# Nanophotonic devices for optical interconnects

Kresten Yvind

Some material borrowed from

D.A.B Miller (Stanford)

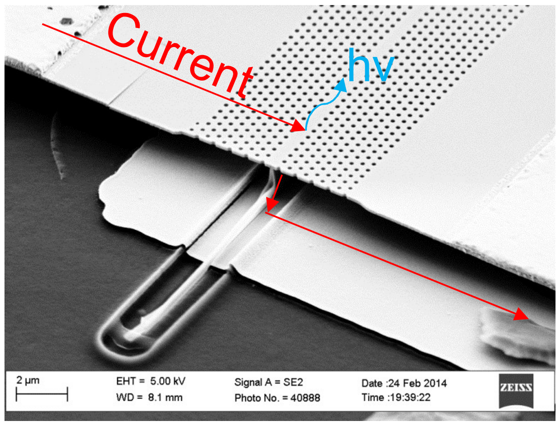
IBM

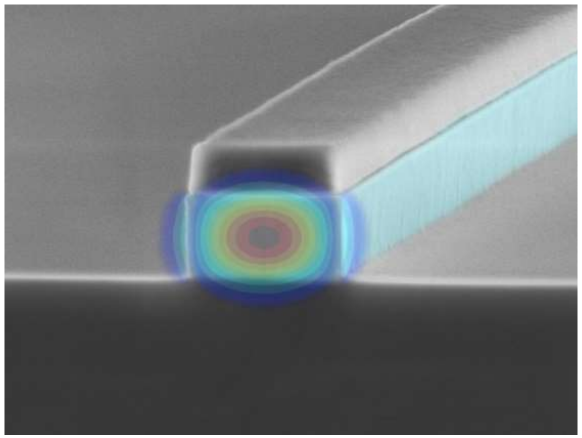
Jesper Mørk (DTU)

**DTU Fotonik**
Department of Photonics Engineering

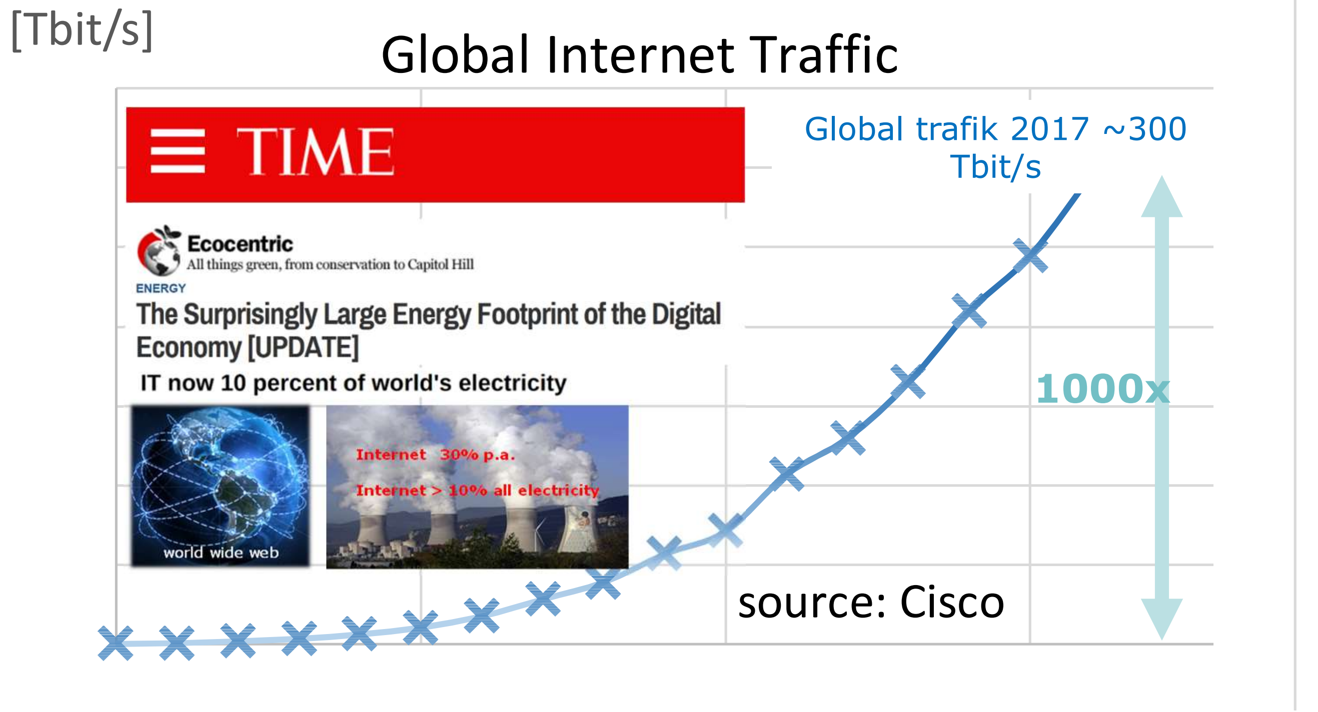
# Outline

- The challenge of the internet and electronic chips
  - Electrical versus optical interconnects.
  - How low can you go (the quantum angle)
  - Devices
- Technology
  - Silicon photonics
  - Photonic crystal devices



# Challenge of the internet:
# Growth and energy consumption




For every bit sent on the internet a million bit are sent within the datacenter

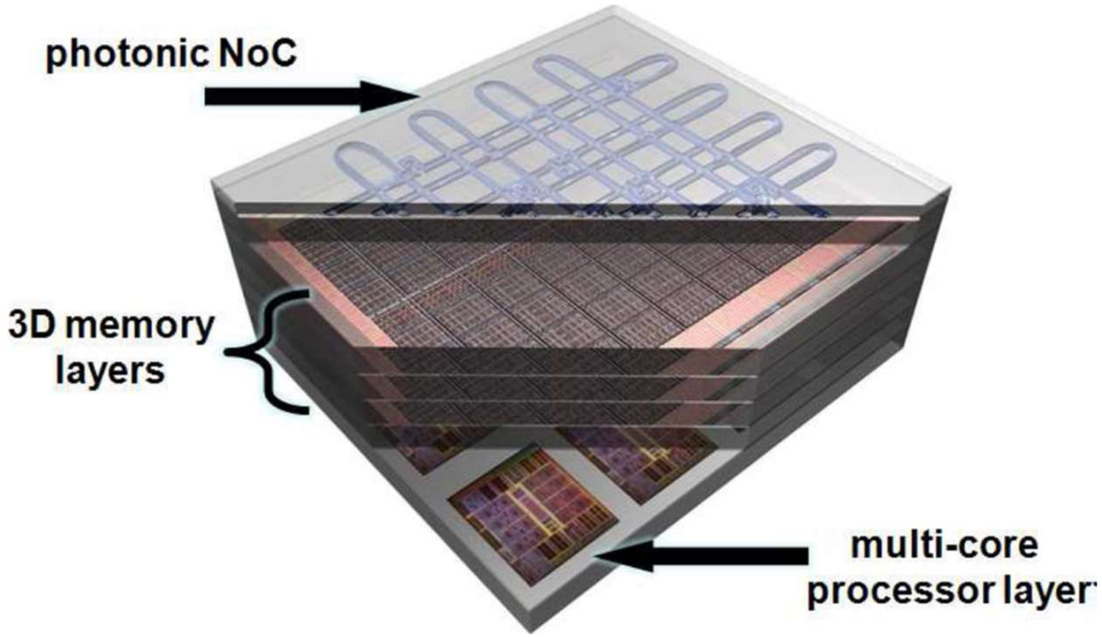
Usergrowth since Y2k: ~1000%

Traffic growth since Y2k: ~1000x

**All information created since the dawn of times to y2k is transmitted every day.**

# Solutions?

- Better photonics is part of the solution (photonic integrated circuits: PIC)
- More photonics is another part:




- Replacing electrical communication with optical communication

# Are we talking about an optical computer?

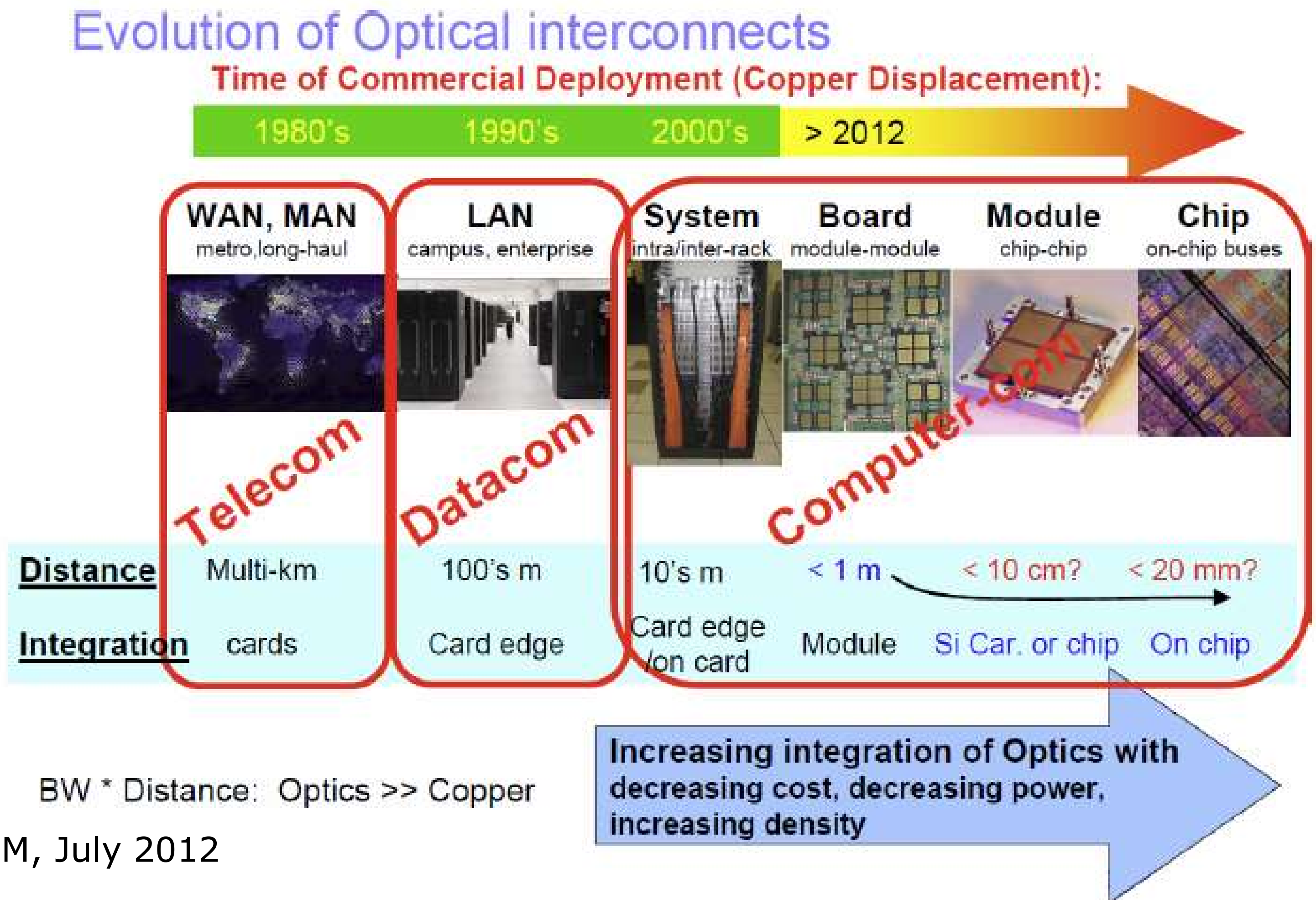
- No.

- Electrons i**nteract strongly** with materials and each other
  –> Logic. Energy cost ~1fJ/bit pr switching event

- Photons **interact weakly** with materials and each other
  –> Communication. Almost loss-less transmission

- No quantum coherence. Classical computing. Room temperature,…

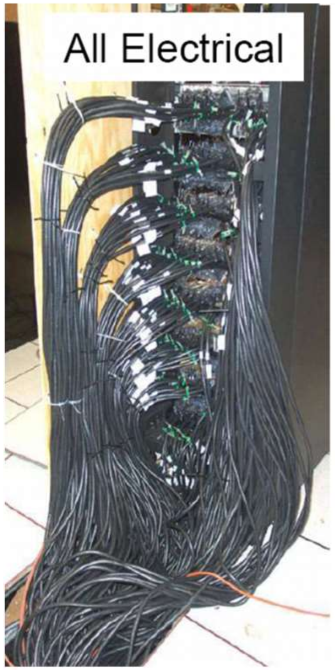
## Optical communication replacing electrical communication

