# Nanophotonic Waveguides and Photonic Crystals in Silicon-on-Insulator

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**19 April 2004**

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*http://photonics.intec.UGent.be*

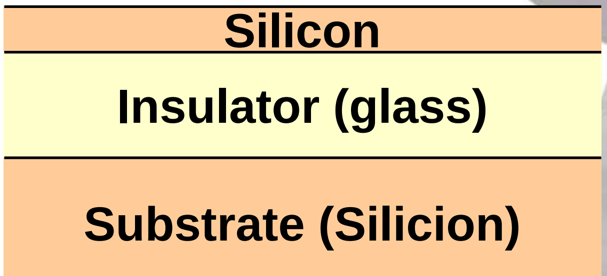
# Nanophotonic Waveguides and Photonic Crystals in Silicon-on-Insulator

nano = small
on a scale of
1nm = 1 billionth of a meter

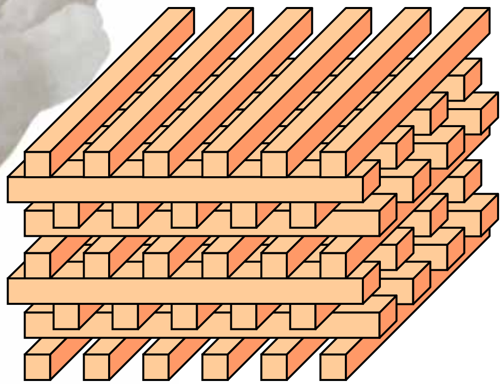
photon = elementary
particle of light

guiding of light waves
along a given path

A material consisting of a thin
layer of Silicon on top of a
layer of glass (isolator)




A periodic stacking
of materials



# Overview of this presentation

## Background

- What's the use?
- How does a waveguide work?
- What's a photonic crystal?

## Foreground

- Nanophotonic waveguides
- What are the difficulties?
- Can we make it?
- What comes out?

# Overview of this presentation

## Background

- **What's the use?**
- **How does a waveguide work?**
- 

**= What will we use it for?**

## Foreground

- **Nanophotonic waveguides**

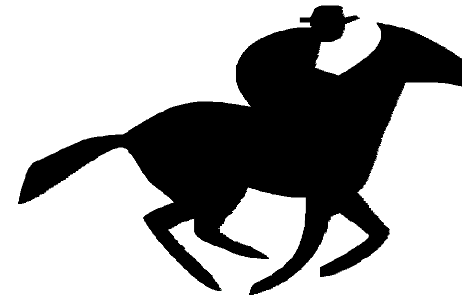
**Answer: Telecommunication**

- **Can we make it?**
- **What comes out?**

# Telecommunication

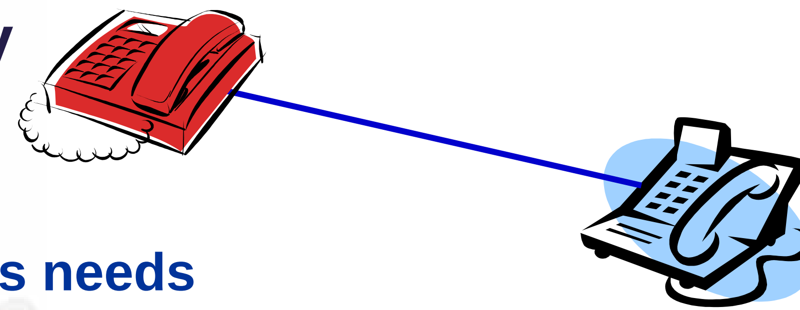
## Bring information from A to B

## Long ago: on foot, by horse, ship, ...



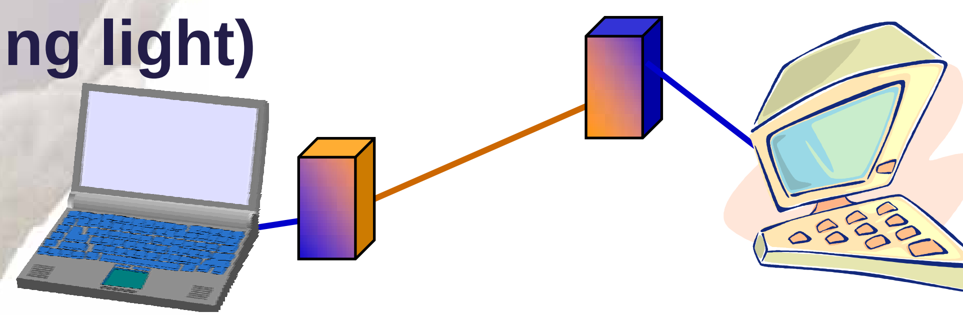
- Slow
- Much capacity

## 19th, 20th century: elektricity (telegraph, telephone,...)



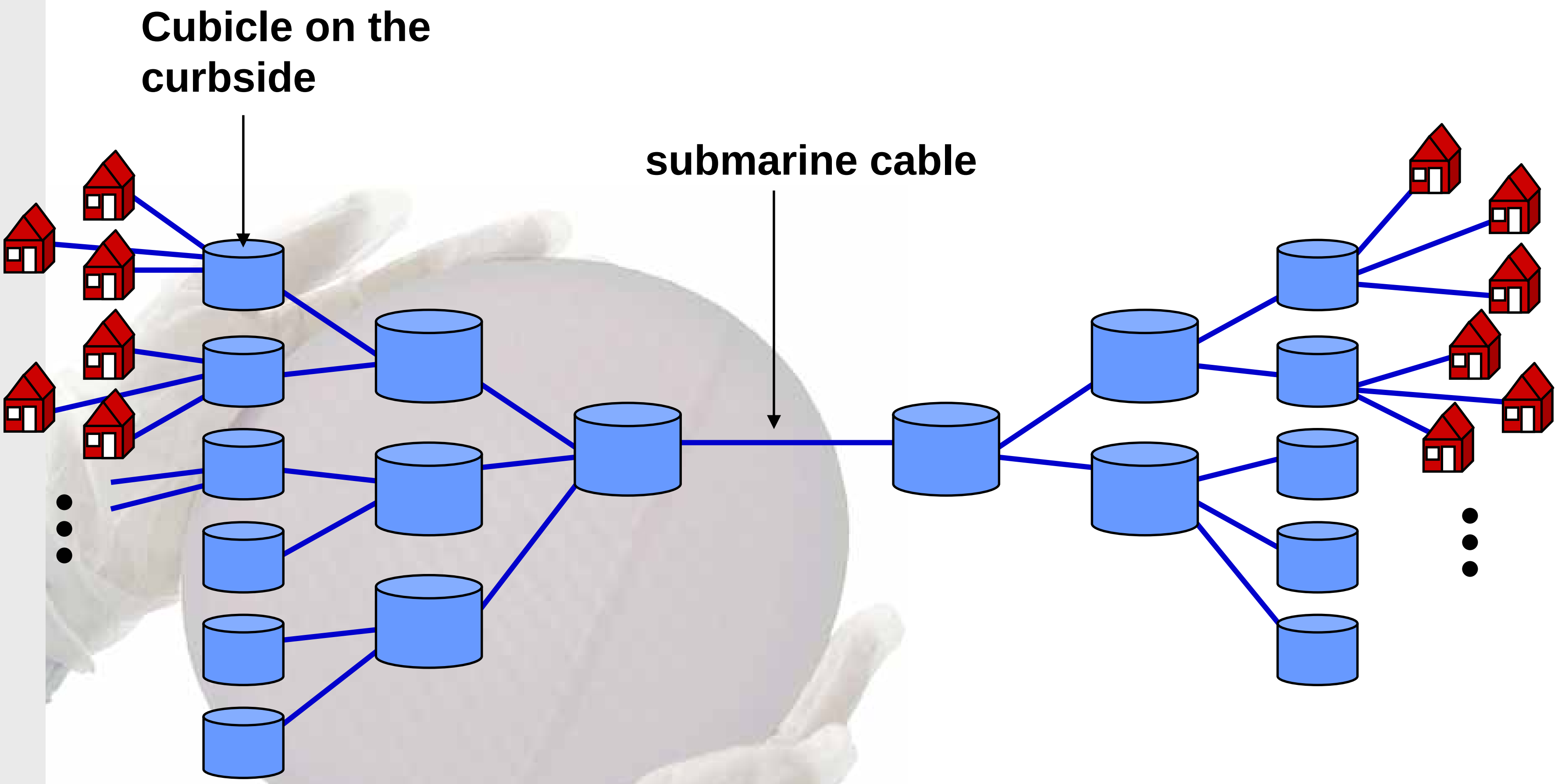
- Fast
- Insufficient capacity for today’s needs

## Now: Optical fibers (using light)

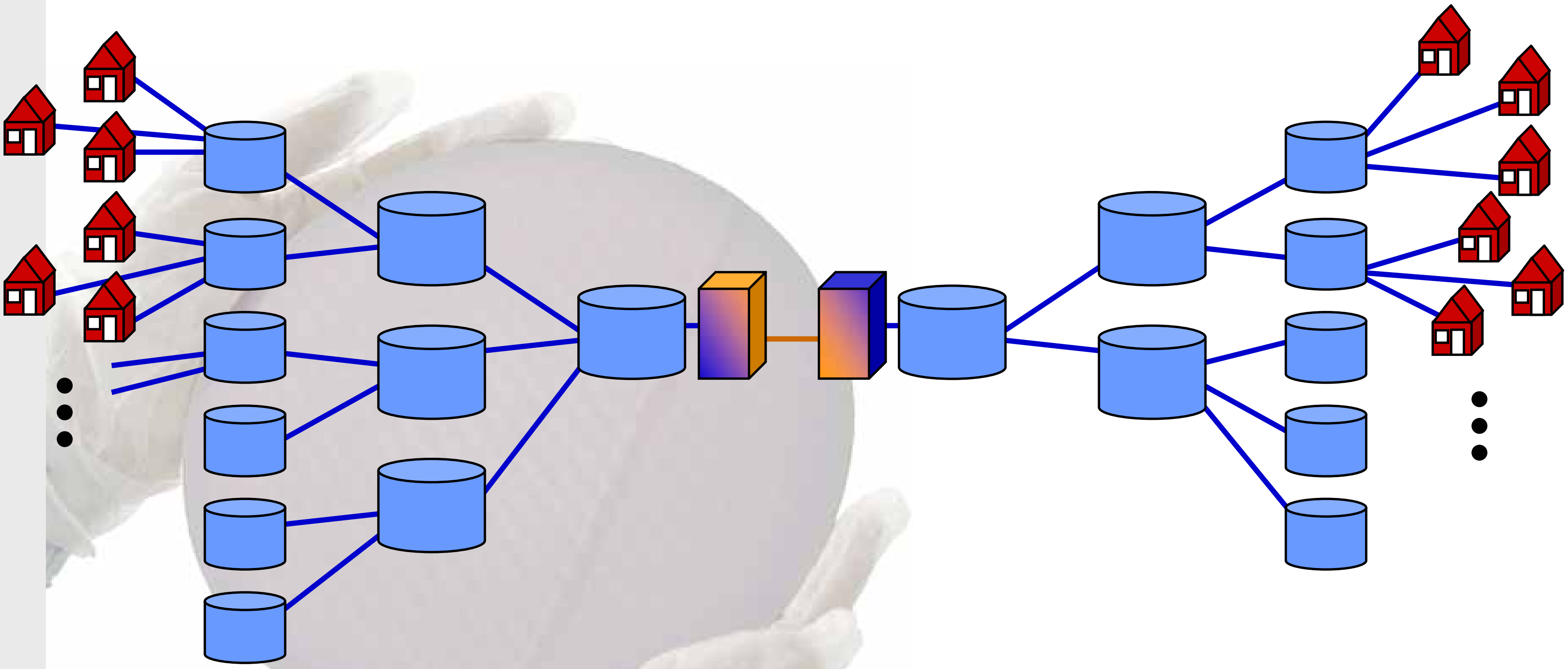


- Fast
- Large capacity
- Long distance

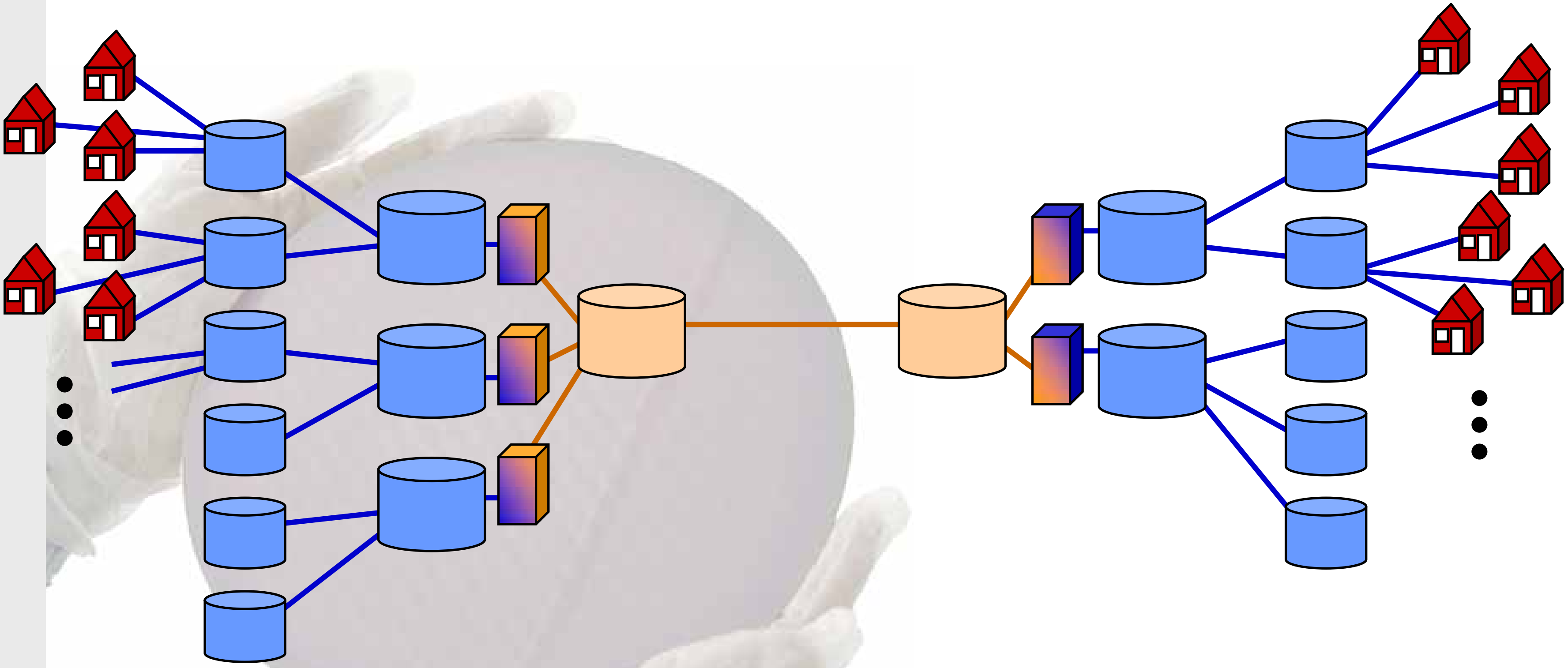
# Telecommunication networks



# Telecommunication networks

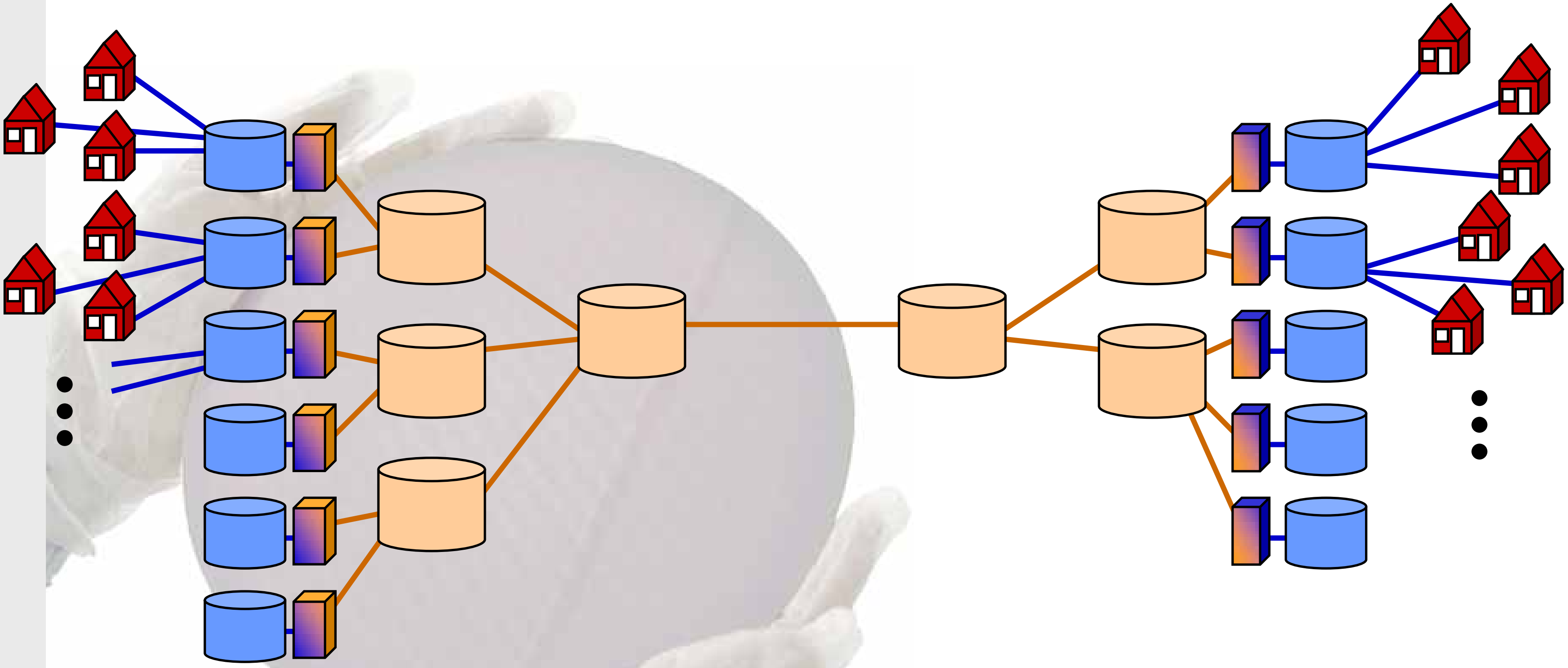


# Telecommunication networks



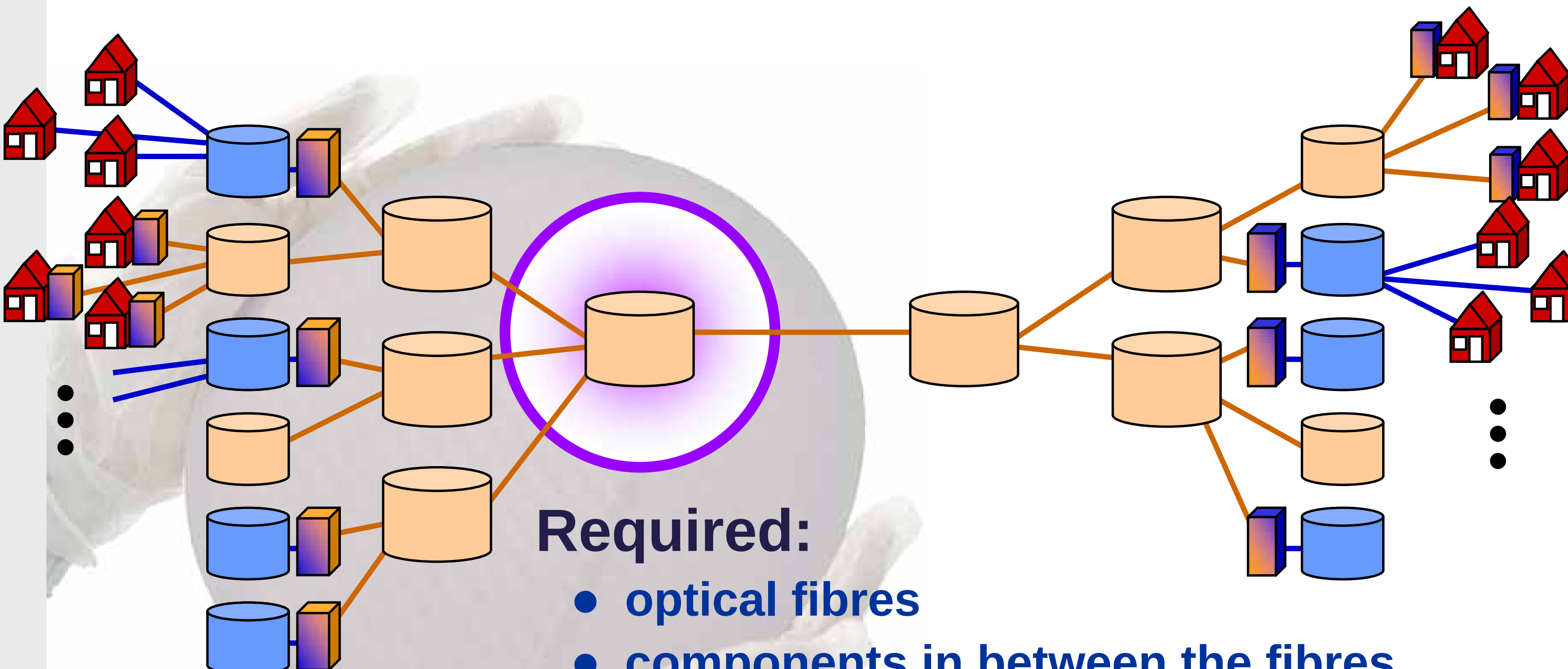
# Telecommunication networks

## Fibre to the curbside



# Telecommunication networks

## Fibre to the home



**Required:**

- optical fibres
- components in between the fibres
- electro-optic conversion

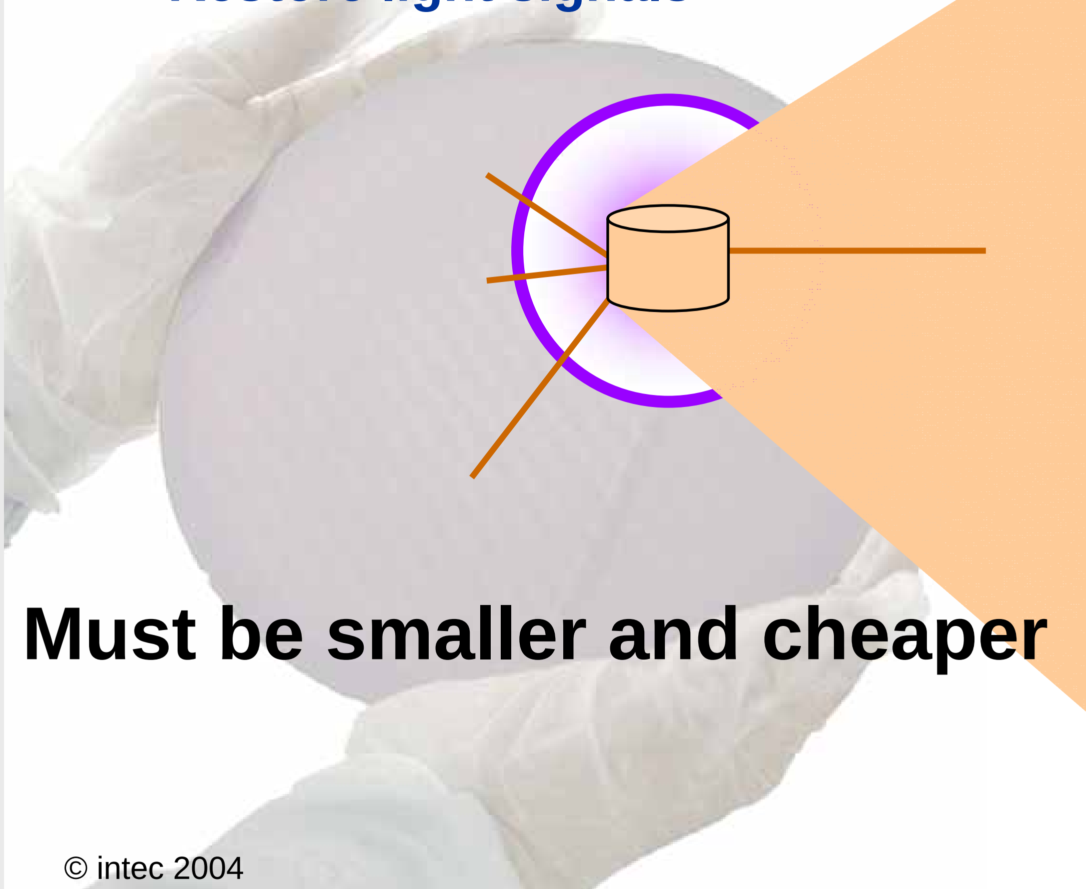
**LARGE QUANTITIES AND CHEAP**

# Components between optical fibres

## must

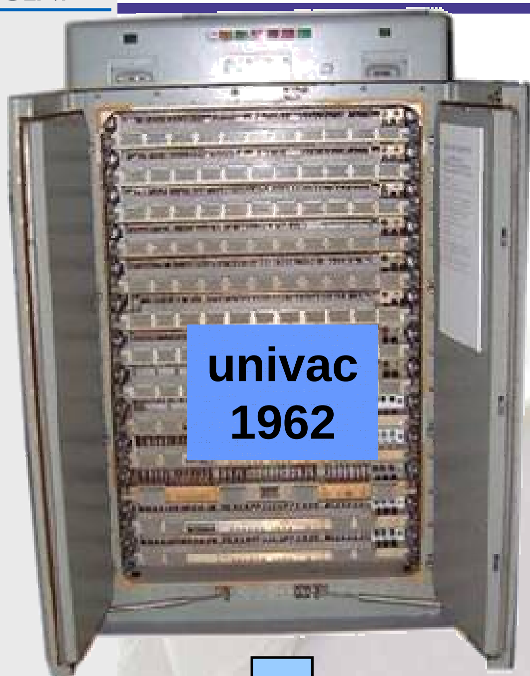
- Amplify light signals
- Distribute light signals
- Restore light signals

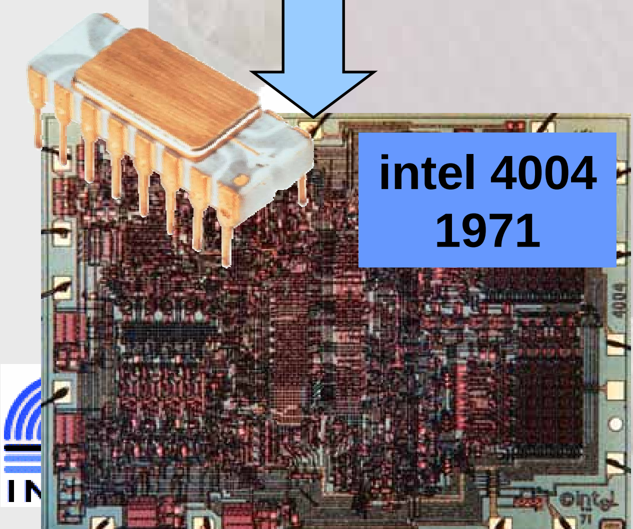
Now: large cupboard



**Must be smaller and cheaper**

# Integrated Circuits




= bringing various functions together on a 'chip'

- **Elektronics:**
  - transistors
  - metal wires for electrical connections between components
- **Fotonics:**
  - switching functions
  - waveguides to transport light between components


Photonic Integrated Circuit

# Photonic Integrated Circuit

## Waveguides on a ‘chip’

## Problem: taday’s waveguides are too weak

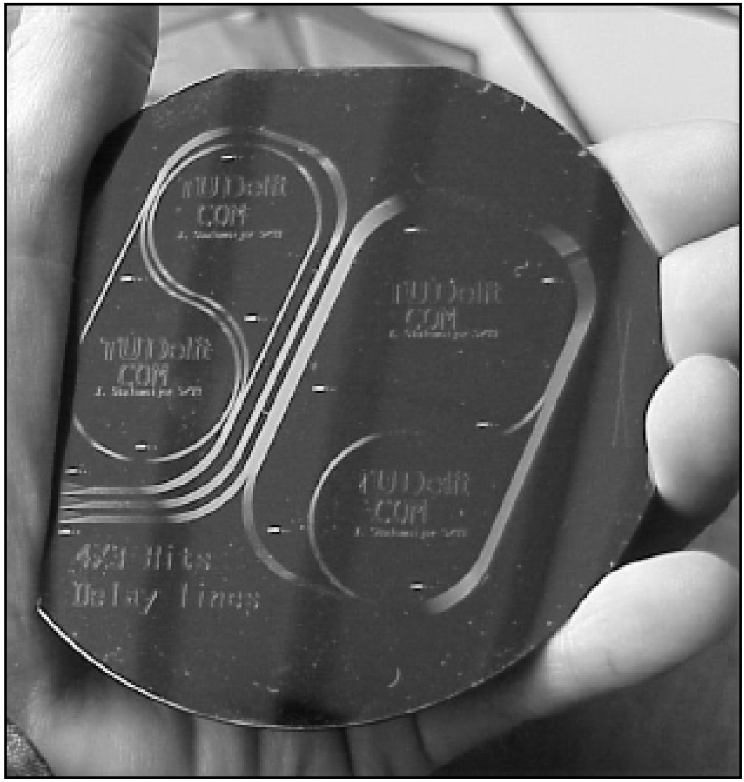
- large bends (otherwise ‘light misses the bend’)

↓

- Few functions on a chip
- Large chip area

↓

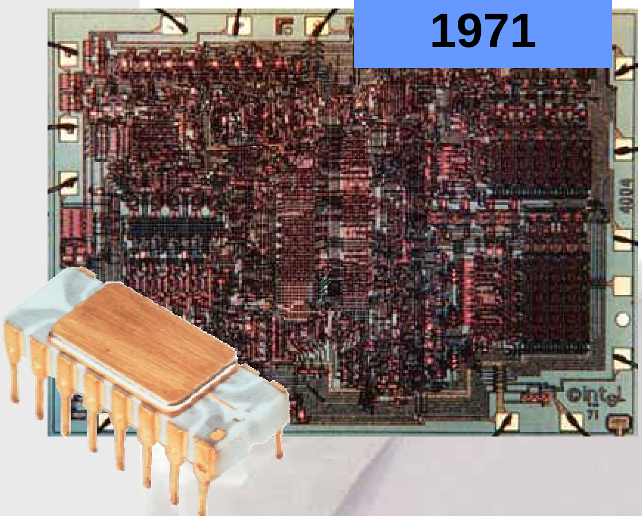
- Expensive components
- Inefficient Fabrication



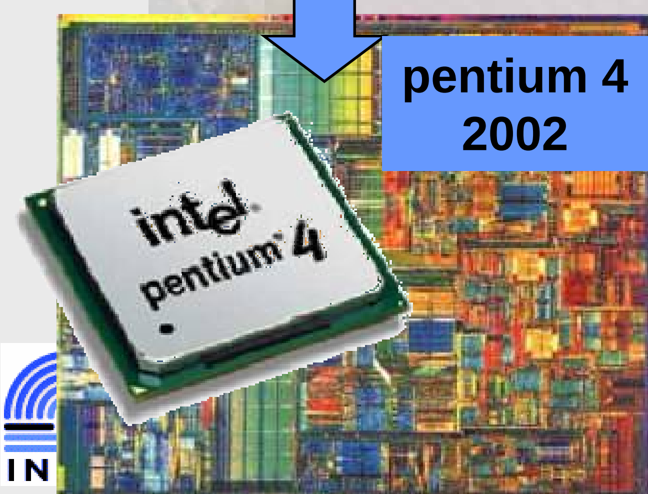
TU Delft, 1999

# Integration of multiple functions

intel 4004
1971



pentium 4
2002




More functions on a single circuit:

- Reduce size of individual functional elements
- Connections between elements (waveguides) must be smaller
  - narrow waveguides
  - sharp bends

TU Delft
1999

NANOphotonic Integrated Circuit

# Overview of this presentation

## Background

- What's the use?
- **How does a waveguide work?**

**What is light?**
**How can we guide light?**
**What is a good waveguide?**

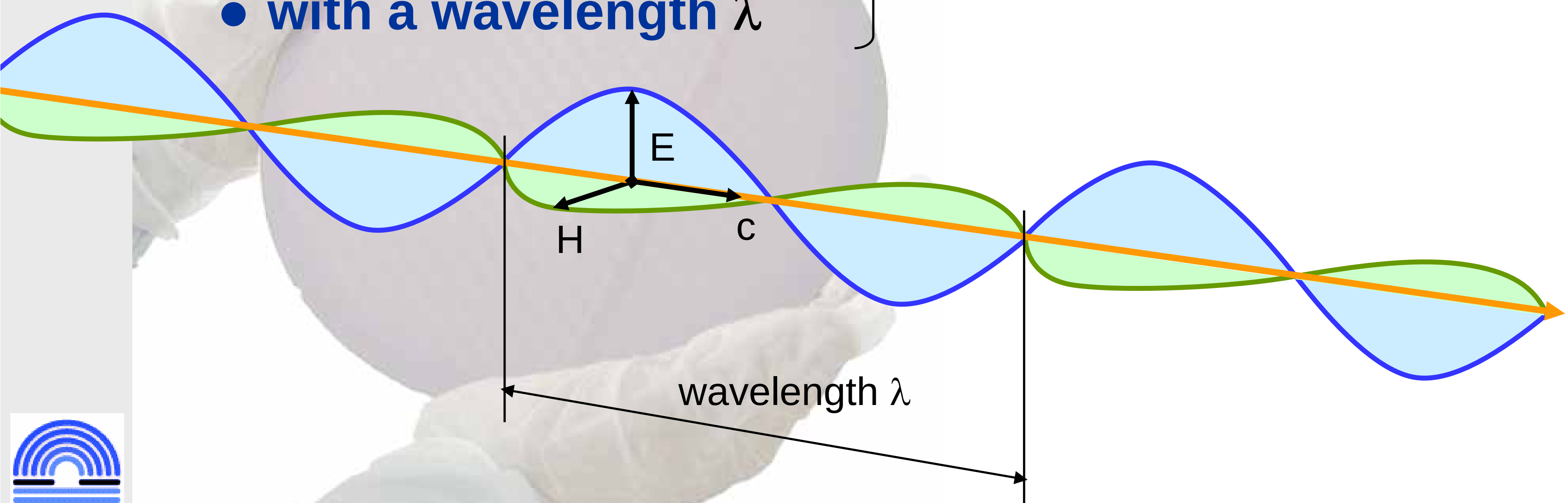
- What are the difficulties?
- Can we make it?
- What comes out?

