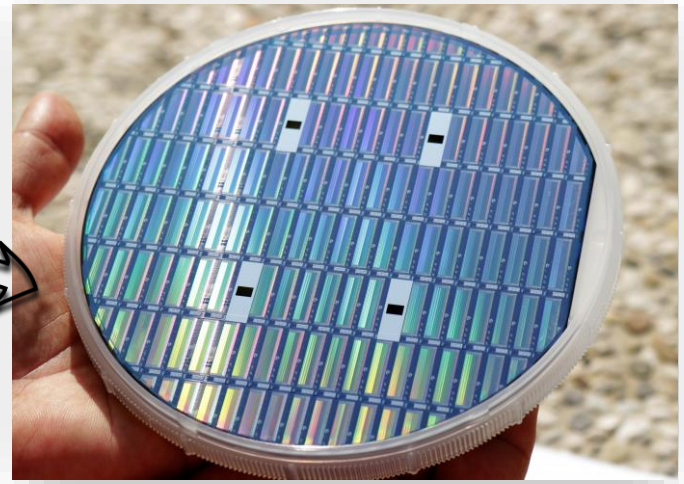


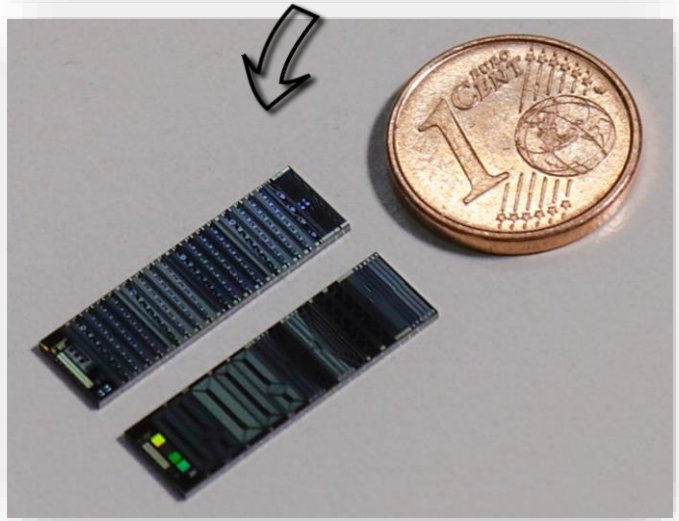
# Integrated Photonics – towards miniaturization



In a close analogy to miniaturization of bulk electronics into chip integrated circuits and devices…







Sqeesing the area by million times !
Volume reduction by 11 orders of magnitude !

# Integrated Photonics – how it works?

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# Integrated Photonics – basic principles



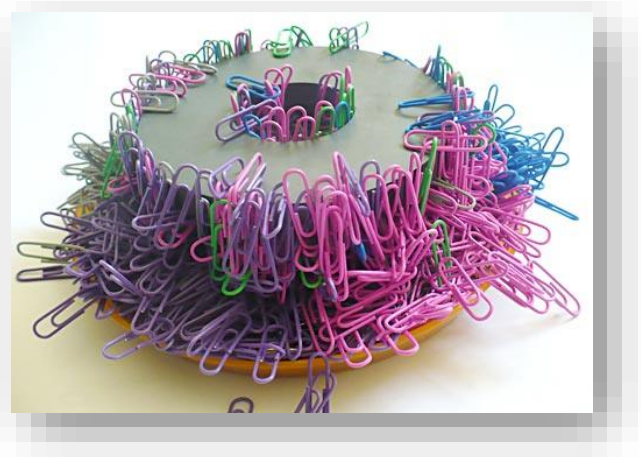
The light signals propagate through a chip relaying on the phenomenon of

WAVEGUIDING

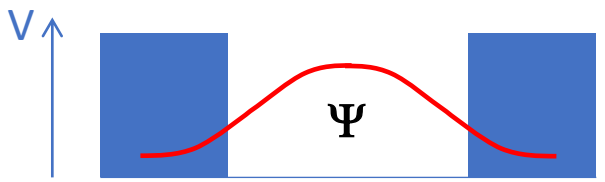
1. Light confinement
2. Continuous Total Internal Reflection

## 1. Light confinement

The ELMAG radiation tends to concentrate where the **material dielectric constant (refractive index) is higher**

