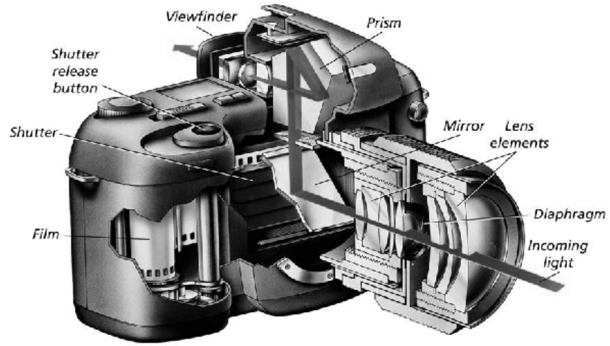
Manipulating quantum information by optics and photonics in a quantum teaching lab

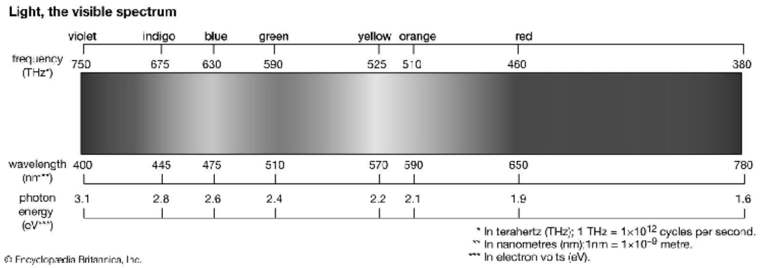
https://www.saxion.nl/nieuws/2023/mei/zijn-we-klaar-voor-de-quantumcomputer

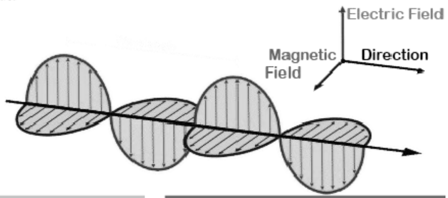
Optical instruments

Telescopes, cameras, and microscopes all uses lenses and mirrors to produce images