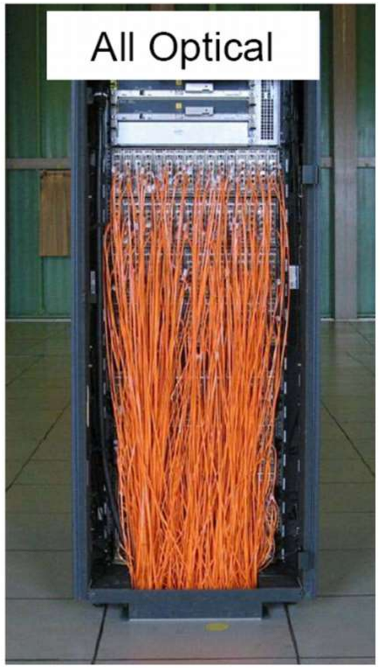


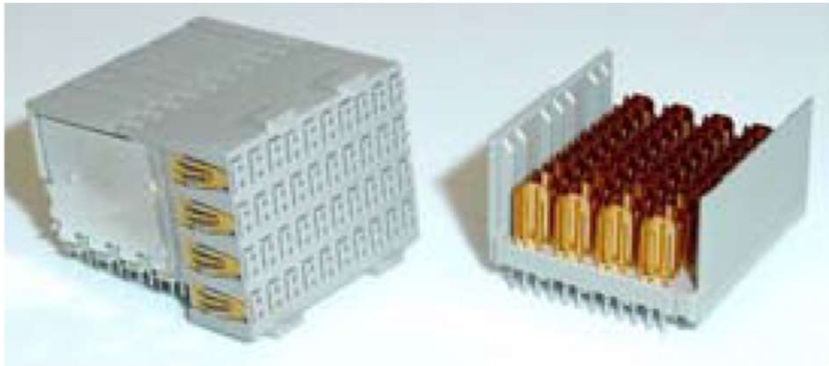

M. Taubenblatt, IBM, July 2012

# Size is part of the answer

For communication photons are
 ”smaller” than electrons



**HM-Zd 10Gbps connector**
**40 differential pairs**
**(25mm wide)**

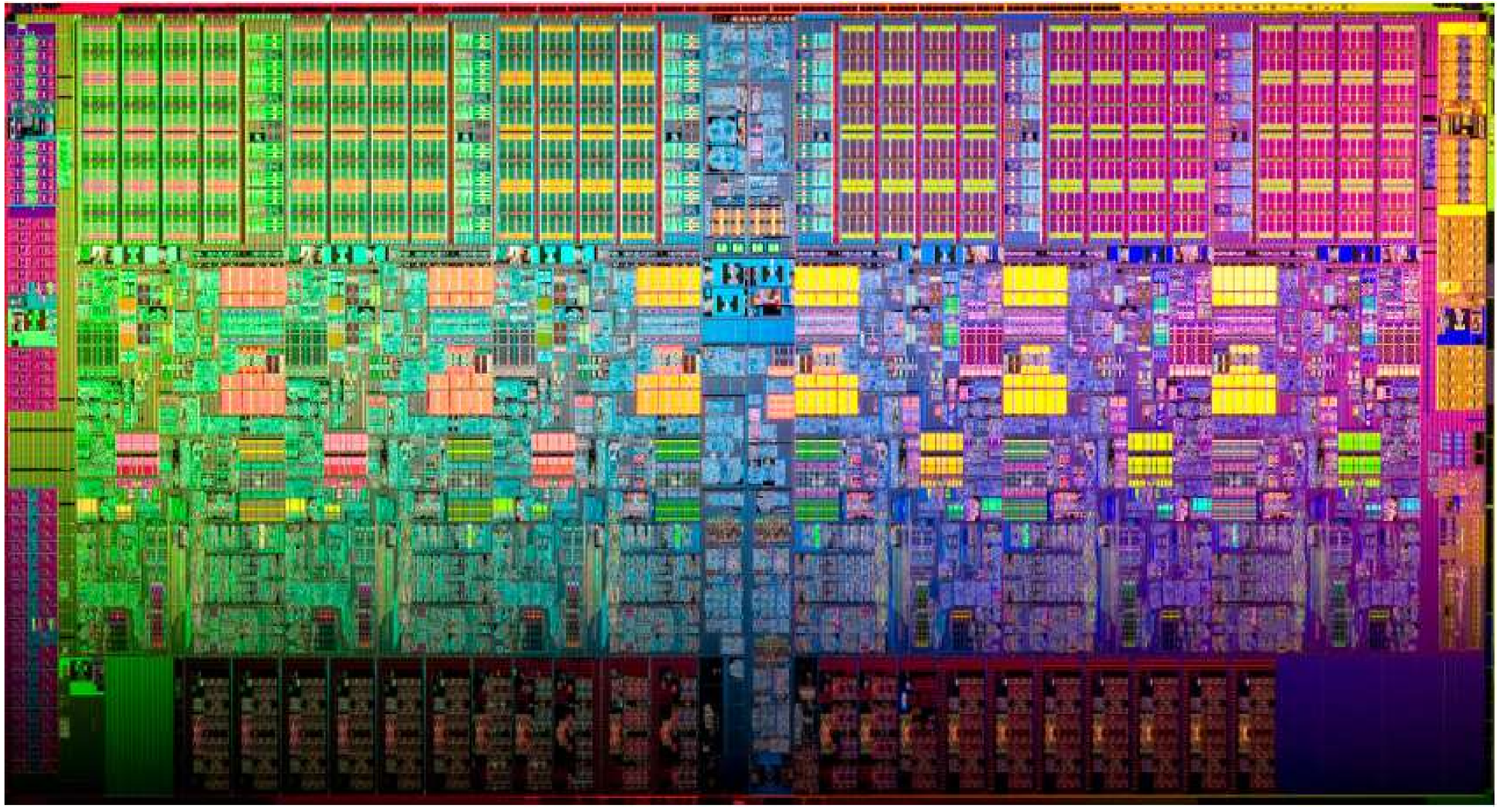
**MT fiber ferrule**
**48 fibers, extendable to 72 or 96**
**(7mm wide)**

(Sometimes, photons are smaller than electrons!)

6 Optics for Next Gen Servers IBM Research

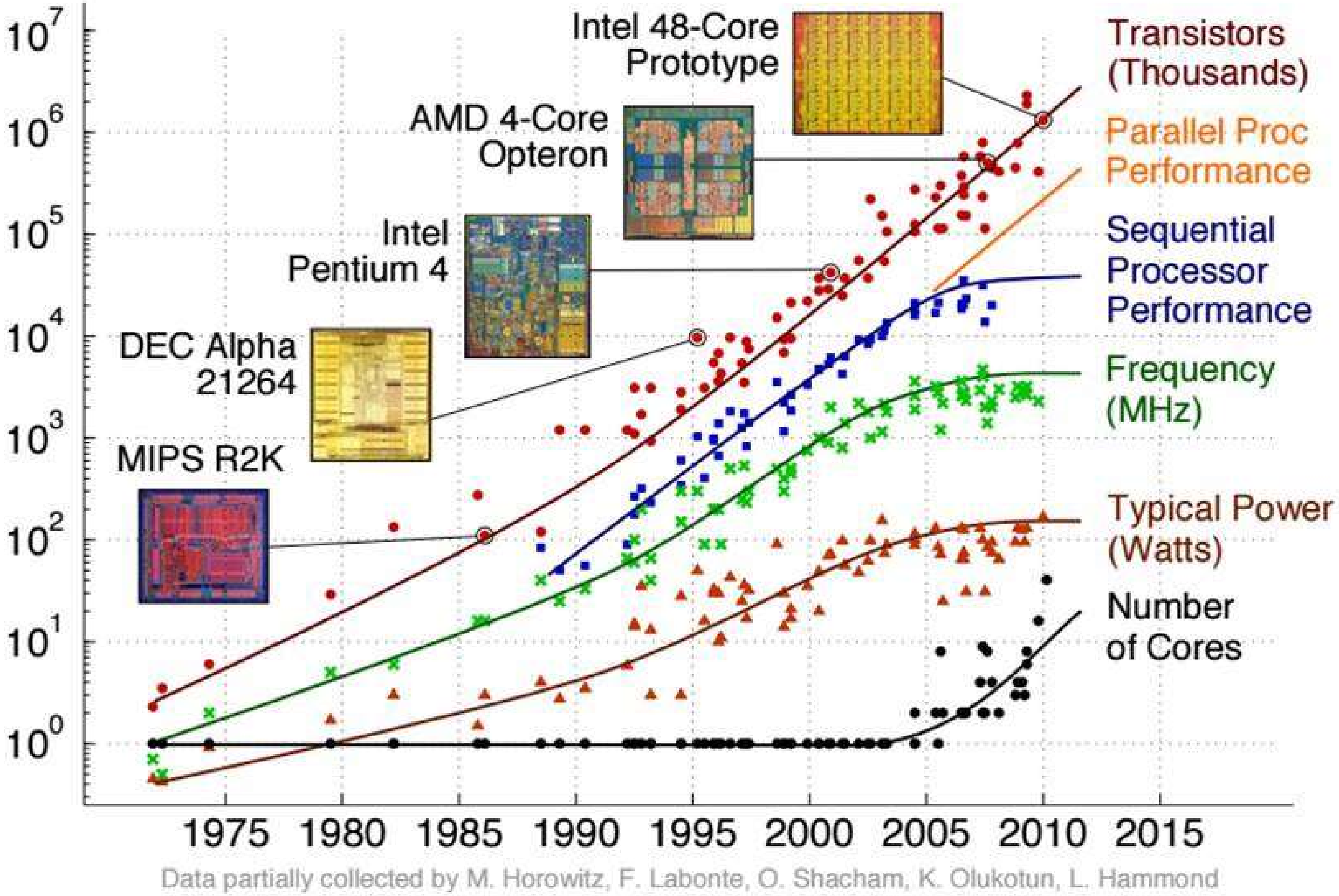
Ultimately the total bandwidth is also limited by the available size

# Energy is another driver



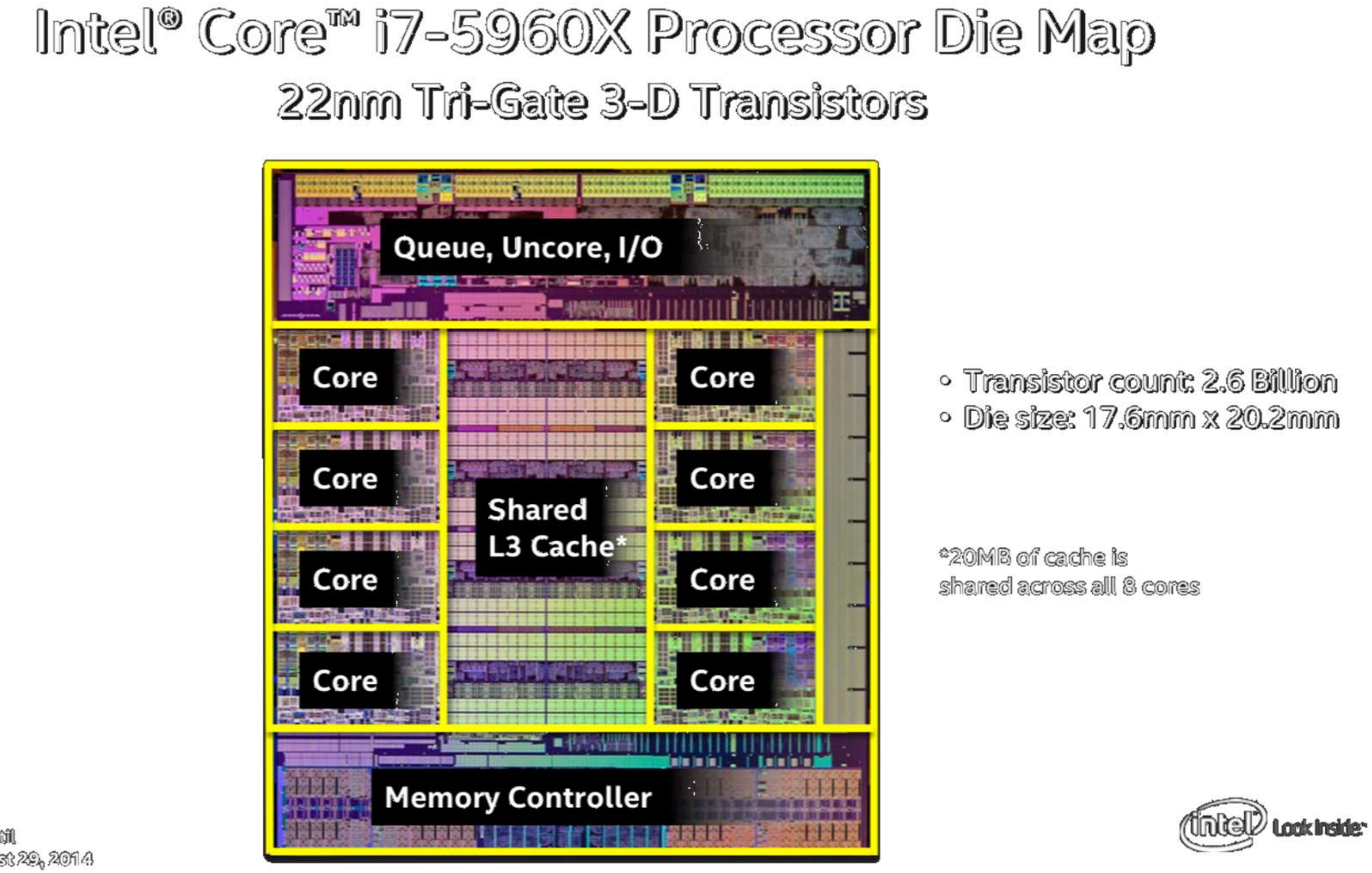
Cost $$ is main inhibiter. (+ complexity)

## CPU scaling

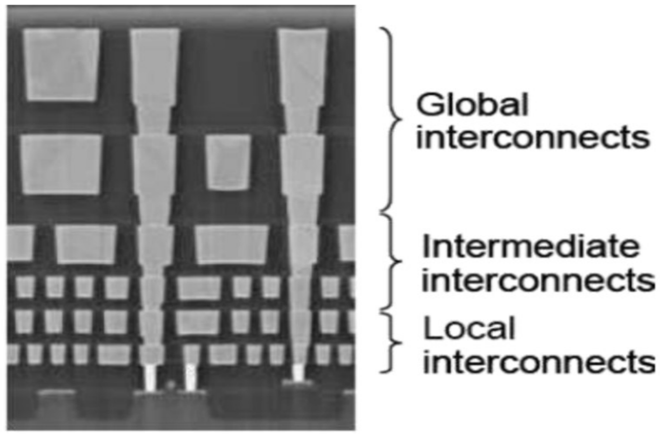



Even though we can make transistors smaller and faster we cannot dissipate the increased power.

# Interconnects in integrated circuits




- >50% of gates for interconnects (incl. repeaters)
- Interconnect power does not scale.
- Dominant for smaller technology nodes.