# Light = Electromagnetic Radiation

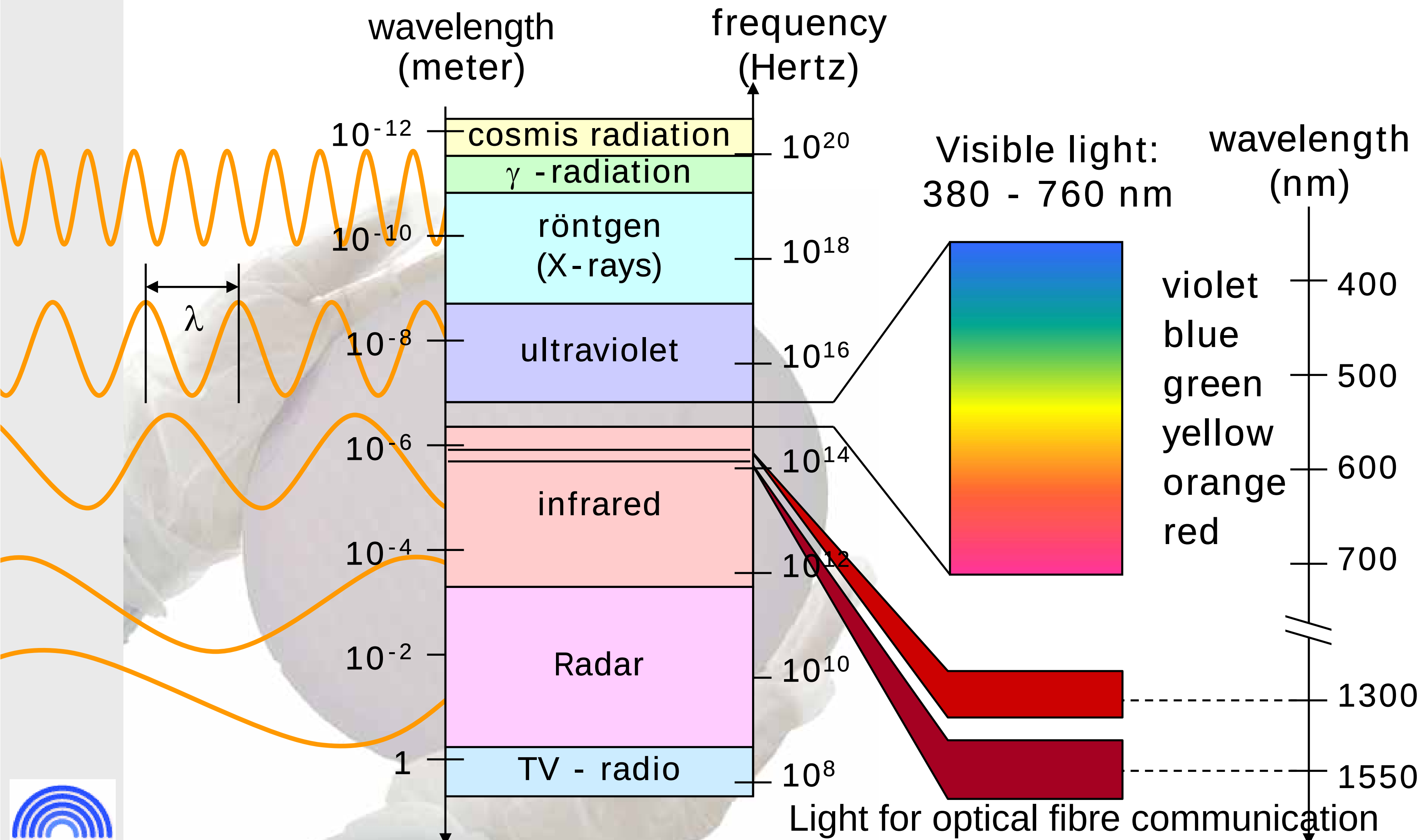
## Ray of light ≈ Electromagnetic wave

- Propagates at speed of light **c**
- Electrical oscillation **E**
- Magnetic oscillation **H**
- Oscillation frequency **f**
- with a wavelength **λ**

$$f \times \lambda = c$$



# Electromagnetic Radiation



# Propagation of light

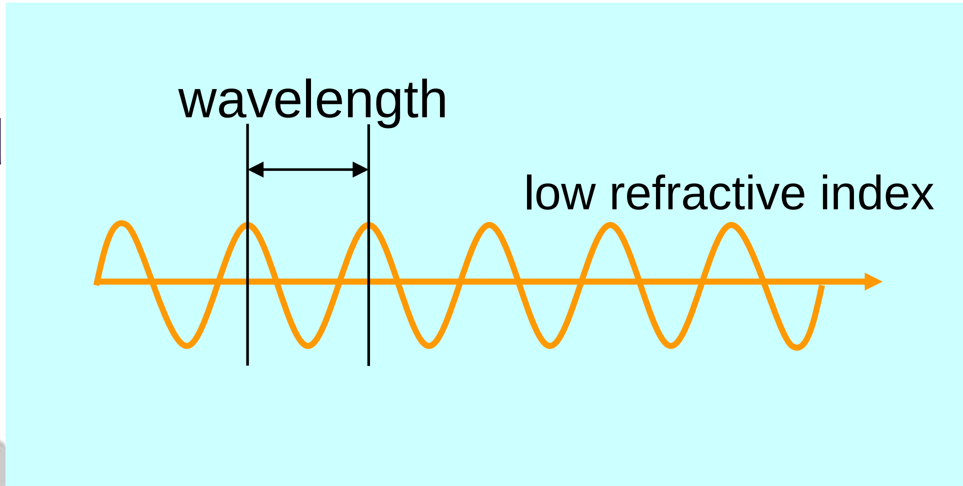
In vacuum: light propagates at the speed of light **c**

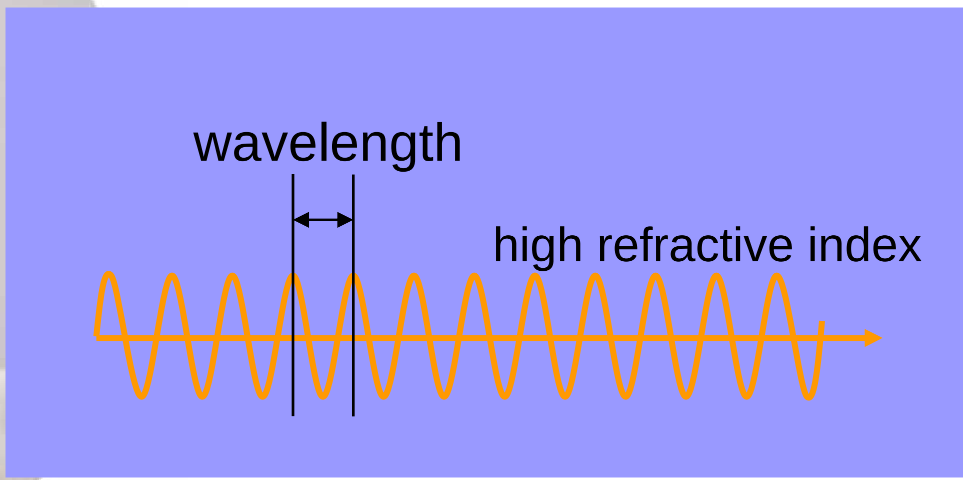
In material: light propagates **n** time slower

↓

refractive index **n**

wavelength becomes **n** times shorter for the same frequency



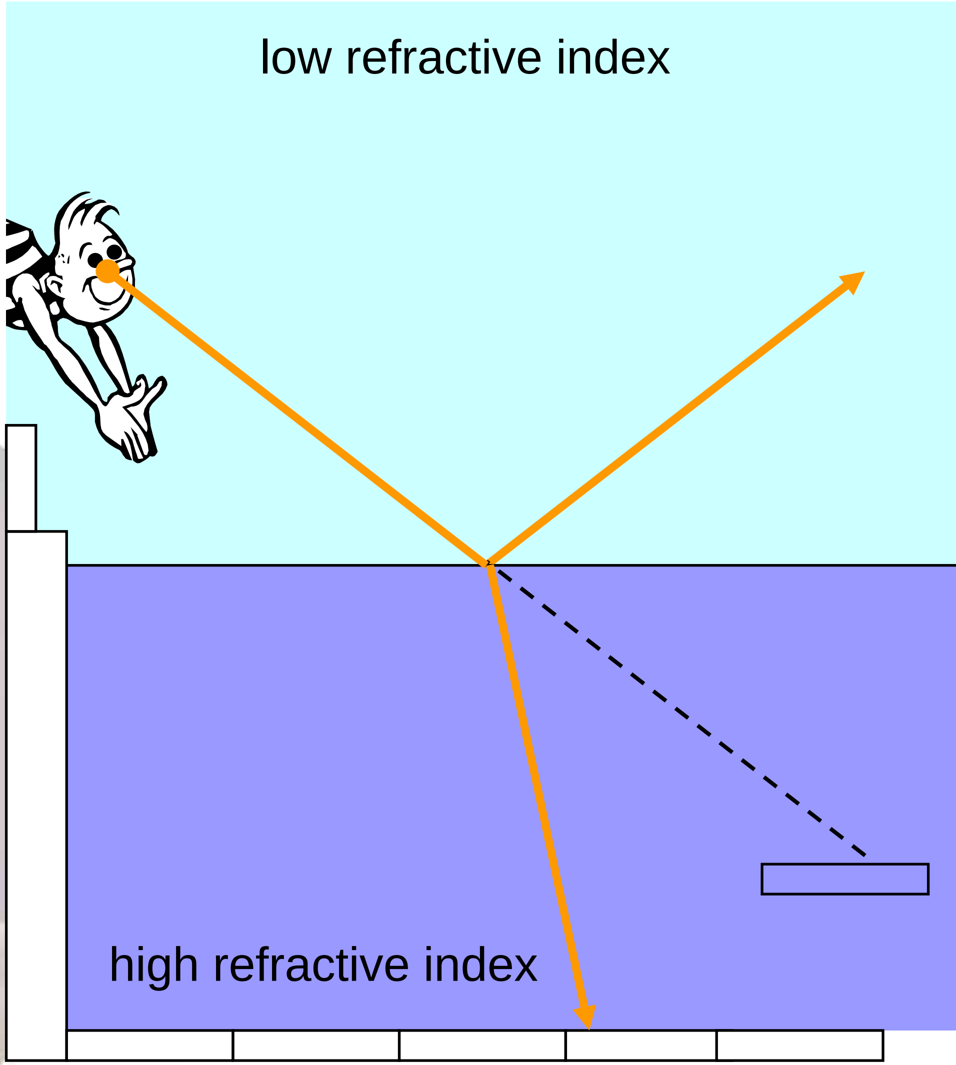



# Light at an interface

## Change in refractive index n

- Light rays change direction
- Light is partially reflected

## Effect is more pronounced with a stronger contrast in refractive index



# Total internal reflection

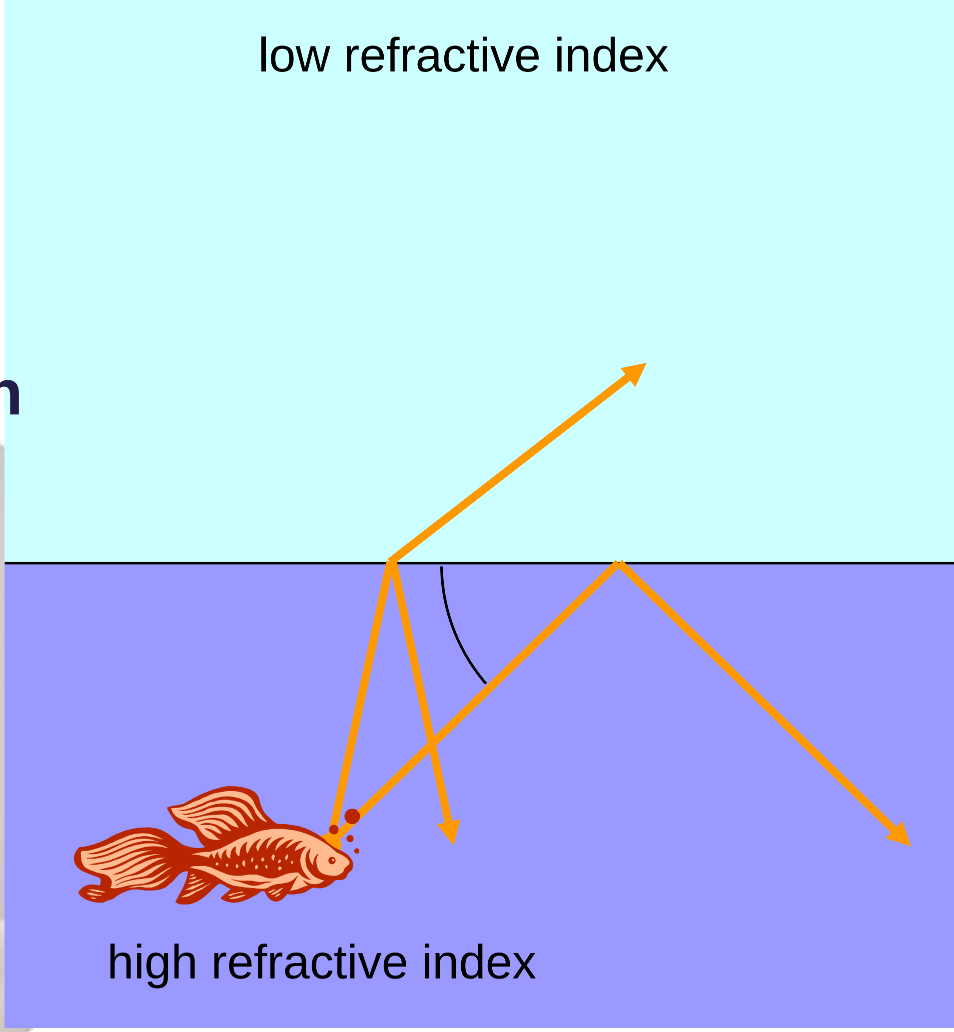
**Van 'inside to outside':**

**Very oblique rays are totally reflected**

**= Total internal reflection**

**The critical angle with the surface is larger for a stronger contrast in refractive index**

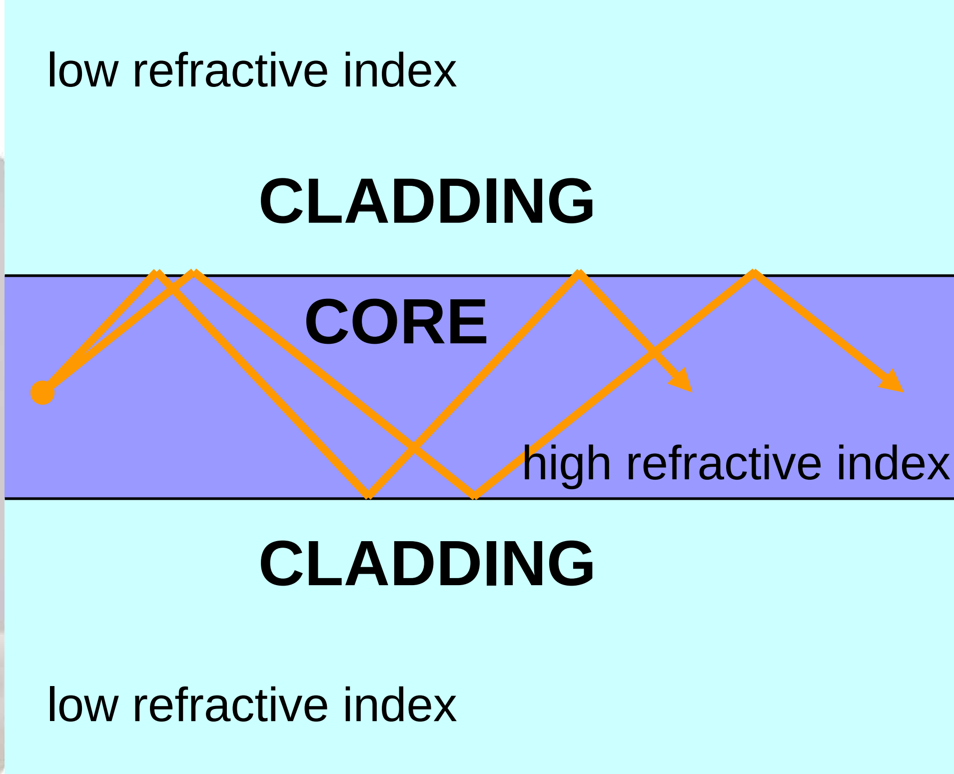
**(less oblique rays are also reflected)**



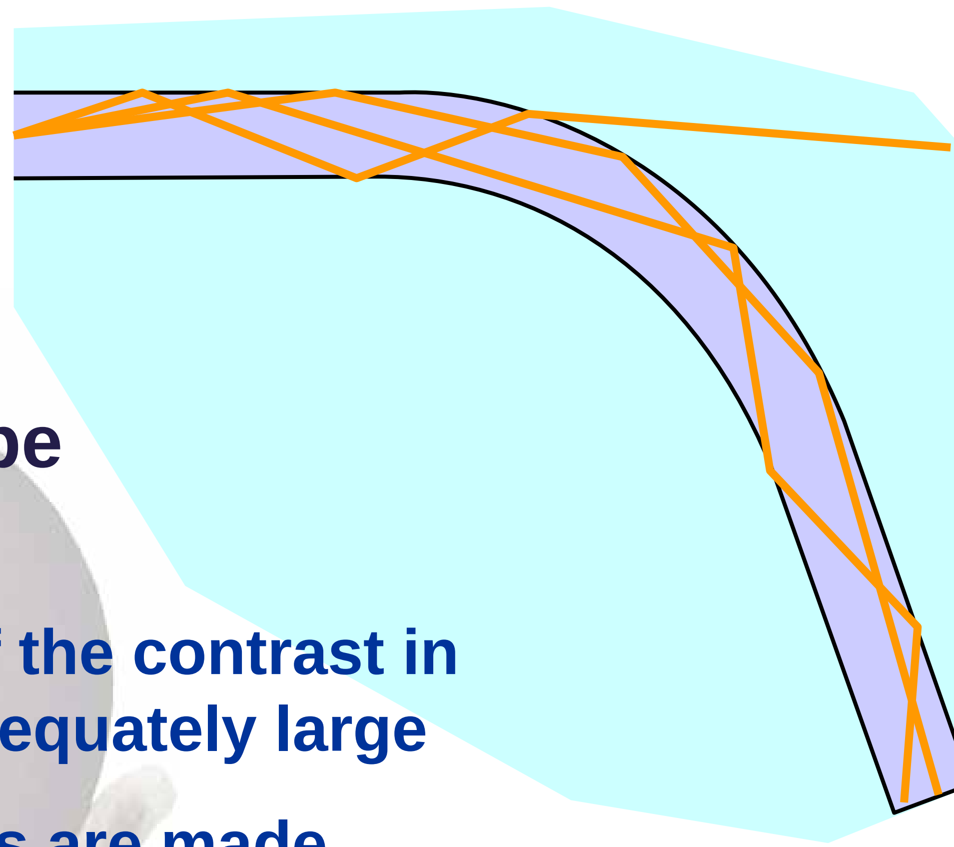
# Layered (Slab) Waveguide

**'Sandwich' of material with a high refractive index between material with a low refractive index**

**Light is guided by total internal reflection in a core of high refractive index surrounded by a cladding of low refractive index**



# Bends in waveguides



Some rays can escape from the waveguide

- Better confinement if the contrast in refractive index is adequately large
- Less loss if the bends are made sufficiently wide

Sharp bends possible with large refractive index contrast

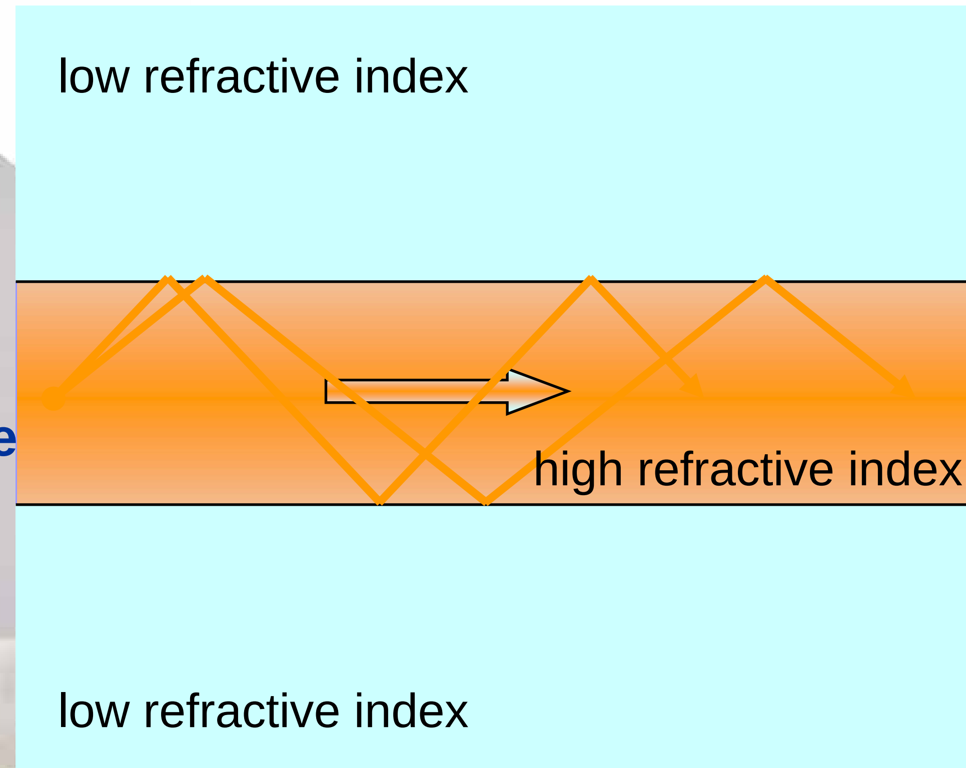
# Mode of a waveguide

**Thin core: Rays are an inaccurate model**

**Light is located in a smeared-out ‘blob’ in and around the waveguide core**

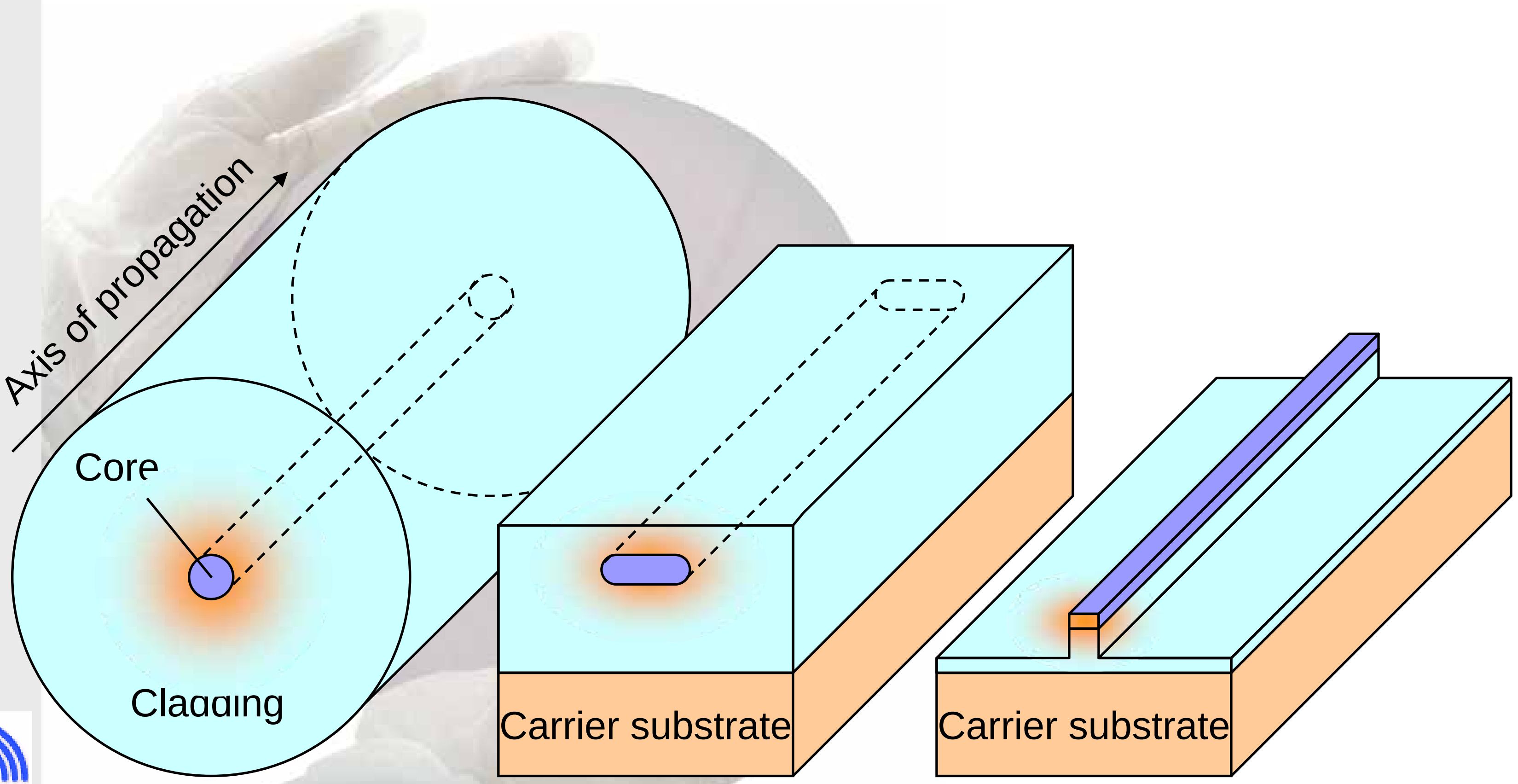
**= a mode**

- **a mode propagates as a single entity**
- **Guided modes: remain localised around the core**



# Waveguides

## Refractive index contrast in more directions: confine light in a core

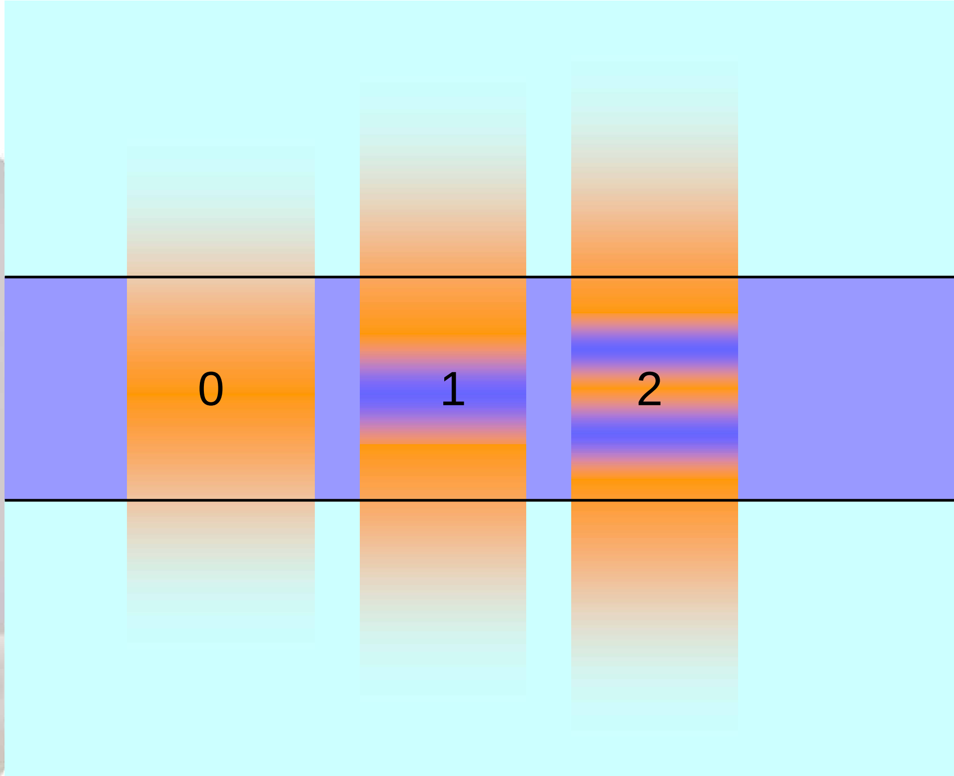


# Guided modes in a waveguide

**Some waveguides can support multiple guided modes**

**Mode 0 (ground mode) is the most useful**

- **best confinement: Smallest cross section**
- **most elegant distribution (no zeroes)**




**We'd like a waveguide that only supports a ground mode (= single-mode waveguide)**

# Single-mode waveguide

**For telecommunication: Waveguides should guide only a single mode:**
**Core must be sufficiently large**

- Optical fibres (low refractive index contrast): Core diameter ~ 10µm

**Larger refractive index contrast**
**smaller core**

- Waveguides in Silicon-on-Insulator (high index contrast): Core ~ 0.2 x 0.5µm.