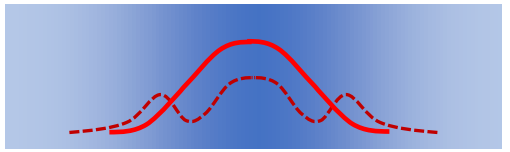


*Quantum Mechanics*



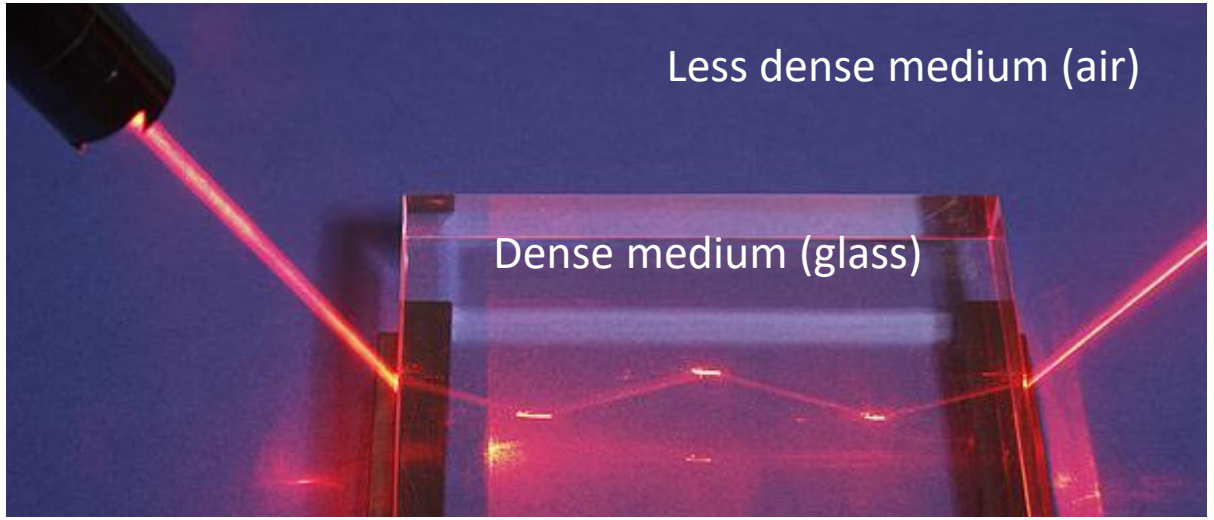

The **wavefunction** is concentrated in the **low potential**

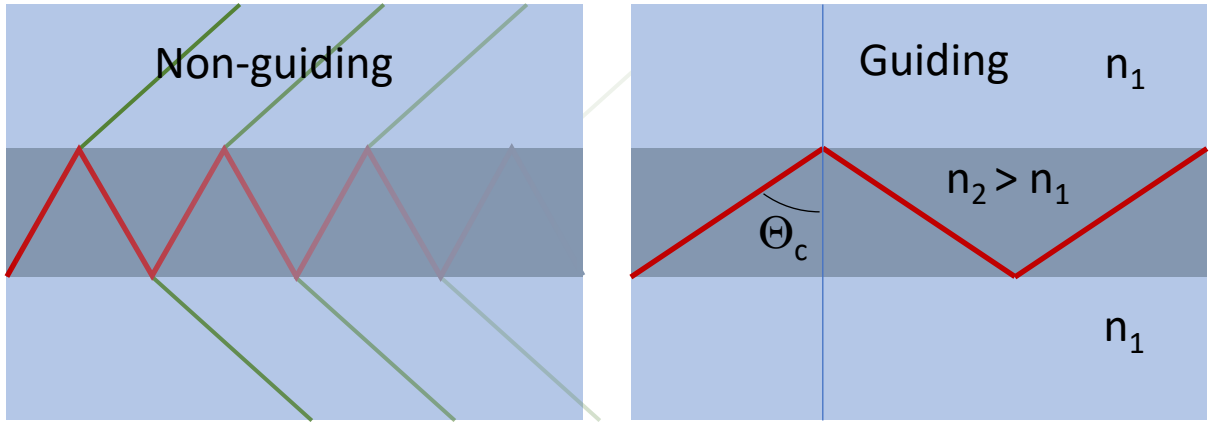
*Electrodynamics*



**The lowest order states** are concentrated in **higher $\varepsilon$ region**

## 2. Continuous Total Internal Reflection




$$\Theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right)$$

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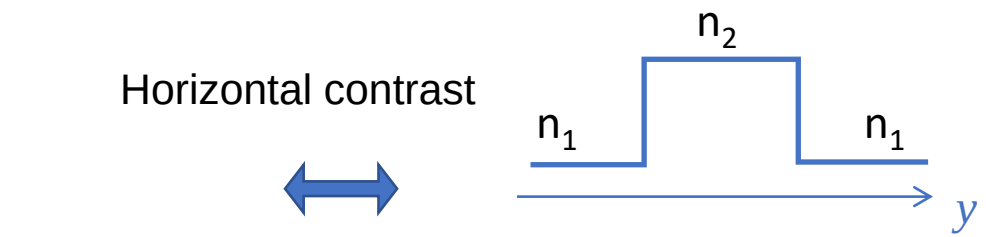
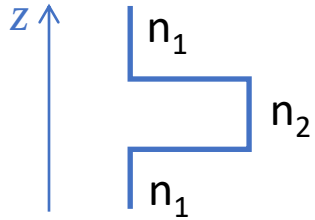
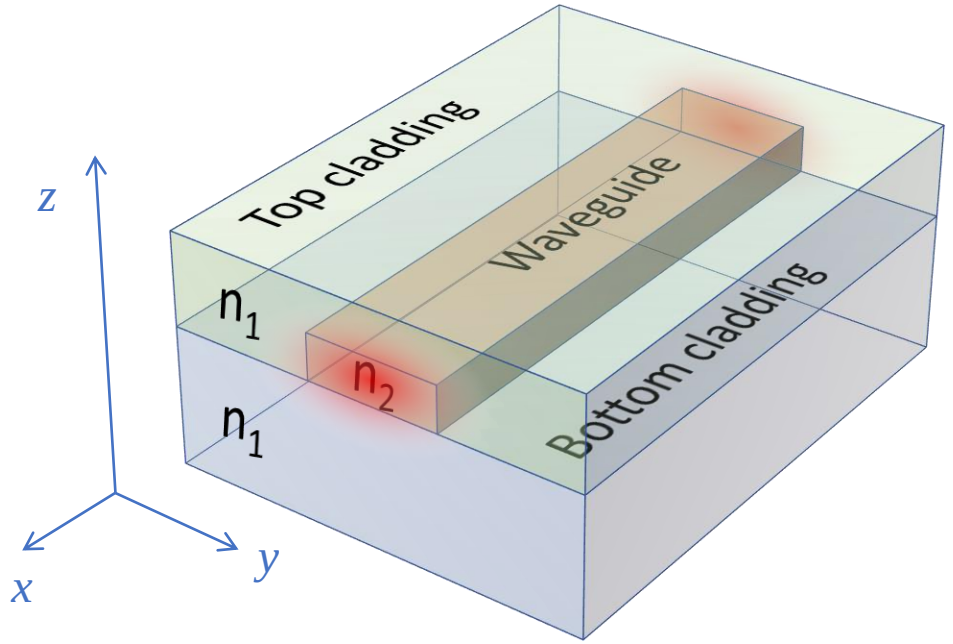



$n_2 > n_1$

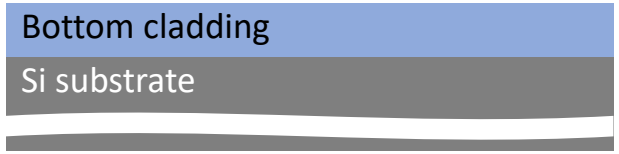


# Integrated Photonics – basic fabrication approach

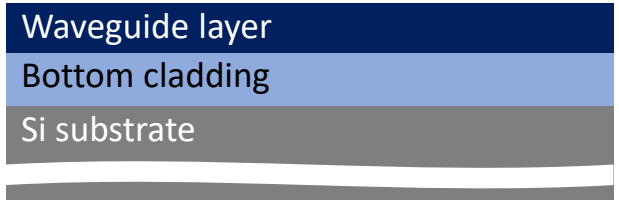


1.


2.




3.

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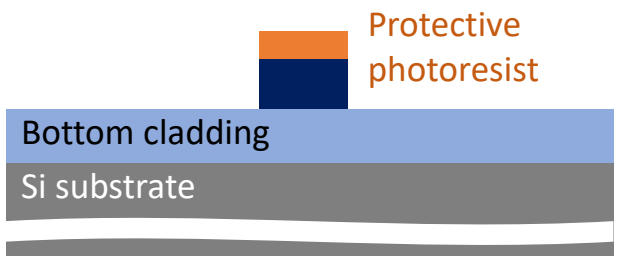
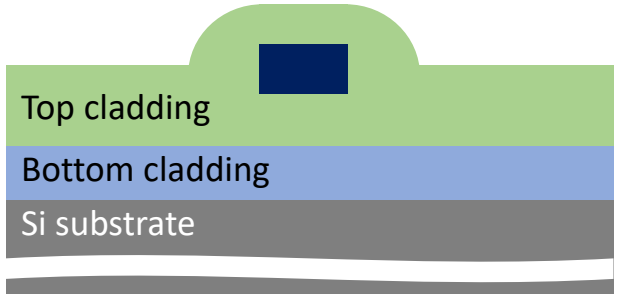



5.

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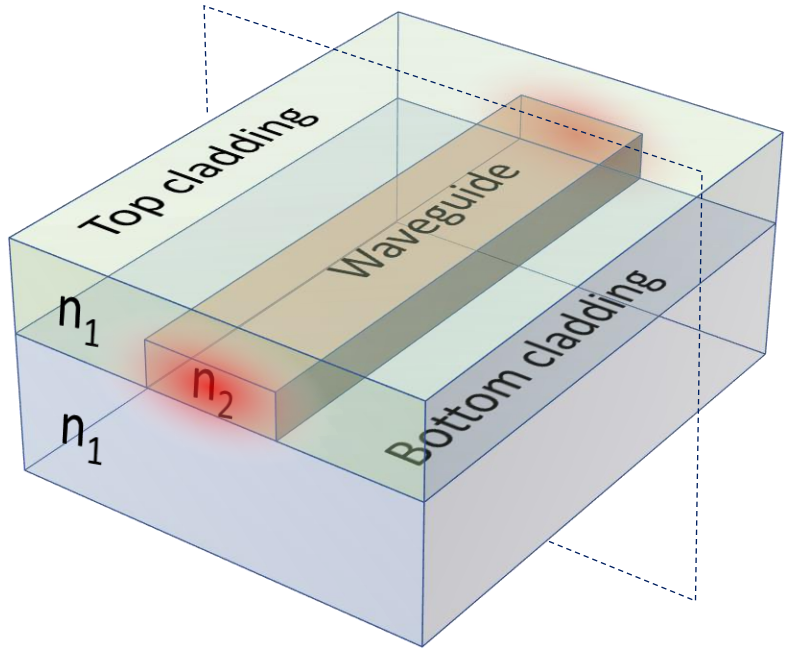
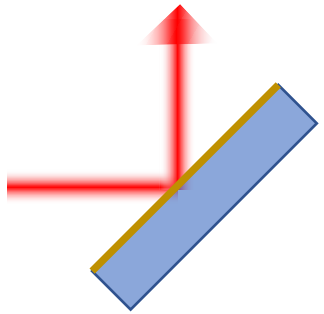


# Integrated Photonics – from bulk optics to integrated components

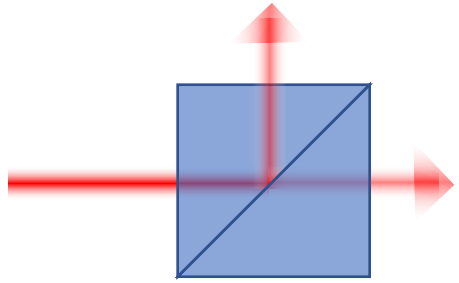


Several basic functions from bulk optics need to be implemented in the integrated photonics approach. Examples are:

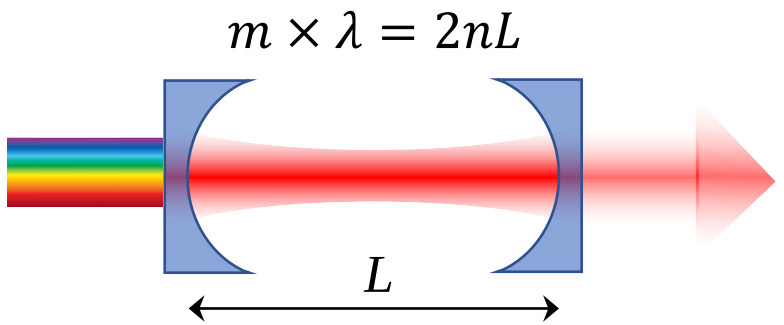
- Mirrors



- Beam splitters



- Resonating cavities



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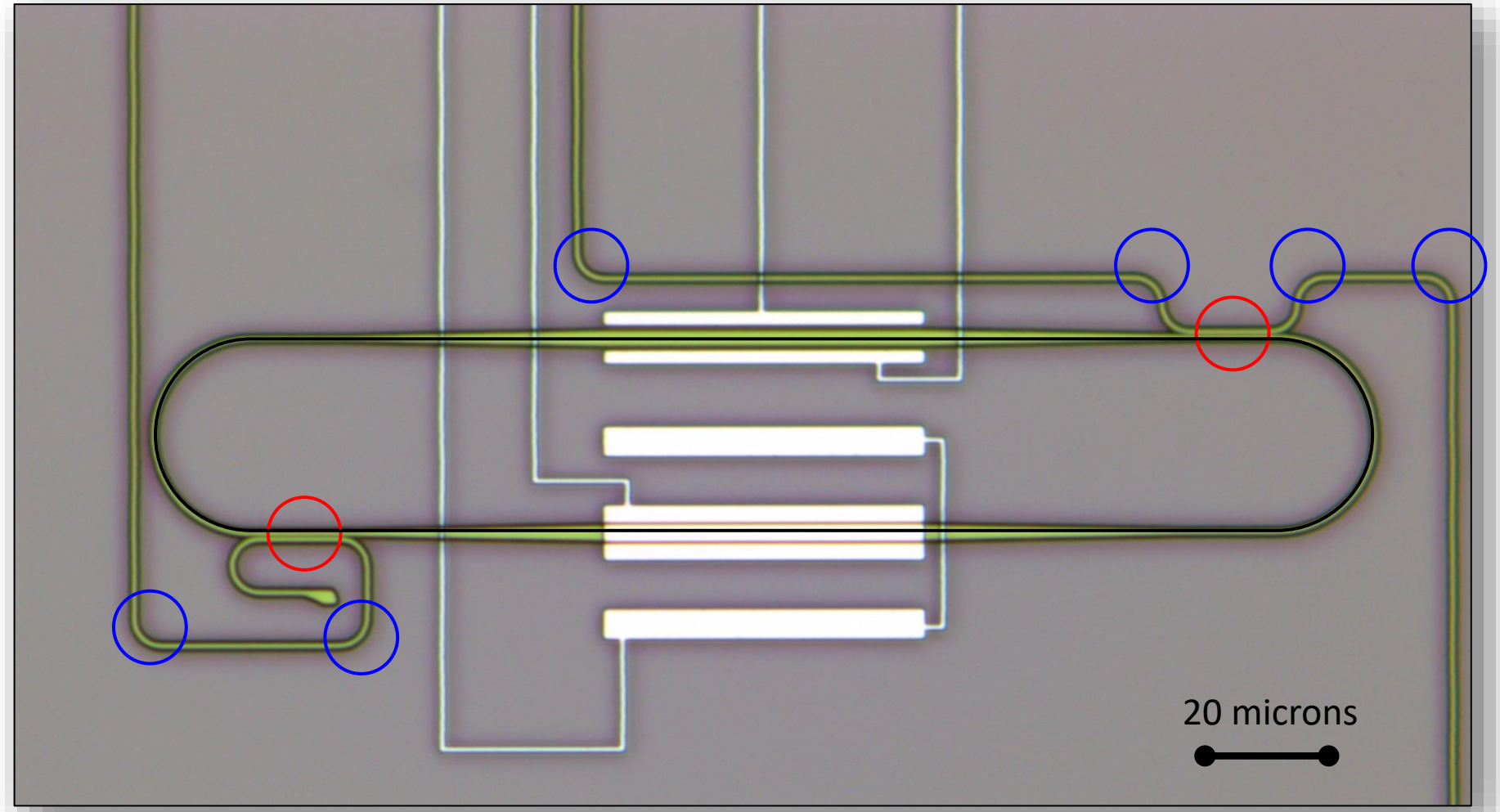
- Mirrors
- Beam splitters
- Resonating cavities



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- Mirrors

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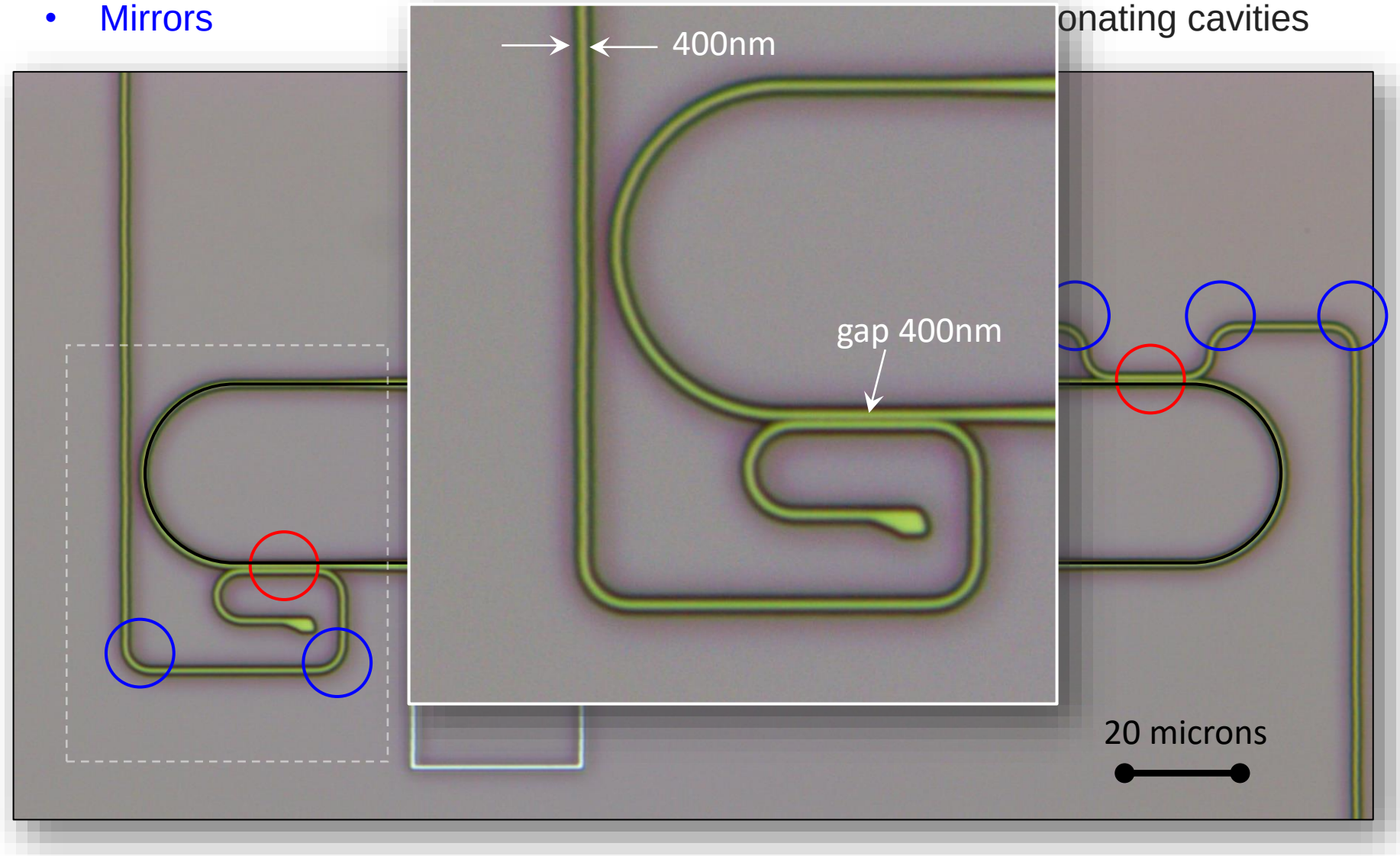


# Integrated Quantum Photonics



By 2040 we will not have the capability to power all the machines around the globe (Semiconductor Industry Association report).

Industry is focused on finding ways to make computing more energy efficient, but classical computers are limited by the minimum amount of energy it takes them to perform one operation.

$$E_{min} = k_B T \ln 2$$ (2.88 x$10^{-6}$ fJoule at RT)

Necessity in turning to radically different ways of computing, such as QUANTUM COMPUTING, to find ways to cut energy use.

**Integrated quantum photonics,** uses photonic integrated circuits to control photonic quantum states for applications in quantum technologies.

As such, integrated quantum photonics provides a promising approach to the miniaturisation and scaling up of optical quantum circuits.

The major application of integrated quantum photonics is Quantum technology:, for example quantum computing, quantum communication, quantum simulation, quantum walks and quantum metrology.