346 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 35, NO. 3, FEBRUARY 1, 2017

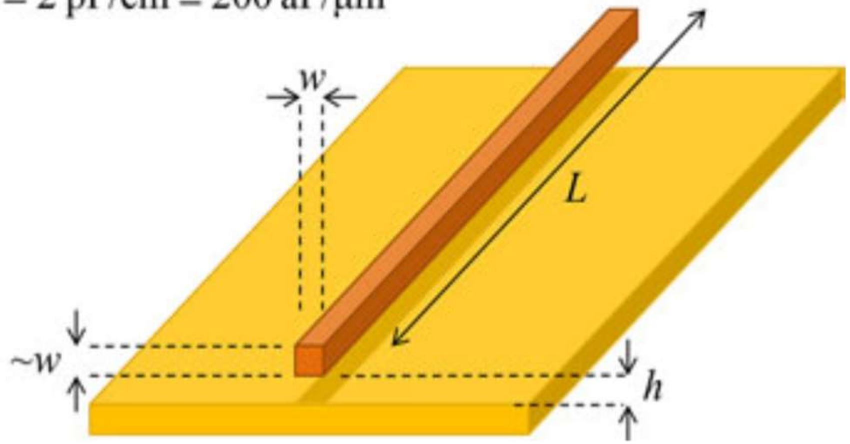
# Attojoule Optoelectronics for Low-Energy Information Processing and Communications

David A. B. Miller, *Fellow, IEEE, Fellow, OSA*

- And many other papers since late ‘80ties

- Wires in ICs
- Coaxial pr length:
  - Capacitance $C_l = \frac{2\pi\epsilon_r\epsilon_0}{\ln(\frac{r_b}{r_a})}$
  - Inductance $L_l = \frac{\mu_r\mu_0}{2\pi}\ln(\frac{r_b}{r_a})$
  - Resistance $R_l = \frac{1}{\pi r_a^2\sigma}$
- Charging wires: E=½CV²
- V~0.8V on chip. Smaller off-chip with driver
- Energy consumption scales with length

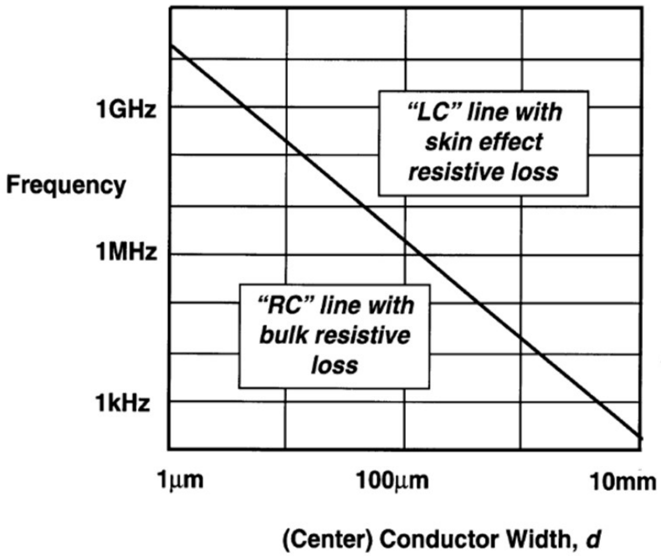
$C / L \simeq 2$ pF/cm $\equiv 200$ aF/µm

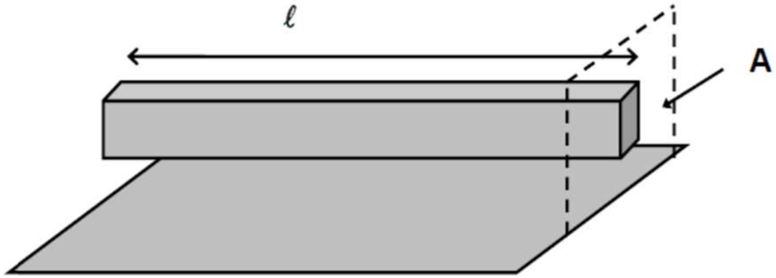


# Bit rate limitation

- Rise time

- Coaxial line pr. length:
  - Capacitance $C_l = \frac{2\pi\epsilon_r\epsilon_0}{\ln(\frac{r_b}{r_a})}$
  - Inductance $L_l = \frac{\mu_r\mu_0}{2\pi}\ln(\frac{r_b}{r_a})$
  - Resistance $R_l = \frac{1}{\pi r_a^2 \sigma}$




- LC limitation (e.g. coax cable) B~$10^{15}$ A/$l^2$ bit/s
- RC limitation (on chip) B~$10^{16}$ A/$l^2$ bit/s
- Equalized LC lines B~$10^{17}$ A/$l^2$ bit/s
  - (losses added at low f)

- Cutting up lines with "repeaters" can increase the capacity on chip (but increases the number of gates)

**bit rate B $\propto$ A / $\ell^2$**

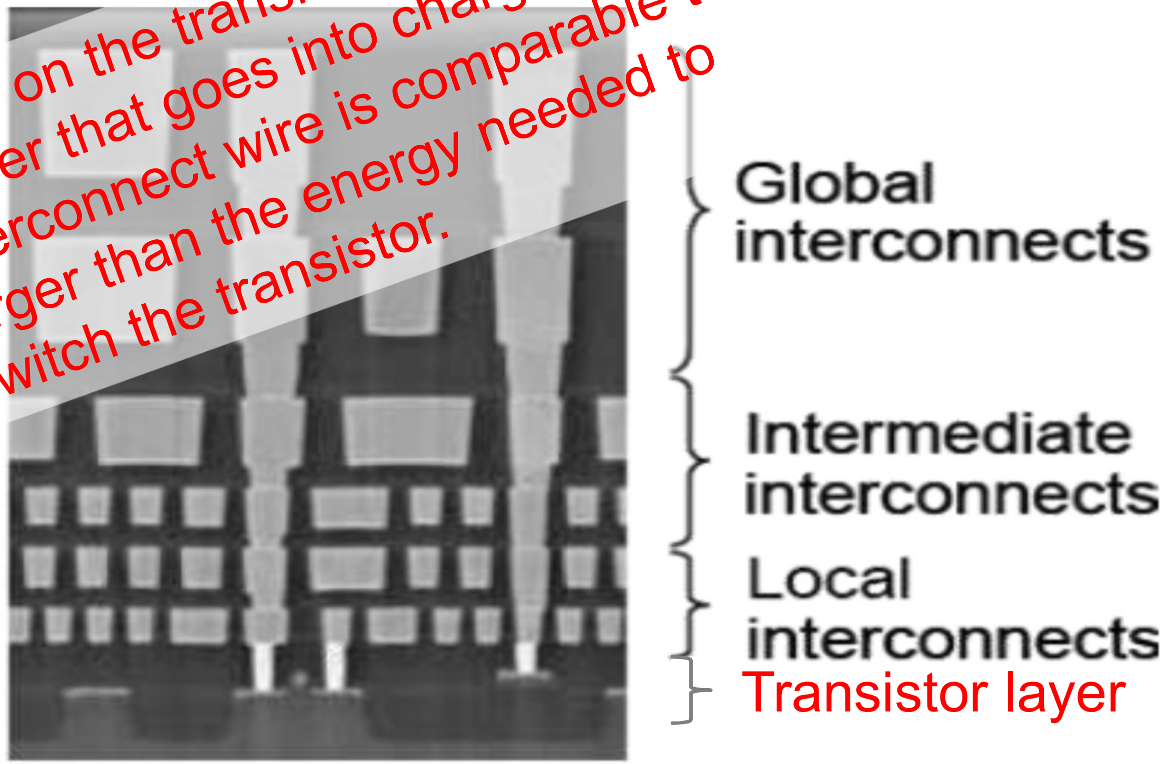
Bit rate limitation when all space is used for wiring

Limits memory bandwidth

# Where does the power go II ?

Even on the transistor level the power that goes into charging the interconnect wire is comparable to/ larger than the energy needed to switch the transistor.

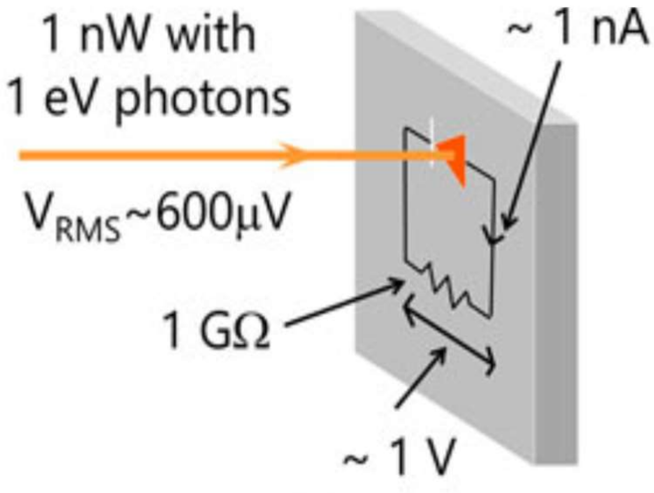
Switching CMOS
$E \sim 1fJ$
Charging wires:
$E = \frac{1}{2}CV^2$
$C \sim 2$ pF/cm
$E \sim 1fJ$ for $10\mu m$

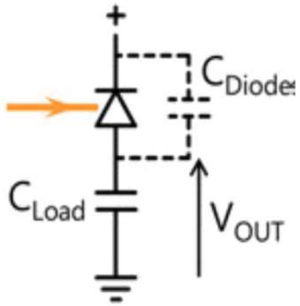



**Significant increase in energy consumption with distance**

# Optics has fundamental advantages

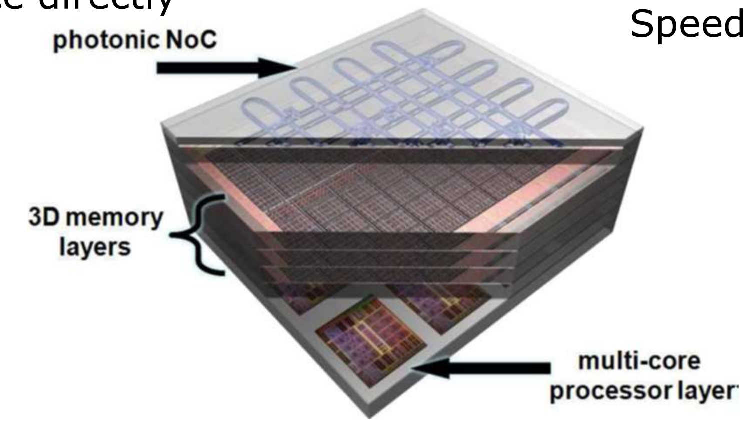
- Transmission loss very low
  - We only need to charge the gate of the transistor attached to the photodetector
    - Quantum impedance transformation
  - Little delay and distortion (omit CDR)
- However
  - Efficient conversion from electrical to optical signals and back is needed.
  - Optical modulators with external light source
  - Or on-chip efficient low power lasers (or LEDs)
  - Detectors with very low capacitance directly coupled to CMOS gate.
  - Low loss photonic circuits



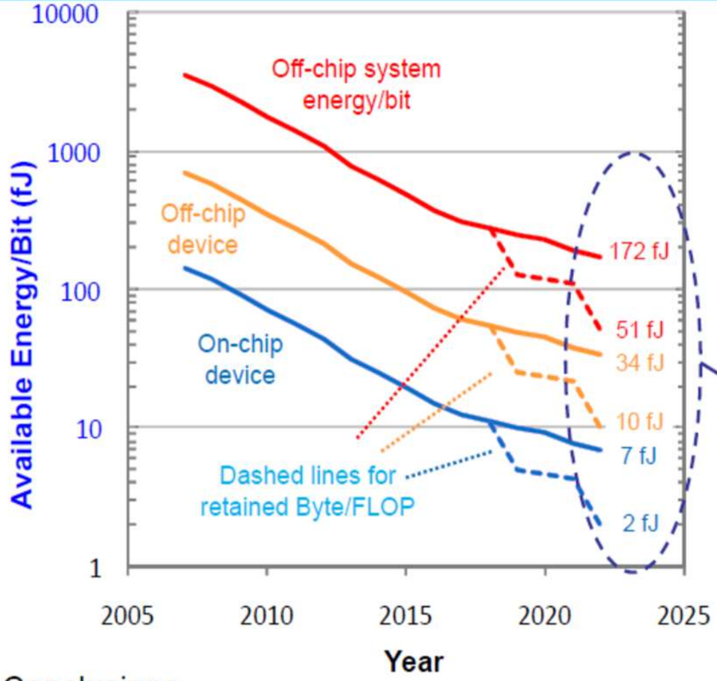




Speed: 1/RC

Miller (1989,2017)



# Available energy for interconnects




Total chip power limited to ~ 200 W

- Limits total system energy per bit

Dashed lines presume we retain Byte/FLOP ratio in the later years

Allowable total energy per bit communicated
based on 20% of power for each of off-chip and on-chip interconnect, and device energy being 20% of total energy/bit

1.6 fJ = 10000 photons @ 1.24um

Conclusions

- 50 – 100 fJ/bit system energies are low enough for off-chip interconnect
- Optical output devices need to have energies of ~ 10 fJ for desired I/O in later years
- Even lower energies desirable for on-chip interconnect

June 18, 2012, Nonlinear Photonics David Miller, Stanford 32

# What is the lowest energy we can use to transmit information?

Low bit error rate (BER) needed

- BER $10^{-12}$=1 error/100s for 10GBit/s, 1link
  - > error correction employed (cost energy and latency)
- BER $10^{-20}$=1 error/28 hours for 10GBit/s, 100,000links

1 photon?

Assuming perfect detector (100% absorption, no noise):

Probability of absorption during propagation

$$P = 1 - \exp(-\alpha \cdot L) \sim \alpha \cdot L = BER$$

Loss $\alpha = 0.1cm^{-1}$ (low for integrated wg)

Maximum transmission length: $L < \frac{BER}{\alpha} = \frac{10^{-12}}{10m^{-1}} = 0.1pm...$

We need more than one...