# Reducing waveguide circuits in size

**Today's circuits: Large bend radius**

**Reduce bend radius:**

**increase refractive index contrast**

**From 1.46-to-1.44  to 3.45-to-1**

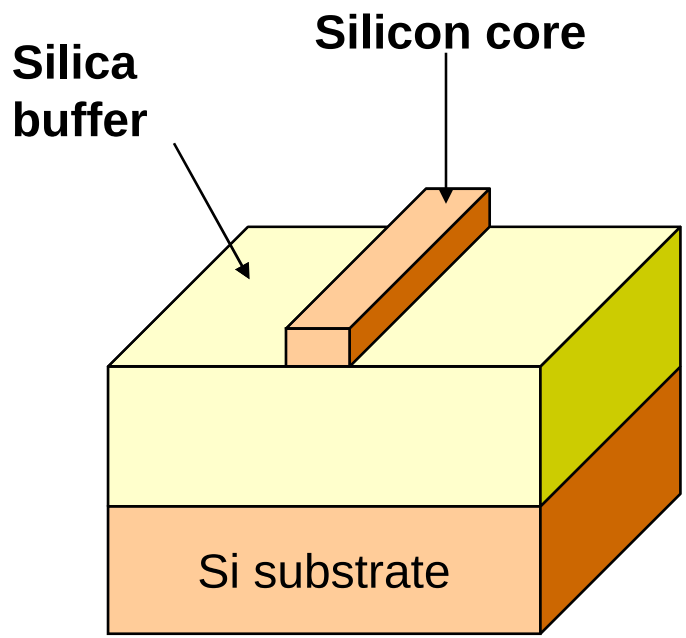
**SILICON-ON-INSULATOR**

**Keep only one guided mode:**

**Reduce dimensions**

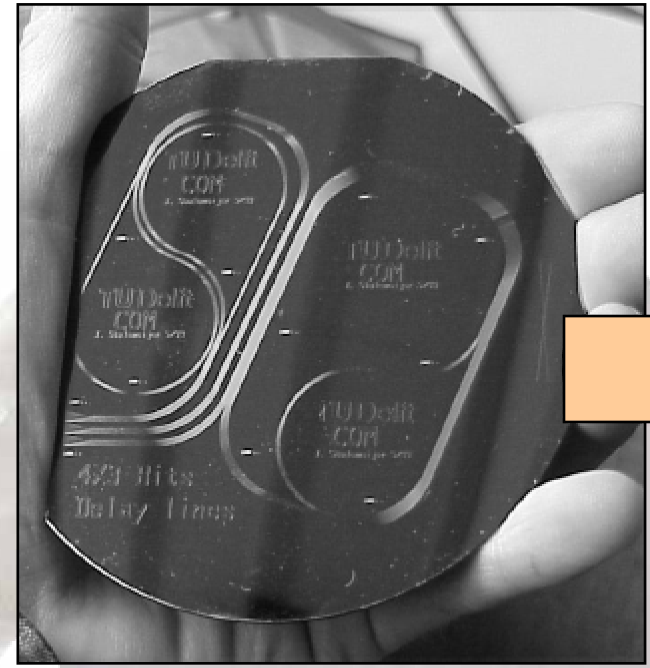
**From 10µm to 0.5µm**

**'PHOTONIC WIRES'**

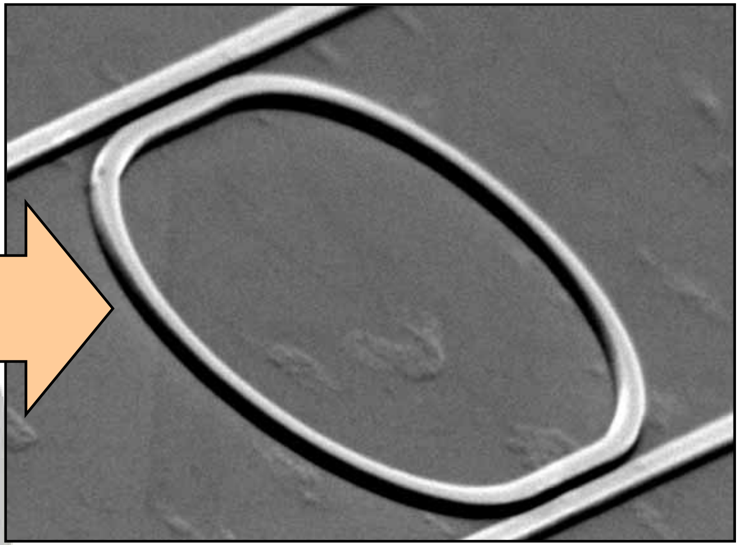


# Waveguide circuits

**1999**




**2003: ‘Photonic wire’**



**Silica-on-Silicon**

**Contrast: 1.46 to 1.44**

**Bend radius = 2cm**

**Silicon-on-Insulator**

**Contrast: 3.45 to 1**

**Bend radius = 5µm**

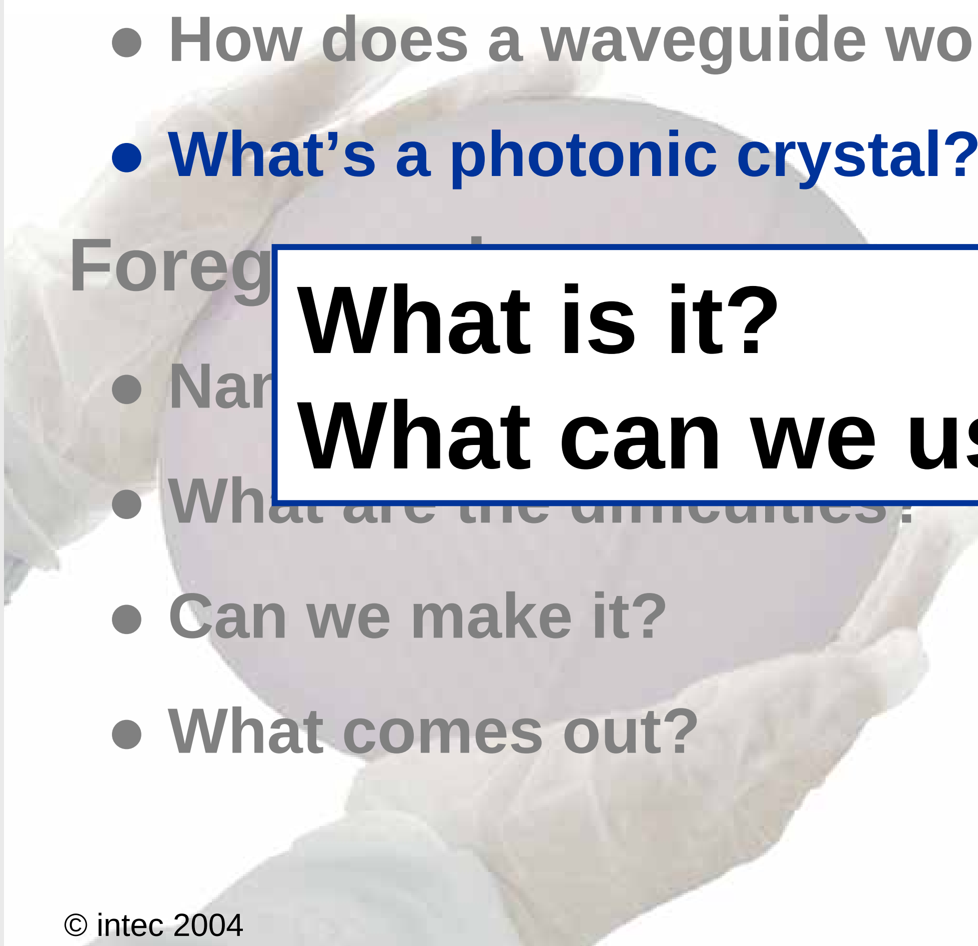
# Overview of this presentation

## Background

- What's the use?
- How does a waveguide work?
- **What's a photonic crystal?**

## Foreg

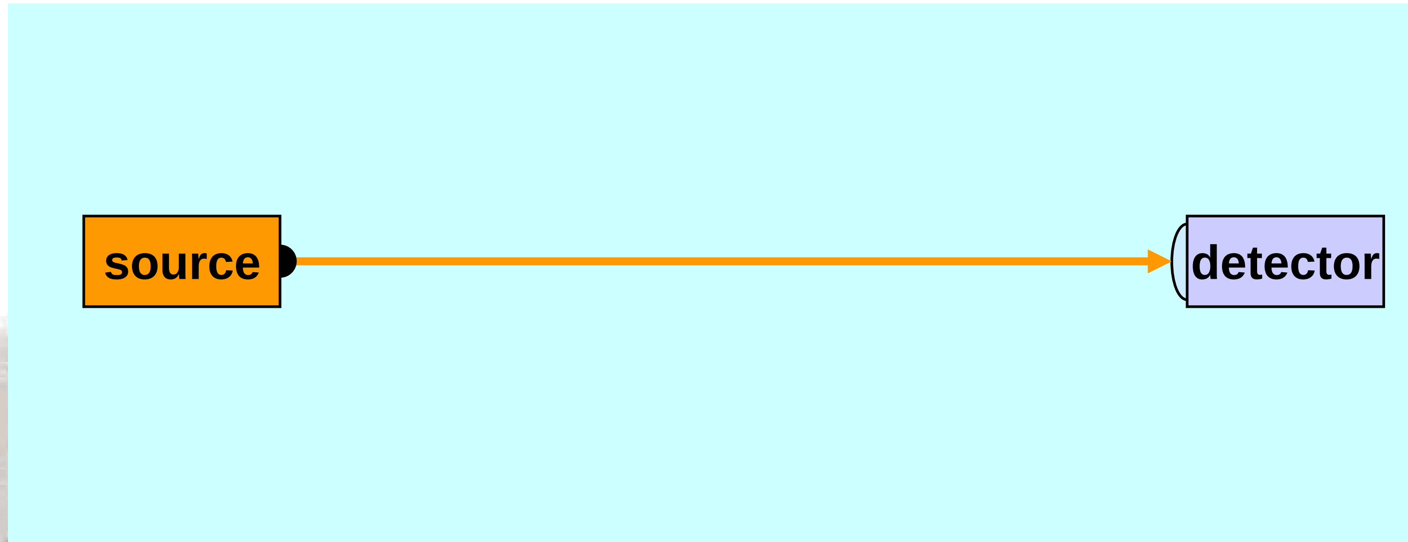
- Nar
- What are the difficulties?
- Can we make it?
- What comes out?