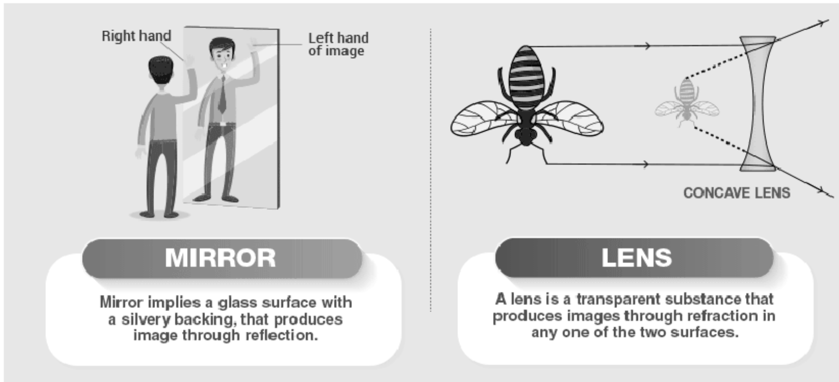


Introduction to optics

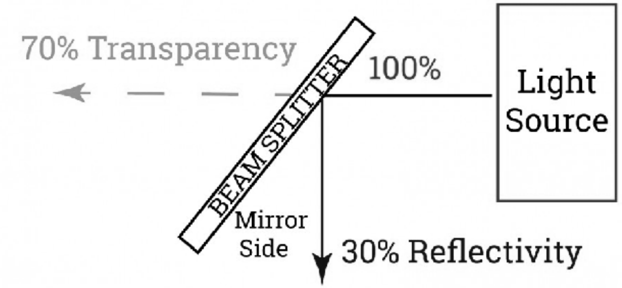


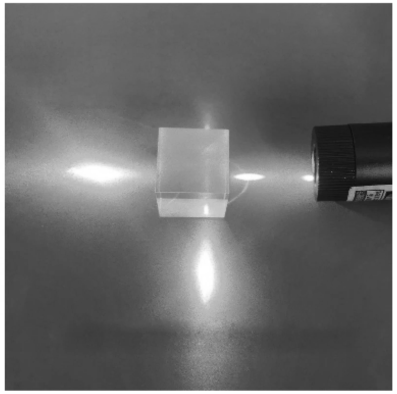


Basics mirrors and lenses

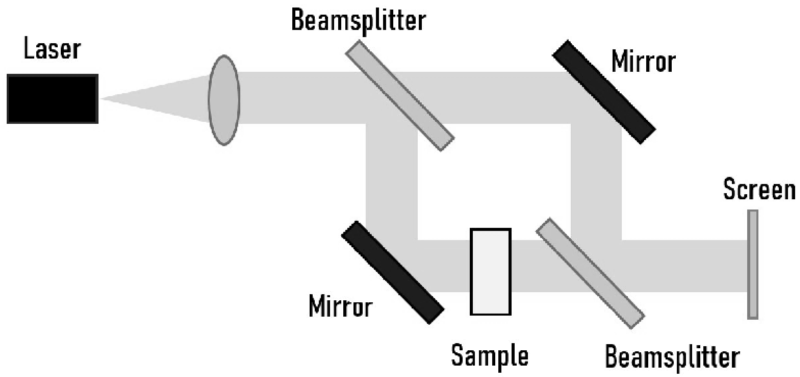


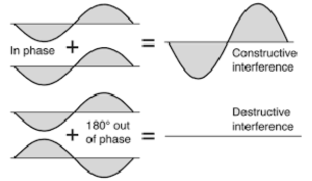
Beamsplitters

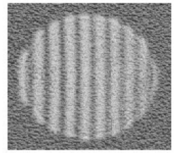




Combination of beam splitters: MZI

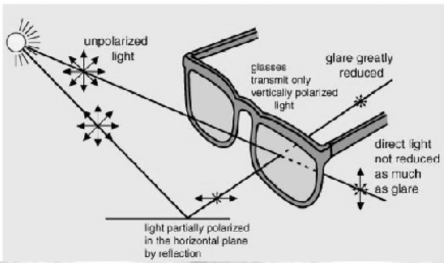




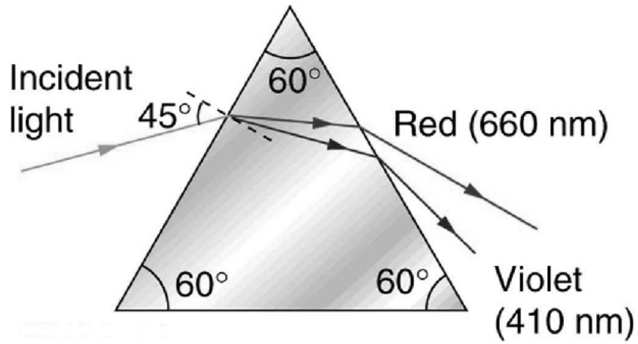


Polarization

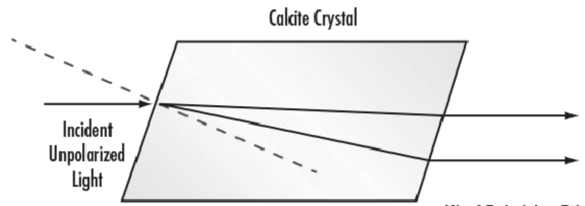
Many sunglasses have vertical polarizing filters to remove glare reflected from horizontal surfaces.

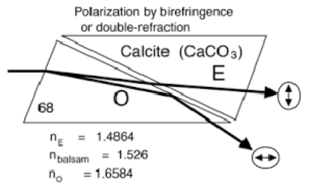


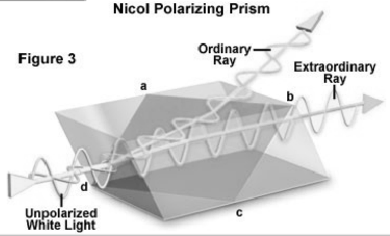
(Chromatic) Dispersion of light ($n_{violet} > n_{green} > n_{red}$)