"Quantum limit" (assuming poisson distribution) at detector: 27 photons/"1"bit for error rate $10^{-12}$.

Detector needs to be able to detect single photons at bit rate

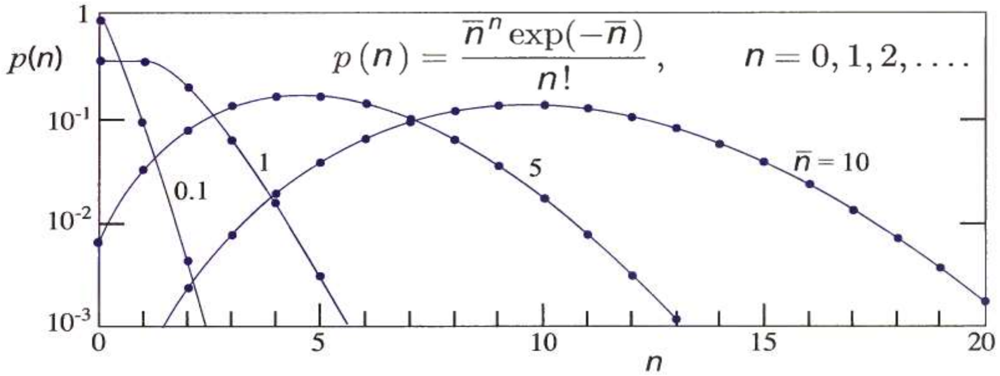
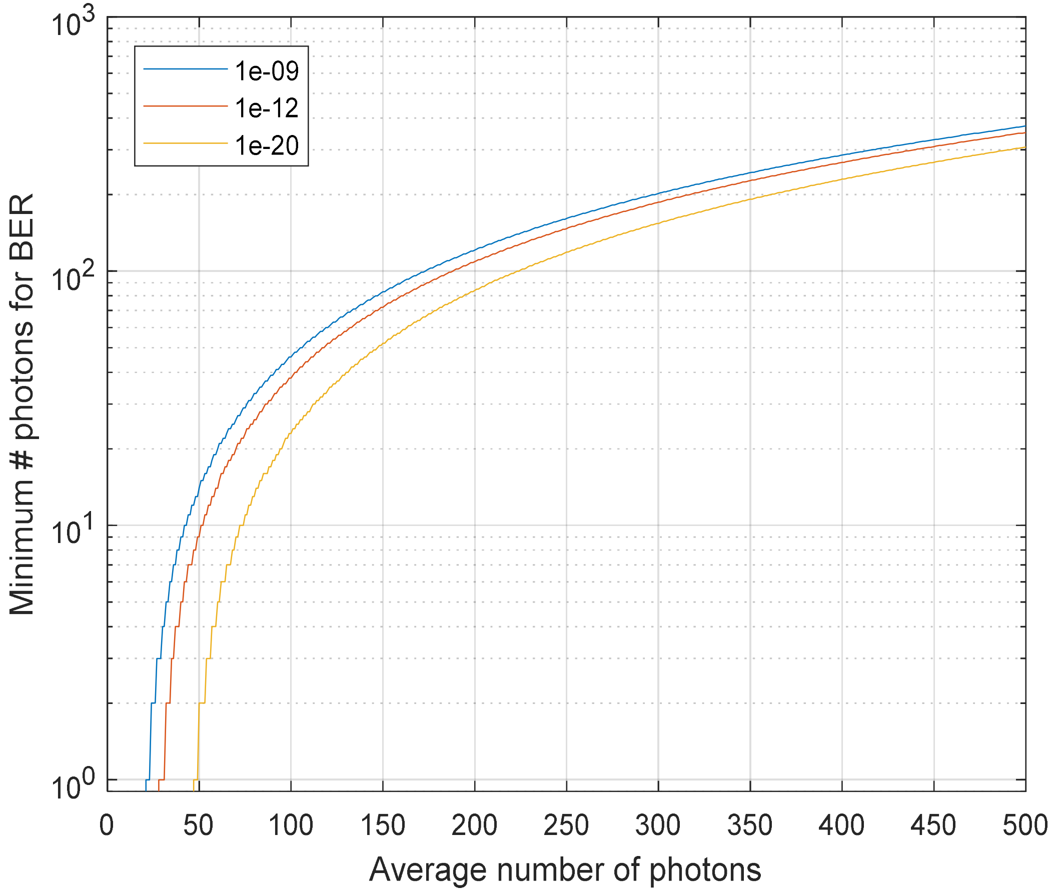
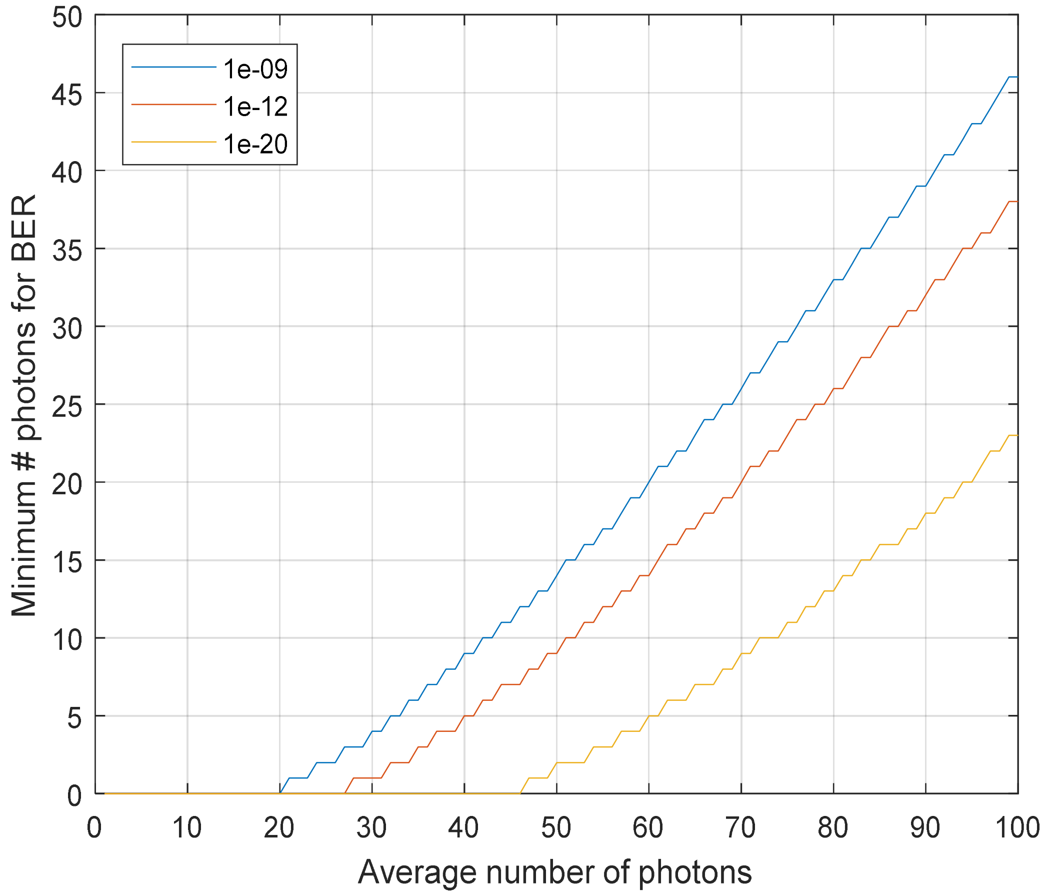



**Figure 12.2-5** Poisson distribution $p(n)$ of the photon number $n$.

| **Average photons in "1"** | **Min photons in "1" ($p(n)<10^{-12}$)** |
|---|---|
| 27 | 1 |
| 52 | 11 |
| 100 | 39 |
| 200 | 110 |
| 5500 | 5000 (~todays standard) |

# Including BER=1E-20 for onchip connections.



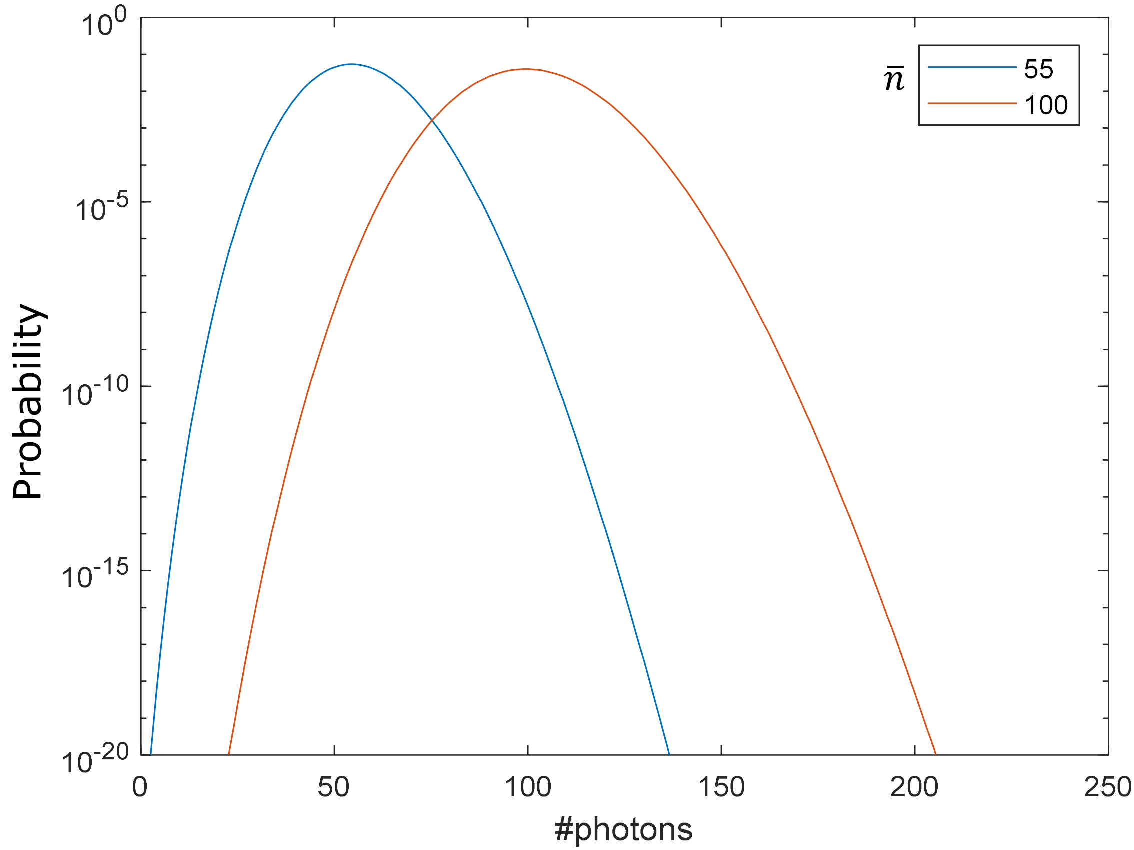



# Photon noise

- "Coherent state". Photons independent of each other.
  - Poisson statistics: receive $n$ given $\bar{n}$ average

    $P_{Poiss}(n) = \exp(-\bar{n})\frac{\bar{n}^n}{n!}$
  - Variance $\sigma_n^2 = \bar{n}$

- Distribution at receiver in normal communication systems

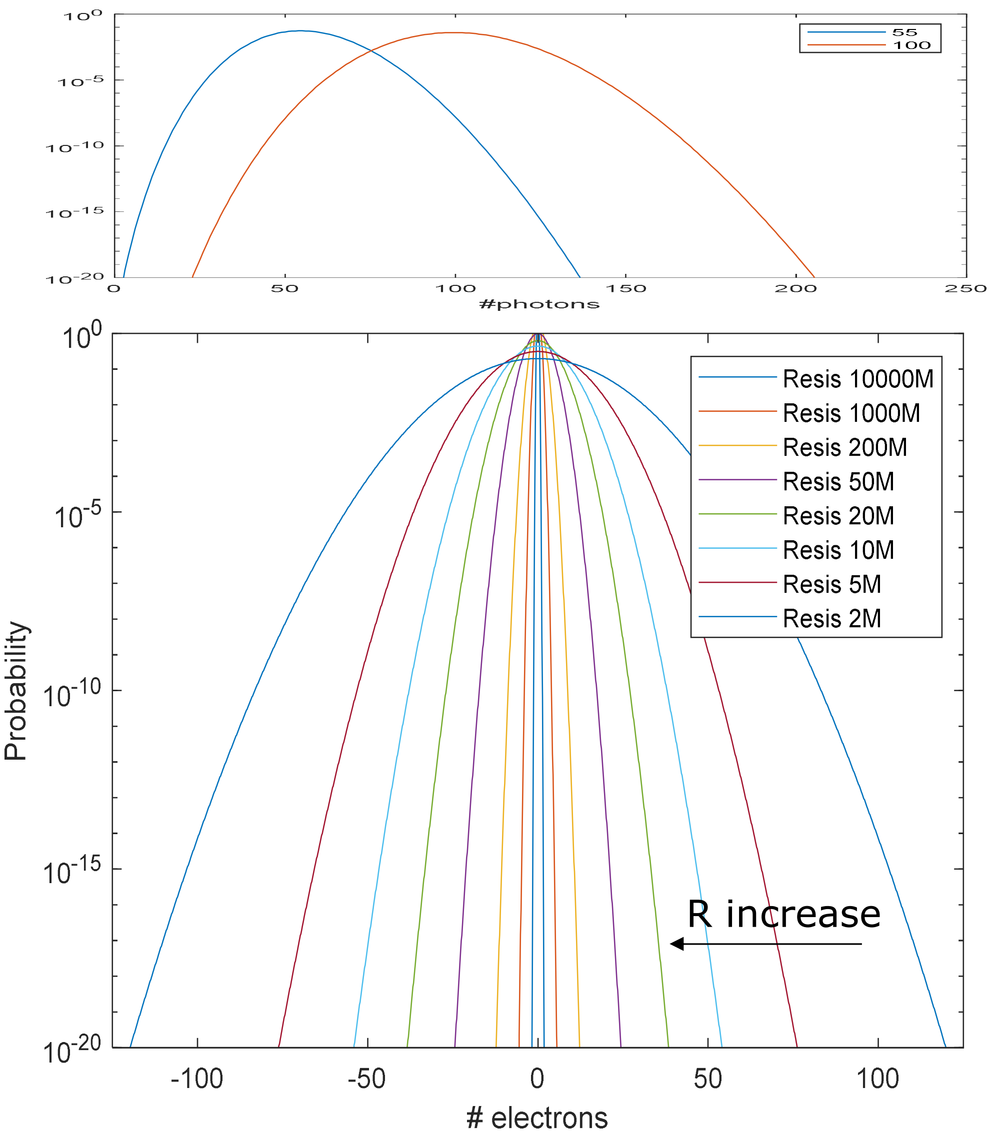


# Thermal noise

- Resistor (electron) noise $\sigma_T^2 \approx \frac{T_{bit} 2 k_B T_R}{q^2 R}$
- $P_{Therm}(x) = \frac{1}{\sqrt{2\pi}\sigma_T} \exp\left(-\frac{x^2}{2\sigma_T^2}\right)$

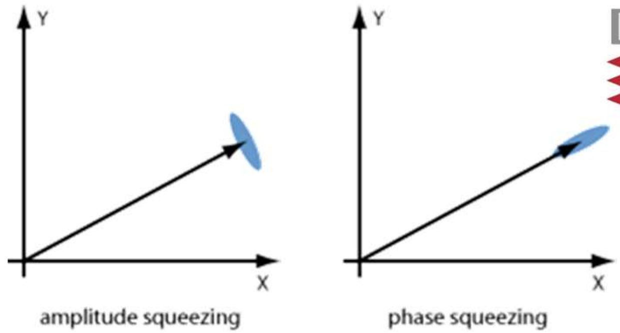
At high resistance the electron noise can be smaller than the photon noise.