From Wiki

# Integrated Quantum Photonics – why is Quantum useful?



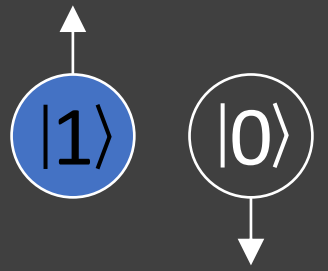
Classical computation – data unit is bit

1 0

Valid output

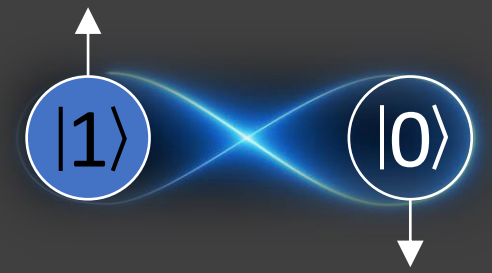
1 or 0

Quantum computation – data unit is qubit




Valid output

$$|\psi\rangle = \alpha \times |0\rangle + \beta \times |1\rangle$$



# Qubit – a two-state *quantum-mechanical* system

- Polarization of a single photon ( ↑ up or ↓ down)

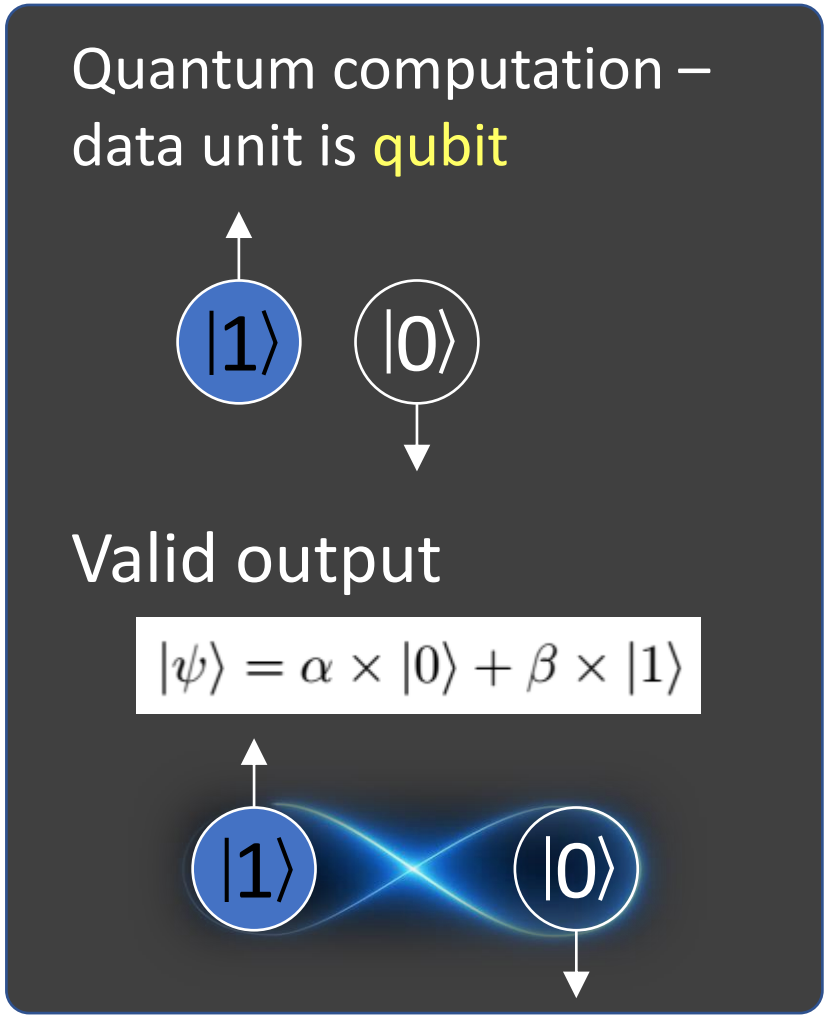
Superposition of two states:

Probability

$0 \rightarrow a^2$ ; $1 \rightarrow b^2$

$$\alpha^2 + \beta^2 = 1$$

store much more information than just 1 or 0, because they can exist in any superposition of these values.



# Qubit – a two-state *quantum-mechanical* system

Classical Bit → One out of $2^N$ possible permutations

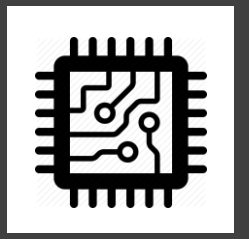
Qubit → All of possible $2^N$ permutations

Qubits are processed all at the same time!

## Exponential speedup

A 3-bit register:

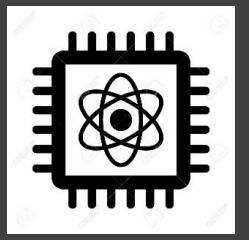
Input
100



Output
011

A 3-Qubit register:

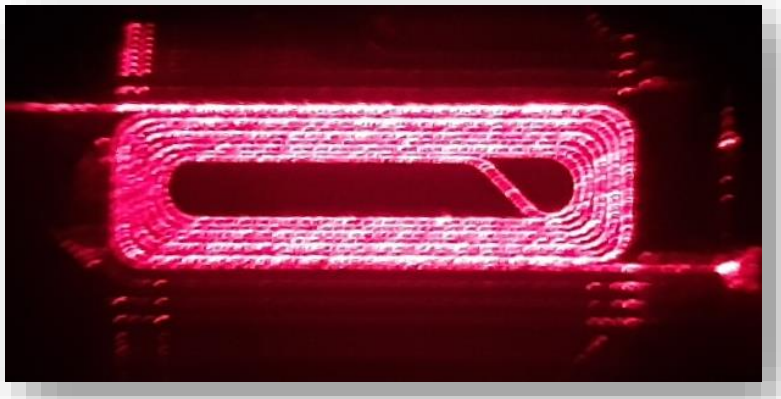
| Input | Output |
|---|---|
| 000 | 000 |
| 001 | 001 |
| 010 | 010 |
| 100 | 100 |
| 110 | 110 |
| 101 | 101 |
| 101 | 101 |
| 111 | 111 |



# Integrated Quantum Photonics – which ingredients to add?



| Component/Approach | Necessity |
|---|---|
| Single photon sources | Quantum optics at single-photon level |
| Phase-shifters | Q-photonic circuit reconfigurability via thermal-tuning |
| Single photon detectors | Detection and electronic readout |
| Scalability | Need to increase number of identical qubits (Quantum Supremacy) |
| Very low loss architectures | Need to increase the efficiency and fidelity |



# The project EPIQUS - Info



Funding: European Commission | HORIZON 2020 https://cordis.europa.eu/project/id/899368

Title: Electronic-photonic integrated quantum simulator platform

Duration: 42 months

Budget: 3.2 M€

Coordinator: Fondazione Bruno Kessler (IT)

Partners: UniTN (IT), UPV/EHU (ES), UniVie (AT), URos (DE), TUW (AT), ETRI (KR), LFoundry Srl (IT)

# The project EPIQUS - Scope



EPIQUS aims to demonstrate a cheap, easy-to-use, performant Quantum Simulator (QS) based on full integration of silicon nitride photonics with silicon electronics.

The core objective of EPIQUS is to set a cornerstone technology – demonstrate the first breakthrough device - which will simulate quantum mechanical problems in a compact device operating at ambient temperatures.

Our vision is to develop a Quantum Simulator by bringing onto a unique semiconductor platform the mature silicon microelectronic (CMOS, digital) and the silicon nitride quantum micro-photonic functionalities.

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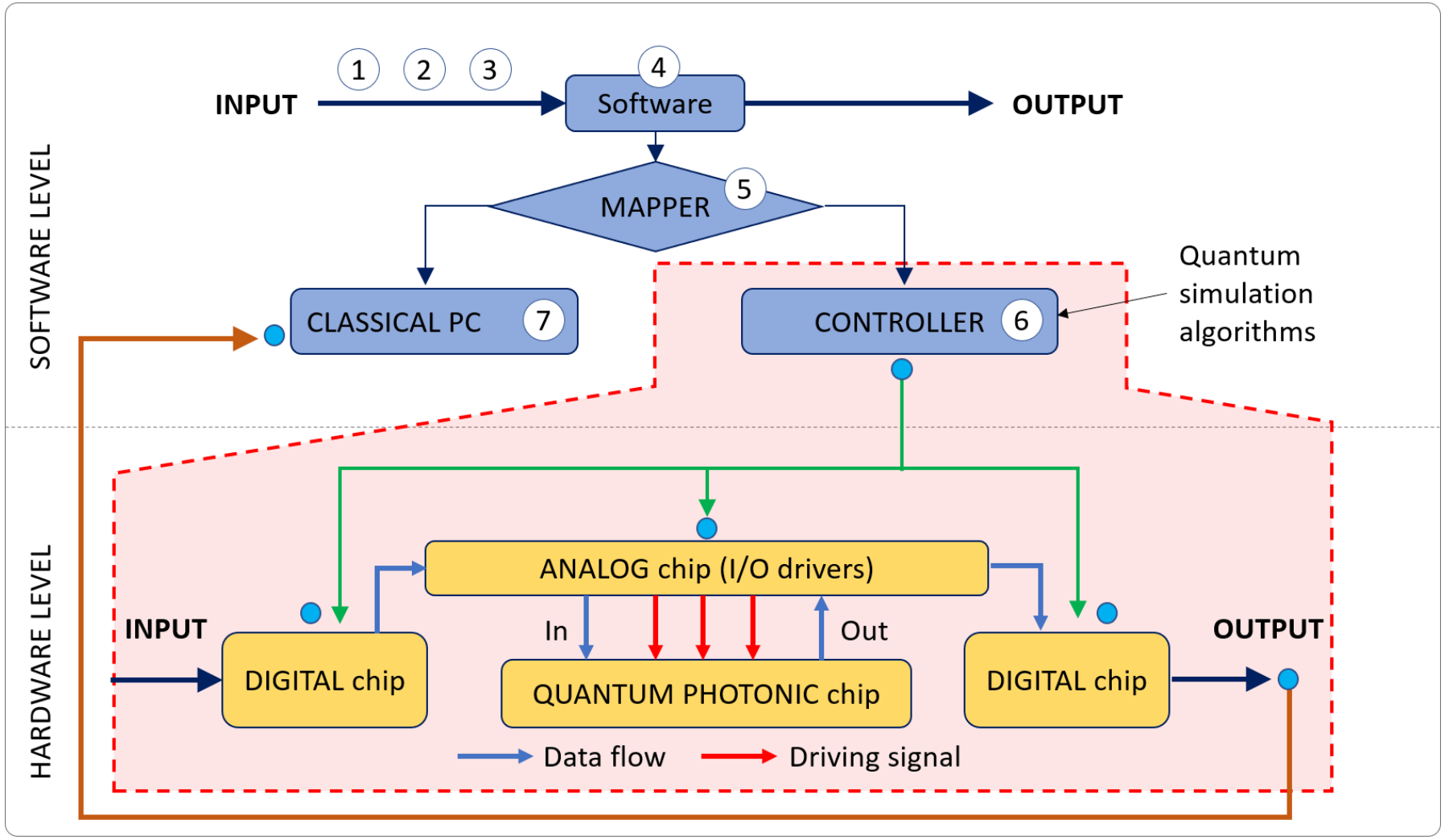