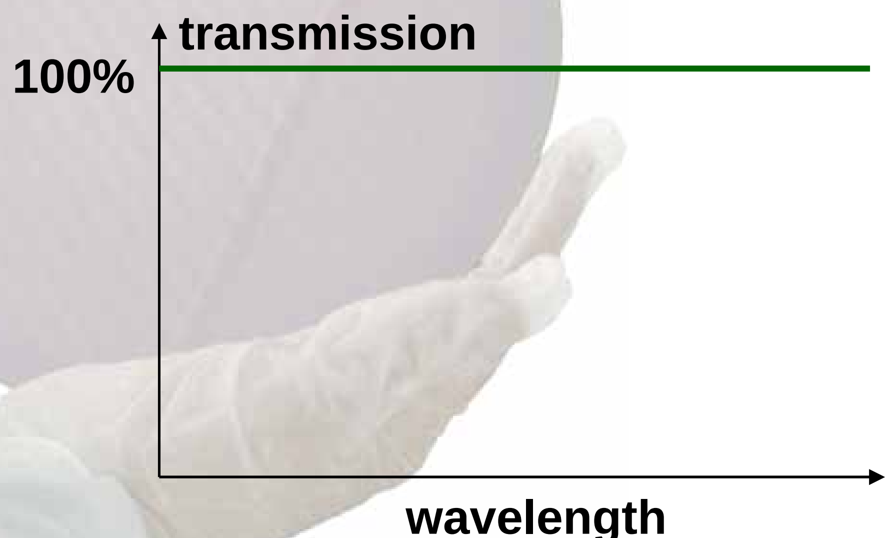


**What is it?**

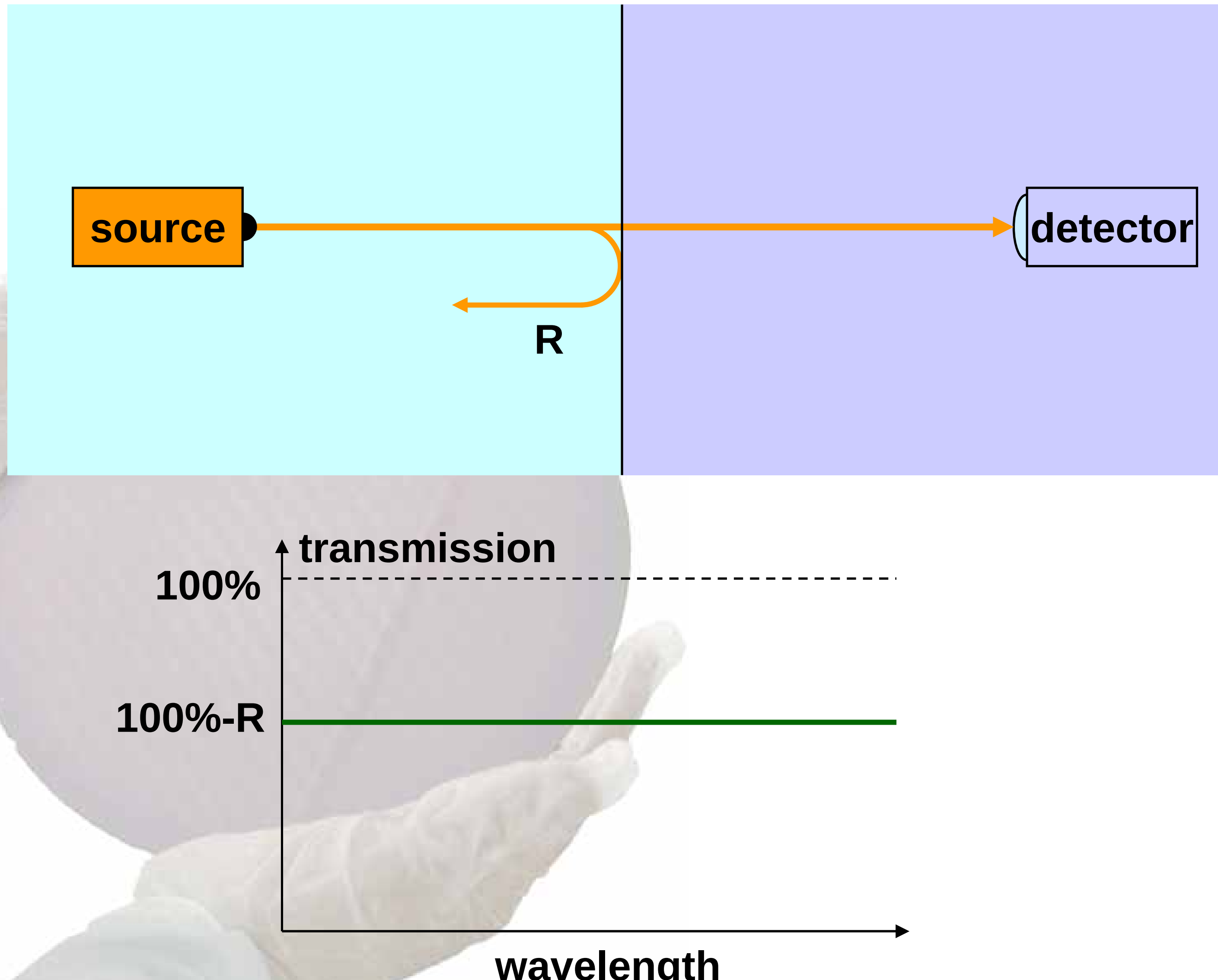
**What can we use it for?**

# A uniform material

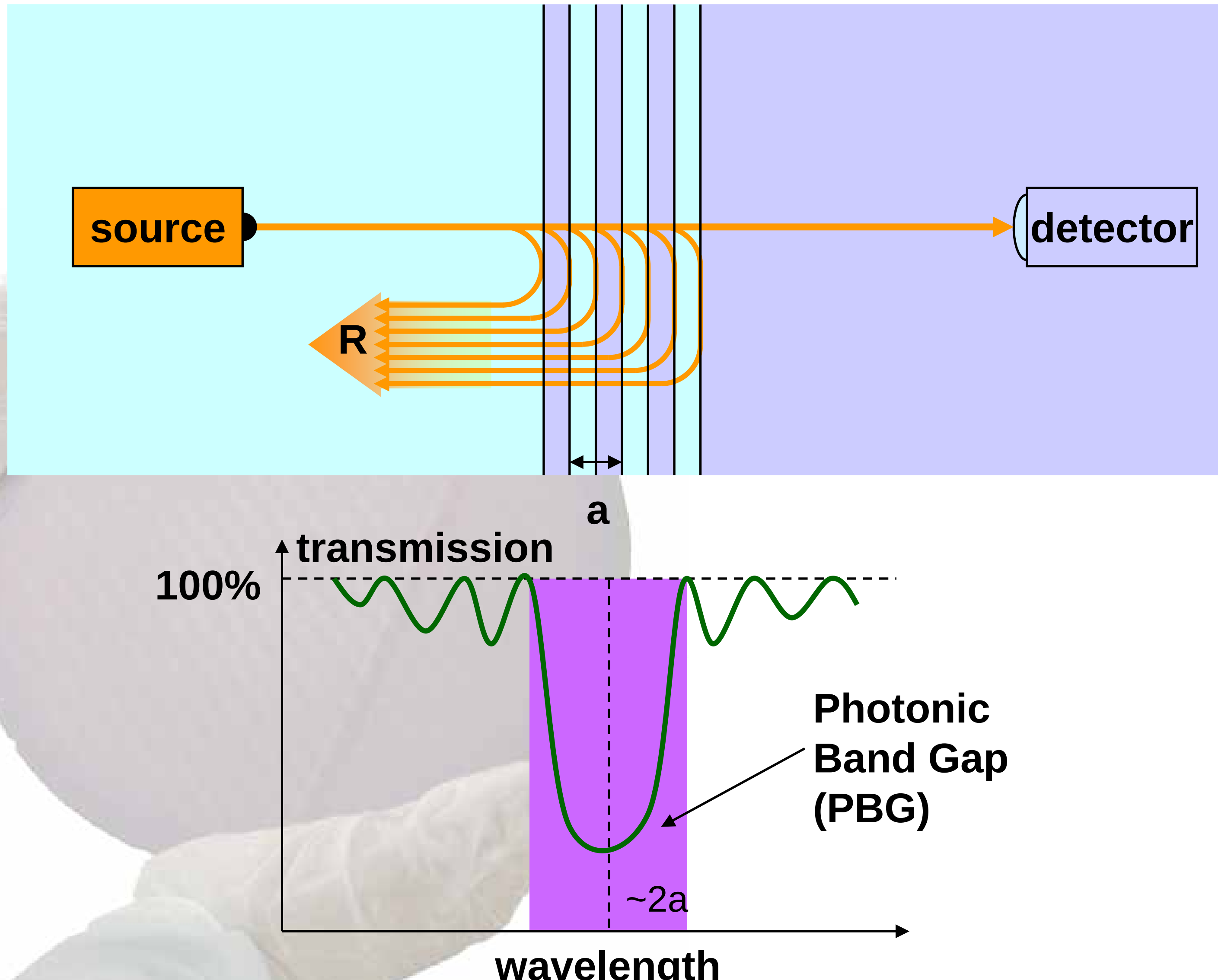


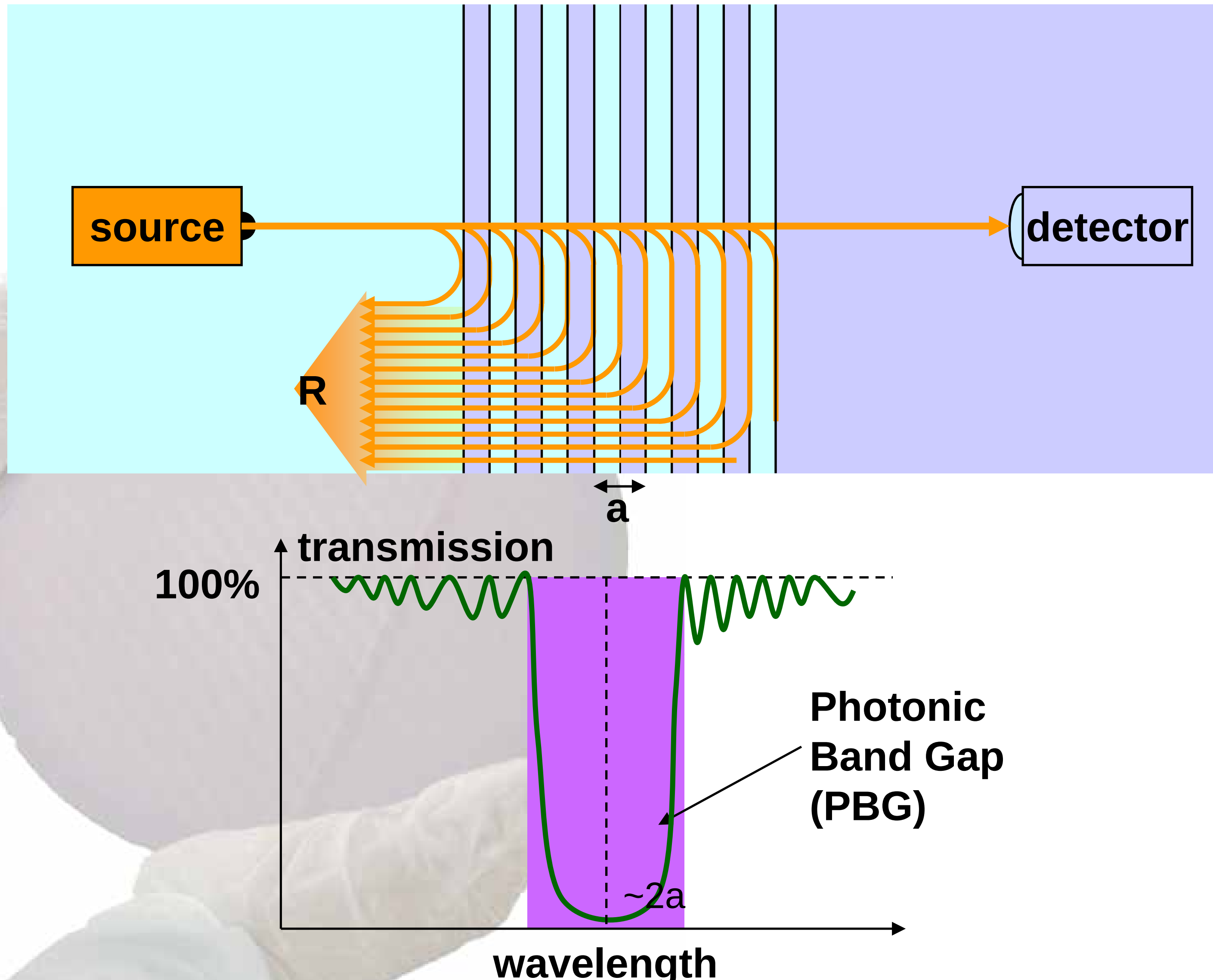
# One interface



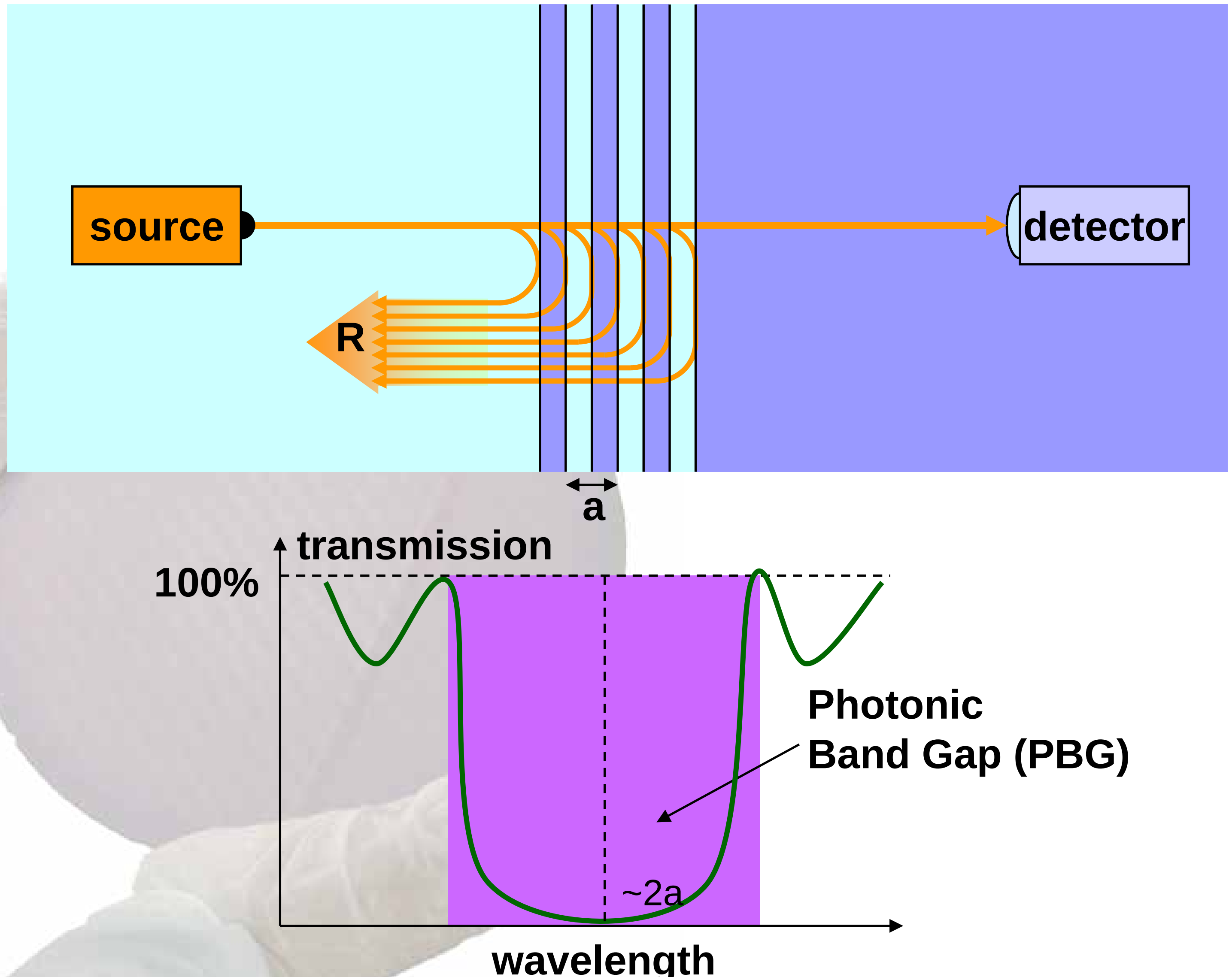
# A periodically layered structure



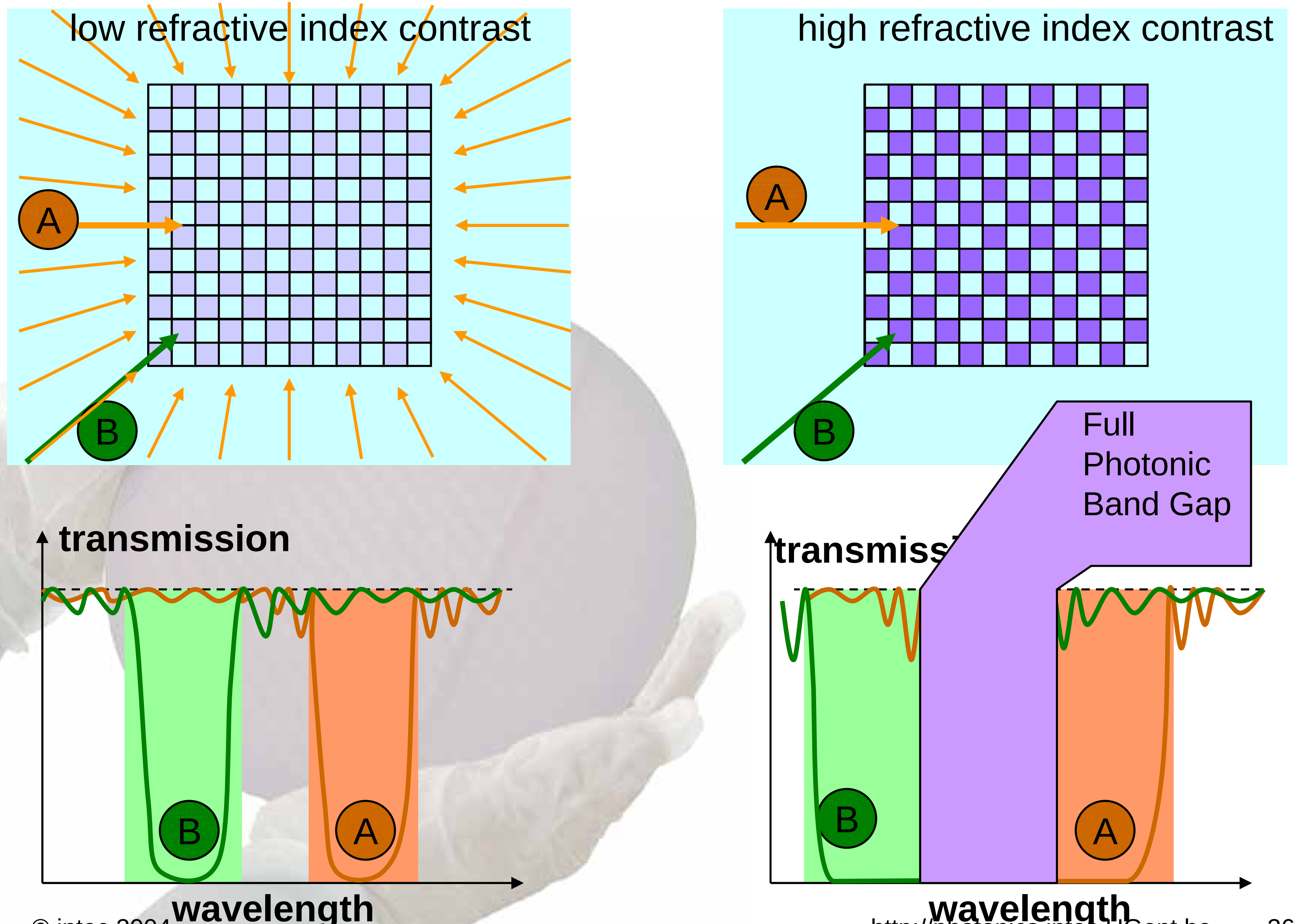
# Additional layers



# Higher index contrast

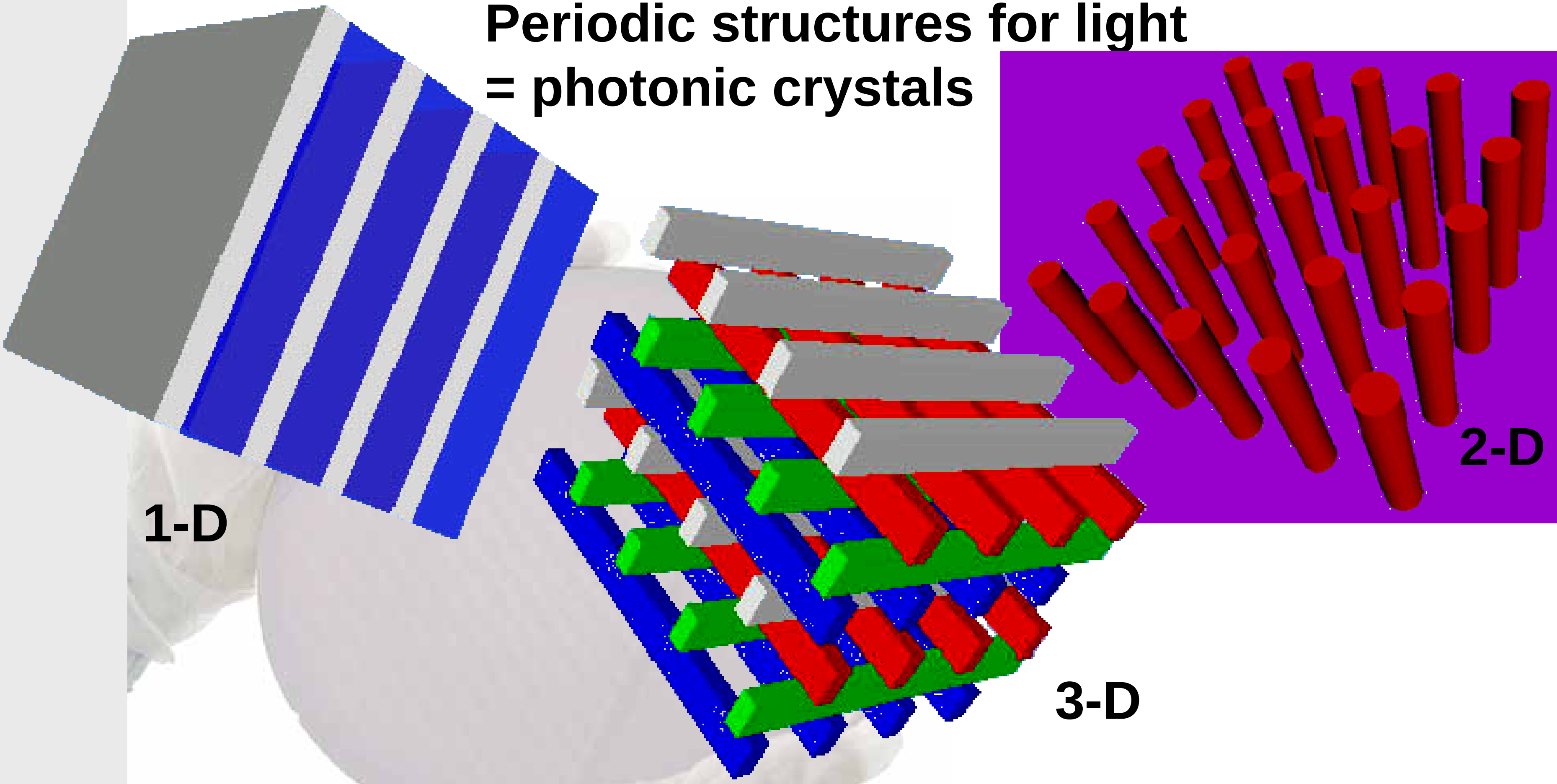


# Periodicity in more directions



# Periodicity in more directions

**Periodic structures for light**
**= photonic crystals**




**High refractive index contrast (larger than 2-to-1) needed for Full photonic band gap**

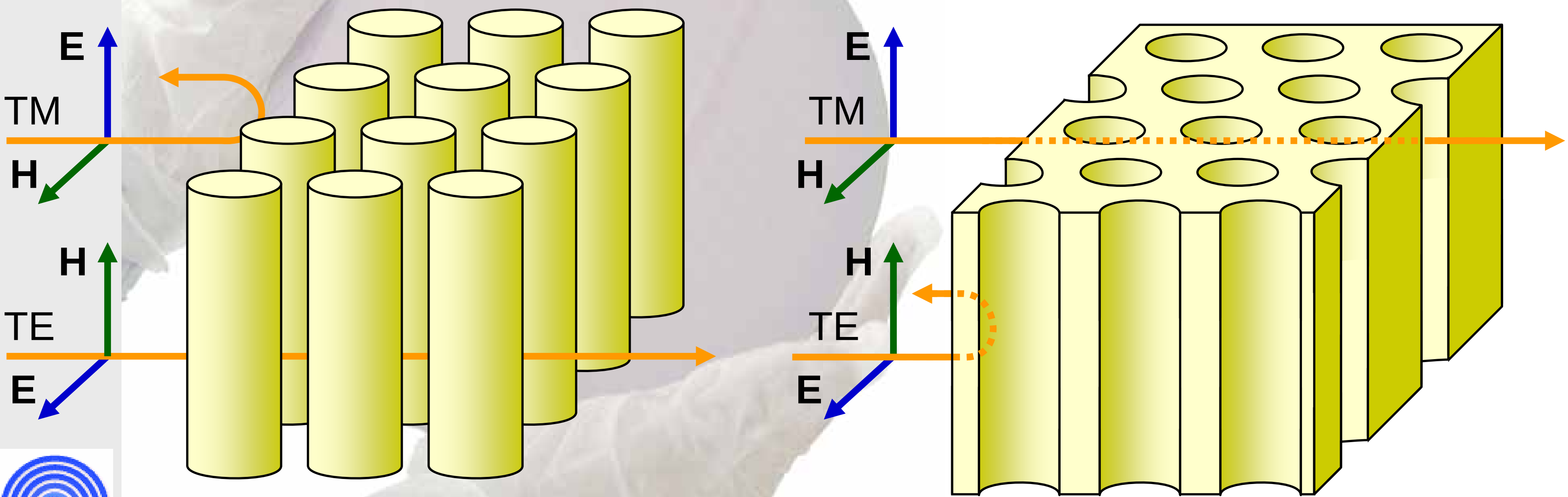
# 2-D photonic crystals

## Pillars in air

- Only a photonic bandgap for light with the electric field parallel to the pillar axis
  (= TM-polarisation)

## holes in material

- Only a photonic bandgap for light with the electric field perpendicular to the pillar axis
  (= TE-polarisation)




**High refractive index contrast needed**

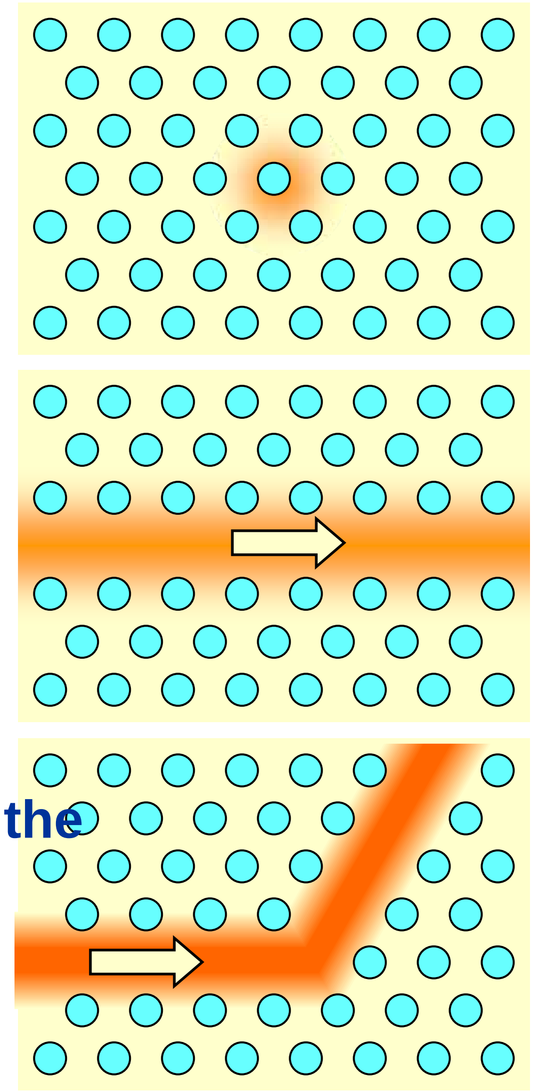
# A cage for light

## Perfect crystal with holes

- No light can exist there with a wavelength in the photonic band gap

## Defect: change holes locally

- Around the defect light can exist with wavelengths in the PBG
- The light cannot propagate away because of the photonic crystal
- e.g. in a line defect light has to follow the defect
  - = a waveguide
  - light cannot ‘miss the bend’

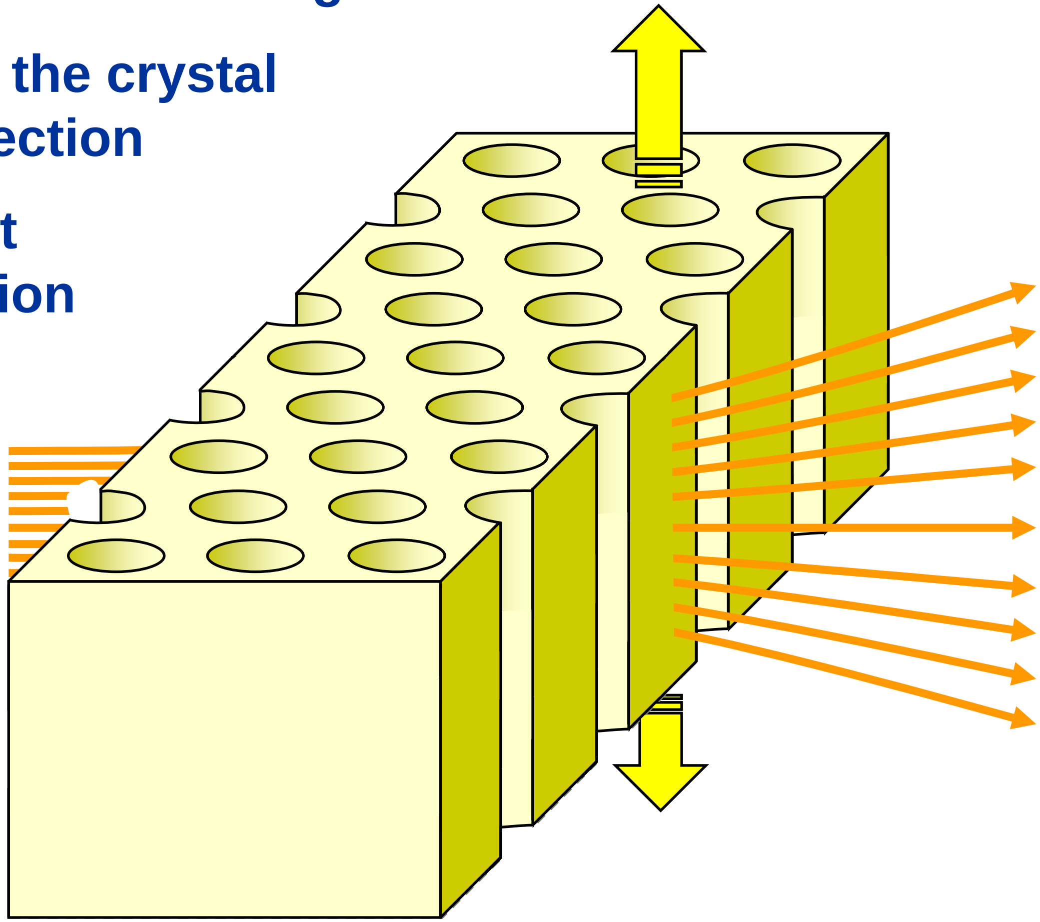


# A waveguide in a 2-D crystal

## Infinitely extended 2-D crystal

- remove one row of holes = waveguide
- Light is confined by the crystal in the horizontal direction
- Light can spread out in the vertical direction

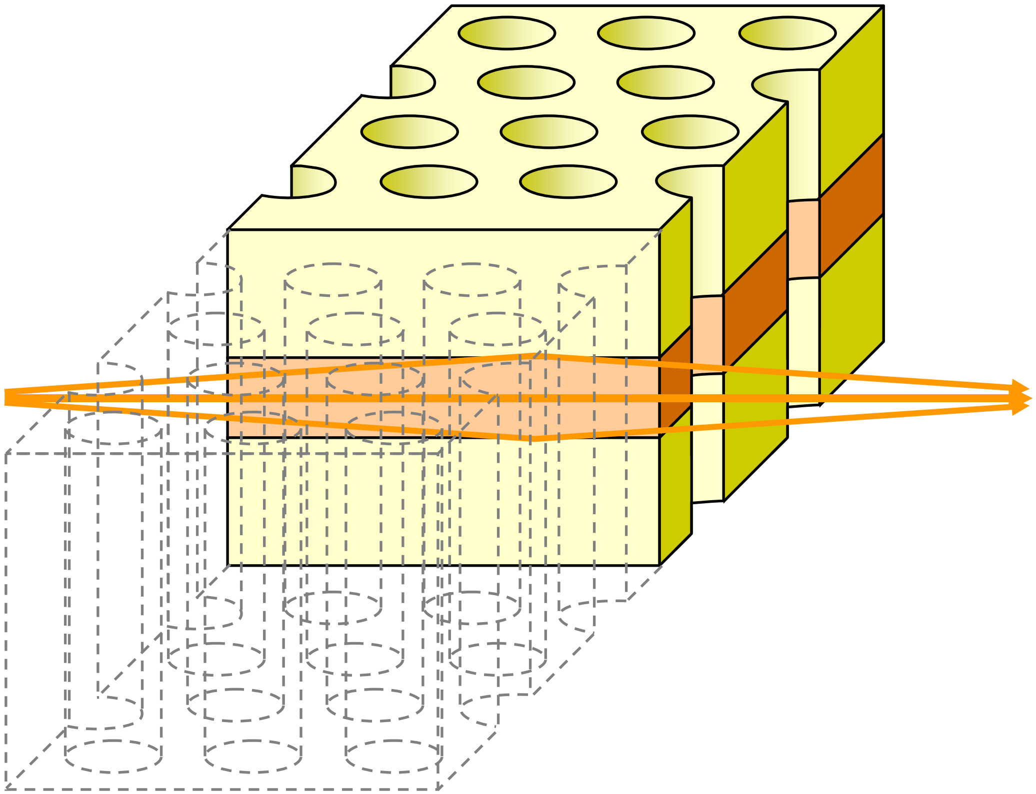
## How do we confine the light vertically



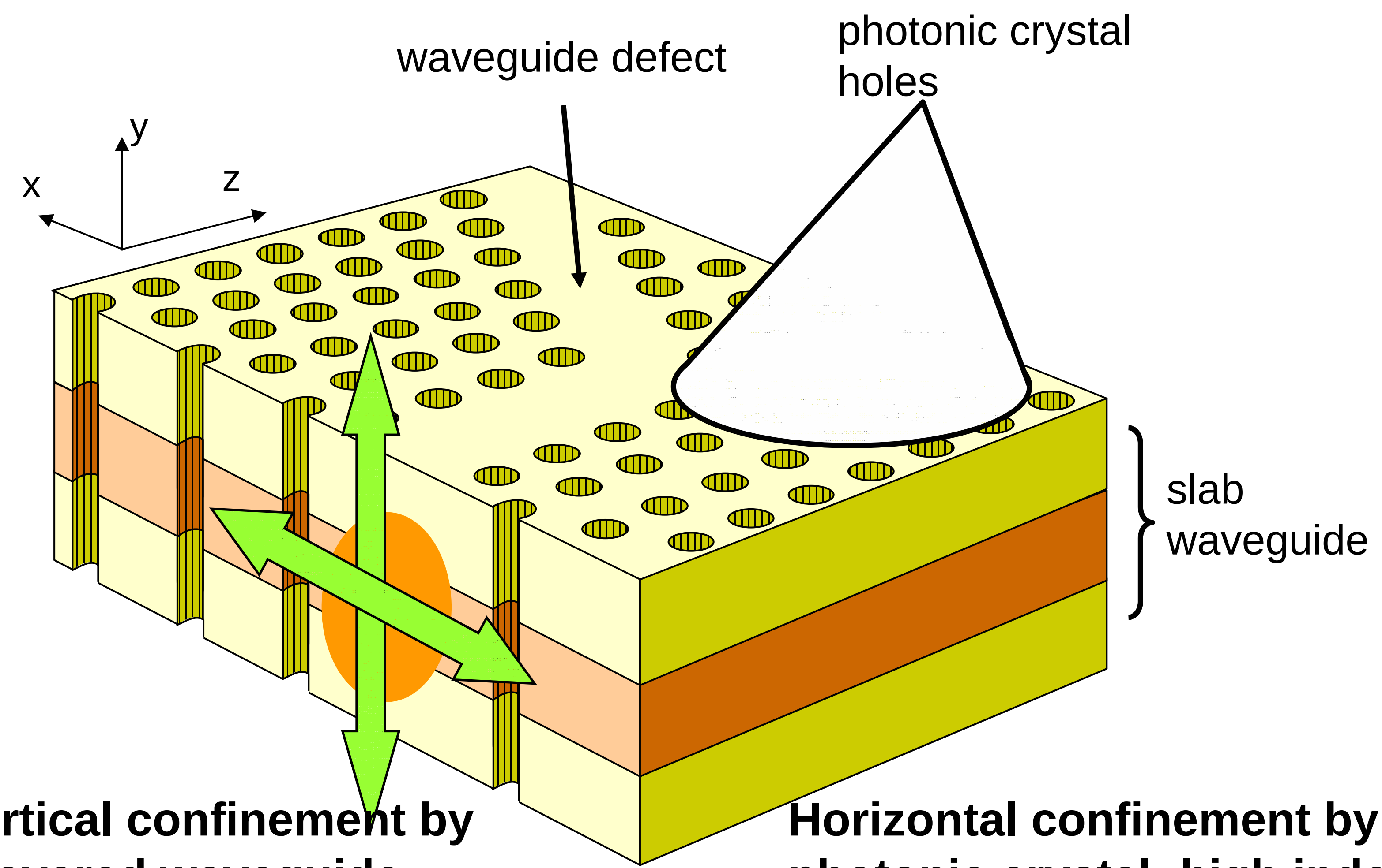
# 2-D crystal + slab waveguide

## Solution: a layered waveguide

- Light is confined vertically by total internal reflection
- or more correct: a guided mode



# Photonic Crystal Slab Waveguide




**Vertical confinement by a layered waveguide**

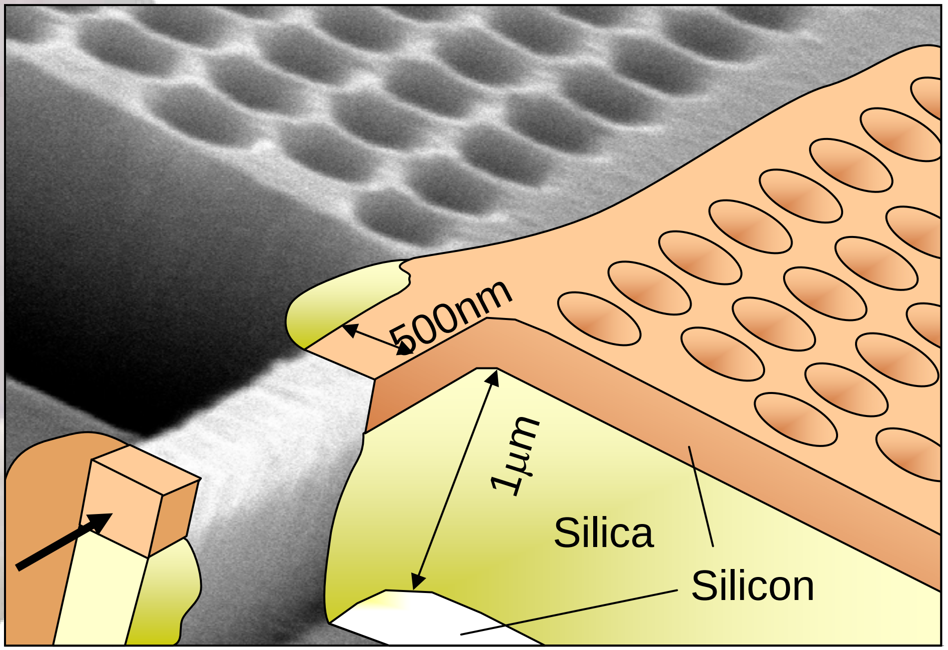
**Horizontal confinement by photonic crystal: high index contrast required**

# Silicon-on-Insulator

## Why this material system?

- **Transparent at telecom wavelengths (1550nm en 1300nm)**
- **High refractive index contrast**
  - **in-plane: 3.45 (Silicon) to 1.0 (air holes)**
  - **out-of-plane: 3.45 (Silicon) to 1.45 (silica)**

Layer structure:
- 220nm Si
- 1000nm $SiO_2$



# Overview of this presentation

## Background

- What’s the use?
- How does a waveguide work?
- What’s a photonic crystal?

## Foreground

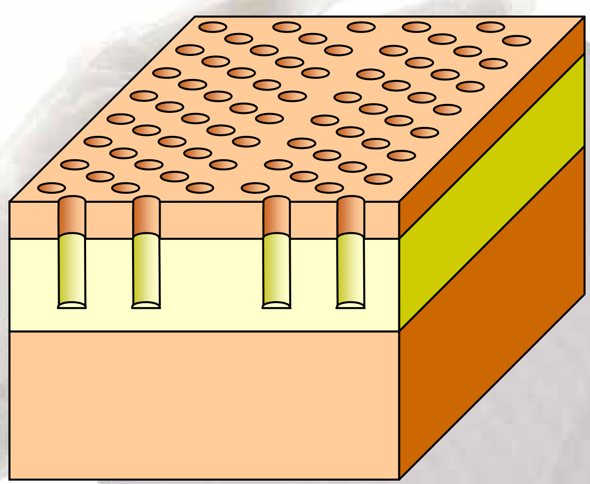
- **Nanophotonic waveguides**
- What are the difficulties?
- Can we make it?

**Photonic wires or crystals?**

# Nanophotonic Waveguides

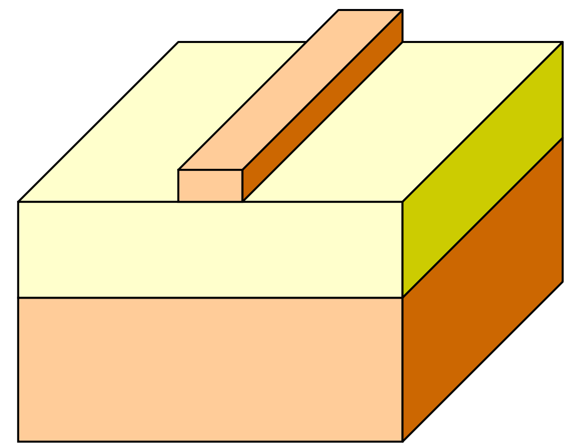
**Photonic Crystals:**

- In-plane: **Guiding by the photonic band gap**
- Vertical: Total internal reflection



**Photonic Wires:**

- In-plane: **Guiding by Total internal reflection**
- Vertical: total internal reflection



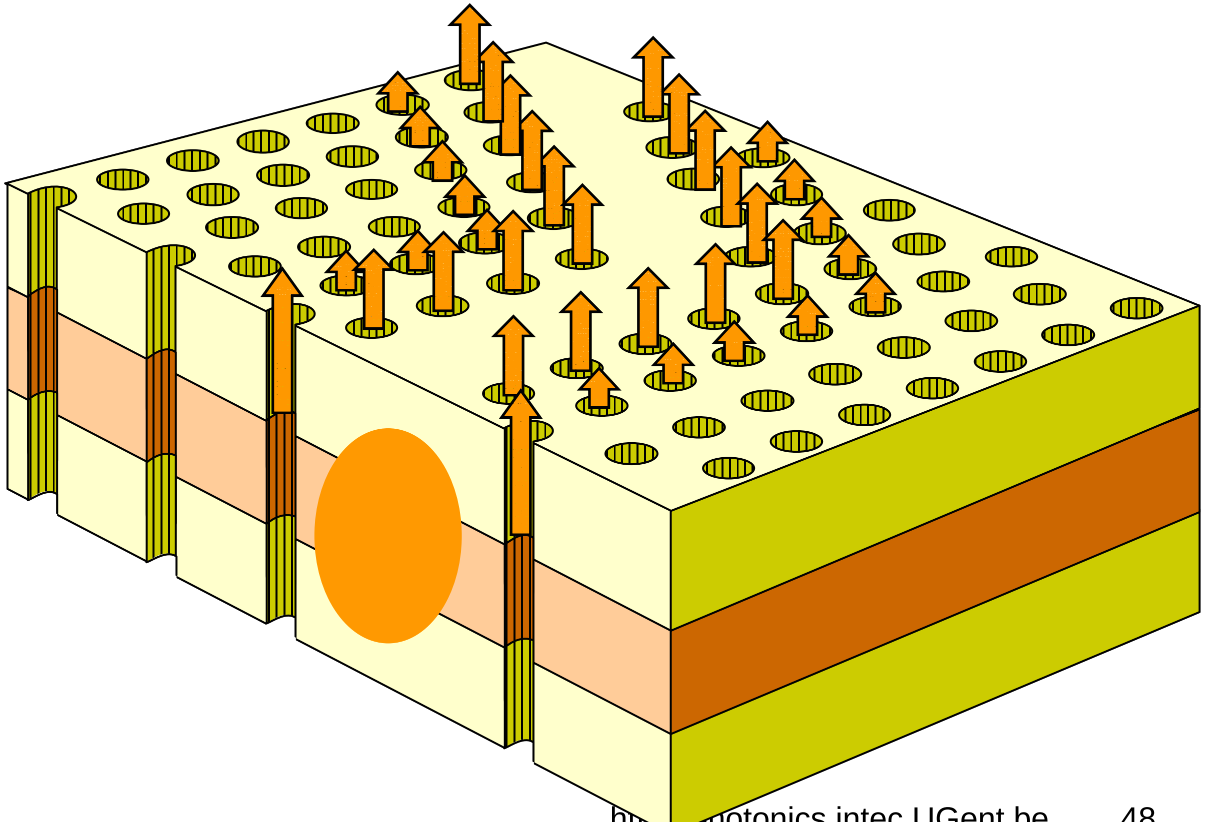
**Both cases:**
**• Details : a few 100 nm**
**• Required precision: <10 nm**
**NANOPHOTONIC waveguides**

# Early days of Nanophotonics

# Losses though out-of-plane scattering

**Photonic Crystal slab: Vertical confinement by layered waveguide**

**But: No vertical confinement in the holes**

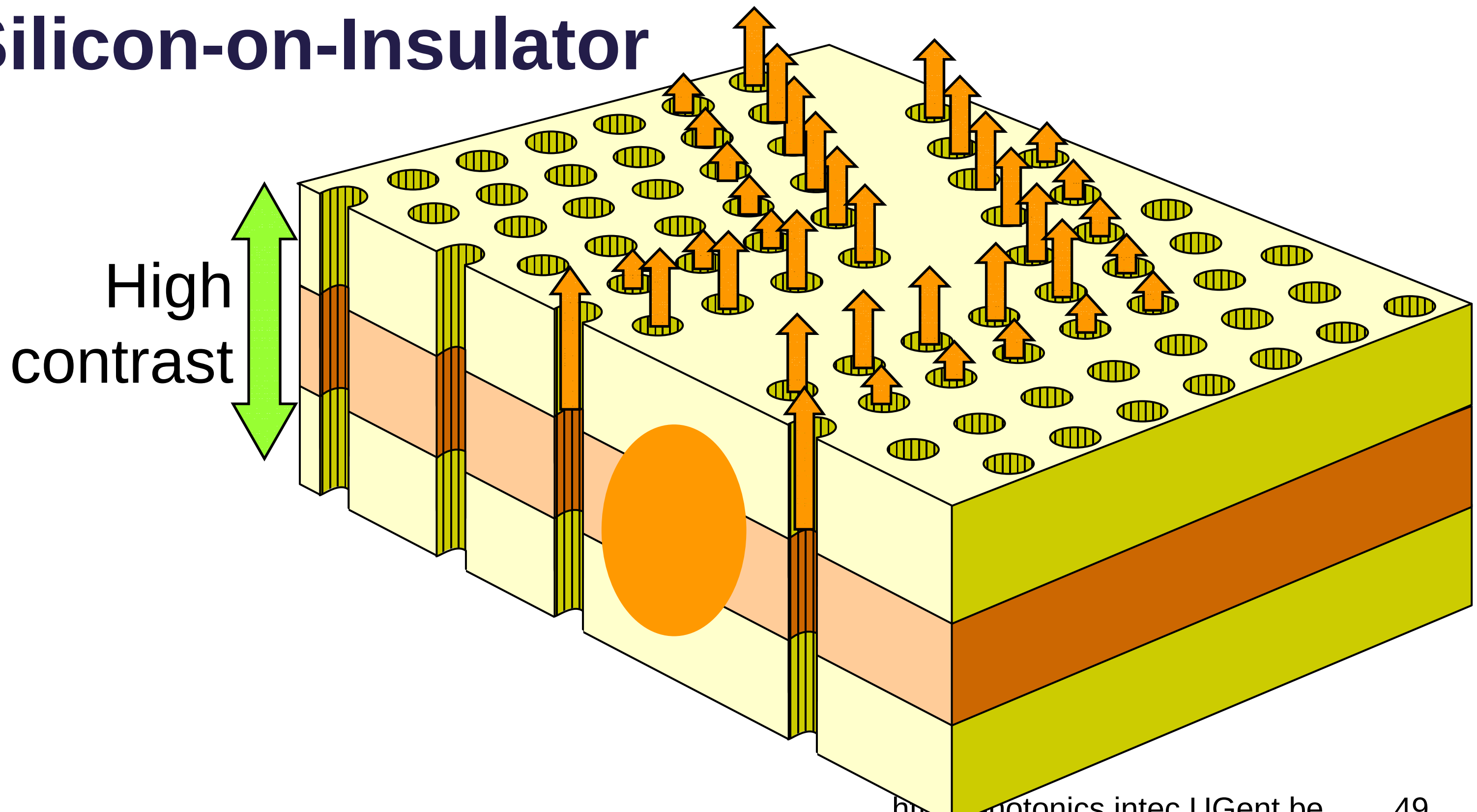


# Losses though out-of-plane scattering

## Hight vertical refractive index contrast:

- No radiation losses in straight sections
- Possible losses in bends, splitters, ...