- Can we transfer these noise properties to the photons?
- What about speed?
  - Ultralow capacitance needed (RC)
- What about energy?
  - Low current ($I^2 R T_{bit}$)
  - Low enough? $((0.1\mu A)^2 \cdot 100 M\Omega \cdot 1\text{ns} = 1 fJ)$

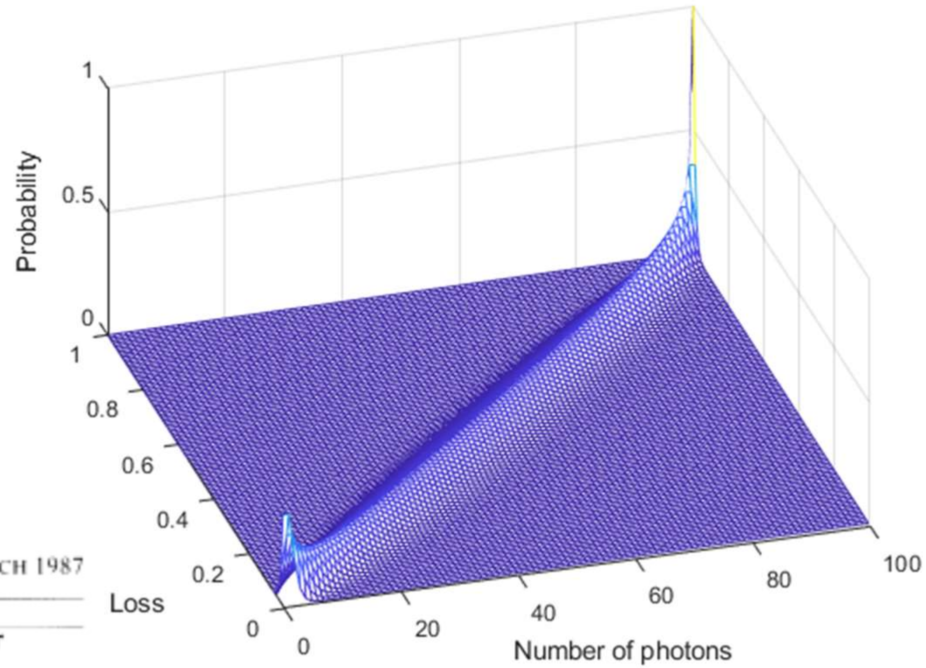


# Can we improve photon statistics?

- Intensity squeezed state
  - >More phase noise (dont care...)
- Constant current (quiet pump) nanoLED
  - High quantum efficiency and high β
- Single mode semiconductor laser driven by constant current high above threshold
  - Gain saturation stabilizes photon number
  - quantum stuff…
- So yes…




So why dont we always do this ?




PHYSICAL REVIEW A VOLUME 34, NUMBER 5 NOVEMBER 1986

**Amplitude squeezing in a pump-noise-suppressed laser oscillator**

Y. Yamamoto and S. Machida
*Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation, Musashinoshi, Tokyo 180, Japan*

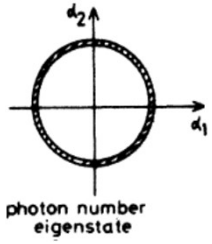
O. Nilsson
*The Royal Institute of Technology, Stockholm, S-10014, Sweden*

VOLUME 58, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1987

**Observation of Amplitude Squeezing in a Constant-Current–Driven Semiconductor Laser**

S. Machida and Y. Yamamoto
*NTT Electrical Communication Laboratories, Musashino-shi, Tokyo 180, Japan*

and




# Distribution evolution: Extreme case

- Assuming starting condition is number state: Number of photons = N ••••••••••••••• •••
- Propagation a certain distance with transmission $T = \exp(-\alpha \cdot L)$
- Probability distribution is just the binomial distribution.

Probability of no absorption in n trials

- Probability of receiving n photons: $P_{bino}(n) = \binom{N}{n} T^n (1-T)^{N-n}$

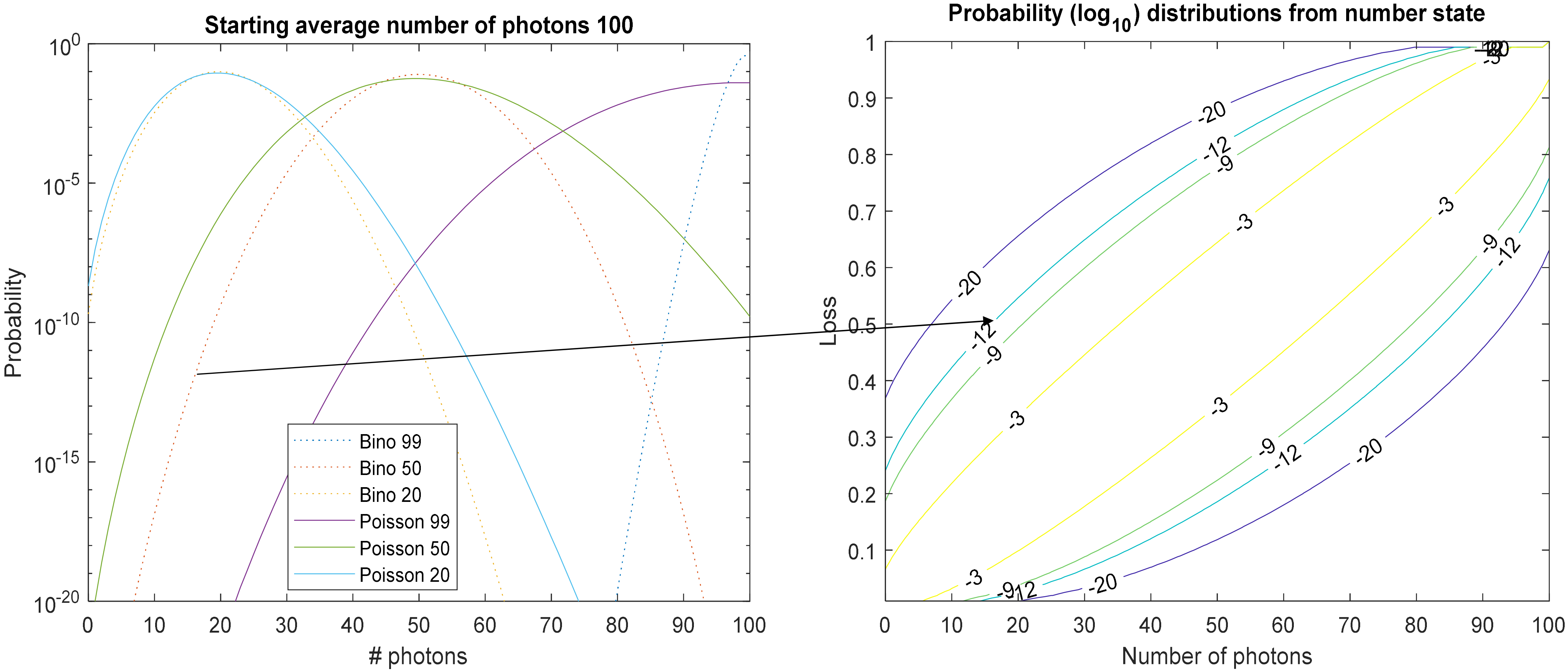
Number of ways to pick n from an ensemble of N $(= \frac{N!}{n!(N-n)!})$

Probability of absorption in N-n trials

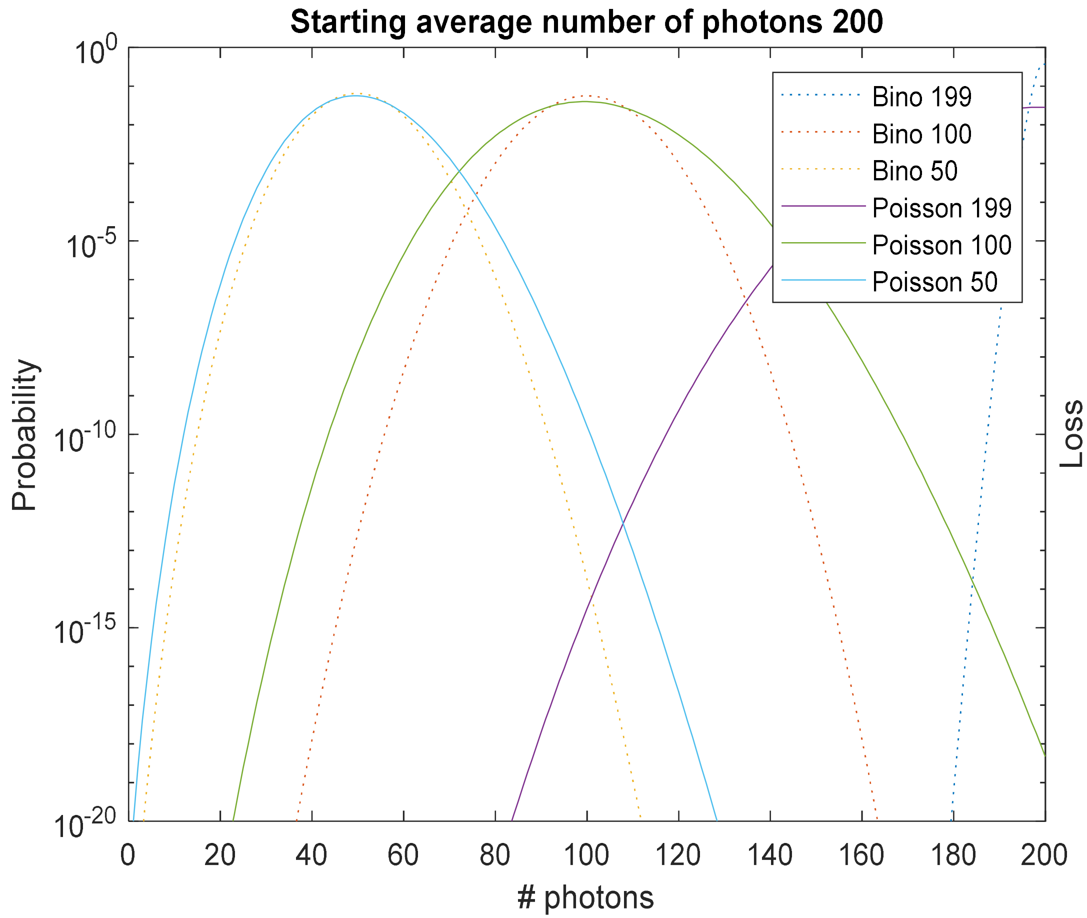
- The binominal distribution limits to the Poisson distribution for small T.