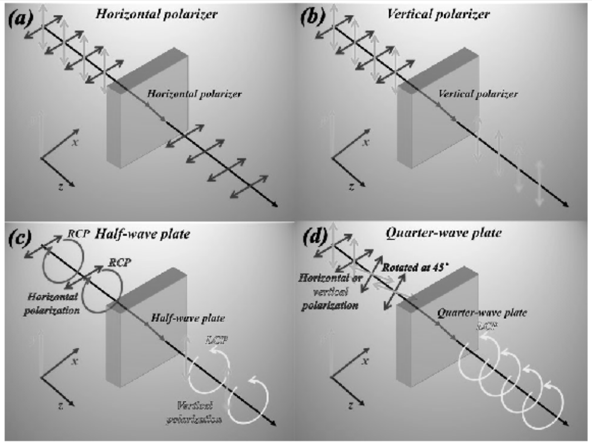
Polarization by birefringence

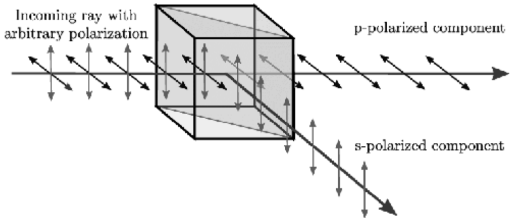






Wave plates and polarizers for polarization manipulation





Introduction Quantum Optics & Quantum Photonics

Optics: what is light?
is a broad branch of physics. It studies the general behavior and properties of light, as well as vision and perception.

Classical Optics:
- Newton etc: particle/ray theory
- Huygens-Young (interference) – Fresnel (diffraction) – Maxwell wave optics

Birth of photons (1st birth of quantum optics)
- Planck's photon (light quantum)
- Wave-particle duality (DeBroglie etc.)

Birth of Quantum Mechanics/physics is also (1st) birth of quantum optics)
- Planck's photons (blackbody radiation)
- Einstein's photoelectric effect
  (these phenomena do not directly prove quantum nature of photons, rather some quantum nature of light-matter interaction)
- Formulation of quantum mechanics: Schrödinger/Heisenberg
- Quantum Field Theory/quantum electrodynamics (QED): Dirac etc.

Photonics is a subcategory of optics that focuses on the science and technology of photons.

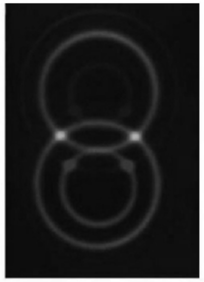
Milestones in Quantum Optics

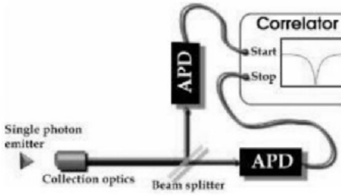
Table 1.3 Selected landmarks in the development of quantum optics, including a few recent highlights. The final column points to the appropriate chapter of the book where the topic is developed

Year	Authors	Development	Chapter
1901	Planck	Theory of black-body radiation	5
1905	Einstein	Explanation of the photoelectric effect	5
1909	Taylor	Interference of single quanta	14
1909	Einstein	Radiation fluctuations	5
1927	Dirac	Quantum theory of radiation	8
1956	Hanbury Brown and Twiss	Intensity interferometer	6
1963	Glauber	Quantum states of light	8
1972	Gibbs	Optical Rabi oscillations	9
1977	Kimble, Dagenais, and Mandel	Photon antibunching	6
1981	Aspect, Grangier, and Roger	Violations of Bell's inequality	14
1985	Slusher *et al.*	Squeezed light	7
1987	Hong, Ou, and Mandel	Single-photon interference experiments	14
1992	Bennett, Brassard *et al.*	Experimental quantum cryptography	12
1995	Turchette, Kimble *et al.*	Quantum phase gate	10, 13
1995	Anderson, Wieman, Cornell *et al.*	Bose–Einstein condensation of atoms	11
1997	Mewes, Ketterle *et al.*	Atom laser	11
1997	Bouwmeester *et al.*, Boschi *et al.*	Quantum teleportation of photons	14
2002	Yuan *et al.*	Single-photon light-emitting diode	6