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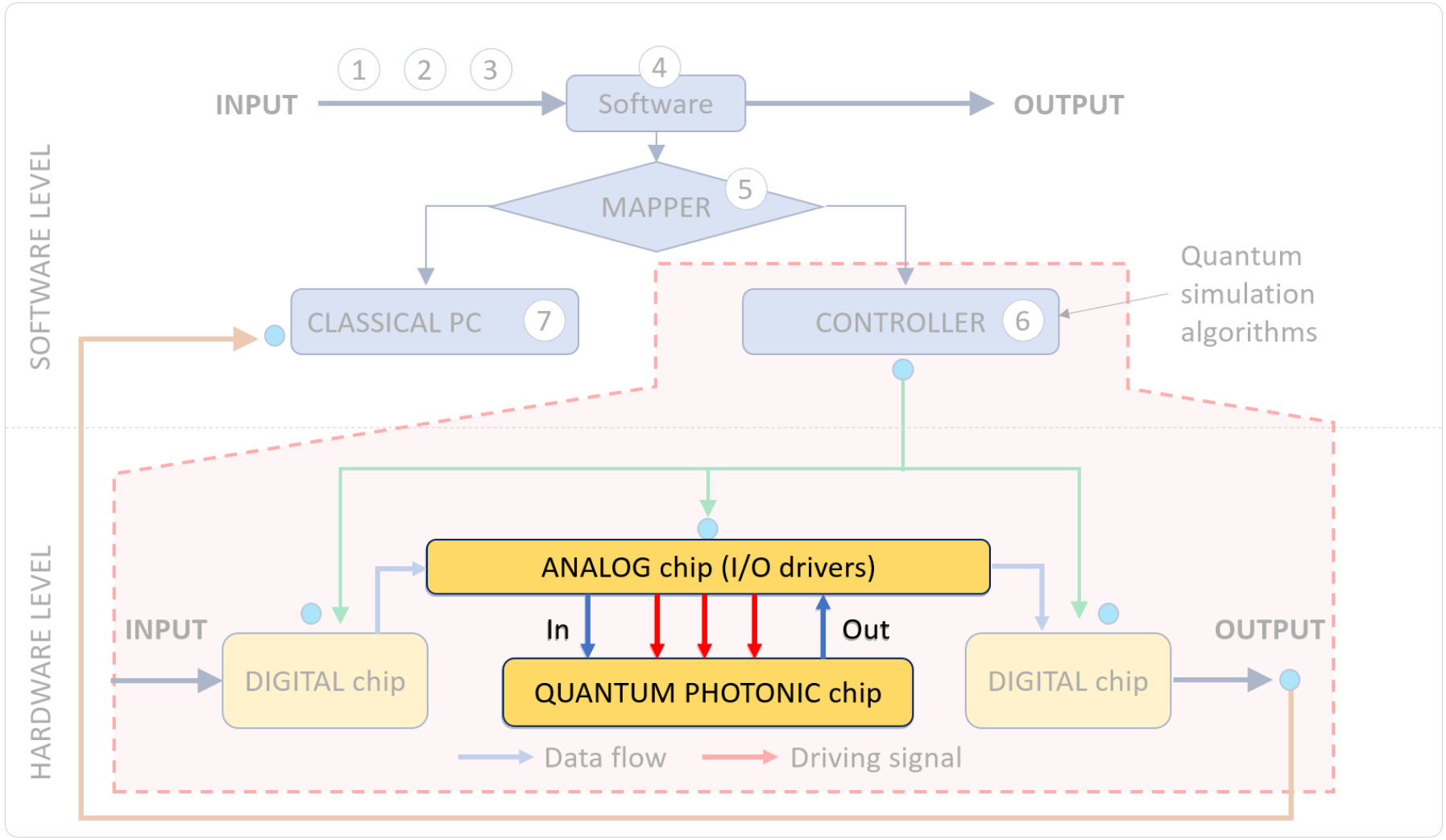

# The project EPIQUS – The approach

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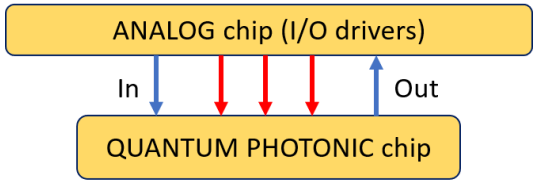
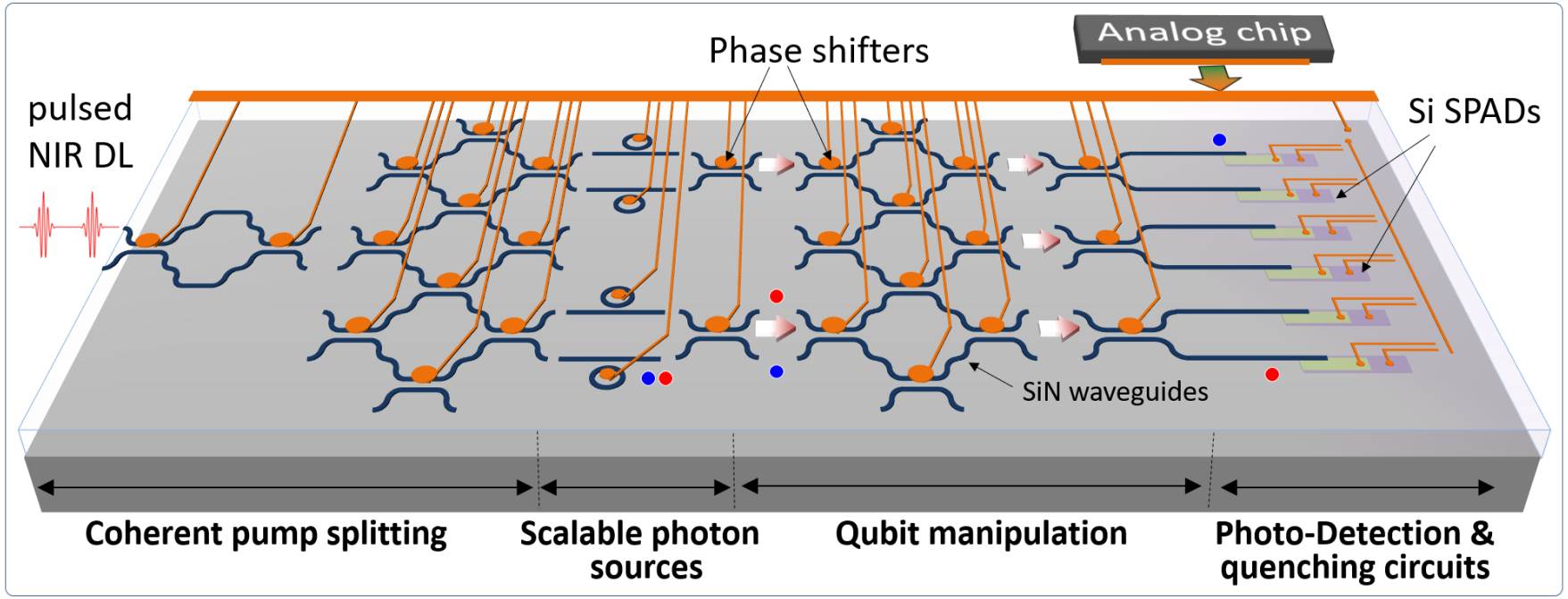