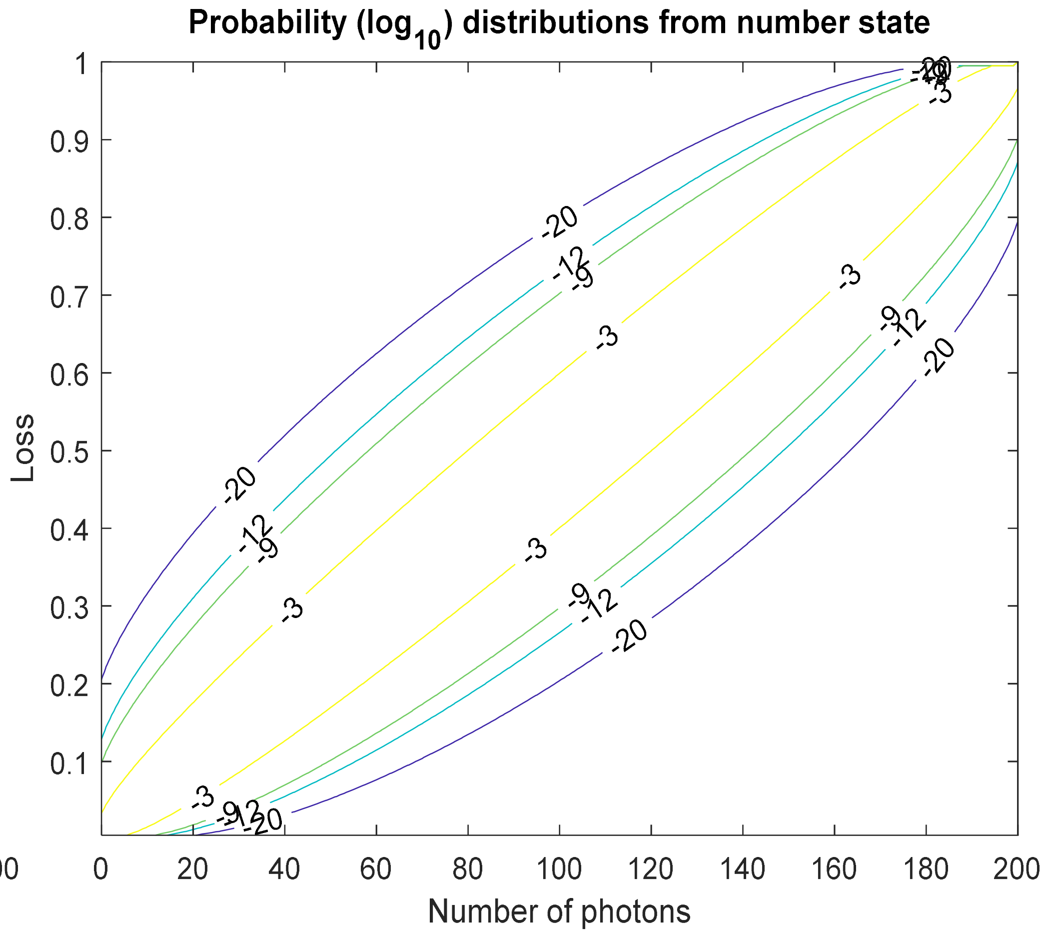
- Probability of receiving n photons: $P_{Poiss}(n) = \exp(-N \cdot T)\frac{(N \cdot \mathrm{T})^n}{n!}$

# Number state vs "coherent state" vs loss, 100

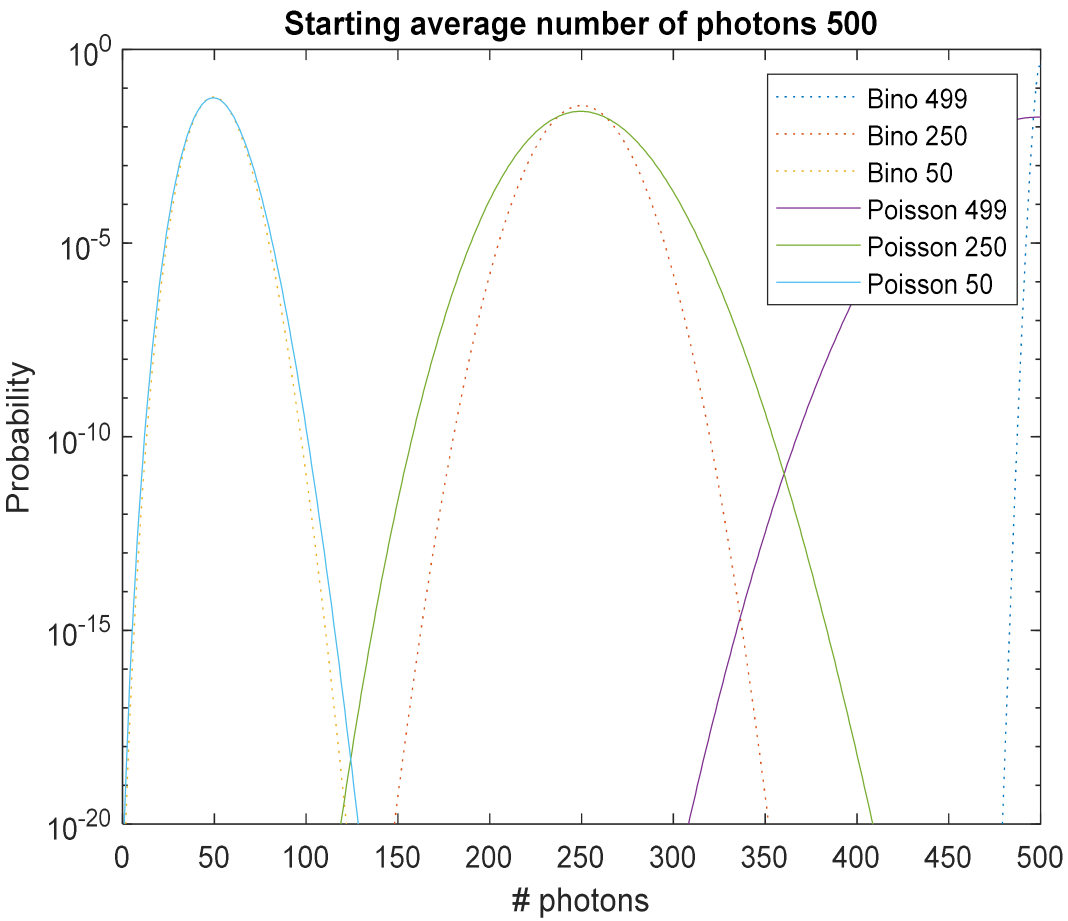


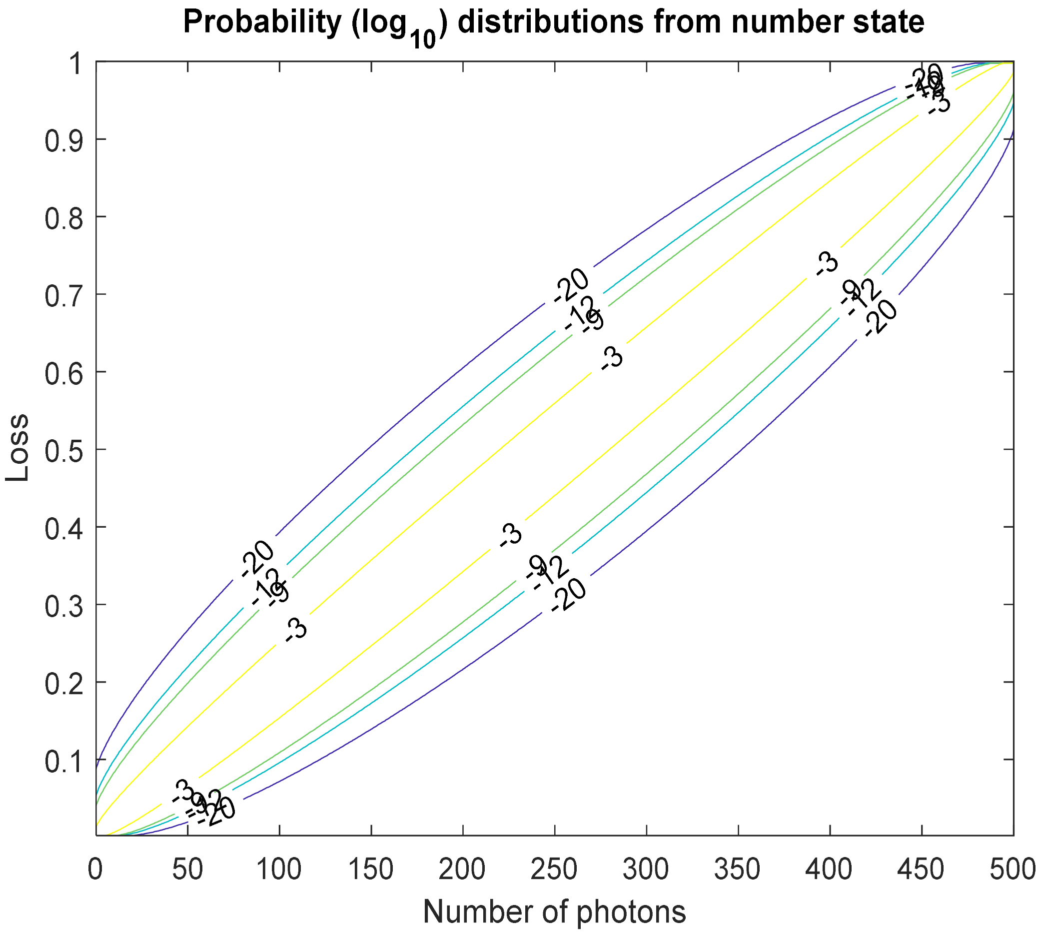
# Starting average number of photons 200



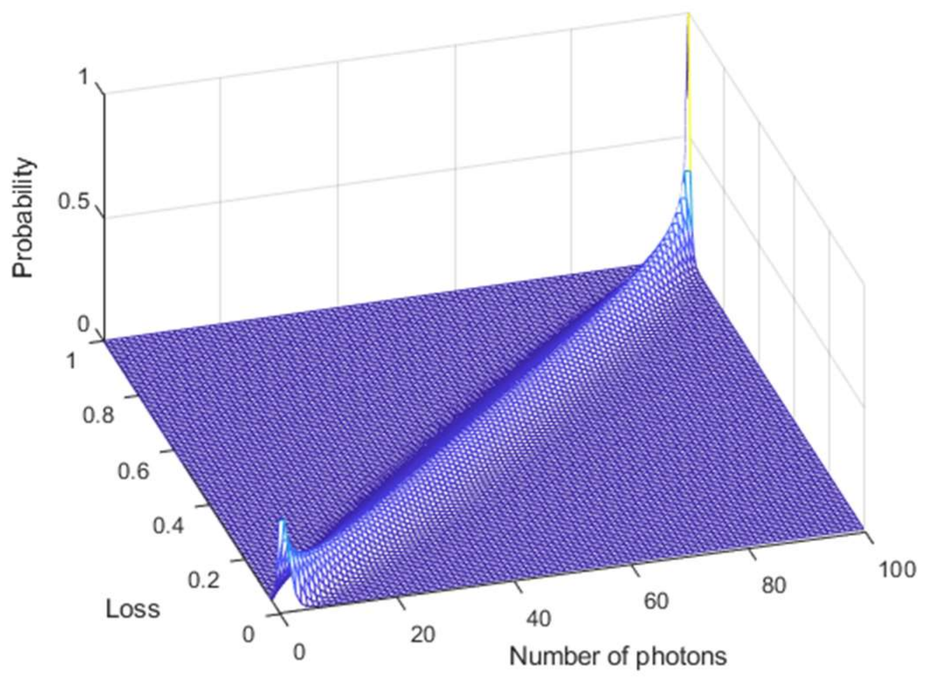
# Starting average number of photons 500



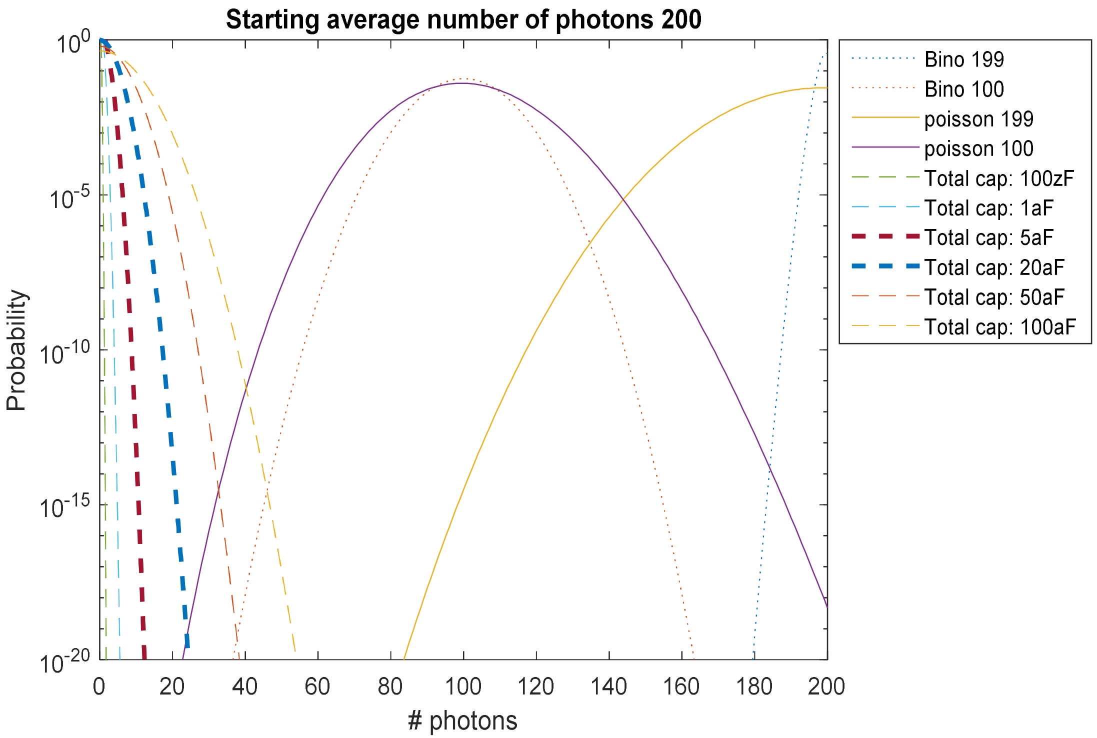
# Squeezing is fragile

- For 3dB losses (including *everything*)
  - Significant effect of perfect squeezing
- 6dB
  - Some effect
- 10dB
  - No effect
- Needed:
  - Efficient emitters
  - Low loss optical components
  - Efficient detectors
  - …

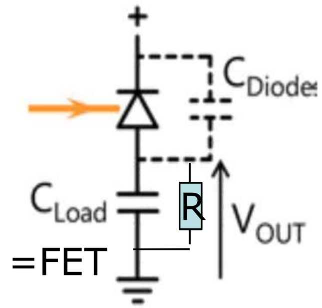


# Noise in detectors

- Assuming only noise from load resistor for ”0”. Independent of frequency for fixed capacitance




$$\sigma_T^2 \approx \frac{T_{bit} 2 k_B T_R}{q^2 R} = \frac{2 k_B T_R C_{tot}}{q^2}$$




Capacitance of FET (+PD) key.