Fox, p.5

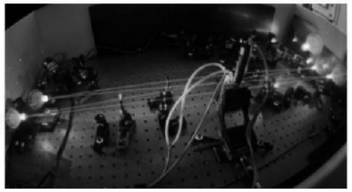
Quantum Optics: study of photons (quantum nature)





photon quantum states (eg. coherent/squeezed/ /number states)

quantum correlation & statistics



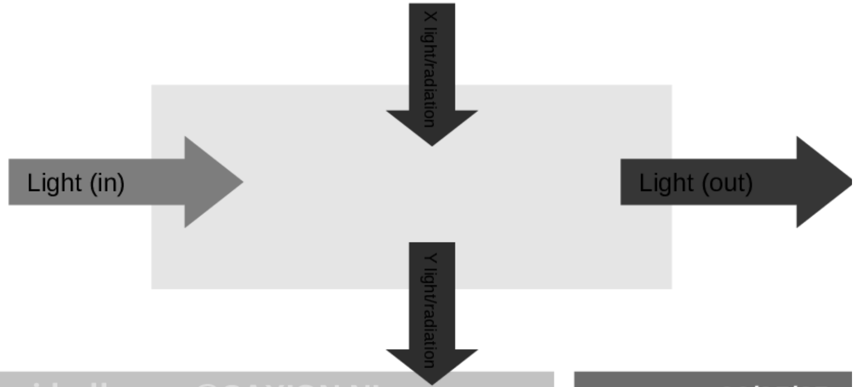
quantum entanglement → quantum information/communication/computing

But we will adopt a *broader* definition

Light-Matter interaction

Quantum optics (broadly defined): Light (radiation) & light-matter interaction where quantum physics matter

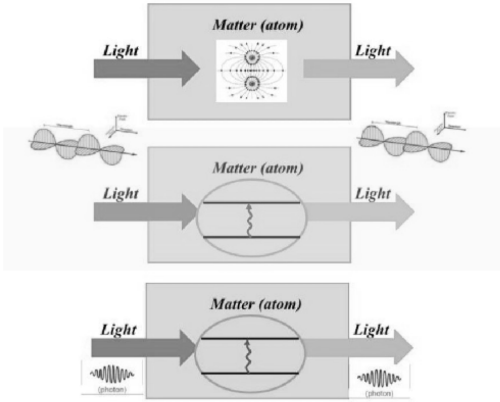
[further generalization: extend from light to other waves (including matter/particle waves)]



Different levels of quantum

Table 1.1 The three different approaches used to model the interaction between light and matter. In classical physics, the light is conceived as electromagnetic waves, but in quantum optics, the quantum nature of the light is included by treating the light as photons.

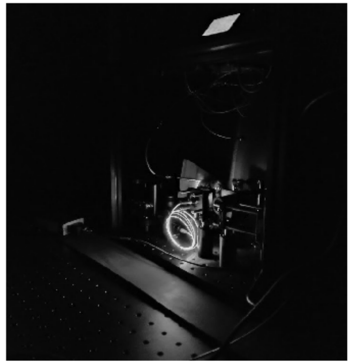
Model	Atoms	Light
Classical	Hertzian dipoles	Waves
Semi-classical	Quantized	Waves
Quantum	Quantized	Photons



The Qubit zoo & zookeeping @Saxion

There's many different ways to build a qubits but choosing the right approach depends on what we want to do with it.

- Superconducting qubits, requirements:
  - (1) cold electronic circuits,
  - (2) superconducting material, and
  - (3) Josephson junctions.
- Spin qubits: e.g. NV centers in diamond
- Ion traps:
- Neutral atoms: low accuracy of gate operiations (drawback)
- Photons (flying qubits)
- Topological qubits



https://www.tudelft.nl/over-tu-delft/strategie/vision-teams/quantum-computing/hardware-software/the-qubit-zoo

Diamond and its color

https://en.wikipedia.org/wiki/Hope_Diamond

A perfect diamond crystal would be **colorless** and transparent to visible light, due to its 5.5 eV band gap (greater than the energy of a visible photon).

Point defects in a diamonds crystal structure can lead to **color centers.**

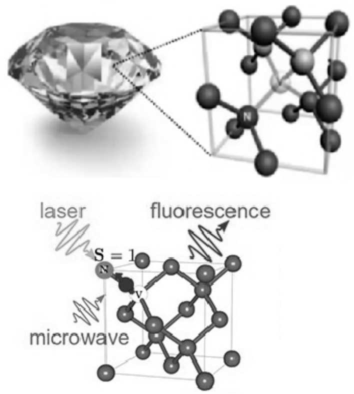
eg. Hope Diamond takes on its beautiful blue coloring because of trace amounts of boron within its crystal structure.

Single boron atoms can substitute for carbon atoms in the diamond lattice absorbing red, transmitting blueish.