## vb. Silicon-on-Insulator

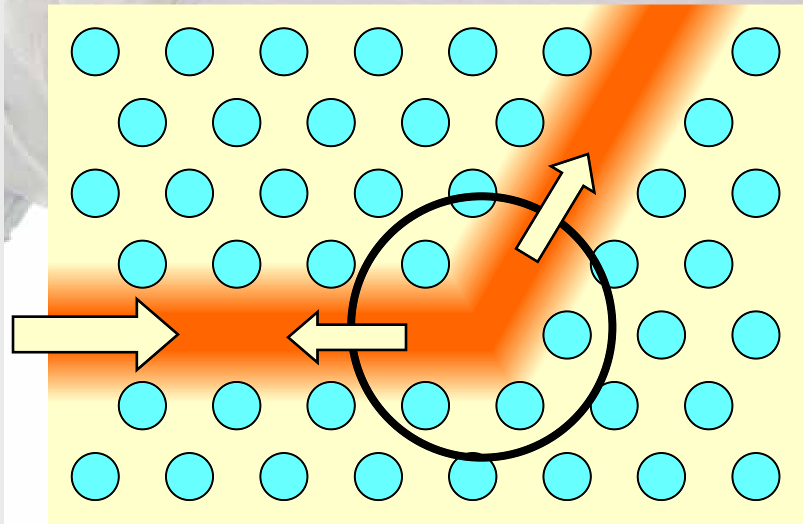


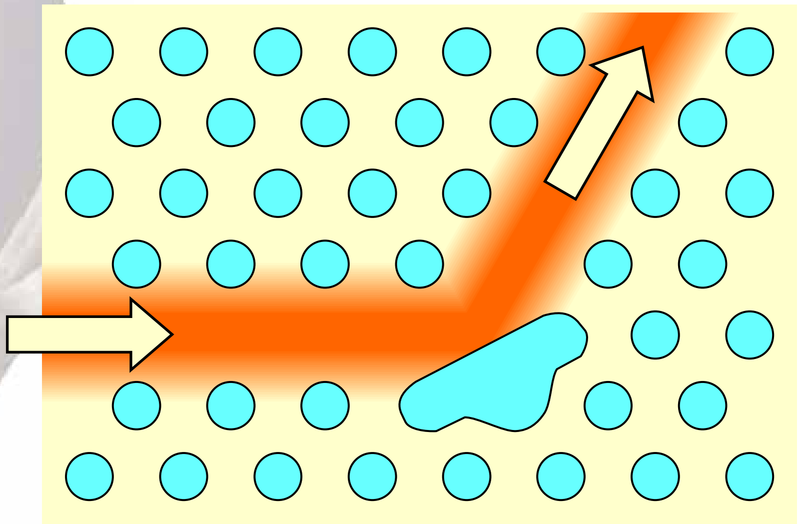
# Bends: not that simple

## In s simple bend:

- Out-of-plane scattering
- Backreflection

## Solution: Optimise the bend geometry (heavy number crunching)

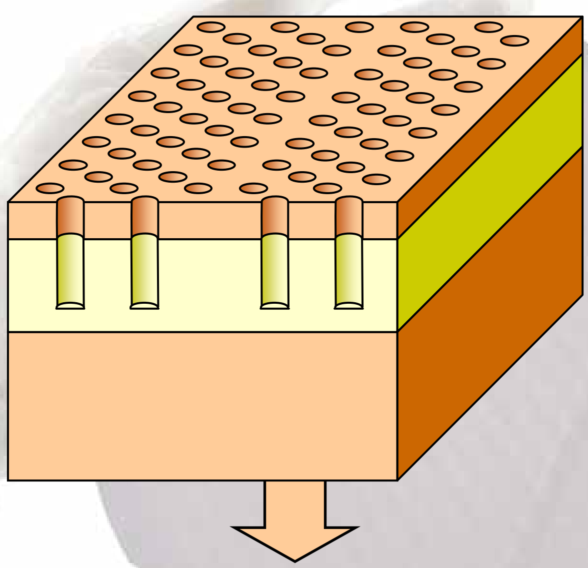




# Nanophotonic Waveguides

**Photonic crystals:**

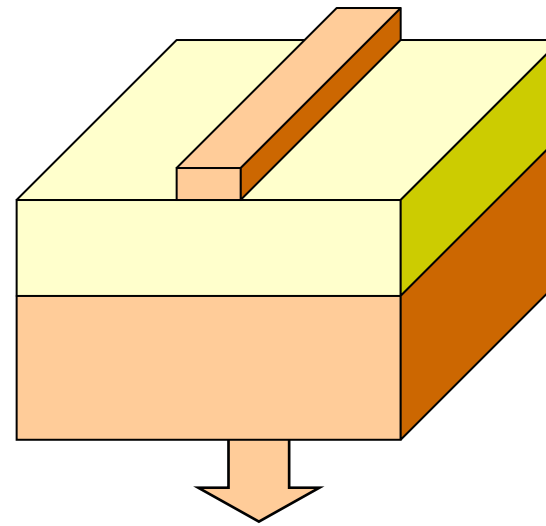
- Many possibilities
- Hard to design
- Losses



Use for compact
functional elements

**Photonic Wires:**

- Simple
- Less loss (given good fabrication technology)



Use for waveguides
(connections between elements)

Good fabrication technology needed

# The troubles of nanophotonics

## Nanophotonic components

### Hard to measure

- What goes on inside the structure?

### Hard to model

- index contrast: 3.5 to 1
- fine details: 150nm - 1μm

### Hard to Make

- high resolution
- precision: <10nm

### Hard to Match

- how to get the light in and out

### Hard to Design

- many parameters
- fabrication tolerances

# The troubles of nanophotonics

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# Overview of the presentation

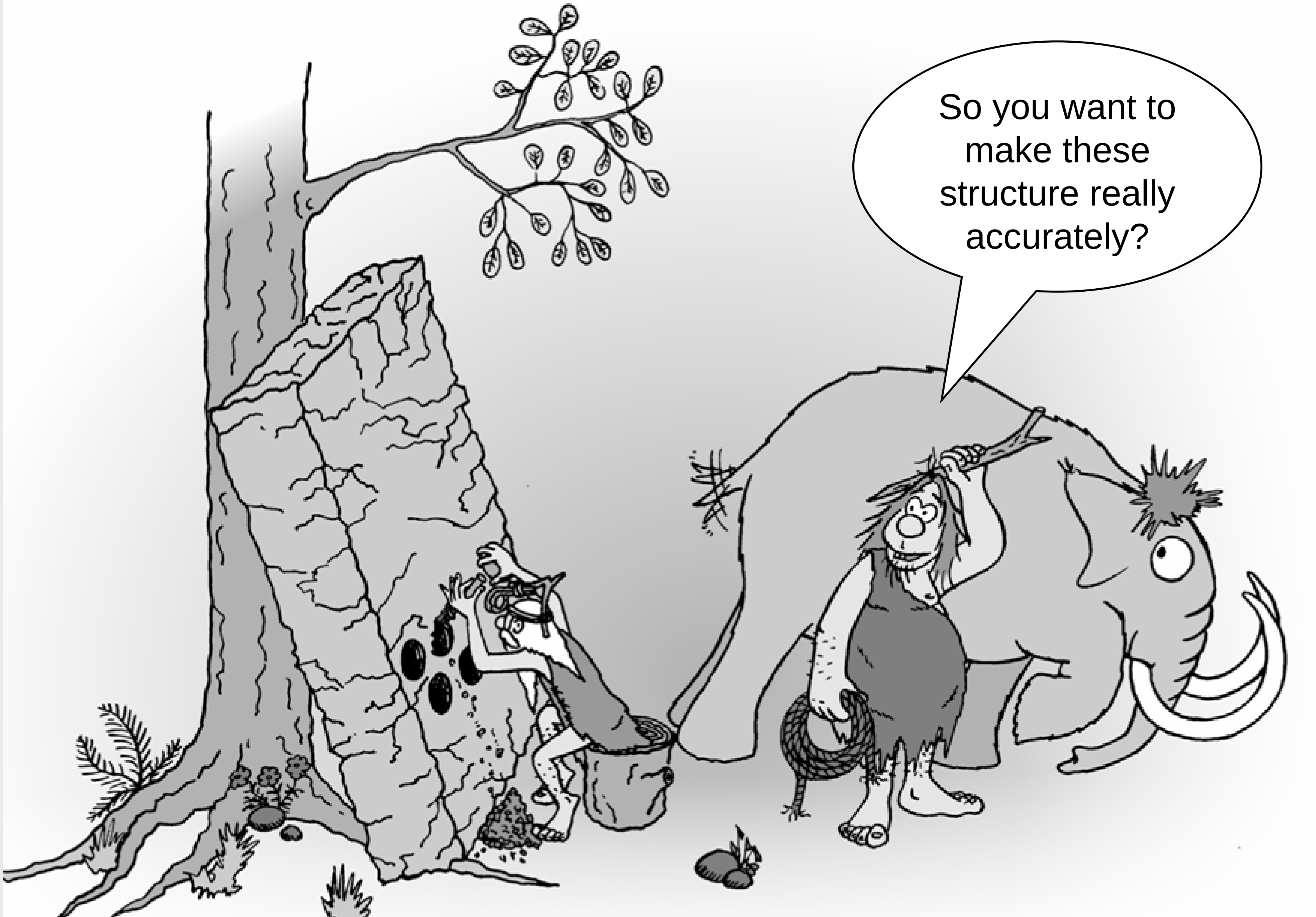

## Background

- What's the use?
- How does a waveguide work?
- What's a photonic crystal?

**Which techniques are there?**
**What do we use?**
**What are the difficulties?**

- Can we make it?
- What comes out?

# Litho-graphy = Stone-writing

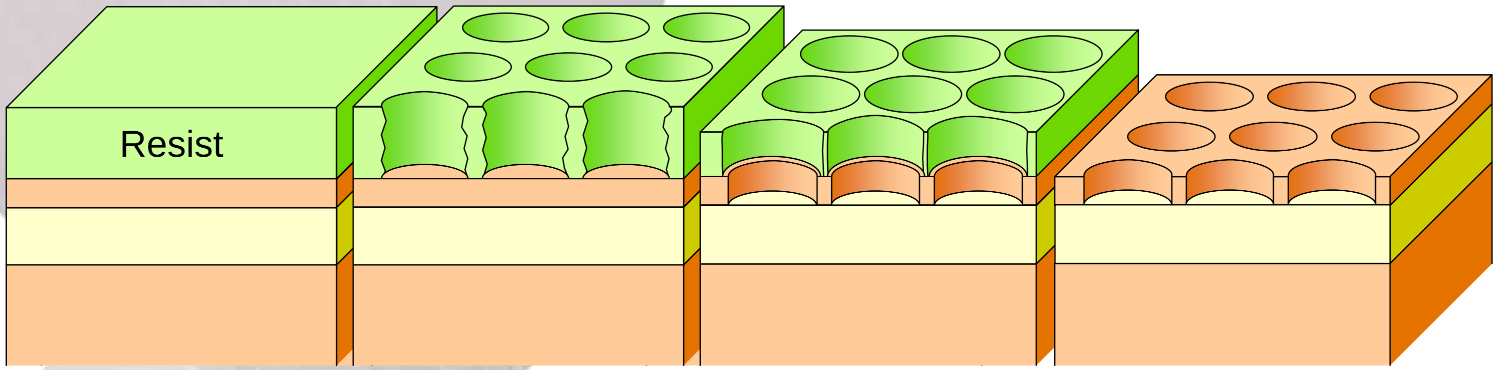


# Lithographic techniques

## Goal: Imprint a pattern into the Silicon

## Solution

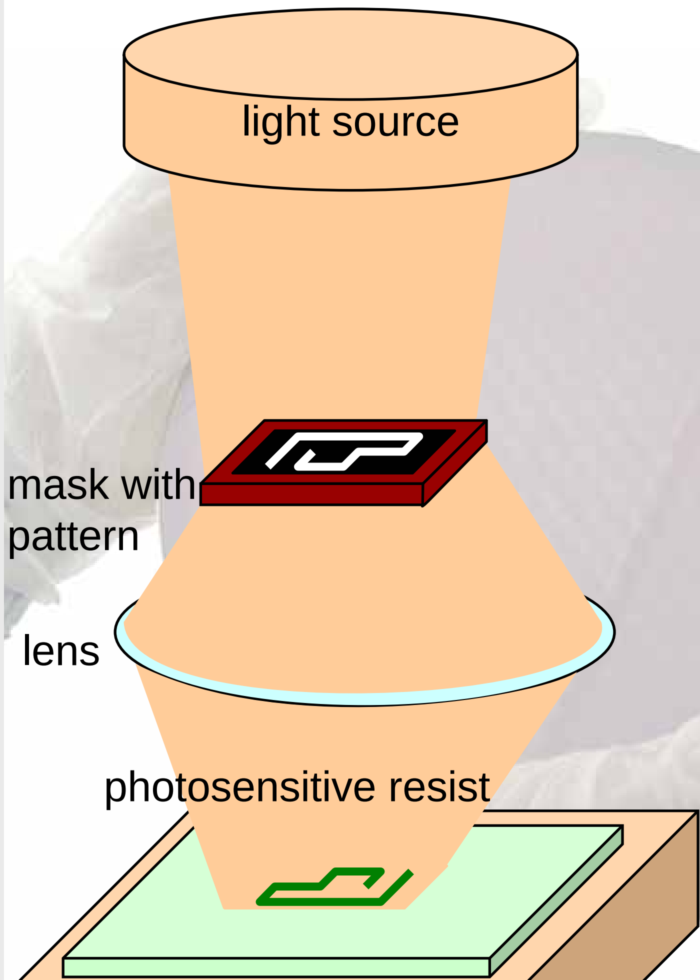
- **Imprint the pattern in a sensitive polymer (resist)**
  **= lithography**
- **Transfer the pattern into the Silicon**
  **= etching**
- **Remove the resist**



# Lithographic Techniques

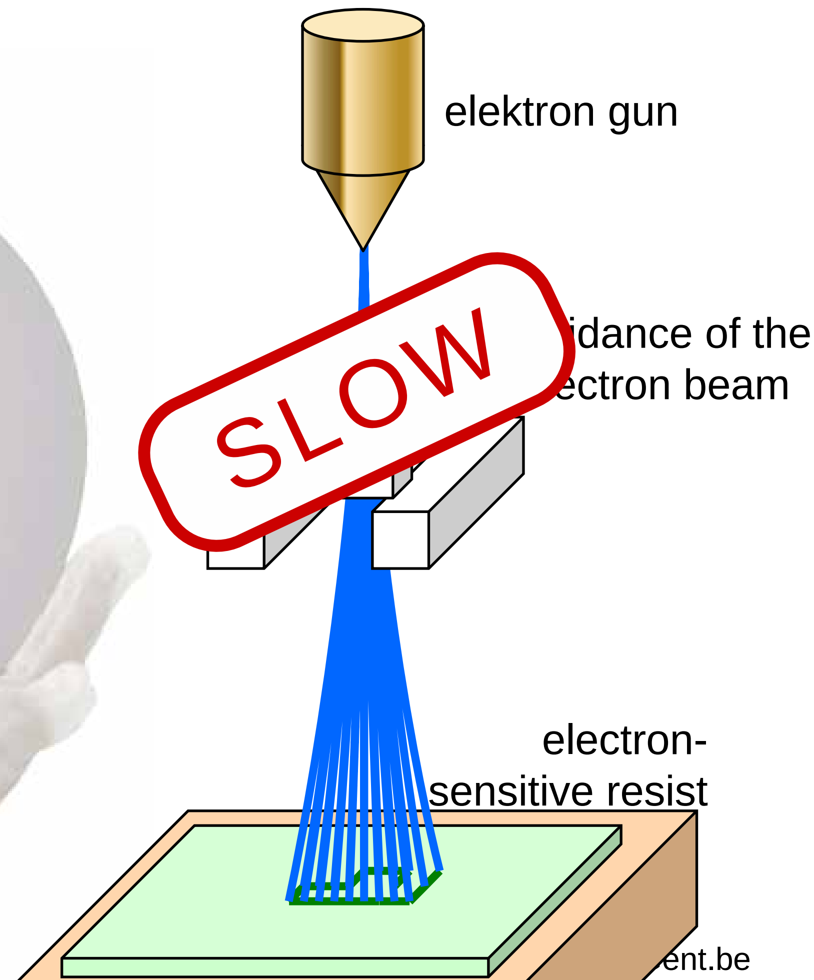
## Optical lithography:

- **Pattern of a mask is projected into the resist**



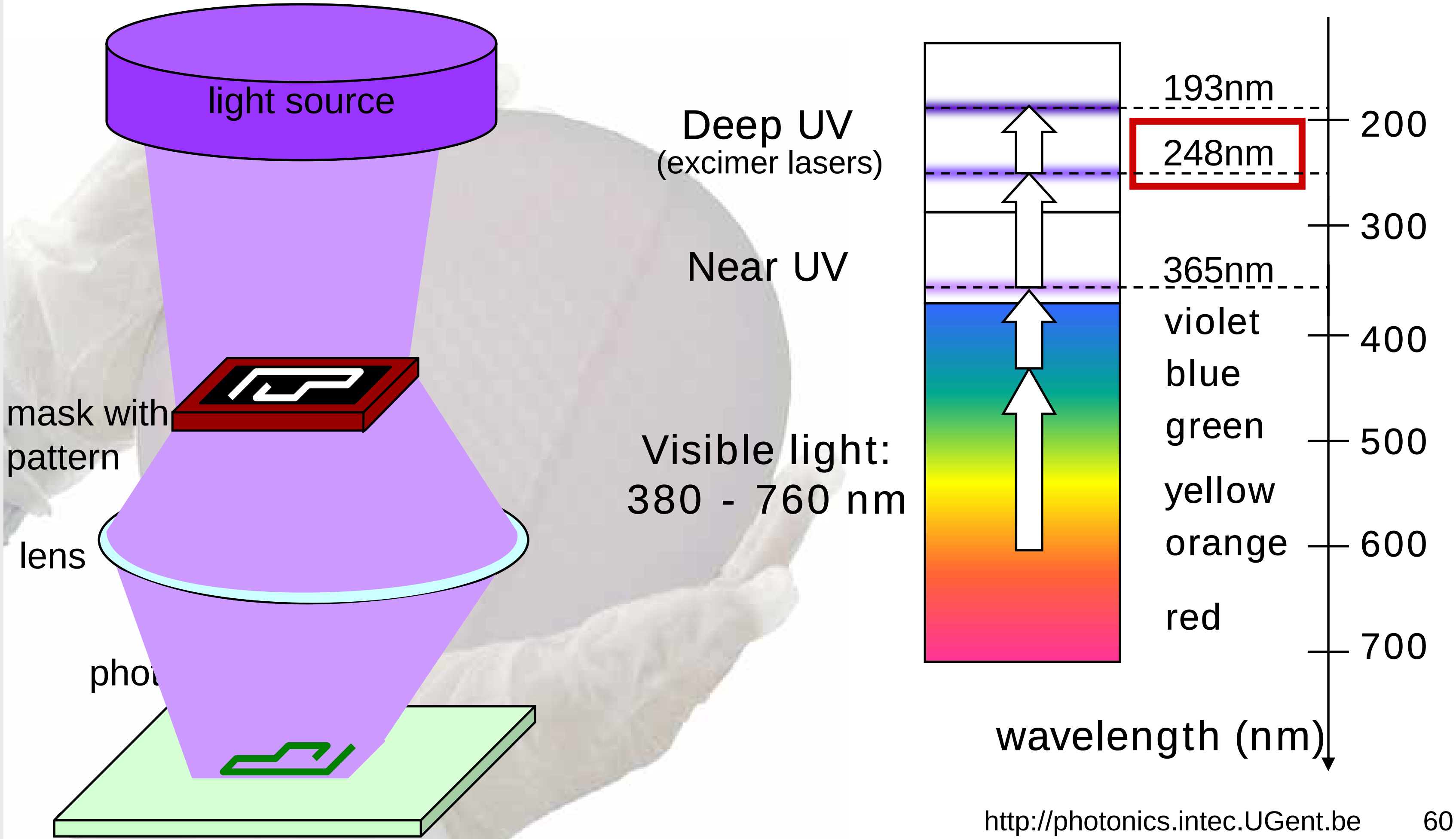

## Electron beam

- **Pattern is written directly into the resist**



# Optical Lithography

- **Size of smallest patternis determined by the wavelength of the projection light source**
- **Shorter wavelength → narrower lines, smaller holes**



# Fabrication in Silicon-on-Insulator

## Facilities of IMEC (Leuven)

- **Research Center for Microelectronics**
- **Use of advanced technologies for the fabrication of CMOS chips :<br>Deep-UV lithography at 248nm and 193nm.**
- **Electronic Chips = Based on Silicon**