Standard PD: 1pF

NanoPD: < 5aF

FET std: 100aF

FET theory: 20aF (?)

Single photon detection:

C < 100zF (-> not OK)

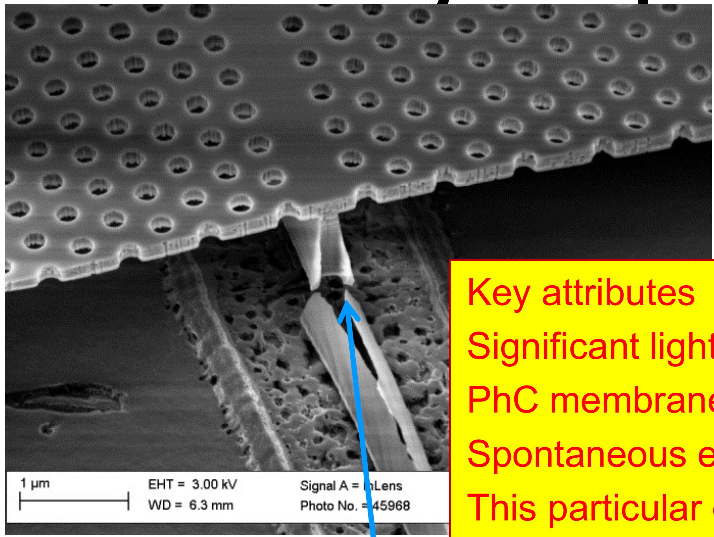
Avalance or low temp

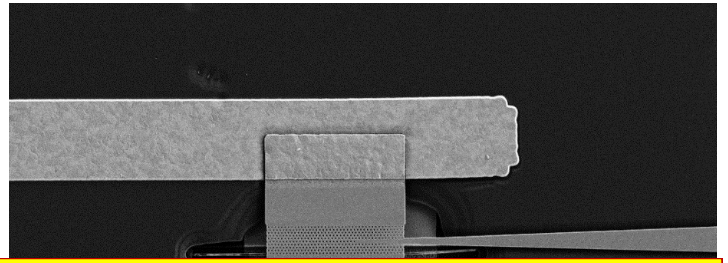
- Dark current can be made small by having small low bandgap volume (Purcell enhancement?).
- High β designs (PHC) will also shield quantum fluctuations

# Devices

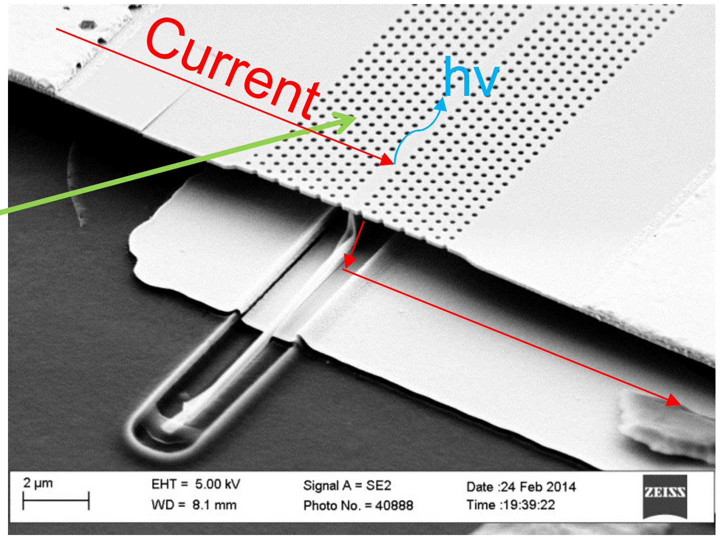
- Key attributes and technology for low energy optical interconnects.

# Photonic crystals platform for active devices



Key attributes
Significant light confinement possible
PhC membrane can be made conductive
Spontaneous emission can be controlled (β)
This particular design was not possible to fabricate with high yield




Pillar for vertical current injection

Photonic crystal slab with heterostructure photonic crystal design

A. Lupi, E. Semenova, L. Ottaviano, K. Yvind

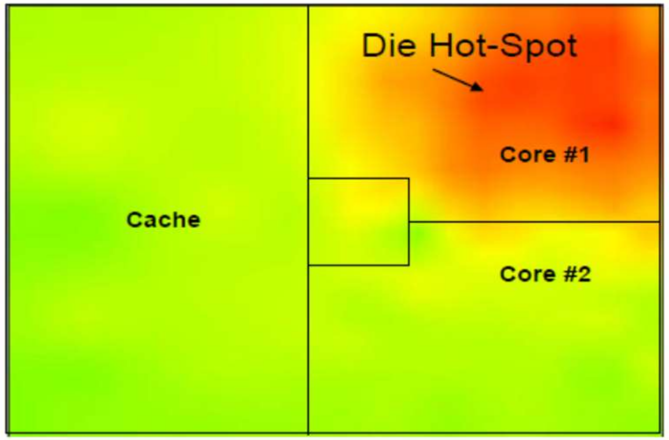
# How should one inplement this?

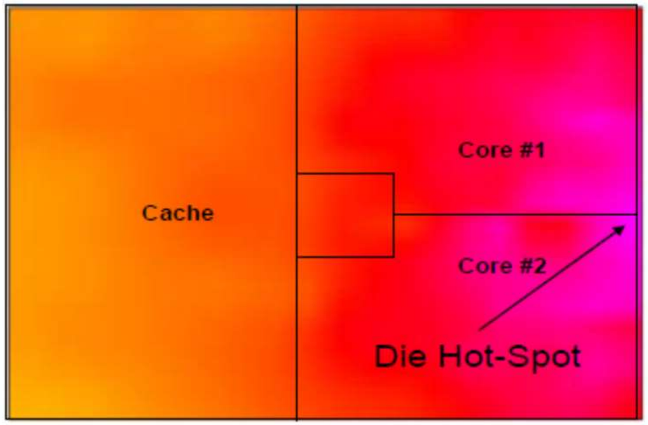
Options:

- Nanolaser, (nanoLED)
- Comb generation (for WDM)
- modulator, resonantly enhanced modulator

- Temperature variation across chips ~40C

- Waveguides

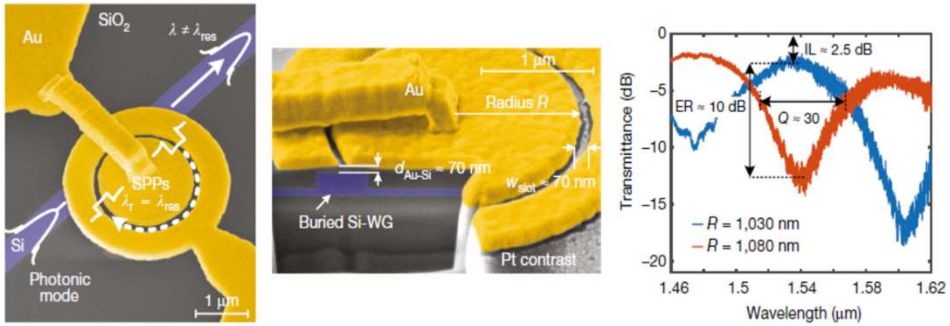



  - Key issues: Cost, yield, cost, energy consumption, cost, reliability.

# Modulator (off chip light source)

- Modulator
  - Large power consumption (laser) moved off-chip. But will use/dissipate power all the time (1W?).
  - Does not necessarily need III-V semiconductors
  - Insertion loss
  - Resonantly enhanced modulators may need to be tuned to external source.
  - Modulator can use pulsed source (global clocking)
  - We do not currently have work on this



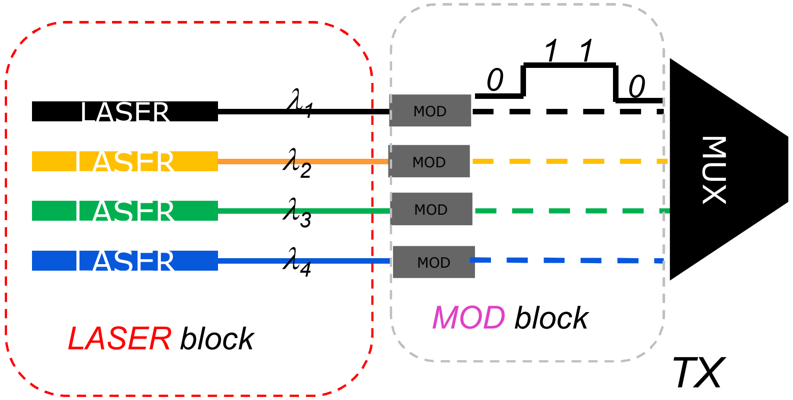

- (David Millers preferred solution)

TABLE II
EXAMPLE LASER AND MODULATOR ENERGY SCALING

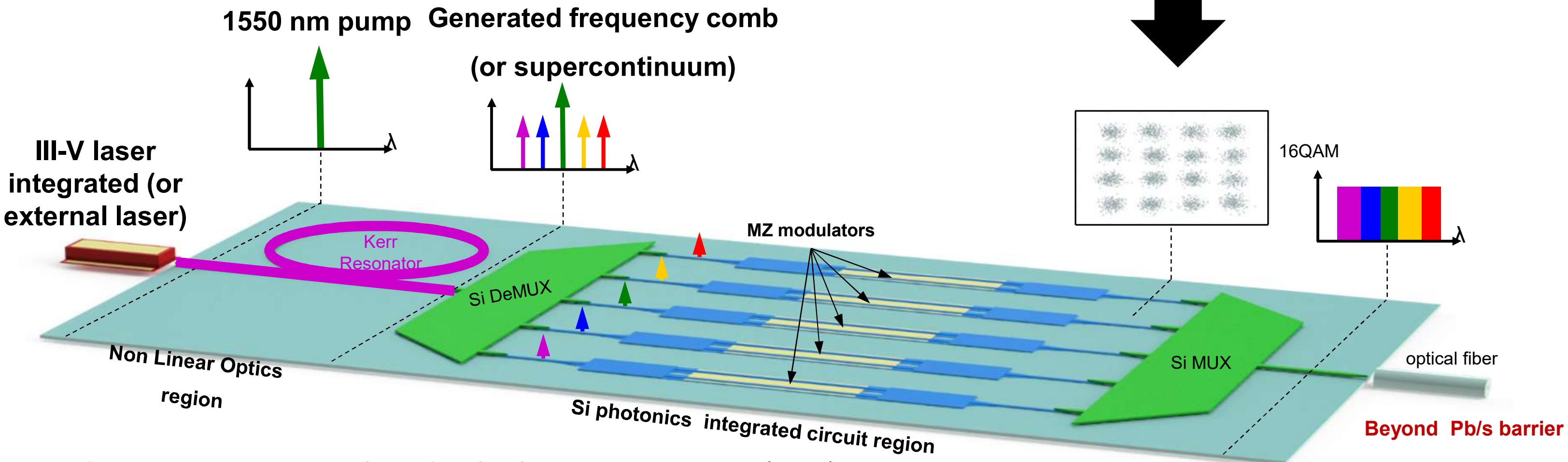
| Active device volume | Operating energy | Optical concentration factor |
|---|---|---|
| **(1 $\mu$m)$^3$** (a) | | |
| laser | ~160 fJ | ~5 (b) |
| modulator | ~5 fJ | ~1 (c) |
| **(300 nm)$^3$** $= 0.027\ \mu m^3$ | | |
| laser | ~4300 aJ | ~200 |
| modulator | ~135 aJ | ~40 |
| **(100 nm)$^3$** $= 10^{-3}\ \mu m^3$ | | |
| laser | ~160 aJ | $\sim 5 \times 10^3$ |
| modulator | ~5 aJ | $\sim 10^3$ |
| **(10 nm)$^3$** $= 10^{-6}\ \mu m^3$ (e.g., a quantum dot) | | |
| laser | ~160 zJ (d) | $\sim 5 \times 10^6$ |
| modulator | ~5 zJ (e) | $\sim 10^6$ |

# Replacing individual lasers in optical transceiver for WDM system

- *Toward ultra-wideband data communication on a nonlinear photonic chip*



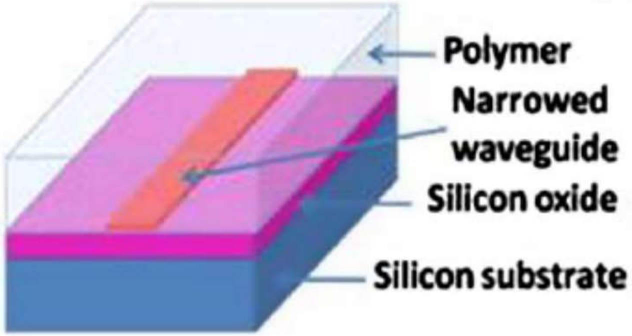

**Replacing TX block (laser emitters) with Kerr-based broadband sources…**



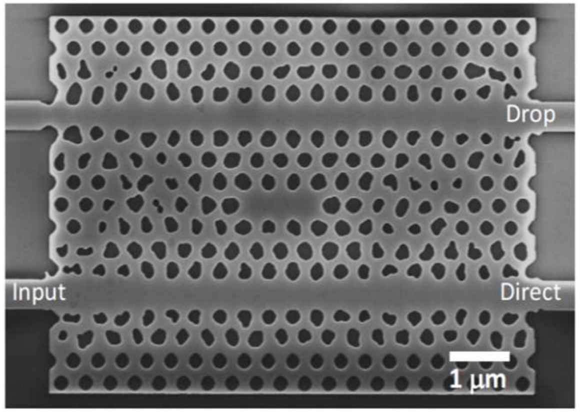

1) H. El Dirani et al., in *Integrated Optics: Devices, Materials, and Technologies XXII*, **1053508** 7 (2018).