## Schematic view of a QS chip



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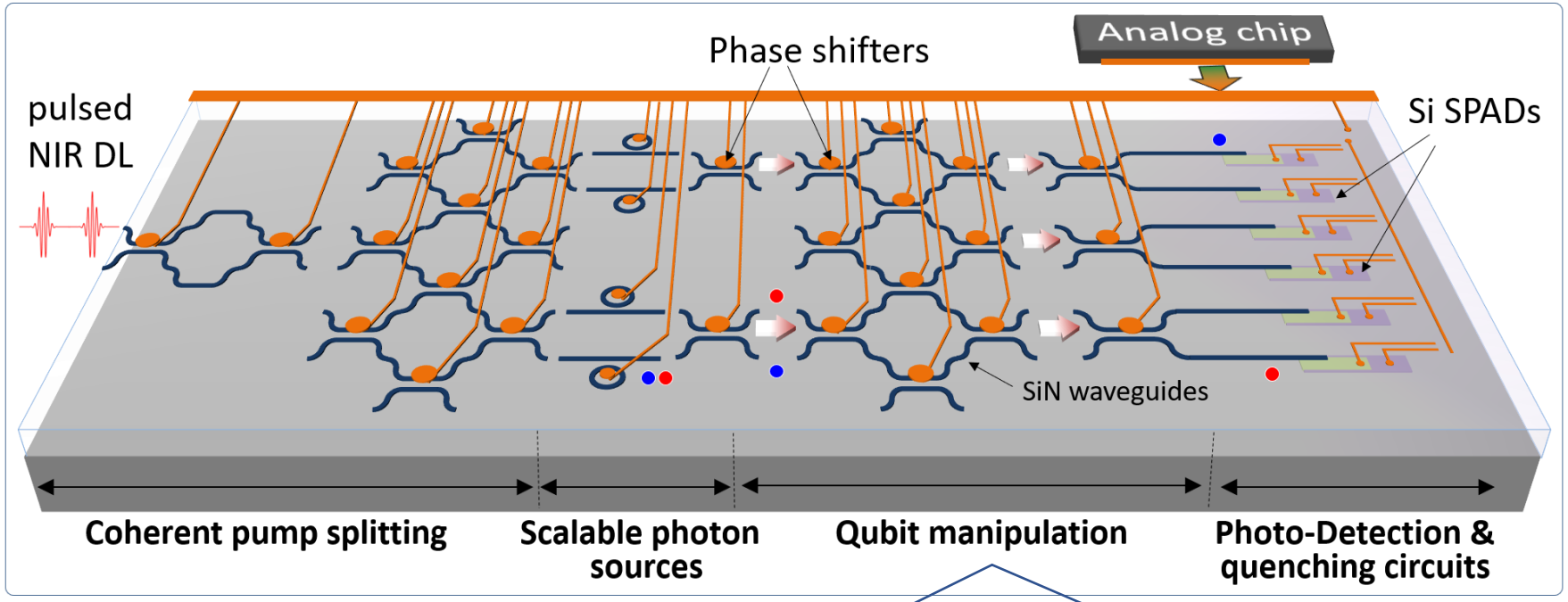
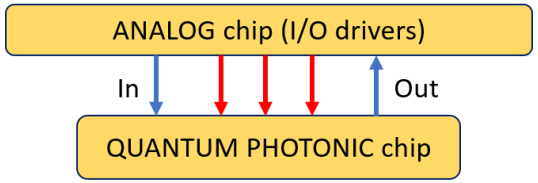
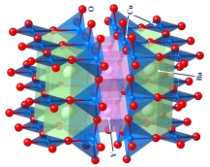



Quantum chemistry



New materials

Many-body interactions

$$\hat{H} = \sum_{n=1}^{N} \hat{T}_n + \hat{V}$$

# The project EPIQUS – The photon source

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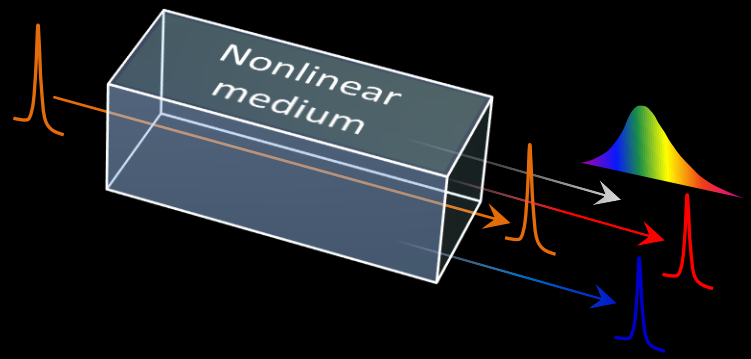
ATTRACT

European Commission | HORIZON 2020

FBK (coordinator) + ETH-Z (partner)

Material's optical nonlinearities

Strong input pulse




New frequencies

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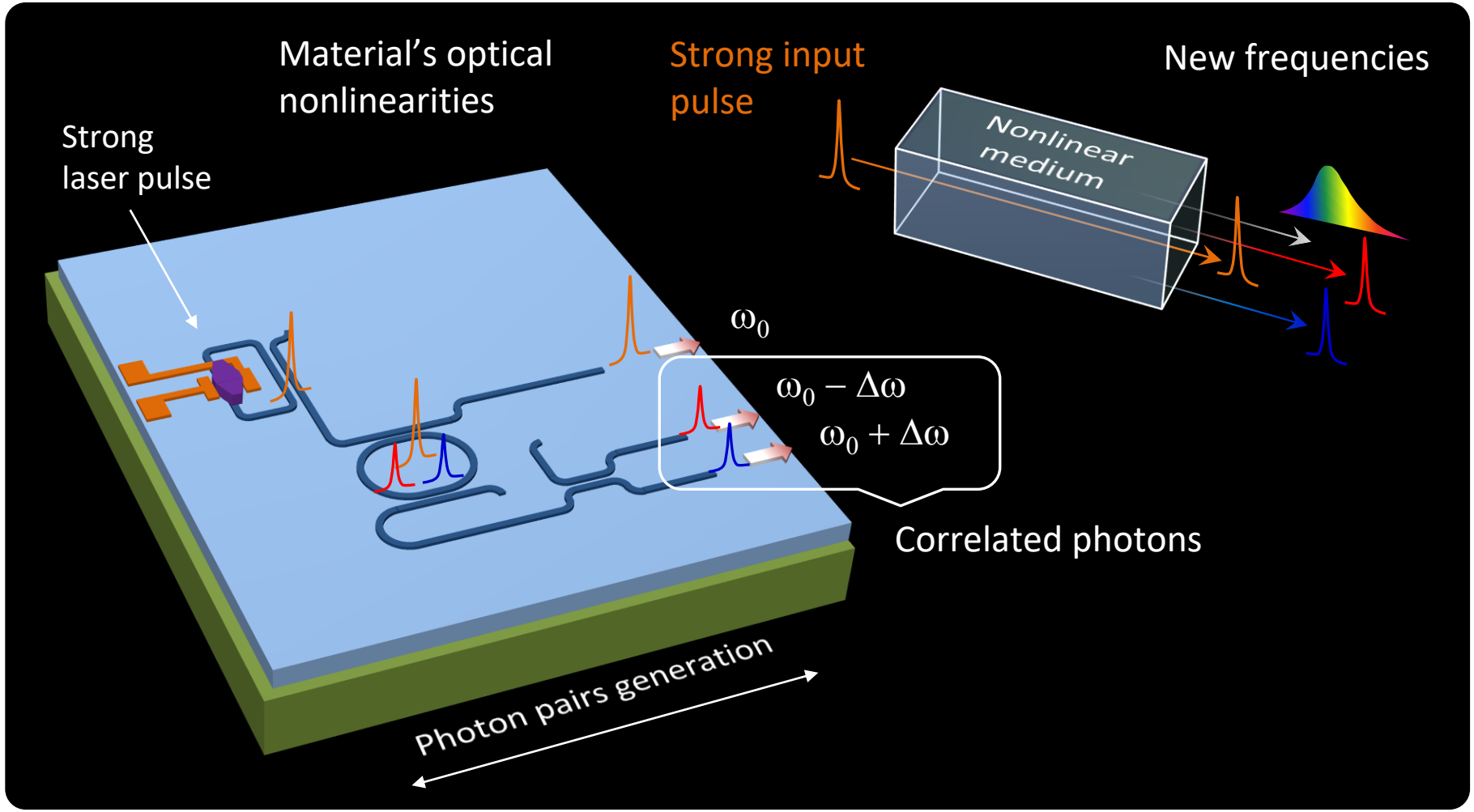
FBK (coordinator) + ETH-Z (partner)