Similarly, an **NV center creates a color center** in diamond.

When a sample containing NV centers is illuminated with green light a **red fluorescence is observed**.

NV centers: an introduction



https://en.m.wikipedia.org/wiki/Nitrogen-vacancy_center

The nitrogen-vacancy center is one of numerous **point defects** in diamond.

Its most explored and useful property is its **photoluminescence,** which allows observers to read out its spin-state.

The NV center's electron spin, localized at atomic scales, can be **manipulated at room temperature** by external factors such as **magnetic**, or electric fields, **microwave radiation**, or light, resulting in sharp resonances in the intensity of magneticthe photoluminescence.

These resonances can be explained in terms of electron spin related phenomena such as quantum entanglement, spin-orbit interaction and Rabi oscillations, and analysed using advanced quantum optics theory.

An individual NV center **can be used as a basic unit for a quantum computer, a qubit**, and used for quantum cryptography.

Further potential applications in novel fields of **quantum communication** and **quantum sensors.**

A unique spin that can be manipulated optically

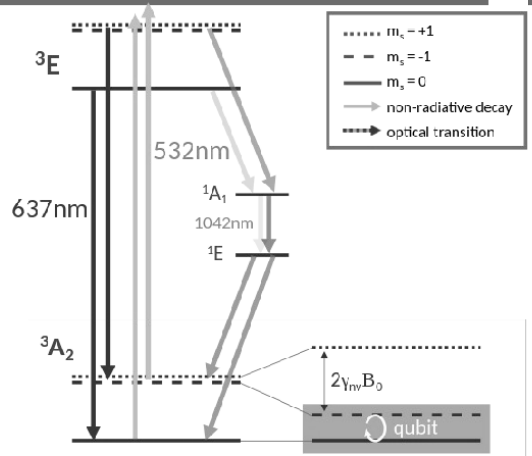
Optical pumping with green light at 532 nm (indicated by the green vertical arrow) induces transitions from the spin-1 ground state |g> to the spin-1 excited state |e>.

Red fluorescence (red downward arrow) back to |g> is emitted over a range of energies.

Both the excitation and the fluorescence transitions tend to **conserve the value of the m_s quantum number.**

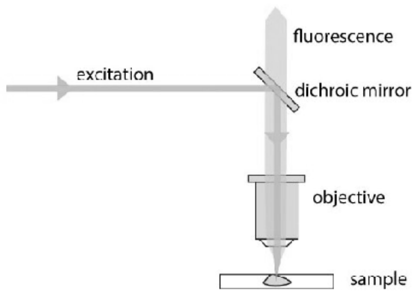
Transitions to and from a long-lived singlet state |s> lead to a preferential population of the m_s = 0 ground state, producing electron **spin polarization of the NV center**.

The relative populations of the substates can be changed if the system is driven with resonant (2.87 GHz) **microwave radiation**.

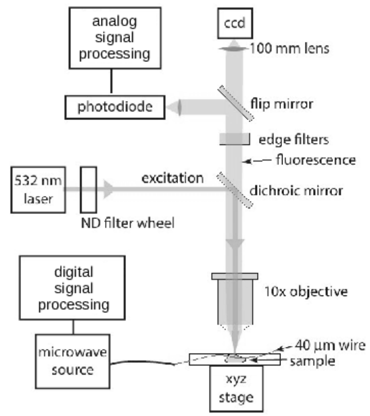


Basic ODMR setup
(optically detected magnetic resonance)

Epifluorescence configuration



ODMR



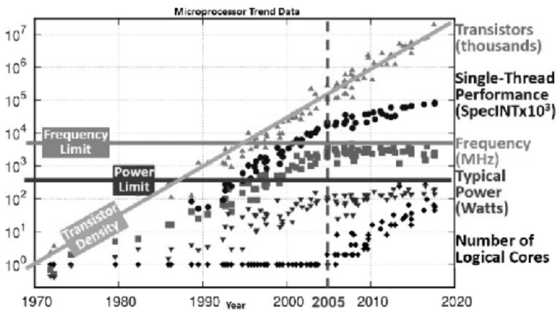
Moore's law

Electro-optics enabled by:

- Advancements in materials science
- Chip architectures
- Quantum Technology

Benefits:

- Faster
- Low-power



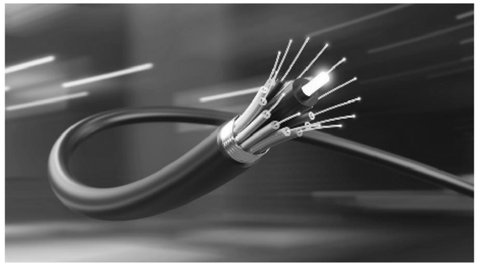
Moore's law

Reaching the limit of physics
Going faster?