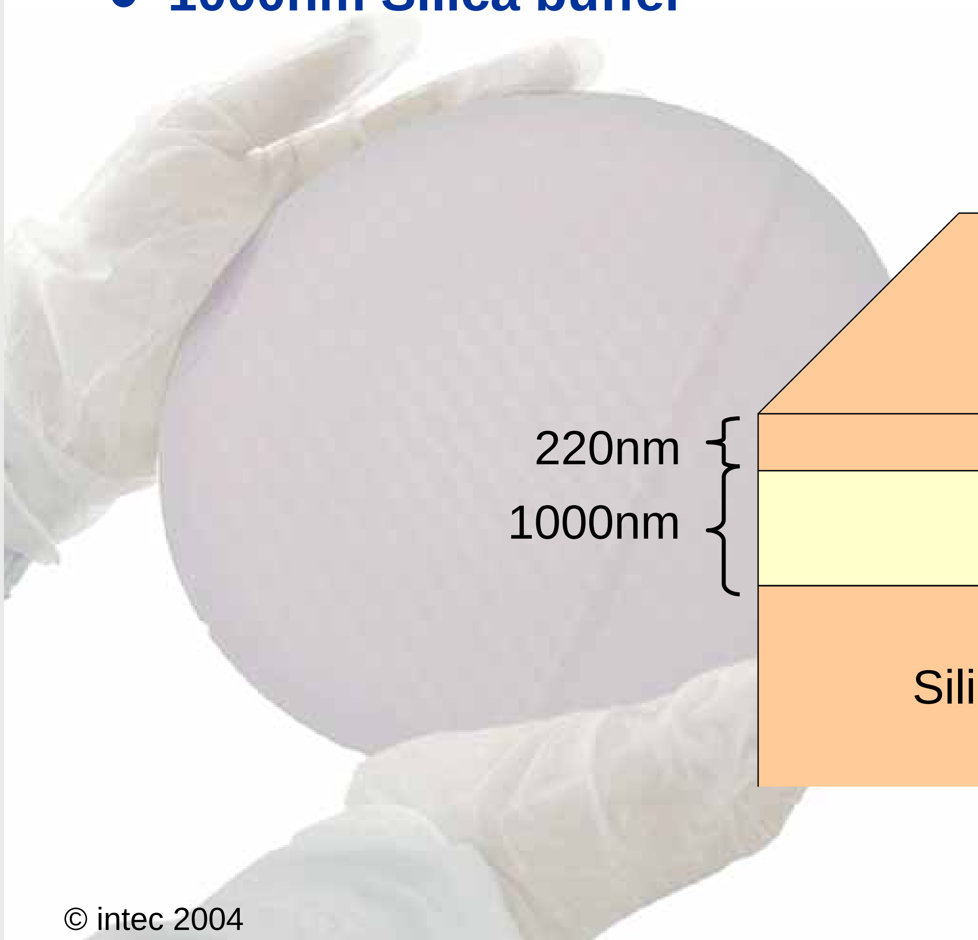
COMPATIBLE
PROCESSES

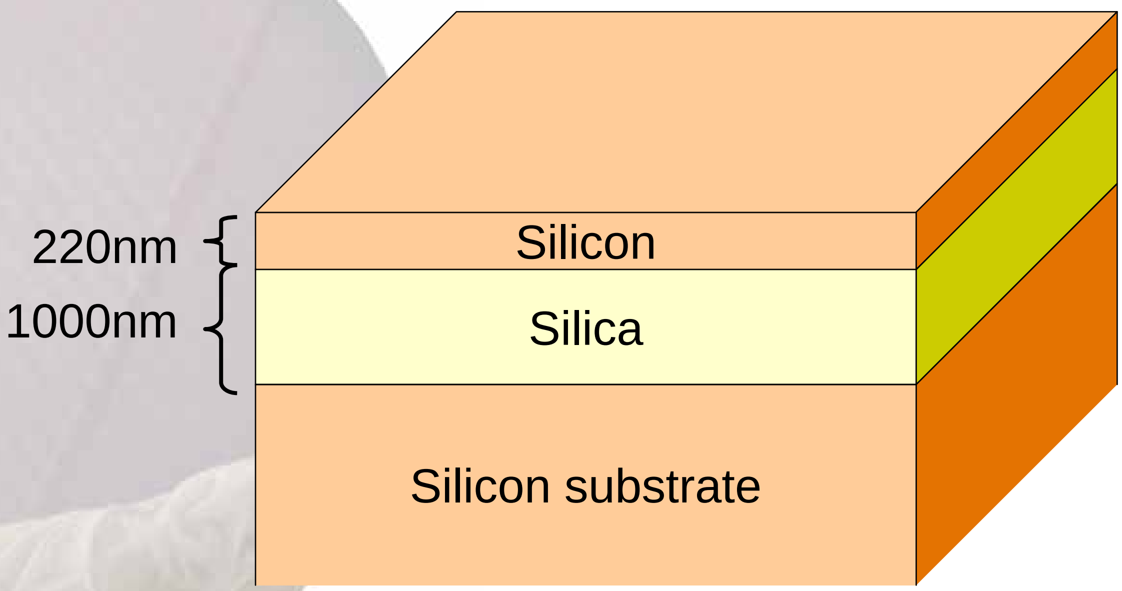
**We use: Silicon-on-Insulator**

# Step 1: A bare SOI wafer

## Layer Structure

- **220nm Silicon**
- **1000nm Silica buffer**

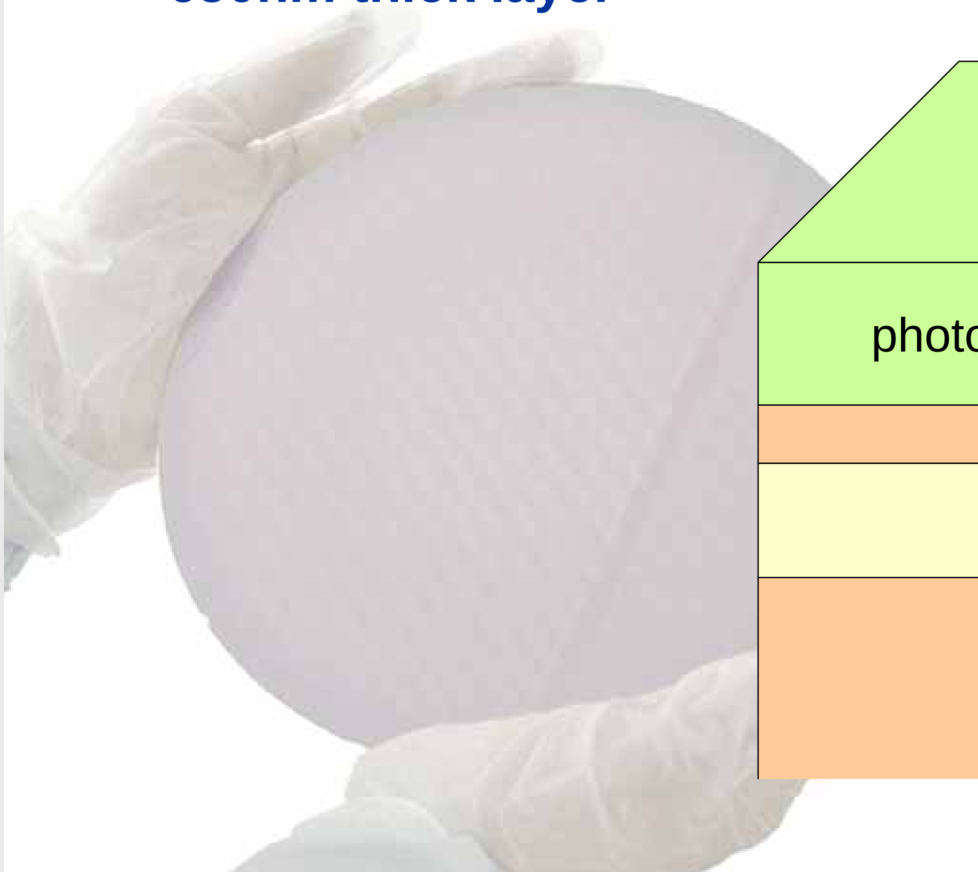


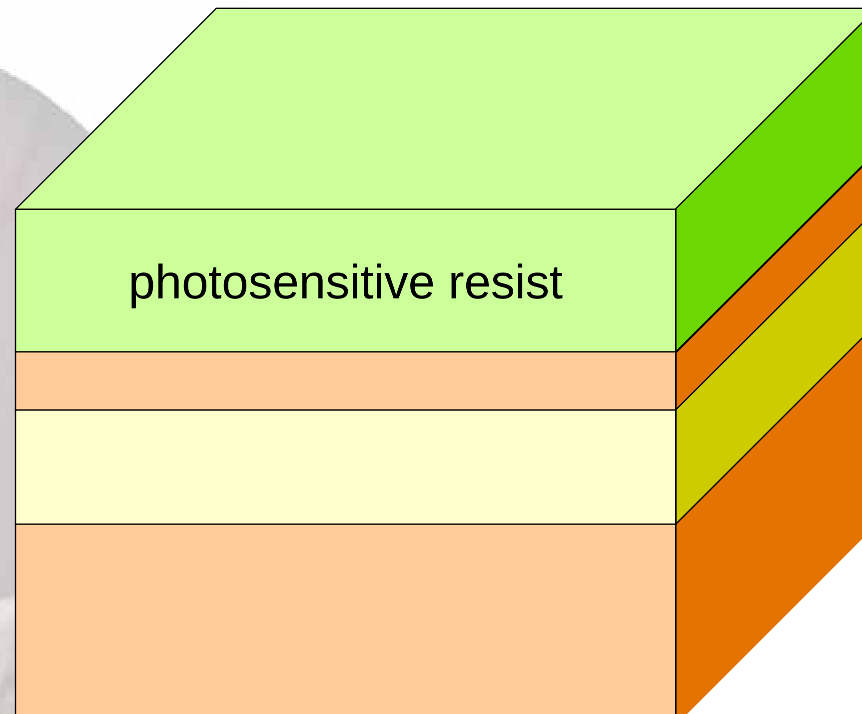


# Step 2: Apply Photoresist

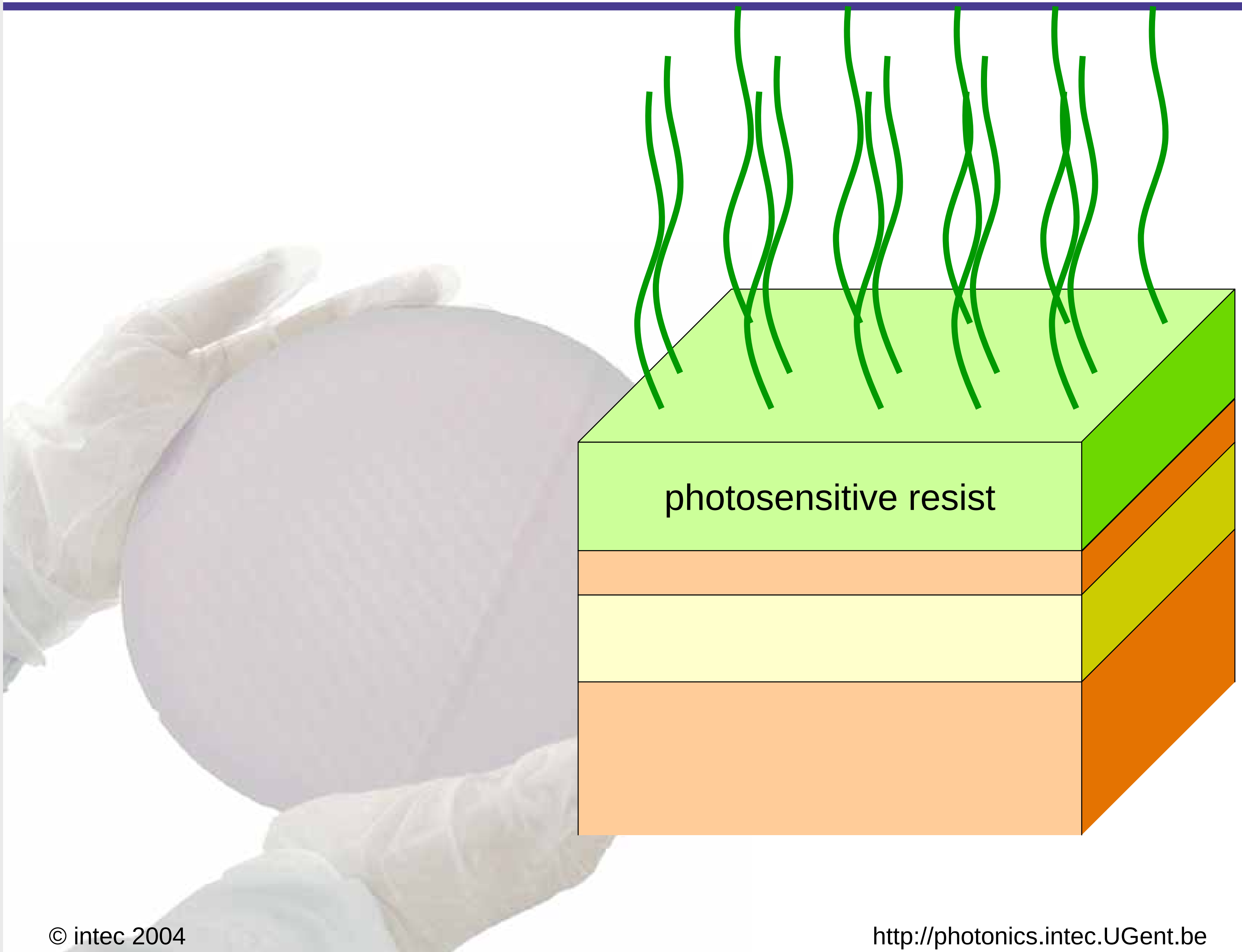
## Photoresist: applied by spinning

- **Shipley UV3**
- **650nm thick layer**





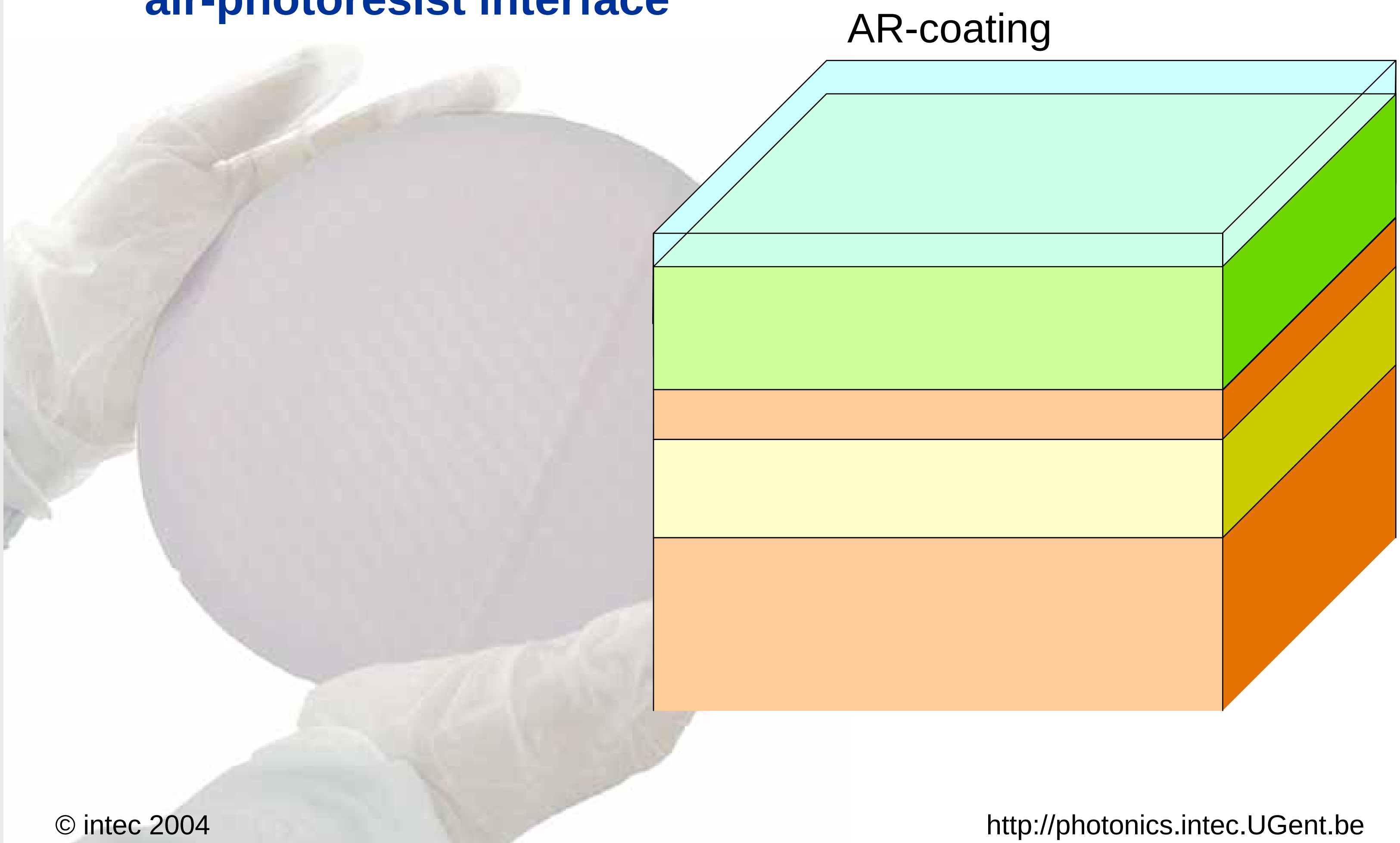
# Step 3: Baking of the photoresist



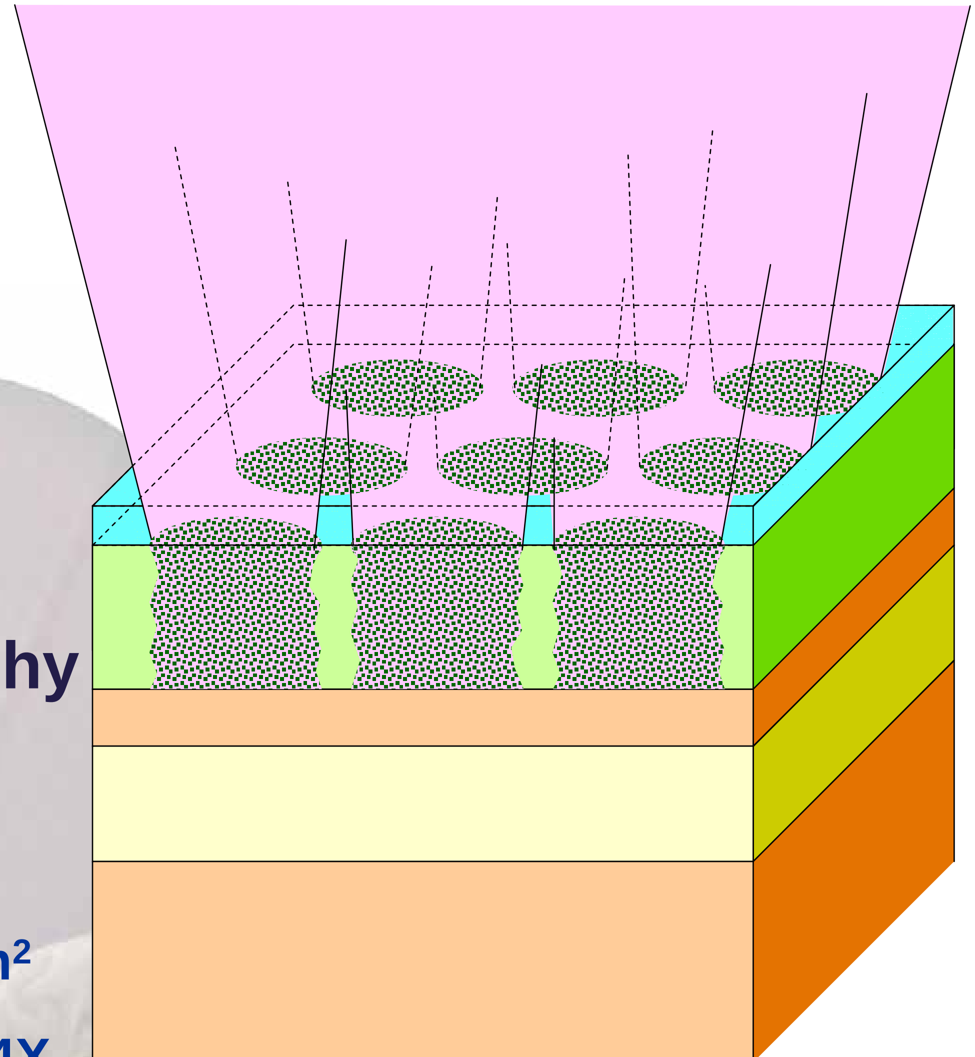
# Step 4: Antireflective coating

## AR coating

- to avoid reflections at the air-photoresist interface



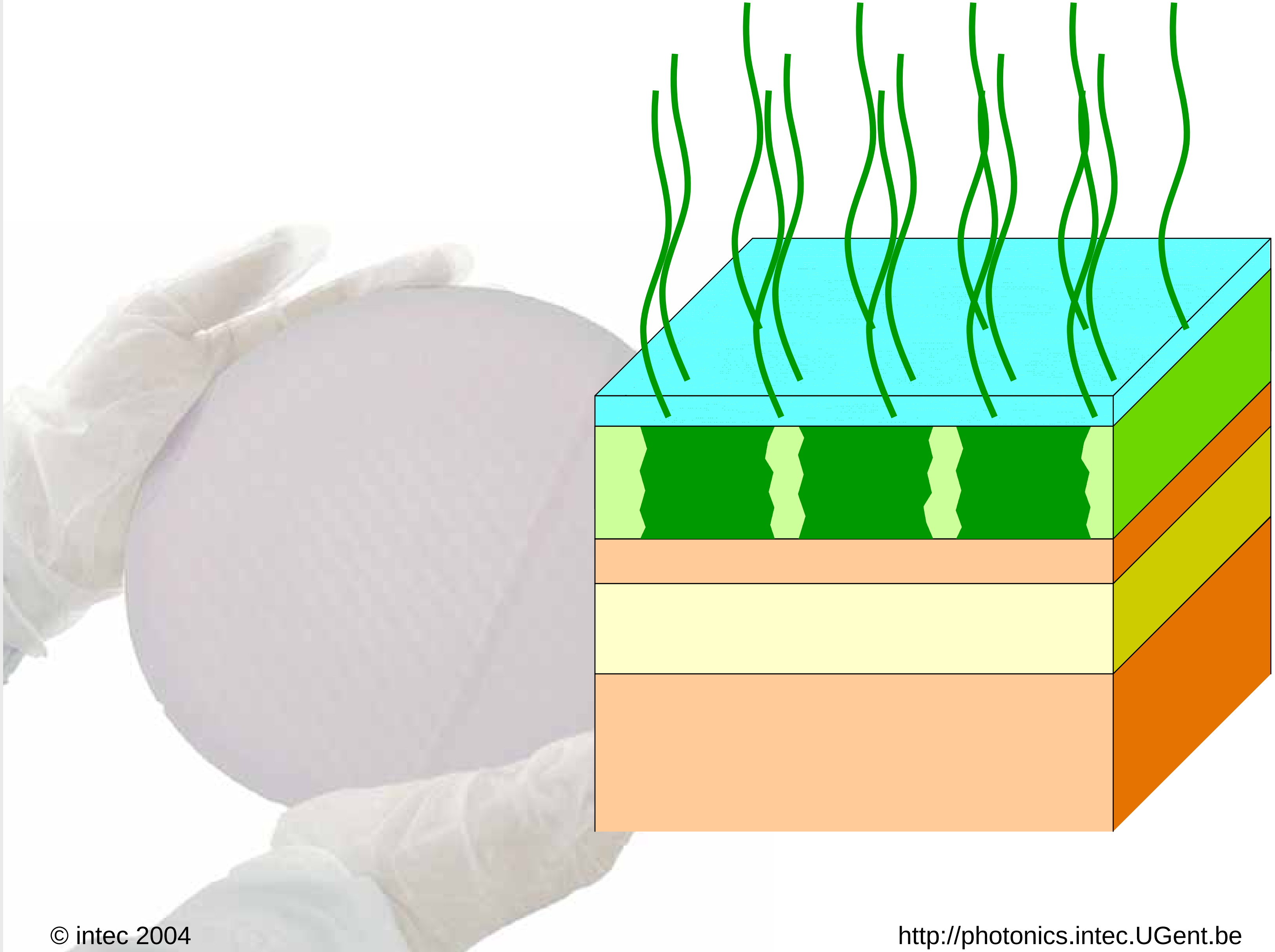
# Step 5: Illumation



## Deep UV Lithography

- Wavelegth = 248nm
- NA = 0.63
- Dose = 10-40 mJ/cm$^2$
- Reduction factor = 4X

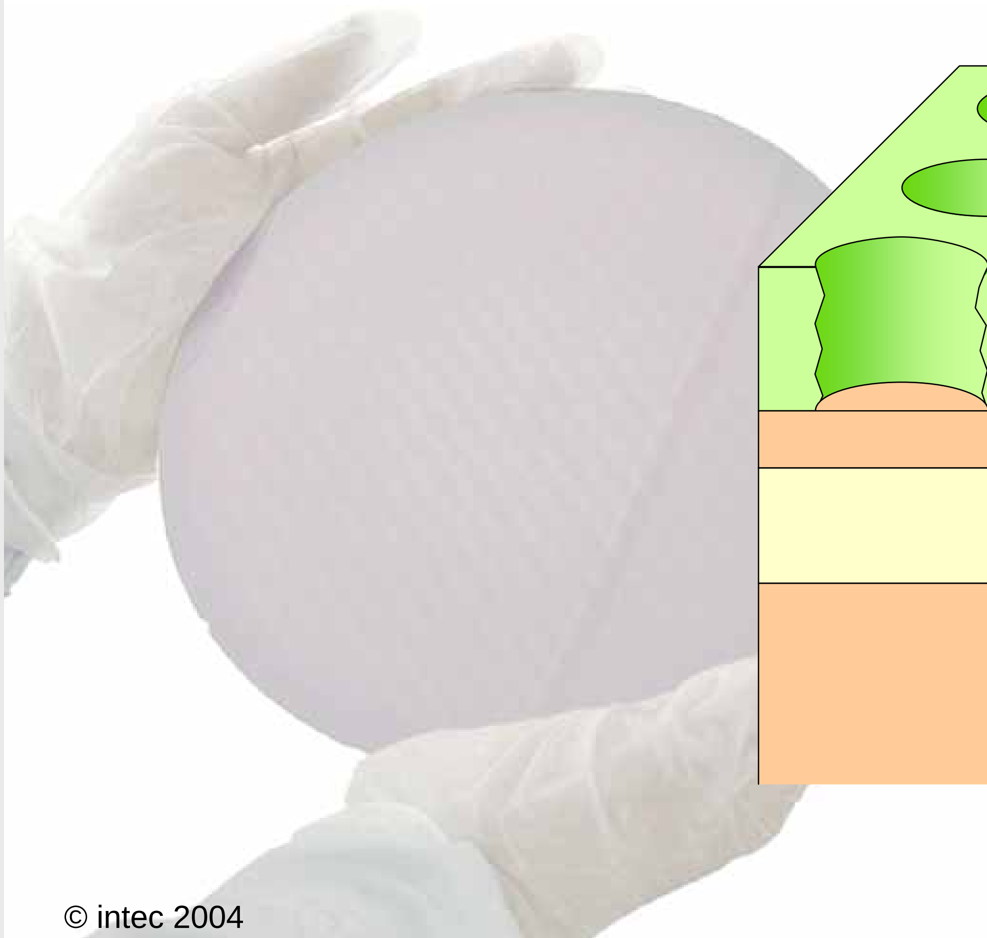
# Step 6: Post-exposure bake

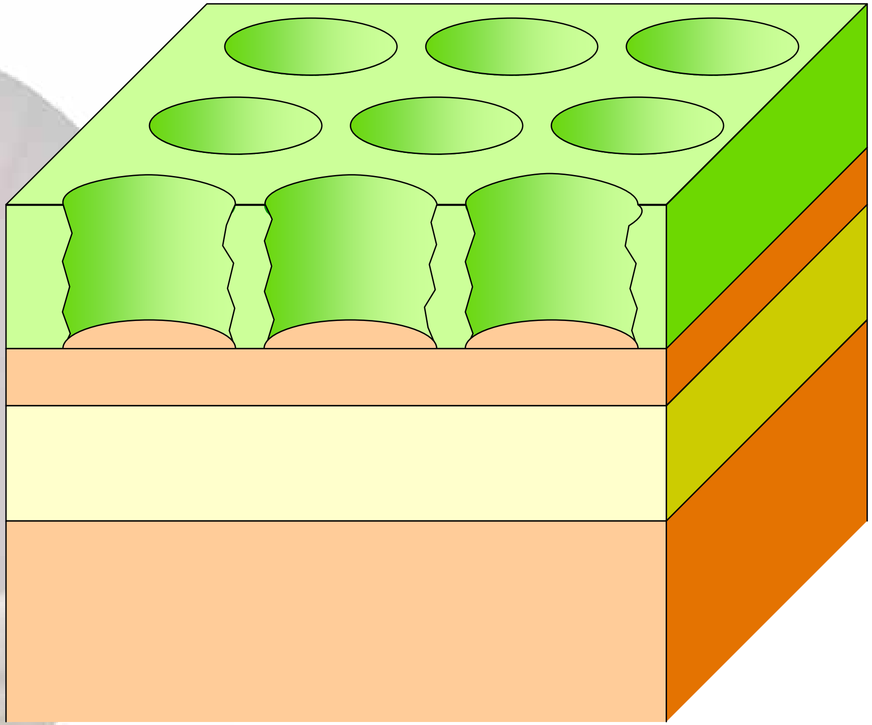


# Step 7: Development of the resist

**Unexposed areas become solid**

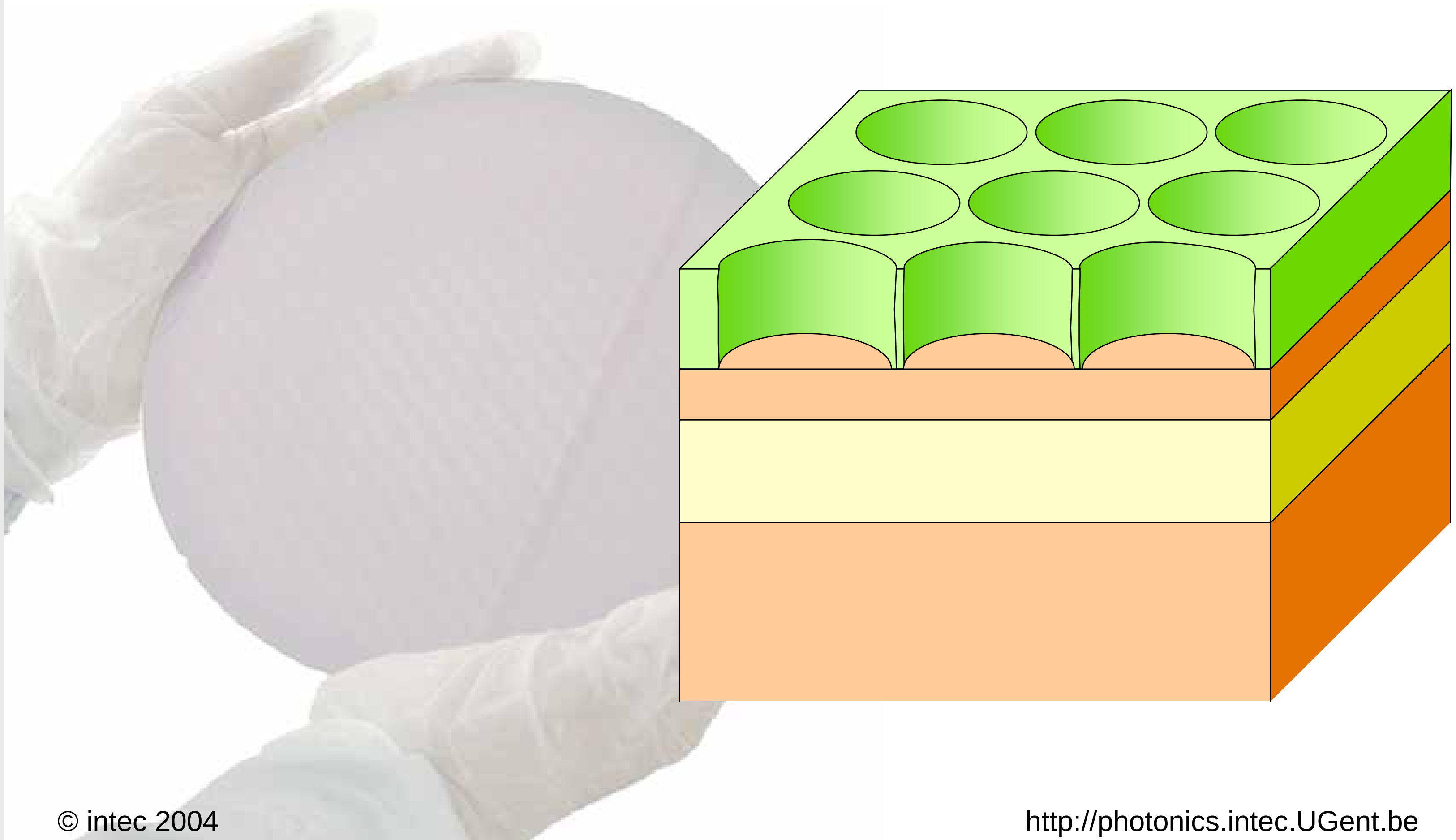
**Exposed areas are dissolved**





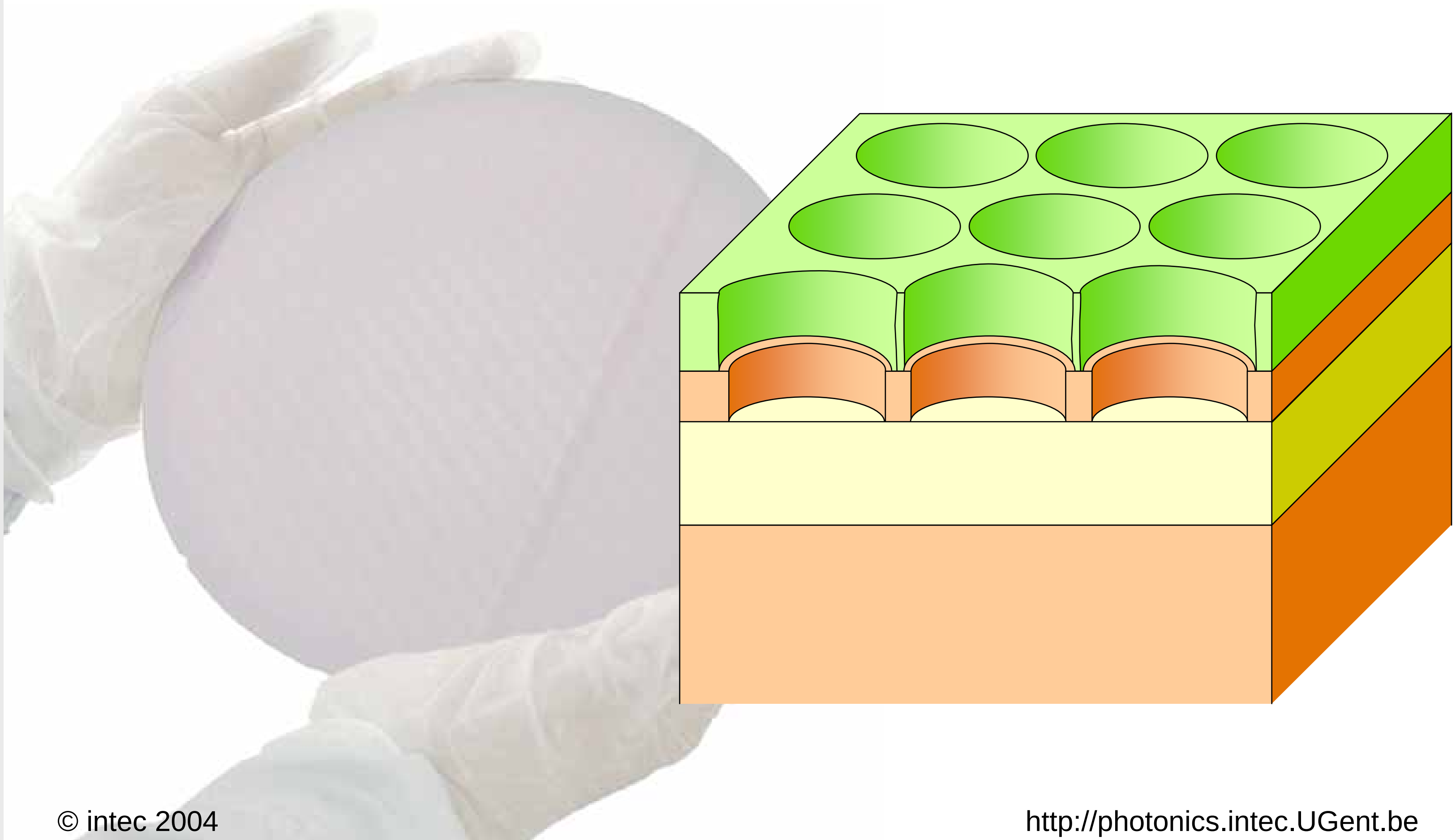
# Step 8: Resist hardening

The photoresist is exposed to a plasma which partially etched the photoresist



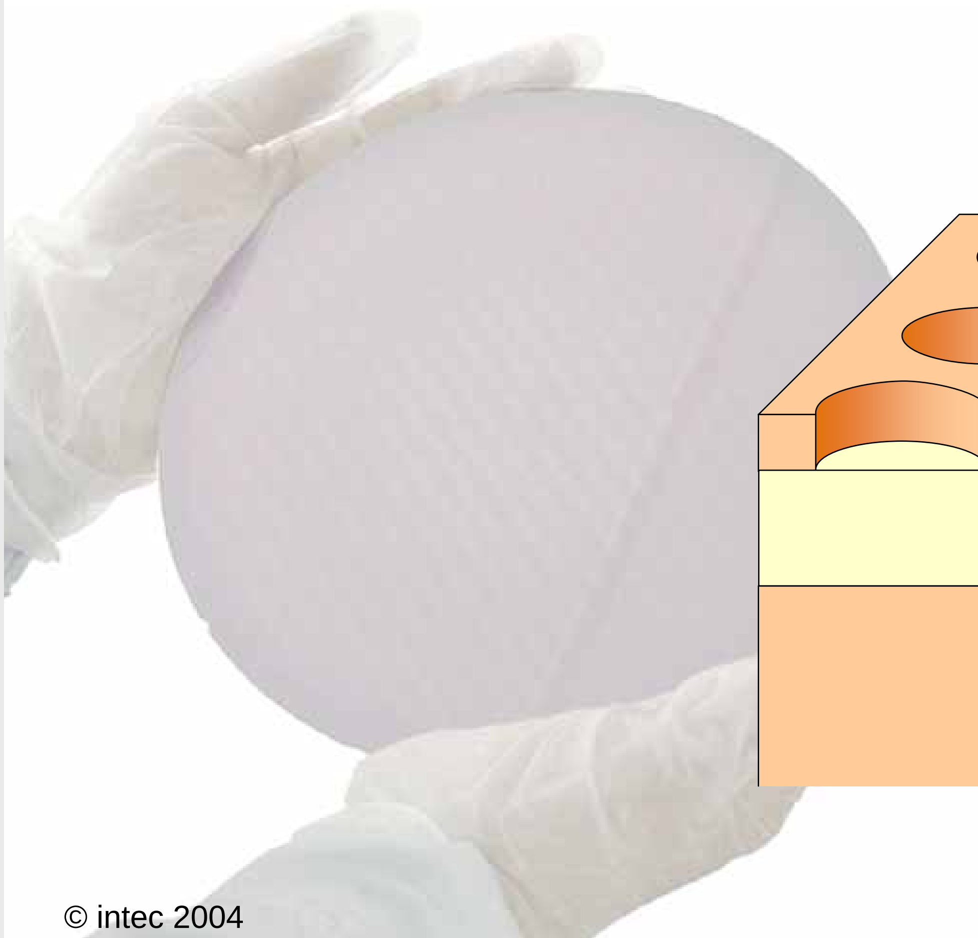
# Step 9: Silicon etch

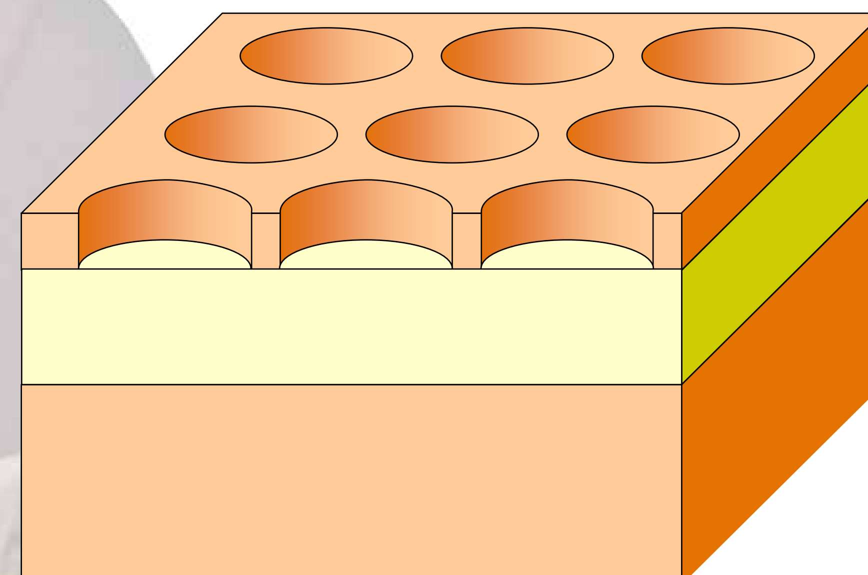
## A plasma etched the Silicon where it is not protected by the layer of photoresist



# Step 10: Strip the resist

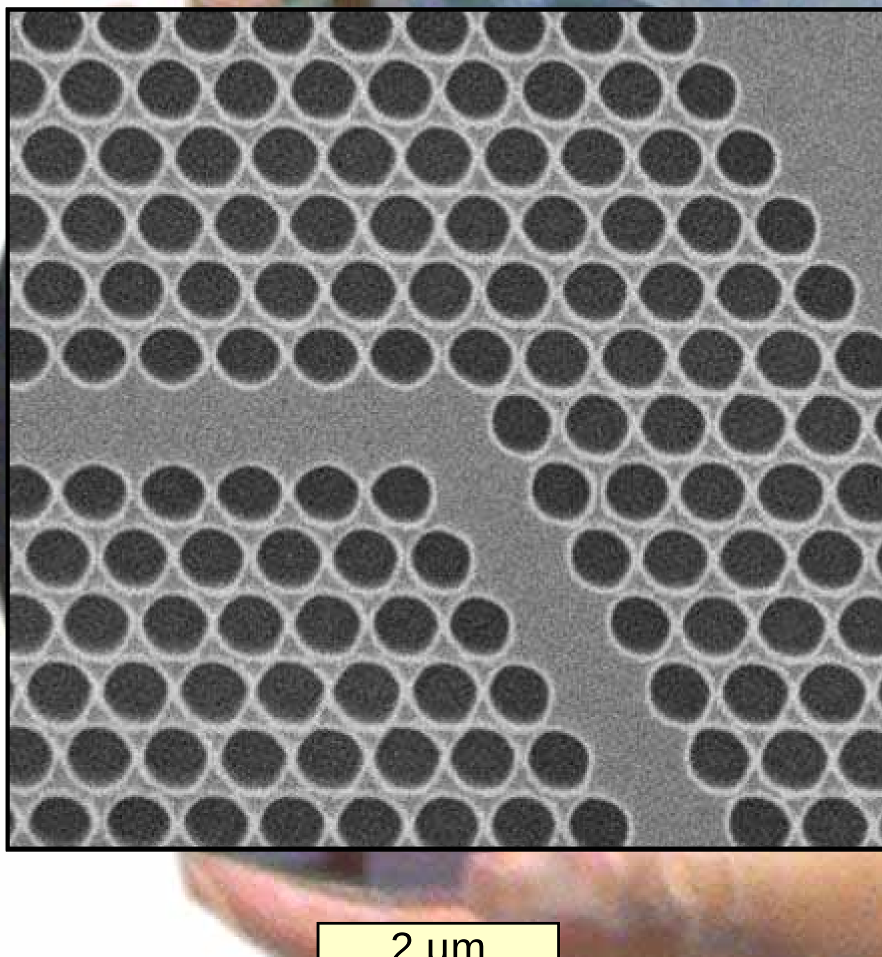
## The residue of the photoresist is removed