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ATTRACT

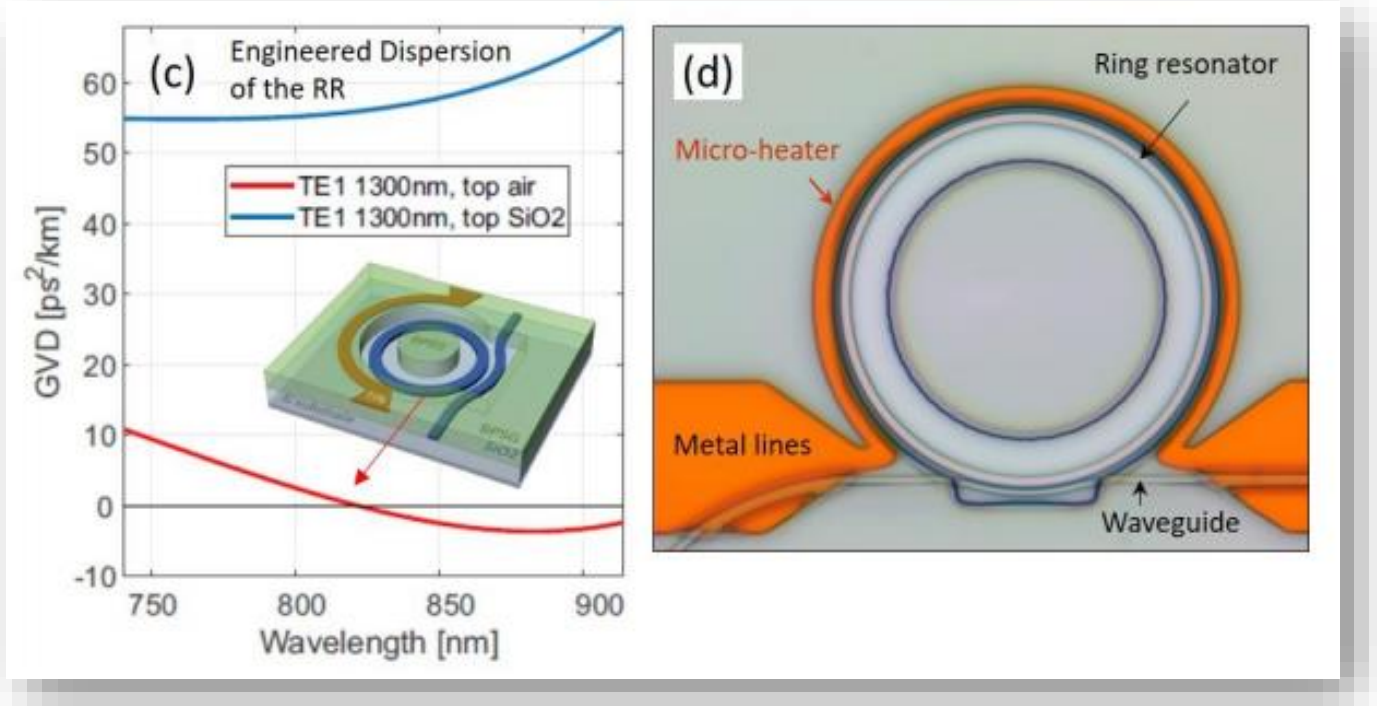
European Commission | HORIZON 2020

FBK (coordinator) + ETH-Z (partner)

Optical engineering of the Group Velocity Dispersion (waveguide cross section form and materials choice)

$$\beta_1(\omega) = 1/v_g = n_g/c = \frac{1}{c}\left(n_{eff} + \omega\frac{dn_{eff}}{d\omega}\right)$$

$$\beta_2(\omega) = \frac{d\beta_1}{d\omega} = \frac{1}{c}\left(2\frac{dn_{eff}}{d\omega} + \omega\frac{d^2n_{eff}}{d\omega^2}\right)$$



# The project EPIQUS – on-chip Single Photon Detection

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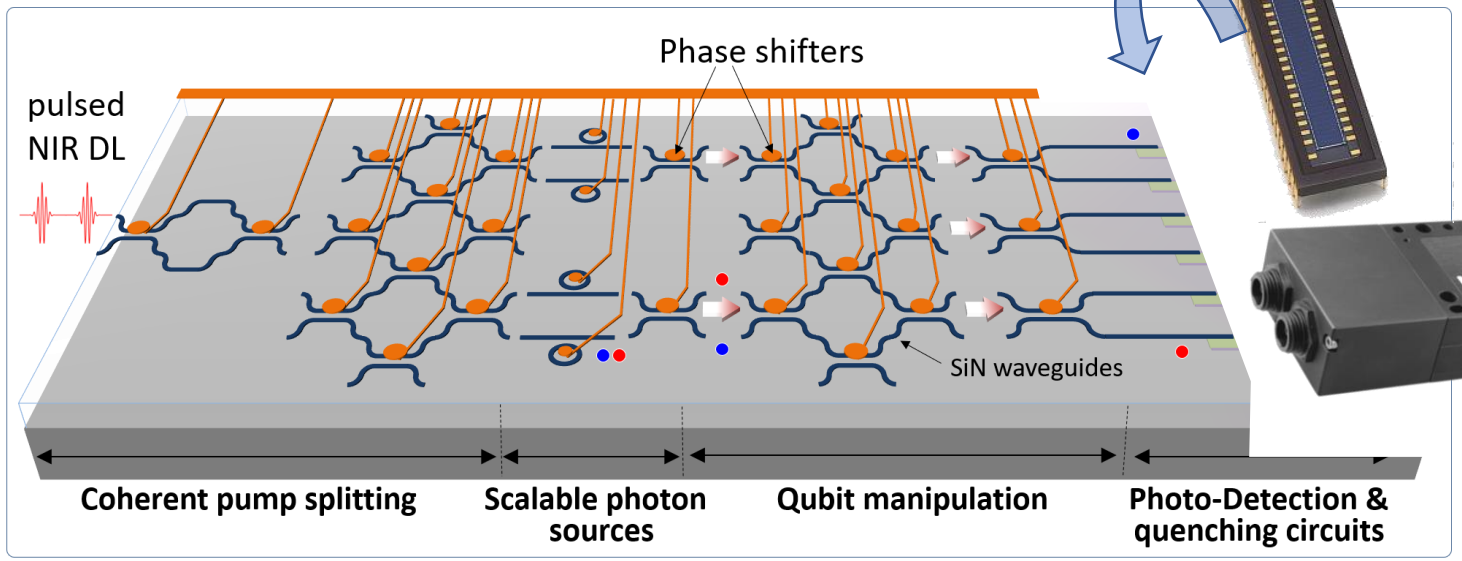
The READOUT OF SINGLE PHOTONS and the CONTROL ELECTRONICS should be improved to increase the efficiency of such systems

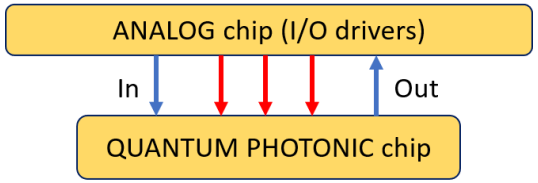
Flip-chip integration of SPAD arrays







Photon Counting Modules



# The project EPIQUS – on-chip Single Photon Detection

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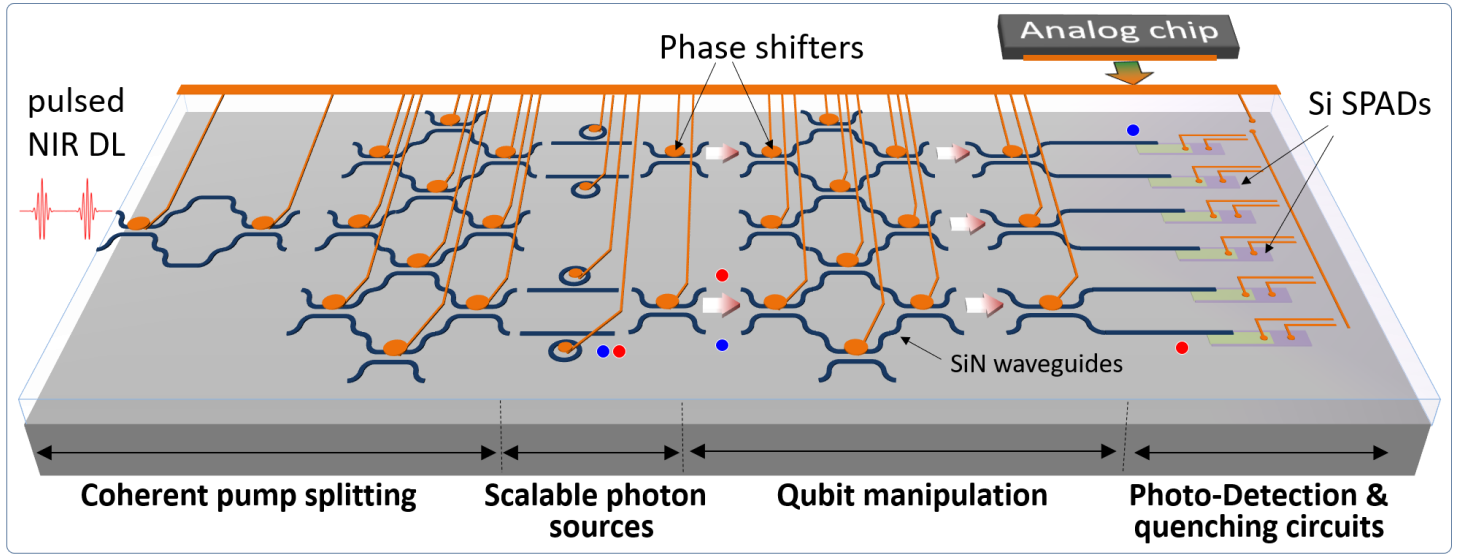
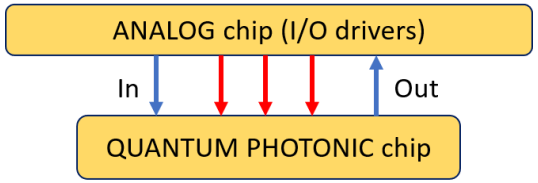
  - Integrated photonics
  - Integrated quantum photonics
- The project EPIQUS
  - Scope
  - **Our approach**
- Conclusions/Perspectives