- Smaller transistors
- Cooling
- Lowering voltages

Higher demand for computer power (AI)
Demand for limiting the power consumption (data centers)

Optics allows for higher frequencies compared to electronics.
Light waves can be superposed, eg. different wavelengths can be transmitted at the same time in the same fiber.



Optical I/O chiplets: transceivers (transmit ánd receive optical signals)

45nm fabrication processes

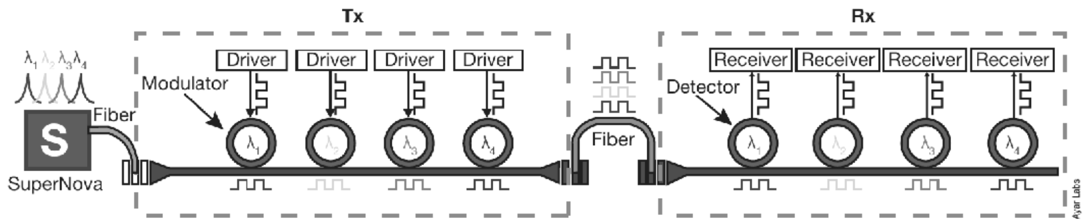
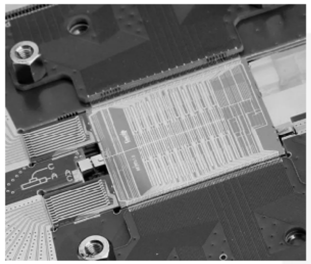
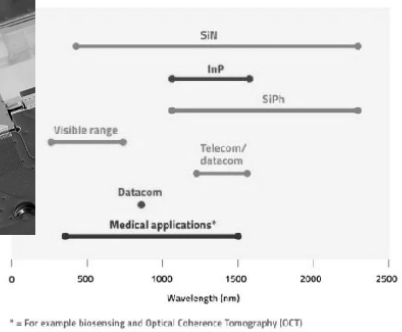


Figure 2. A schematic of Ayar Lab's multiwavelength SuperNova remote light source attached to the company's TeraPHY optical input/output (I/O) chiplet **(Tx)**, which sends its signals through a fiber to a receiving I/O chiplet **(Rx)**.

If photonic signals could be brought closer to the CPUs and GPUs, then data centers would leverage gains in both speed and energy efficiency.

Optical transceivers (transmit ánd receive optical signals)

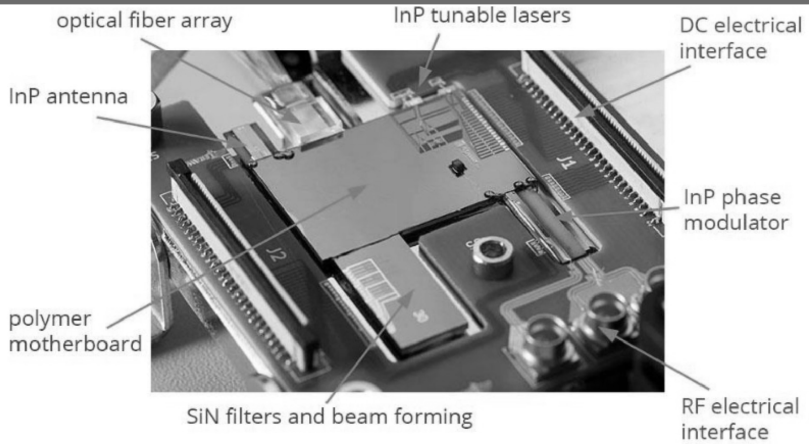




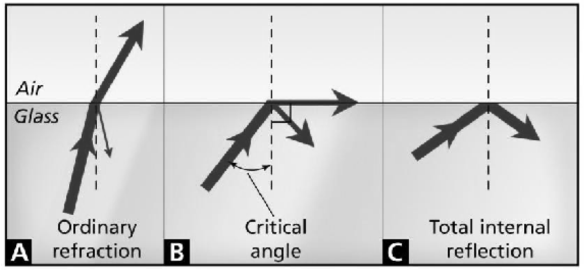
Integration leverages from CMOS technology. However, silicon does not lase and, therefore, integraded photonics solutions require the introduction of unfamiliar materials, such as InP, SiN, LiNb to provide optical functions.