# A fistful of photonic crystals

**8” SOI wafer:**
**Structures are repeated many times**

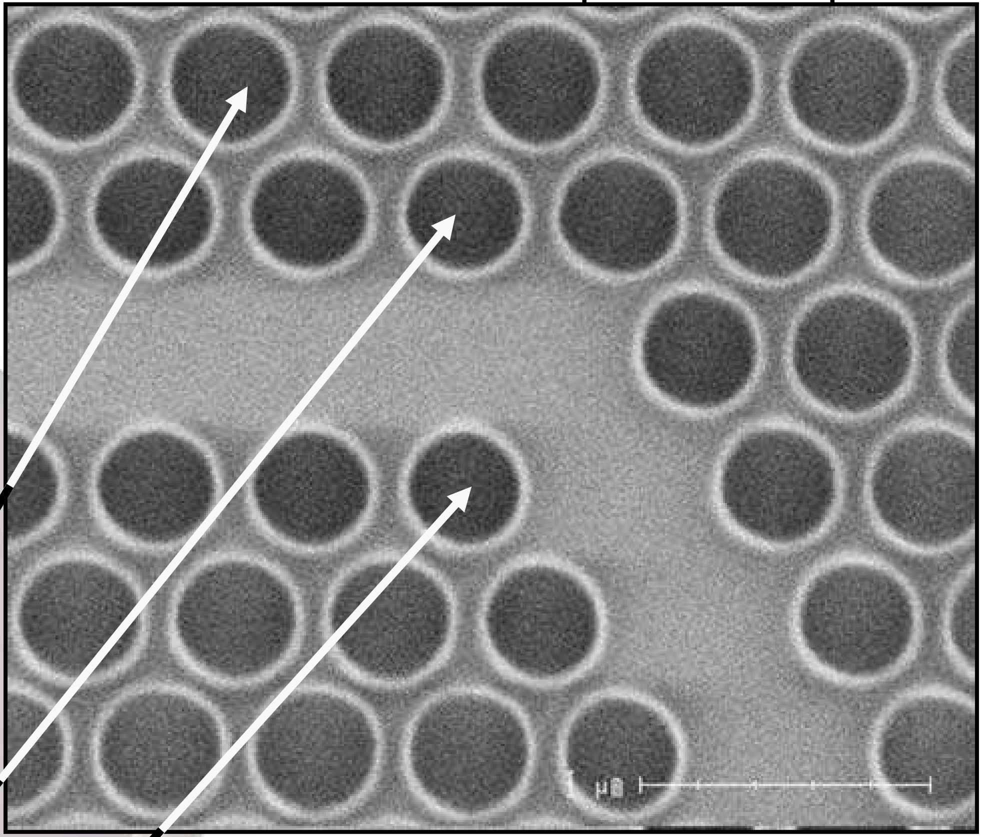


# Problem: Proximity effects

**Problem:**

**Holes near edges differ from holes in the bulk (while they should be identical!)**

photoresist pattern



1um

**hole in the bulk = 420nm**

**Hole on the edge = 380nm**

**Hole on the corner = 350nm**

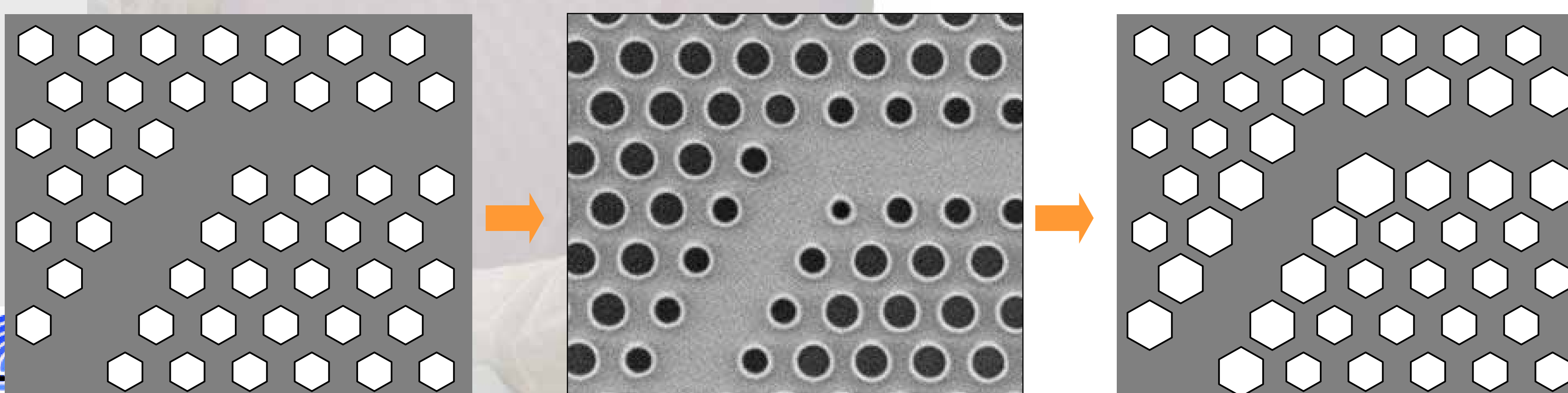
# Solution: Proximity corrections

**The patterns on the mask are altered in such a way that they are imaged correctly in the photoresist.**

**Corrections should be known in advance**

- **Calculate (difficult)**
- **Measure empirically**

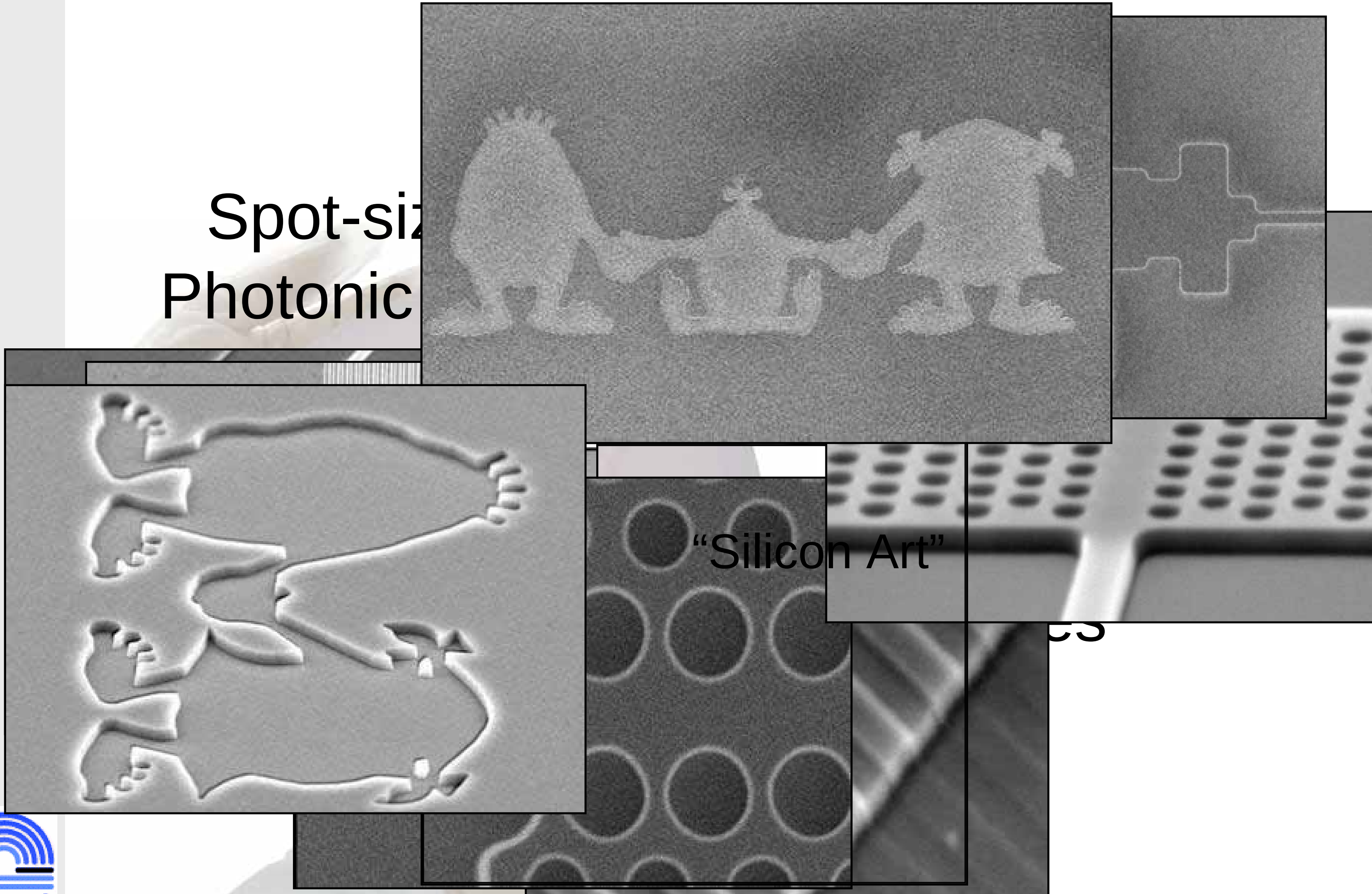
**Desired patroon** **Resulting Photoresist** **Corrected pattern**



# What can we make?

Spot-siz

Photonic



"Silicon Art"

# Overview of this presentation

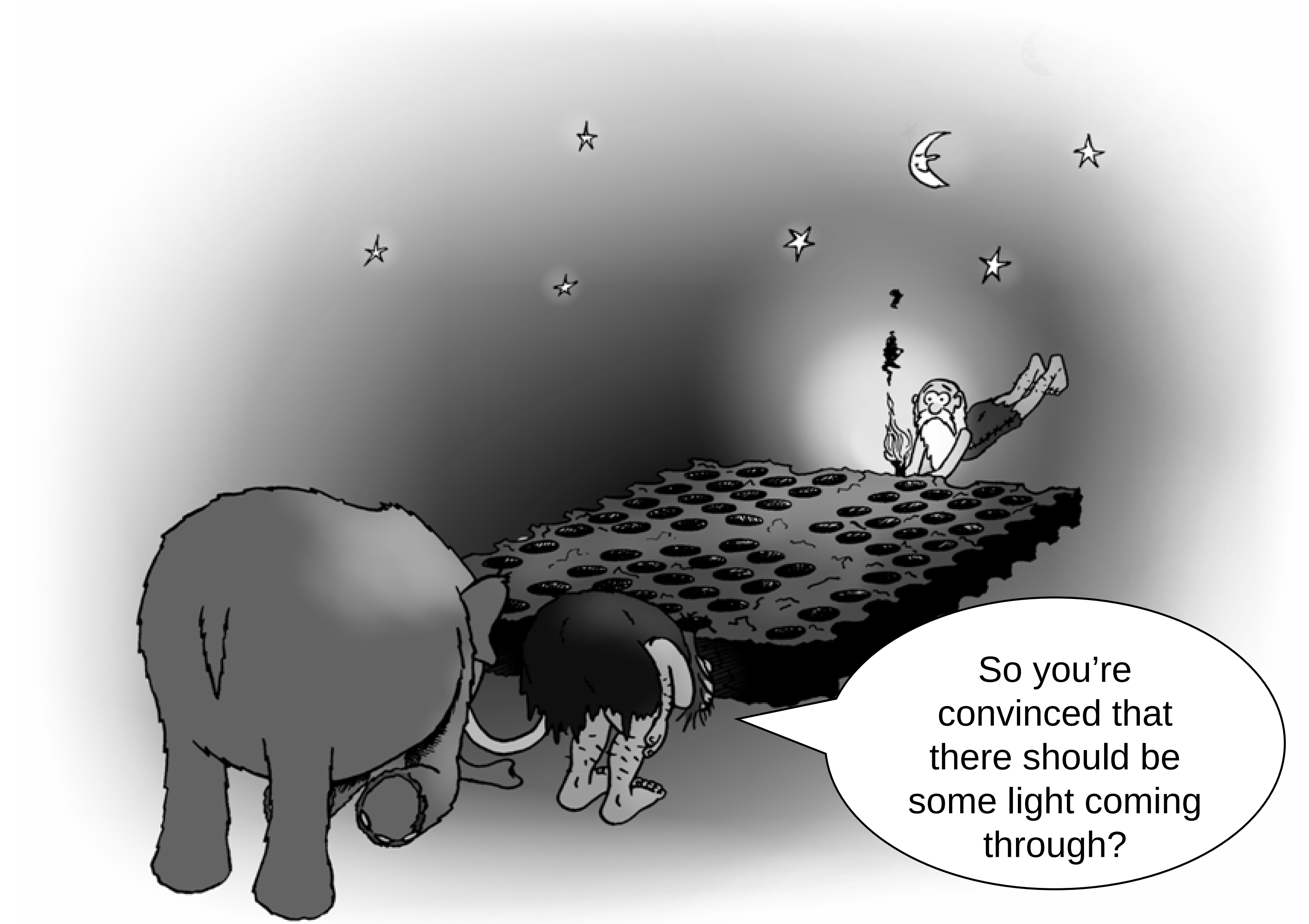
## Background

- What's the use?
- How does a waveguide work?

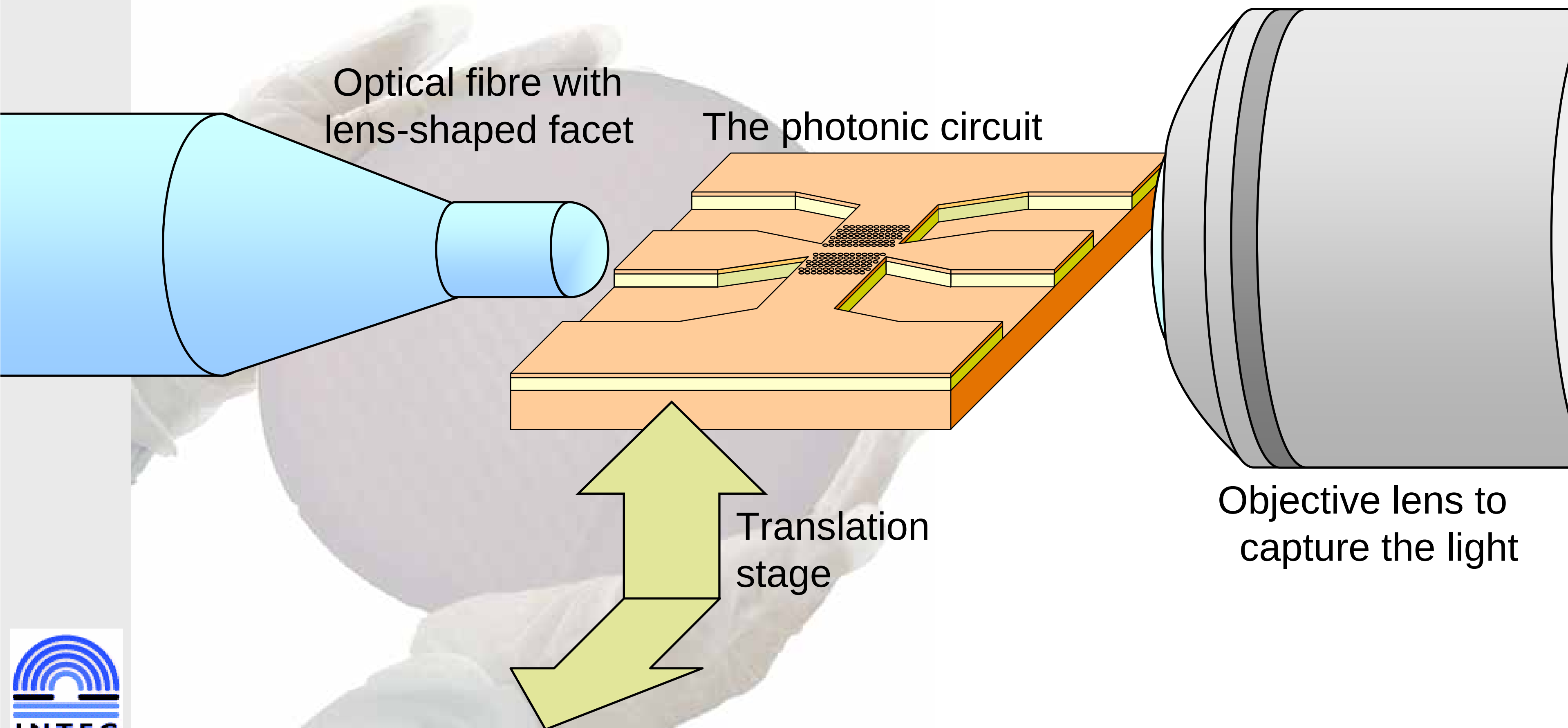
**How do we measure?**
**How good are our waveguides?**

- Nanophotonic waveguides
- What are the difficulties?
- Can we make it?
- **What comes out?**

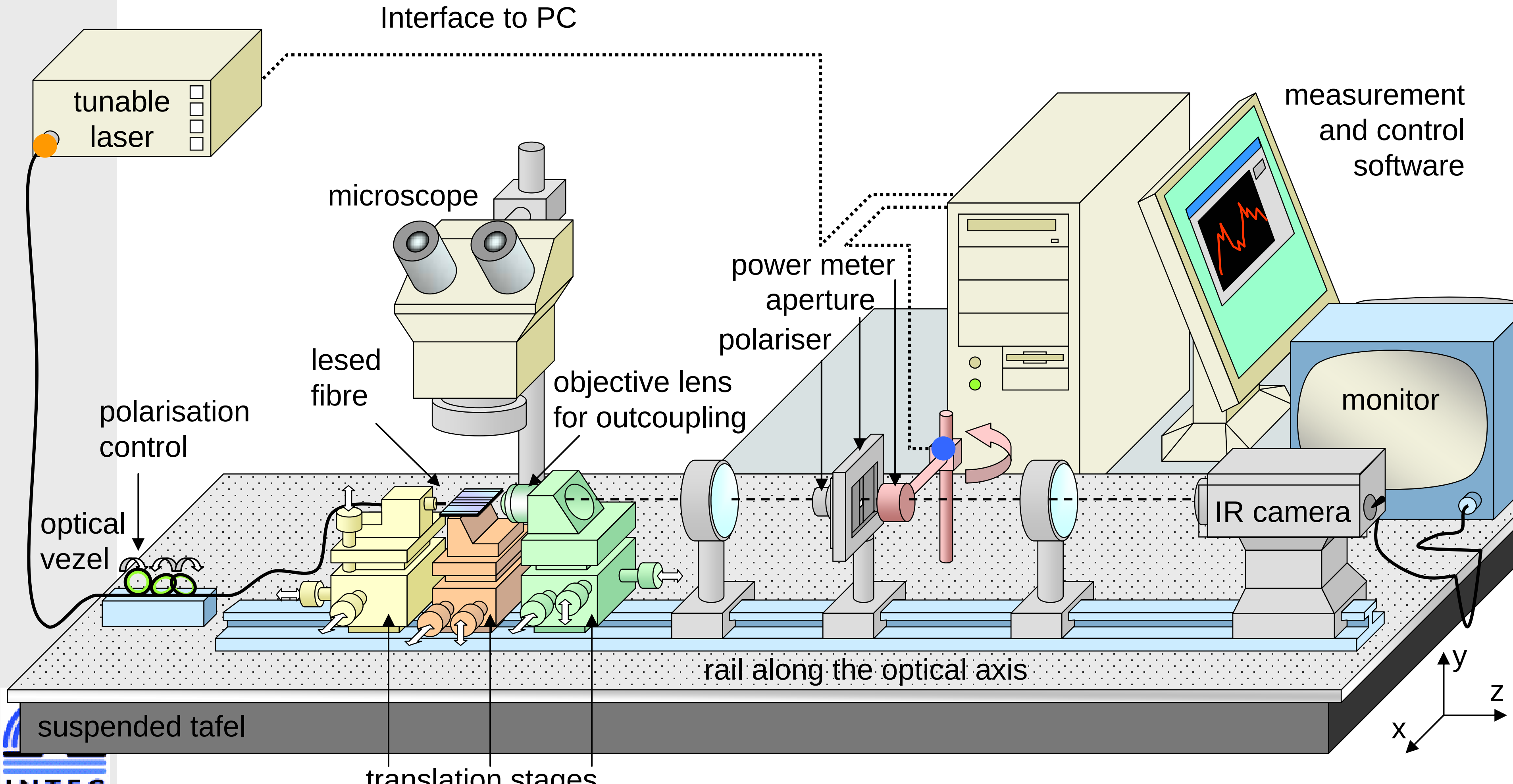
# Measurements



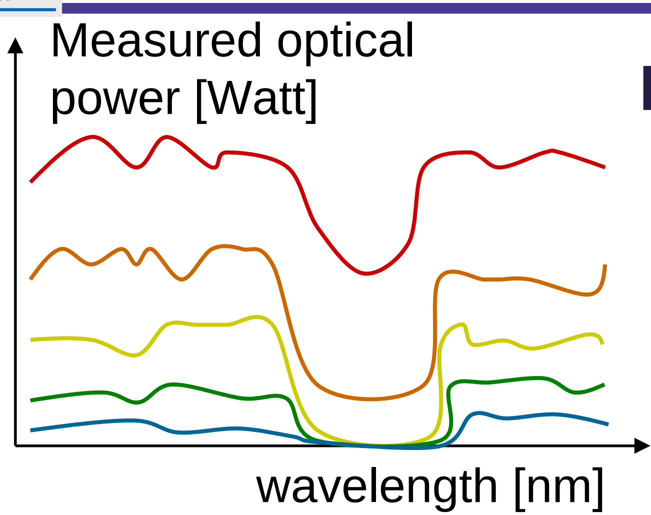
# End-fire measurements



# Measurement Setup

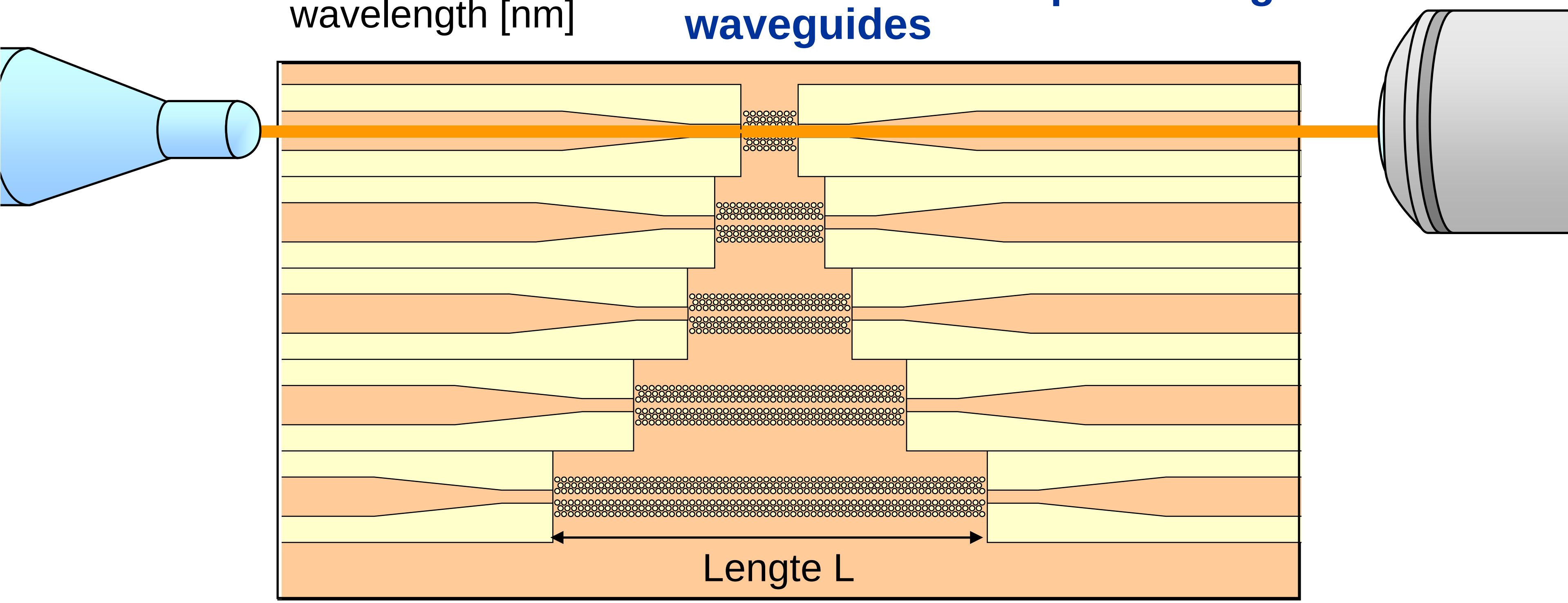


# Measuring waveguide losses

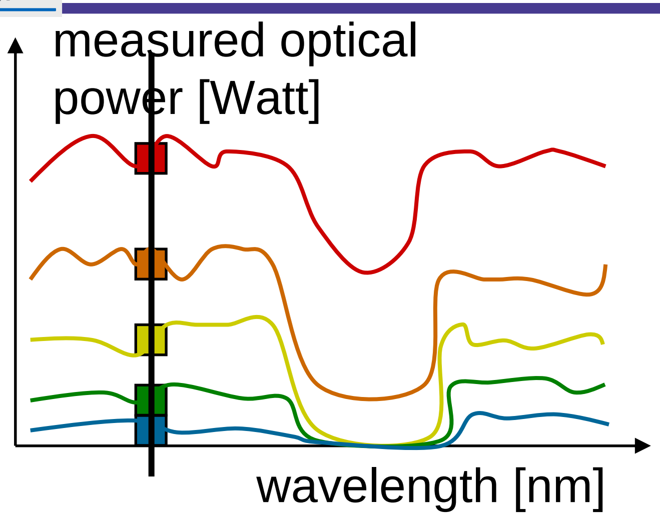


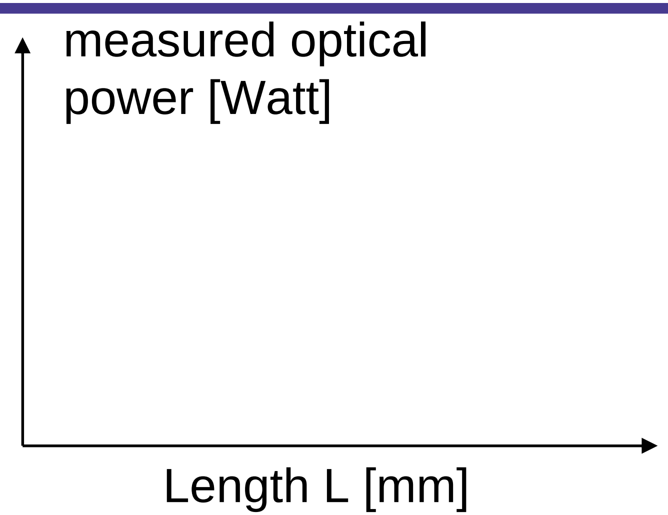

## Measure the transmission

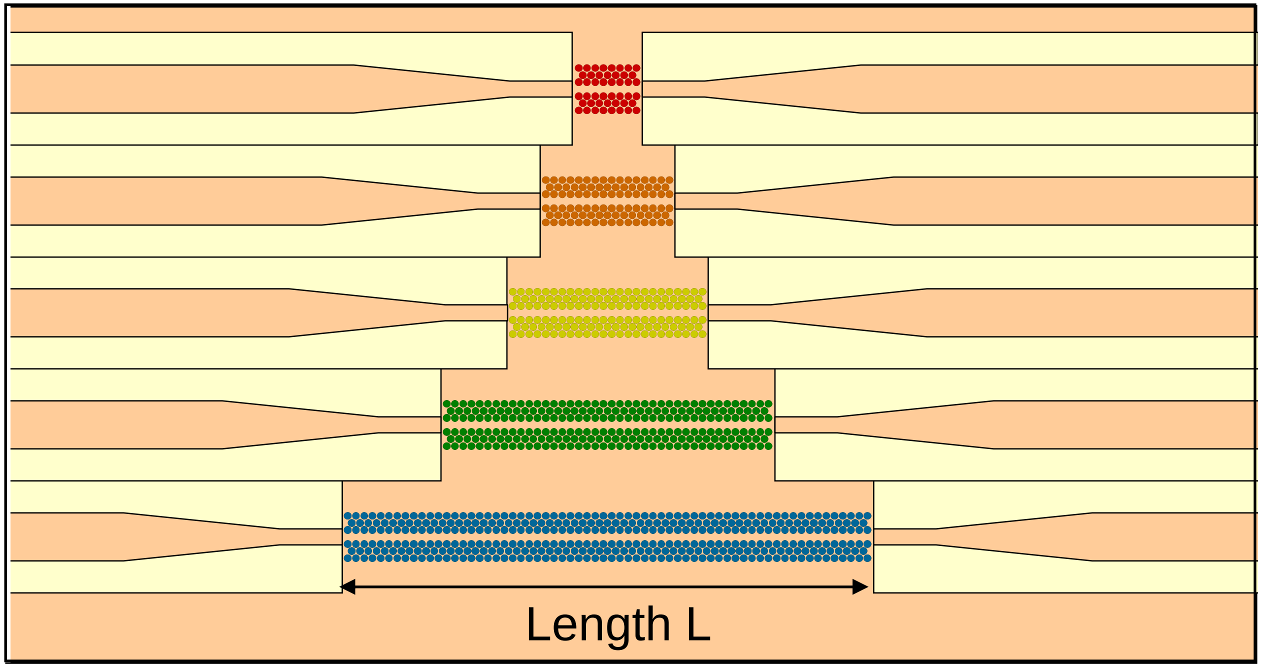
- Measure transmission as a function of wavelength
- Measure transmission for various waveguide lengths
- Transmission drops for longer waveguides