The READOUT OF SINGLE PHOTONS and the CONTROL ELECTRONICS should be improved to increase the efficiency of such systems

We will use a monolithic integration approach to realize a SPAD devcie per each waveguide channel



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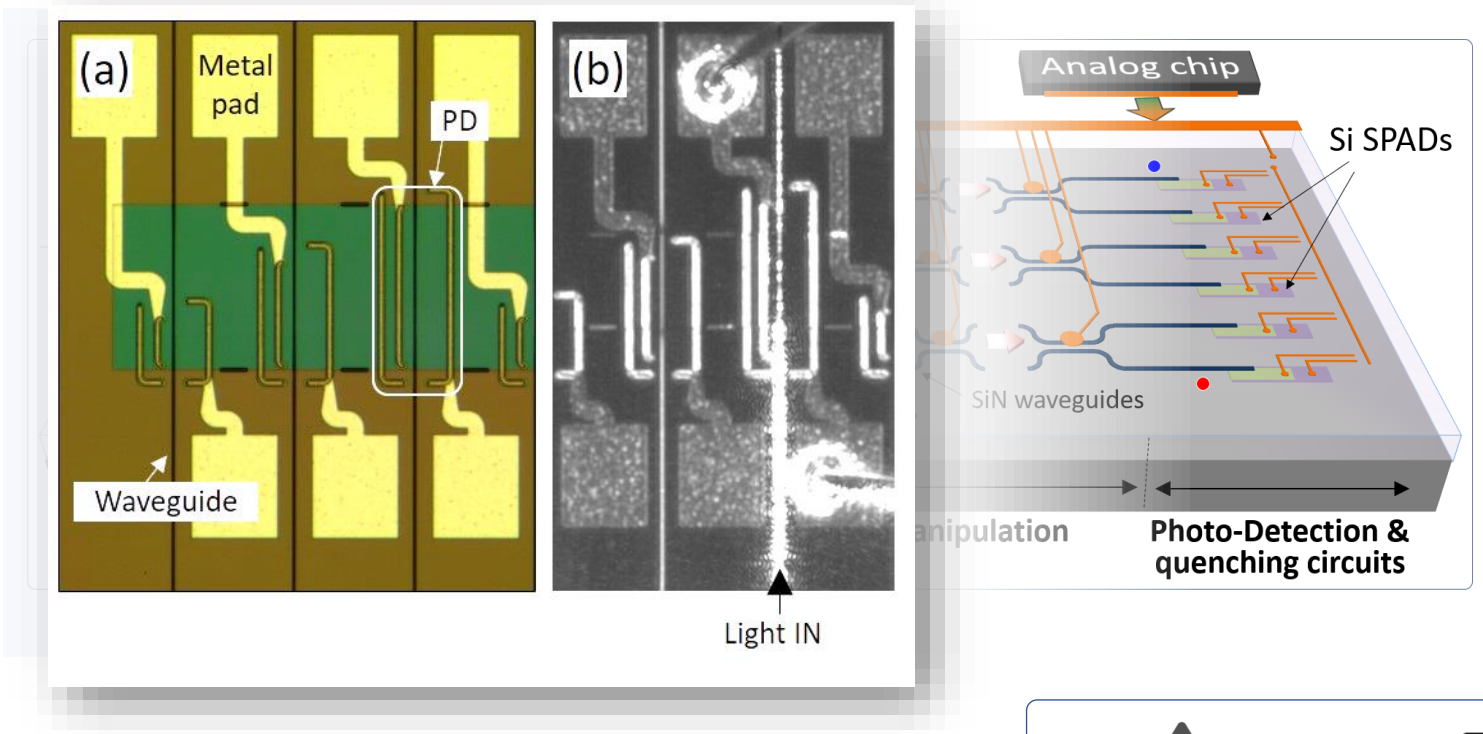


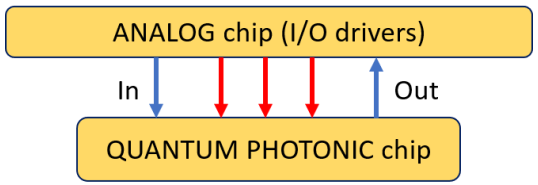


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**Q-PIXPAD**
M. Bernard

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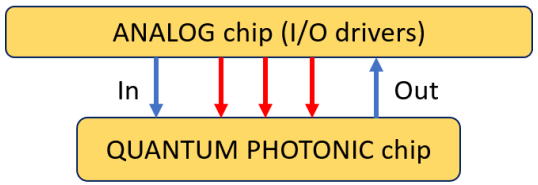


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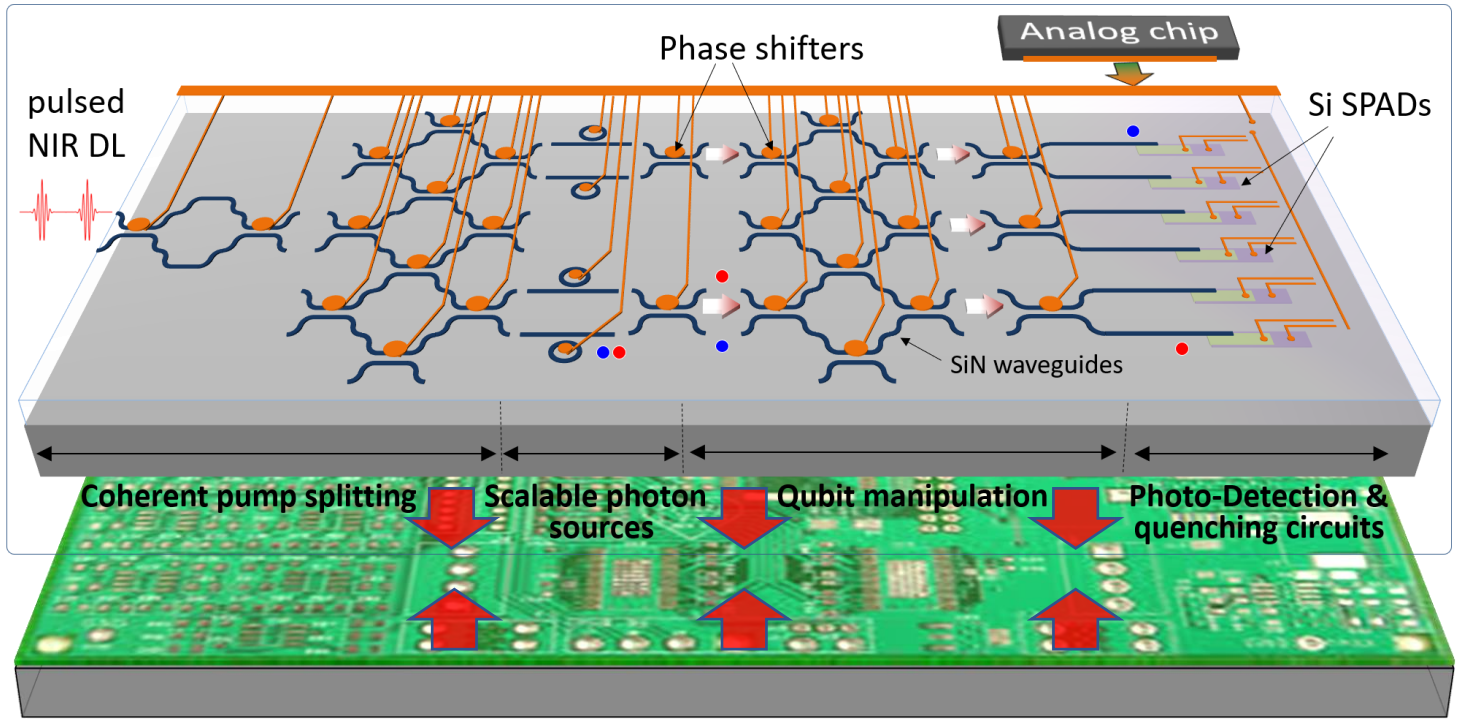


3D bump-bonding to the quantum photonic chip

A 3D bump integration approch will also be used to merge the QS chip with the Control Electronics chip

# Conclusions

- Integrated photonics offers CMOS compatible technolgy which aims at the miniaturization of bulk optical functionalities. Optical waveguides, modulators, and photo-detectors can be integrated within a single device, thus providing a smaller form factor.
- Integrated photonics demonstrates a clear potential advantage (faster and smaller optical interconnections) considering that the next generation of processors will require extremely dense network of copper interconnections.
- Integrated Quantum Photonics promises to steer photonics in a direction quite orthogonal to electronic technologies. In essence the advantage of integrated (quantum) photonics could be simply in fields still not covered by electronics (physical phenomena relaying on wave nature of particles and extremely long coherence times of uncharged particles).

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European Commission

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**Thank you for your attention**