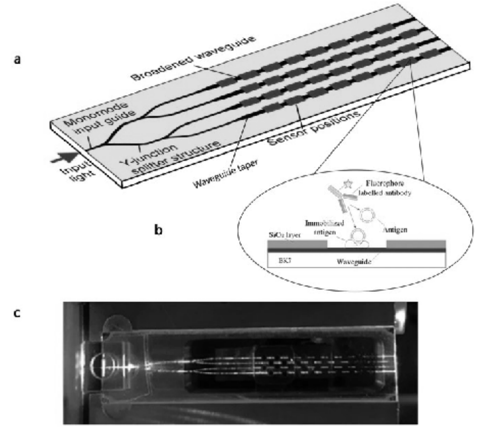
https://www.photondelta.com/news/why-can-silicon-nitride-sin-be-ideal-platform-for-photonic-integrated-circuits/

Hybrid integration – leveraging the best properties of each PIC technology



Total internal reflection



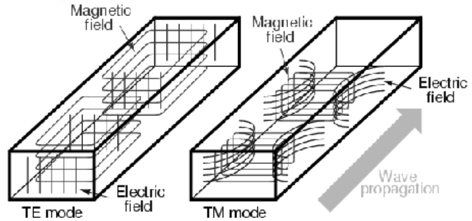


https://doi.org/10.1038/s41598-017-03939-8

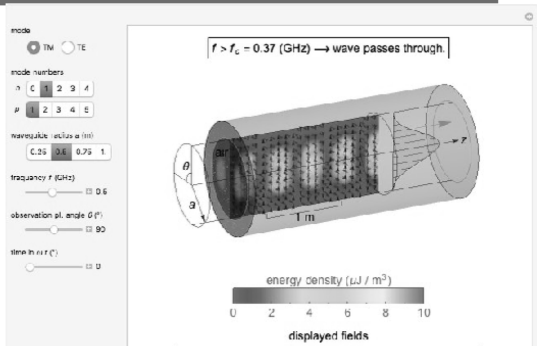
EM waves within waveguides:

https://demonstrations.wolfram.com/ElectromagneticWavesInACylindricalWaveguide/

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{B}}{\partial t}$$



Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points

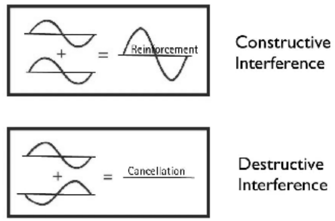


	electric field	magnetic field	Poynting vector (power density)
values	1000 V/m	2.654 A/m	2000 W/m^2
displayed	0.2 m length in red arrow	0.2 m length in blue arrow	1 m length in horizontal graph

Real optical computers (DoF path)

The optical transistor: photons should interact with each other

Idea: Mach-Zehnder-interferometer (MZI)



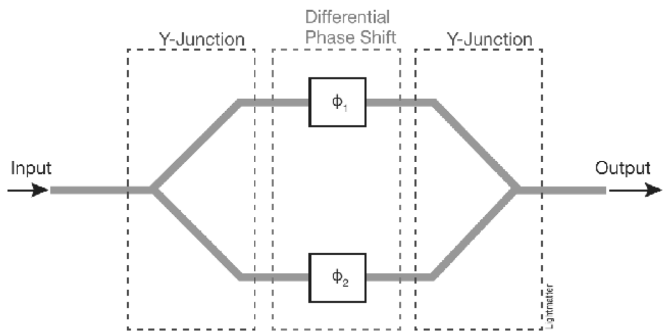


Figure 4. A Mach-Zehnder interferometer (MZI) is a device where one optical input, typically a waveguide, is divided into two arms with adjustable phase delays **(above)**. When a wave runs through it, the wave splits and the partial waves undergo differential phase-shift delays. When the fields of both waves recombine, their interference produces useful effects. See Reference 3.