# Measuring waveguide losses



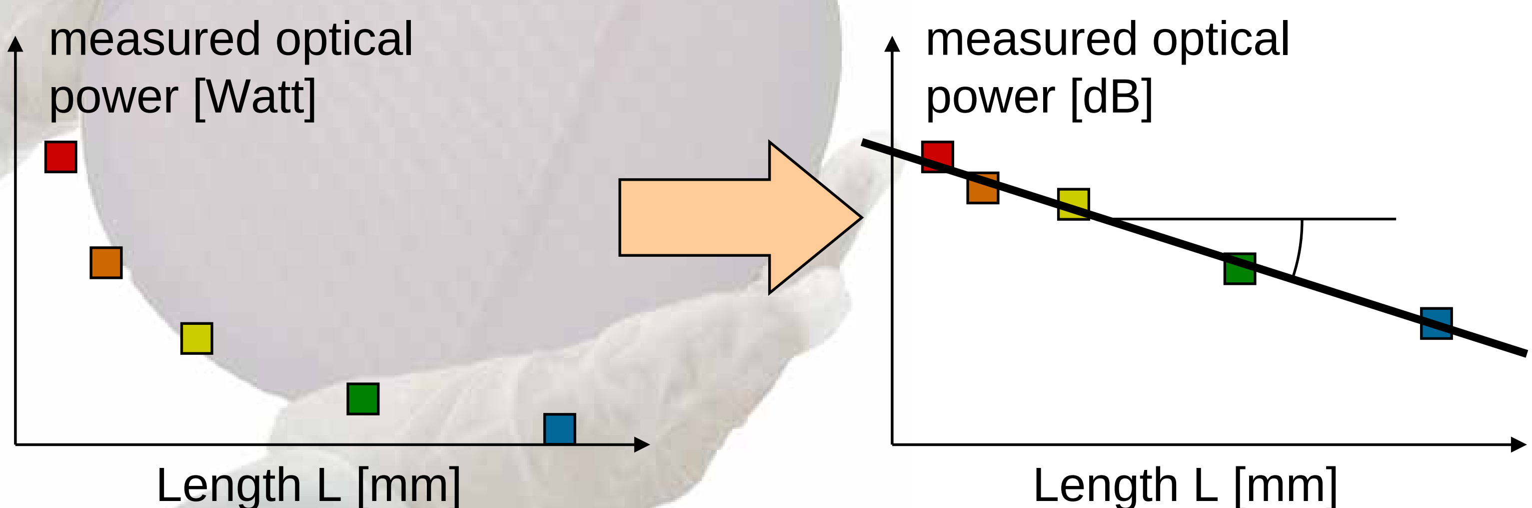
# Waveguide losses

## Express power in dB with respect to input power

- -10dB = 10x drop in power
- -20dB = 100x drop in power

## Waveguide losses in dB/mm:

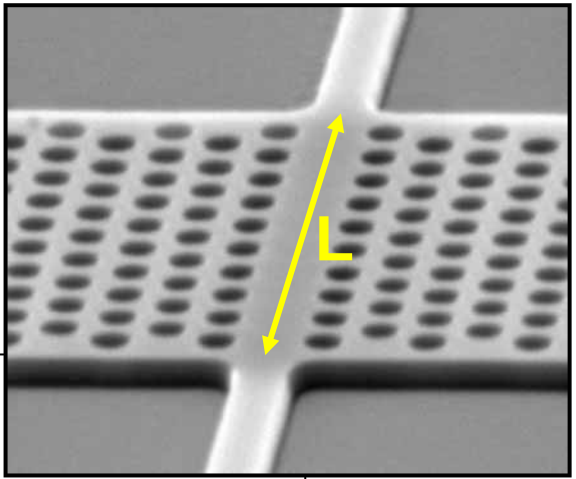
- Measured values are on a straight line
- Slope of the line: waveguide loss in dB/mm

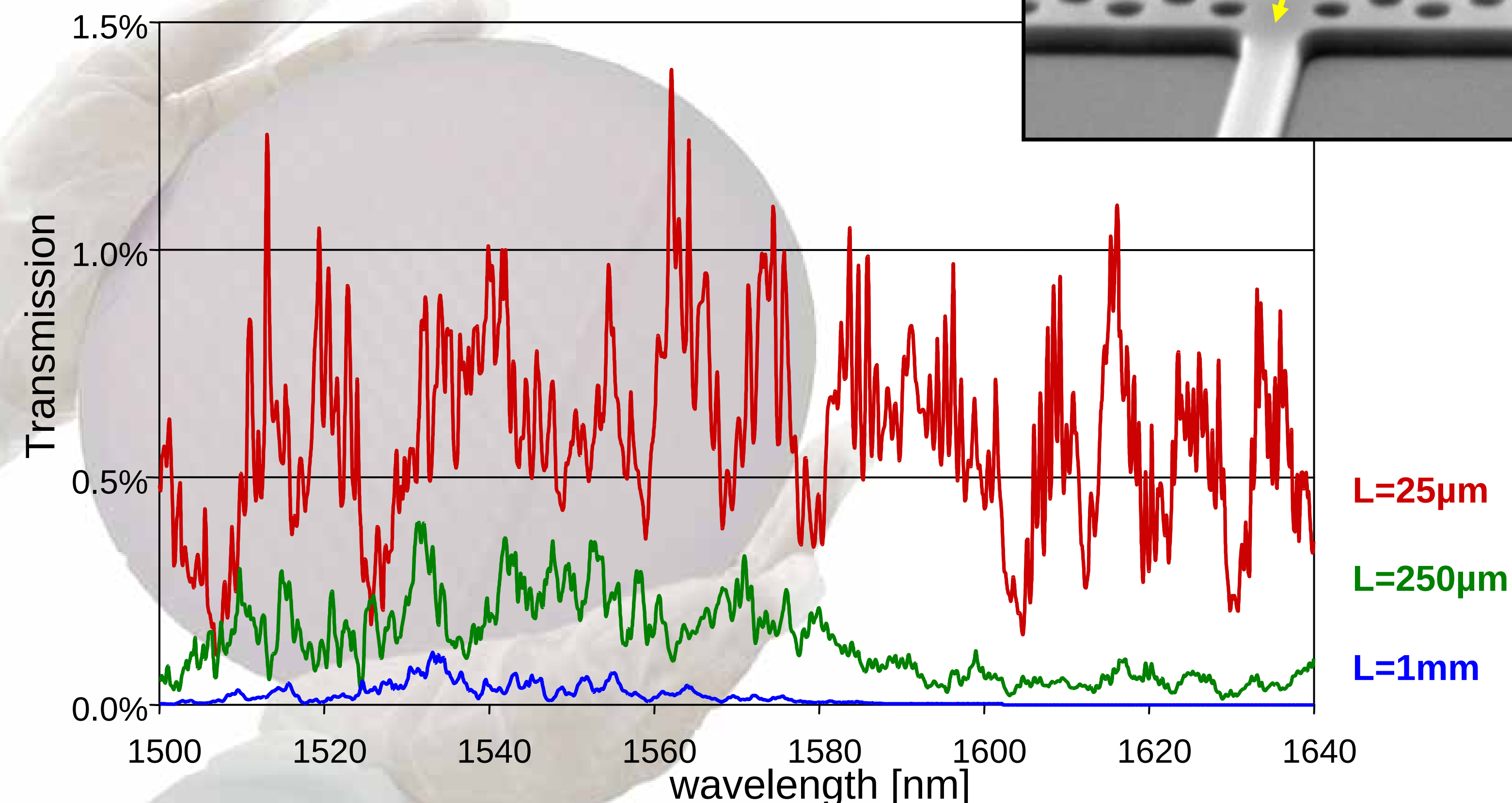


# Photonic Crystal Waveguide

## Measure Transmission

- as a function of wavlength
- for various waveguide length (25, 50, 100, 200, 500, 1000µm)

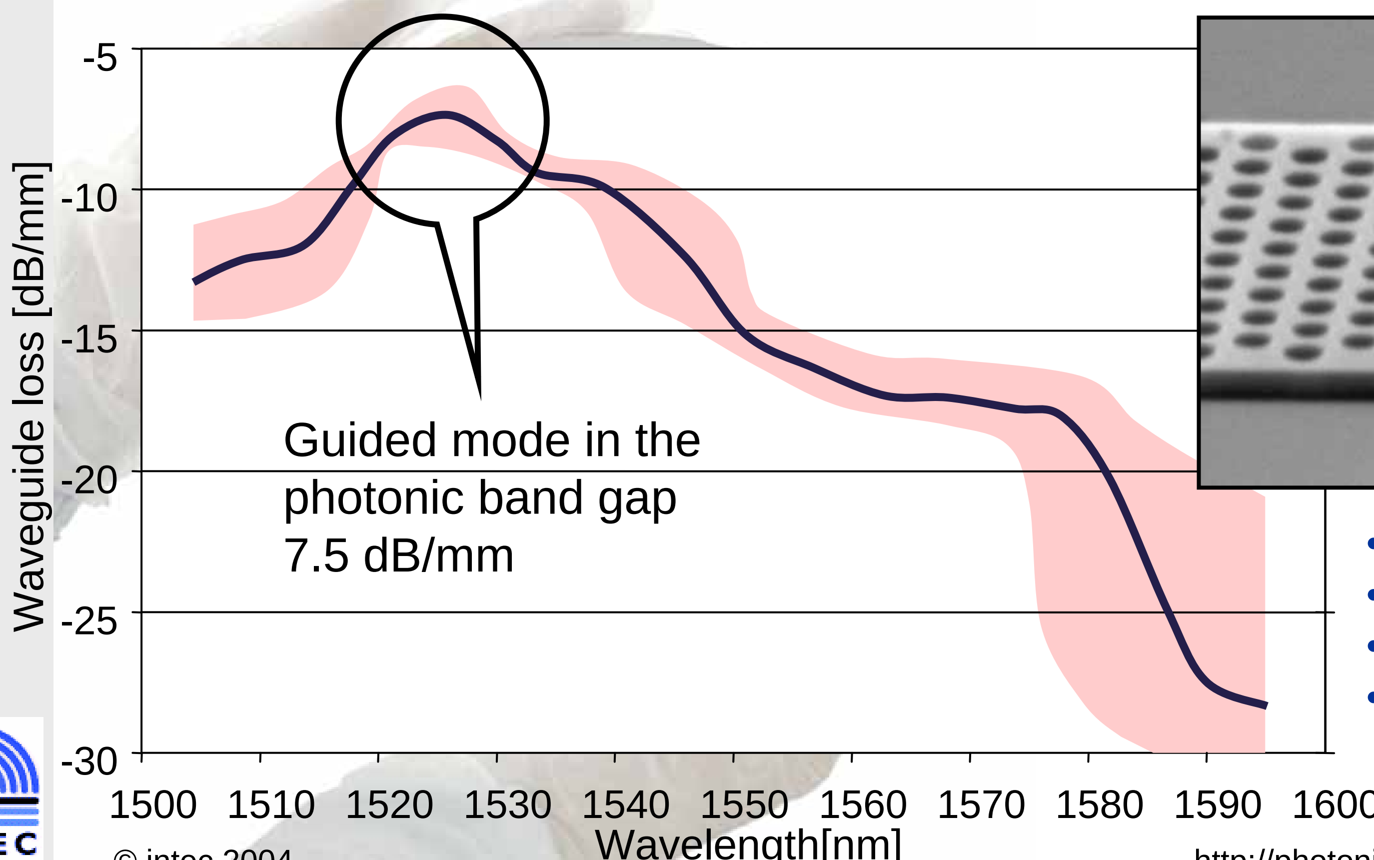


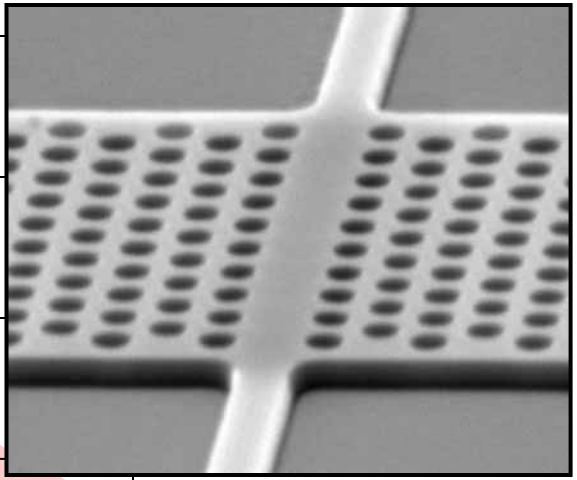



# Photonic Crystal Waveguide

## Behaviour is strongly wavelength dependent

- For some wavelength ranges there is a fully guided mode
- For some wavelength ranges the mode is not fully guided
- For some wavelength ranges there no guided mode at all



- Period: 500nm
- Holes: 320nm
- Silicon-etch
- measurement for TE-polarisation

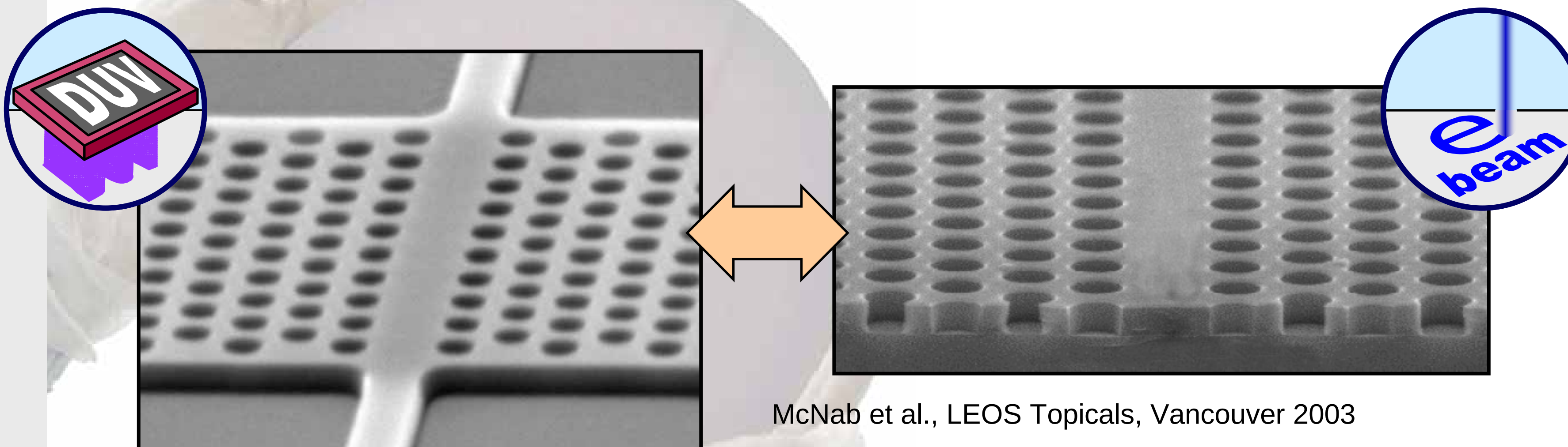
# Photonic Crystal Waveguides

**Our best result:**

**7.5 dB/mm**

**Competition:**

**2.4 dB/mm**

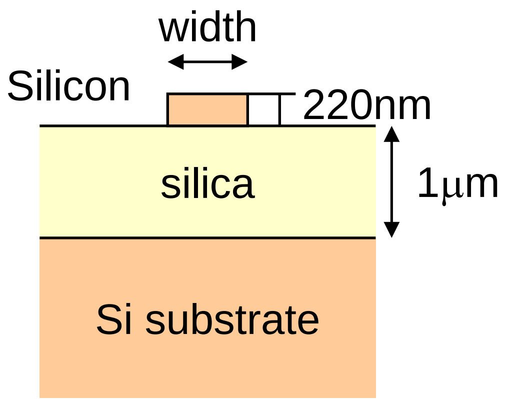


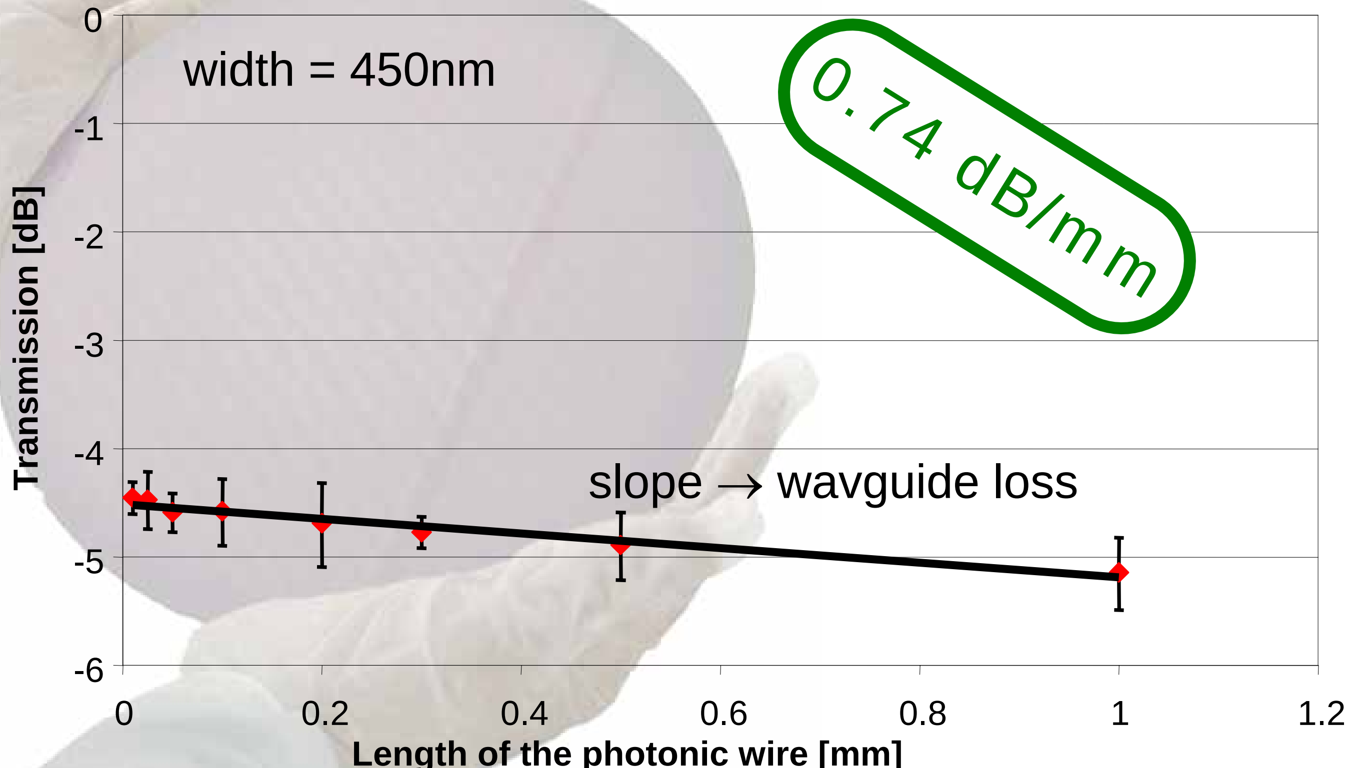

McNab et al., LEOS Topicals, Vancouver 2003

# Losses in photonic wires

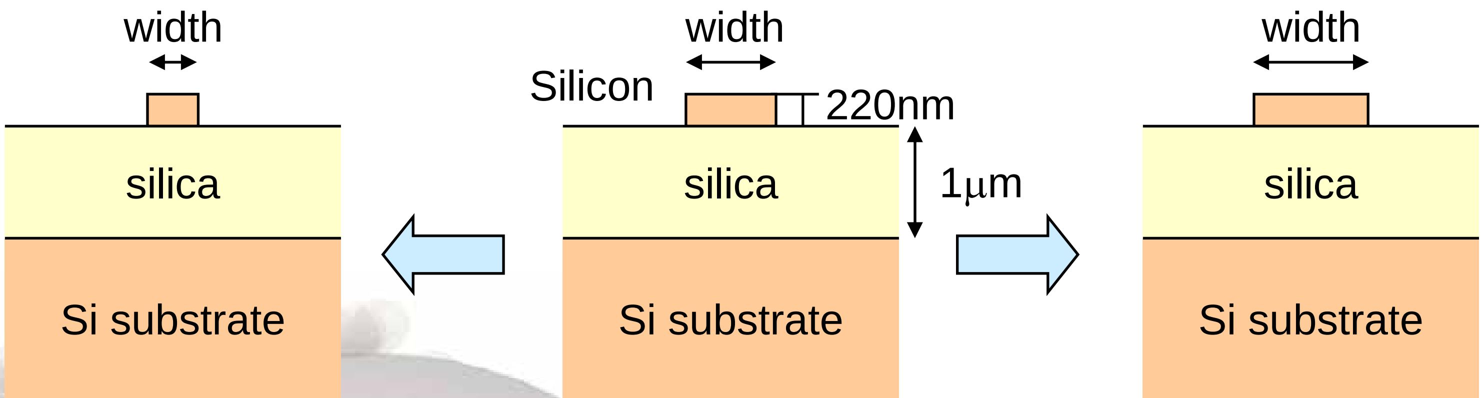
## Photonic wires:

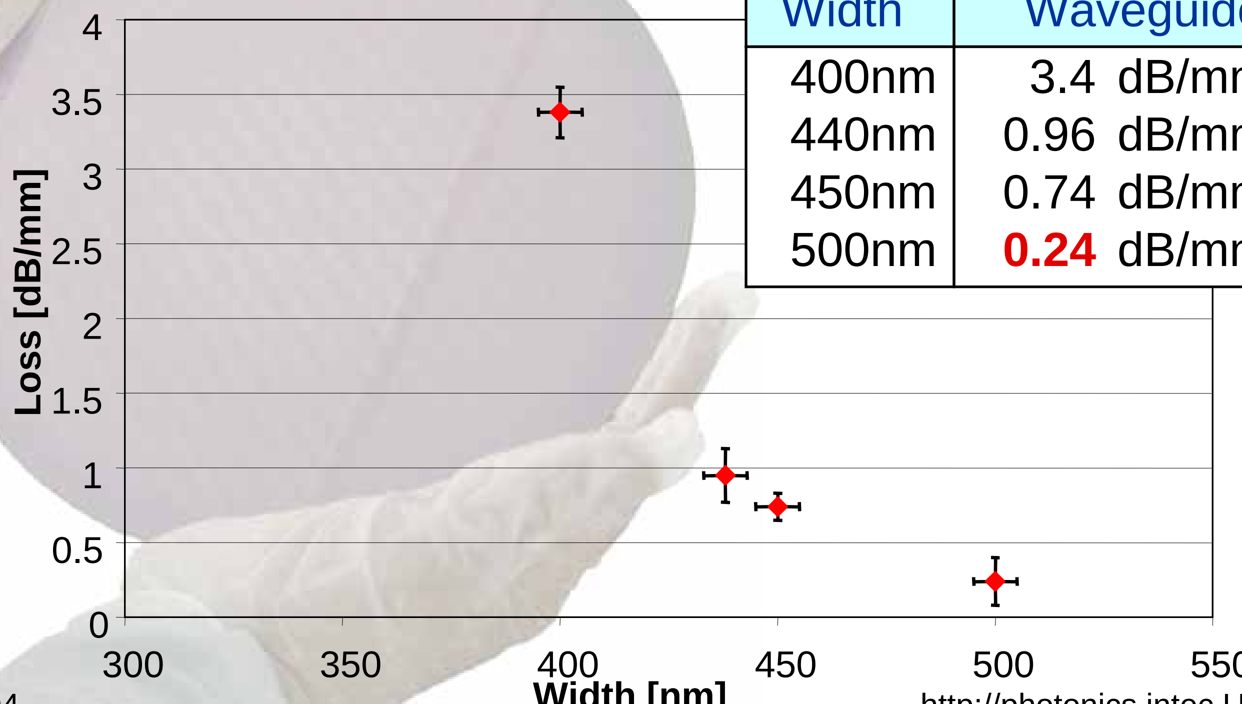
- **Loss less wavelength dependent**
- **Lower loss than photonic crystals**



# Photonic Wires



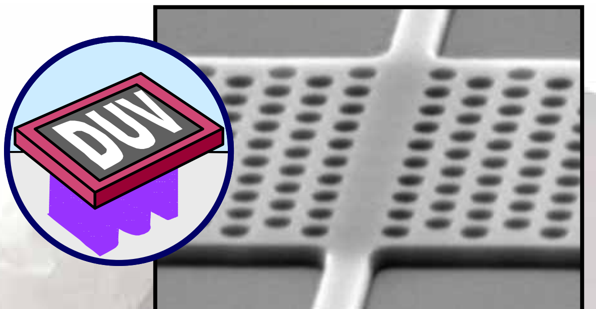




| Width | Waveguide loss |
|---|---|
| 400nm | 3.4 dB/mm |
| 440nm | 0.96 dB/mm |
| 450nm | 0.74 dB/mm |
| 500nm | **0.24** dB/mm |

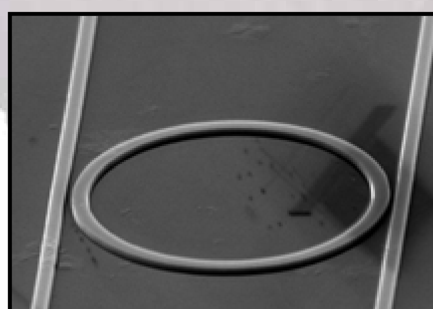
# Waveguide Losses

## Our best results:

### 7.5 dB/mm

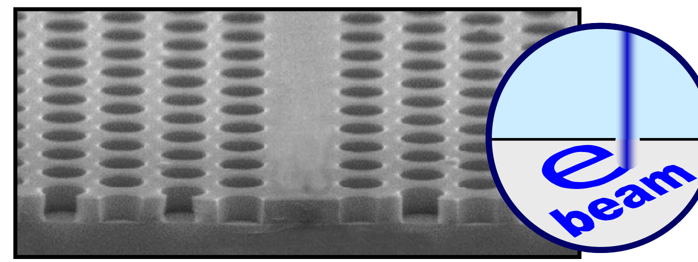



### 0.24 dB/mm



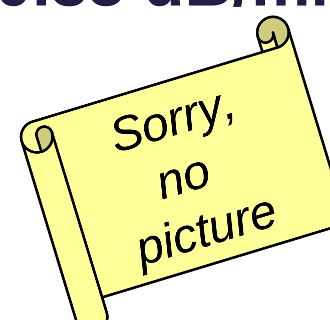
## The competition:

### 2.4 dB/mm




McNab et al., LEOS Topicals, Vancouver 2003

### 0.35 dB/mm




McNab et al. Opt. expr. 11(22) p. 2927

# Summarised

## Wanted: Cheaper components for optical fibre communications

## Compact waveguide circuits

- Photonic wires: perfect for connections
- Photonic Crystals: more suitable for compact functional elements

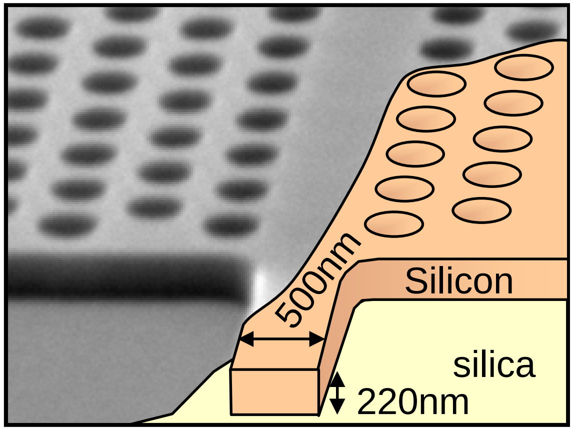
## Fabrication process

- e-beam lithography: fine details, but too slow
- Deep-UV lithography
  - high resolution
  - large throughput
  - commercially proven in CMOS industry

# What have we done?

## Study of losses

- Out-of-plane scattering
- Scattering at roughness




## Fabrication with deep-UV lithography

- Optimised the fabrication process
- Characterisation and study of components

## Measurement results

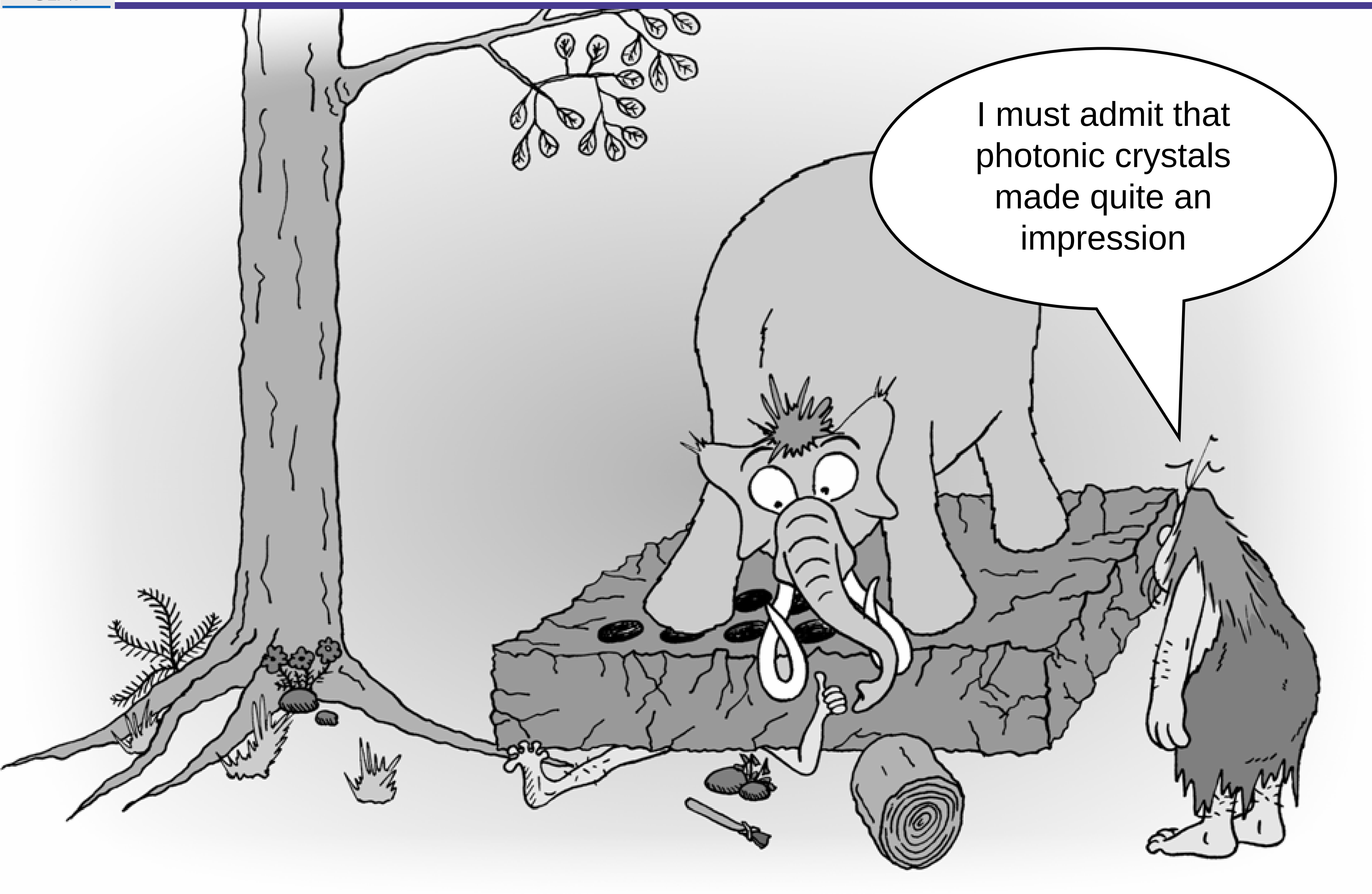
- Photonic Wire: 0.24dB/mm
- Photonic Crystal Waveguide: 7.5dB/mm

# Many thanks to…


- **the IST-PICCO project**
- **the IAP-PHOTON network**
- **The Flemish institute for the advancement of Scientific-Technological research in the Industry (IWT)**

- **Roel and the complete *photonics*-group**
- **The people in IMEC-Leuven involved in the fabrication of my designs**

# Any questions?...



# Some meaningless statistics

± 400’000’000’000 holes etched

- = 0.4 Terahole
- = 3000 holes per second
- = 10 holes on each millimeter around the equator
- = 12 years of e-beam writing

± 30 km straight waveguides

- = 2’000’000’000 dB loss

⇕

roughly equivalent to the combined propagation loss of all submarine cable combined ☺