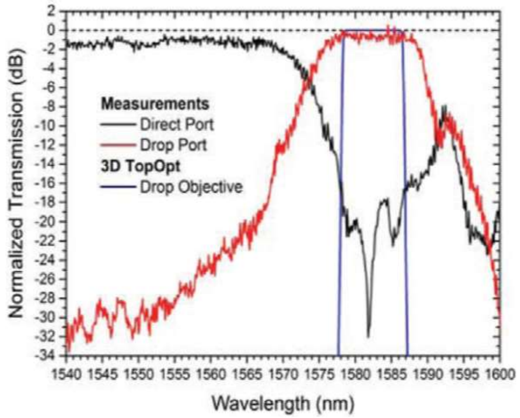
# Passives

- WDM (multiple wavelengths) needed
- How to deal with large temperature differences?
  - Compensation?




  - Broadband flat-top (course WDM)?
- Waveguide losses:
  - Silica fiber <1dB/km (Between racks)
  - Silicon waveguides < 1dB/cm (on chip)
  - Amourphous silicon < 8dB/cm (on chip)
  - Polymer waveguides < 1dB/cm (?, PCBs)
  - Independent of data rate.
  - (nanoplasmonic 4000dB/cm?)




- Couplers <1dB (both grating couplers and inverse tapers good enough for now)
- Wireless (THz) sometimes discussed (would expect ridiculous power and space requirement??)

# Nano Laser

- Aim: 1.5fJ/bit

$$\alpha_i = 1cm^{-1},\ L_c{=}1\mu m,\ I{=}10I_{th}$$

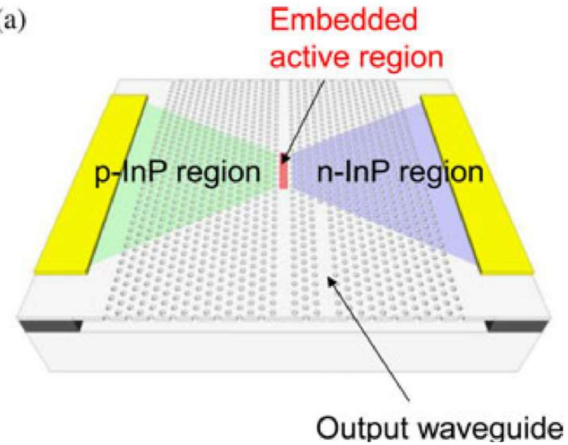
- QW: 500x500x6nm3 -> Q>2E4
- 2 QWires: each 10x30x250nm3 -> Q>2E5
- High efficiency needed to get enough photons

- Efficiency and high temperature operation important.
  - May benefit from QDs on GaAs at 1.1-1.3um (lower Auger)

$$\eta_{wp} = \frac{P}{VI} = \frac{\eta_i \frac{\alpha_m}{\alpha_m + \alpha_i}(I - I_{th})}{IV}$$

$$\Gamma g = \alpha_i \frac{L_c}{L_a} + \frac{1}{2L_a} \ln\left(\frac{1}{R_1 R_2}\right)$$

(a)




S. Matsuo et al., Nat. Phot. **4**, 648 (2010)

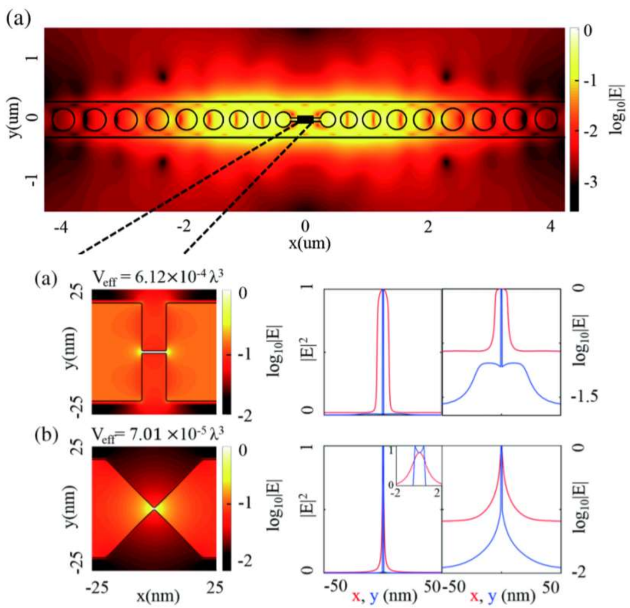
S. Matsuo et al., JSTQE **19**, 4900311 (2013)

## Modulation response of nanoLEDs and nanolasers exploiting Purcell enhanced spontaneous emission

T. Suhr[1,*], N. Gregersen[1], K. Yvind[1], and J. Mørk[1]

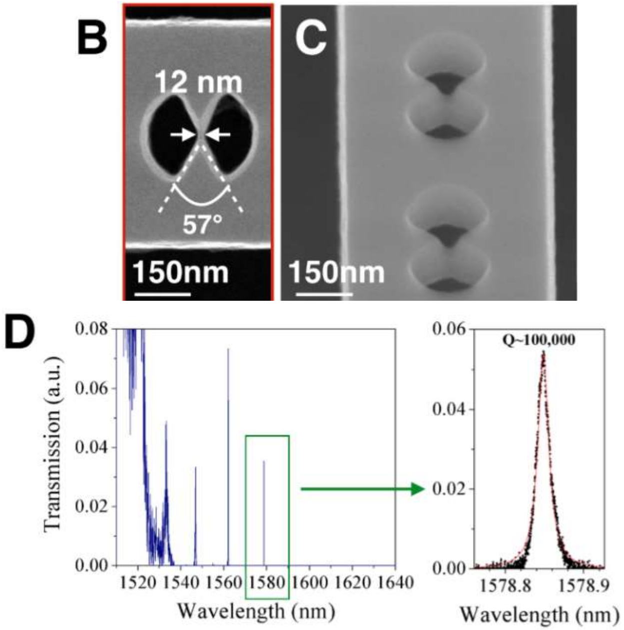
# nano-LED

- Temperature ”insensitive”. Thresholdless
- Small mode volume is key to speed $<0.1(\lambda/2n)^3$
- Can be achieved by metals or special cavities
- Passivation, injection and enough photons key issues.



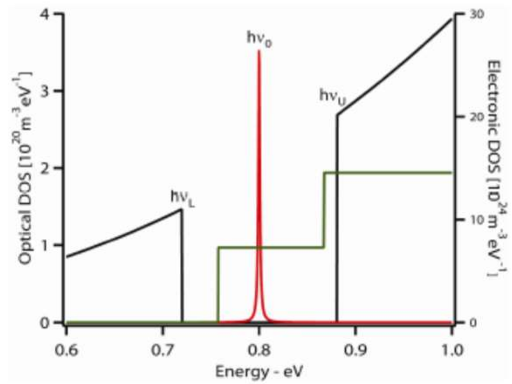

**Self-Similar Nanocavity Design with Ultrasmall Mode Volume Single Photon Nonlinearities**
Hyeongrak Choi, Mikkel Heuck and Dirk R. Englund

*PRL* **2017** 118, 223605




**Experimental Realization of Deep Subwavelength Confinement in Dielectric Optical Resonators**

Shuren Hu et al *arXiv:1707.04672*



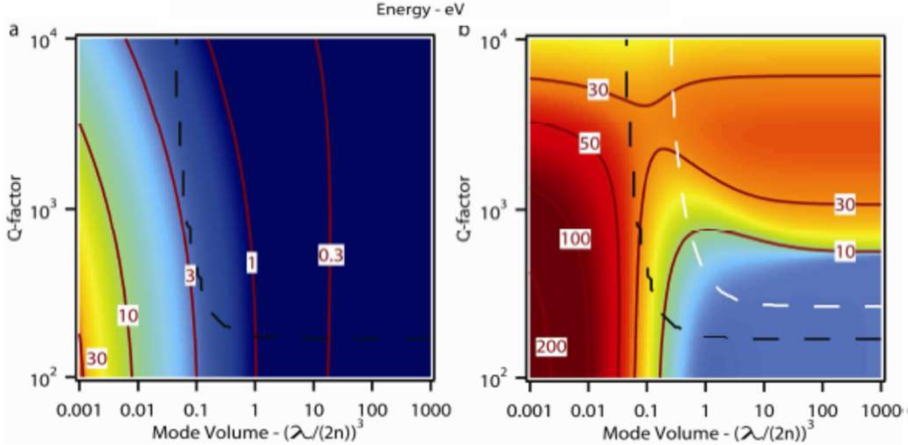




Fig. 4. The 3dB-bandwidth for a) $J = J_0$ and b) $J = 100\ J_0$. The red lines are contours of equal 3dB-bandwidth in GHz. The black line separates the potential laser devices from the LED devices and the white line indicates which of the laser devices that have larger stimulated emission than spontaneous emission at the given pump.

#126340 - $15.00 USD Received 31 Mar 2010; revised 6 May 2010; accepted 9 May 2010; published 12 May 2010

24 May 2010 / Vol. 18, No. 11 / OPTICS EXPRESS 11230

# Detectors

- PiN junction very small ideally <100nmx100nm (i~300nm)
- Must be extremely close to FET (or other thresholding electronics)

- Should be plasmonic or photonic crystal?

- Plasmonic: low Q (broadband). Losses acceptable (?). Will pick up large amounts of vacuum fluctuations (?)

- Photonic crystal: Can PhC shield vacuum fluctuations (lower dark current).

- Dark noise probably does not matter if we receive >X00photons/bit.
- What if we want to make a detector for few photons >10/bit?

# Technology

- Must be compatible with silicon tools and have ridiculous high yield…

# ”Classical” monolithic integration

InP based

Multiple regrowth steps to create multiple active functionalities

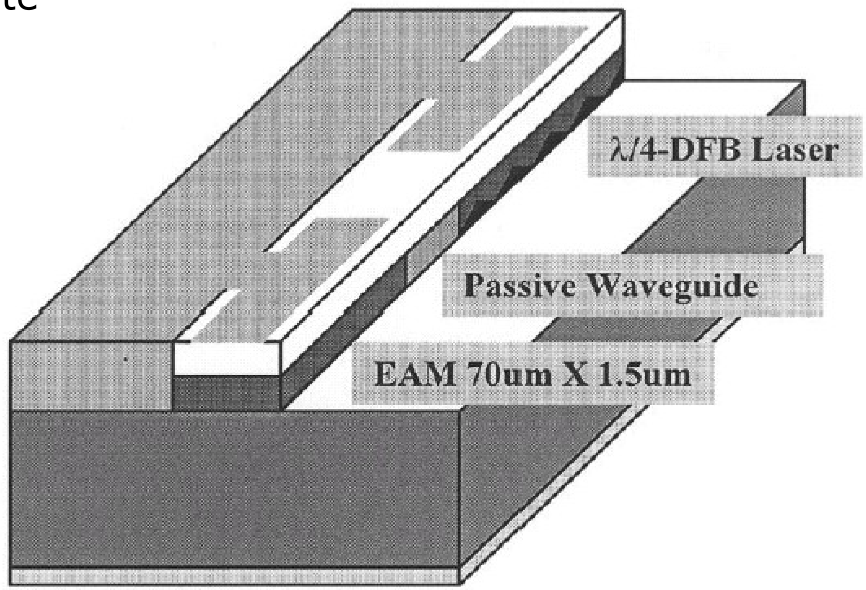
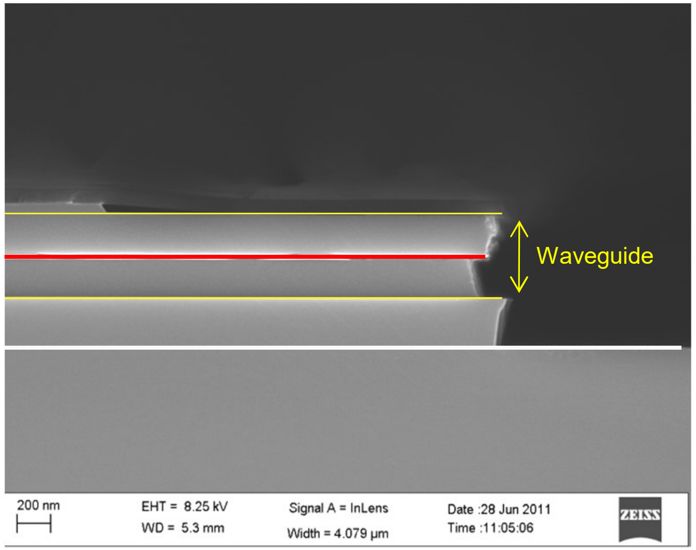


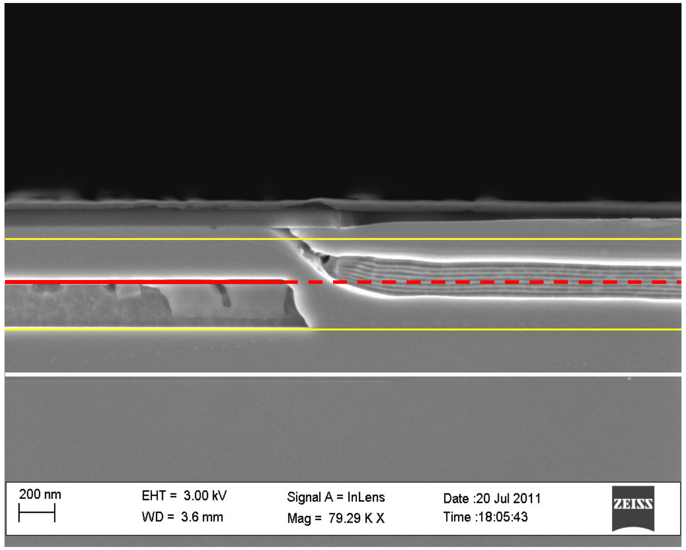

Fig. 1. Structure of the EML.

Electroabsorption modulated laser (EML)

# Our (Irina's) results

- Single QW and MQW buttcoupling.
  - InAlGaAs/InGaAsP



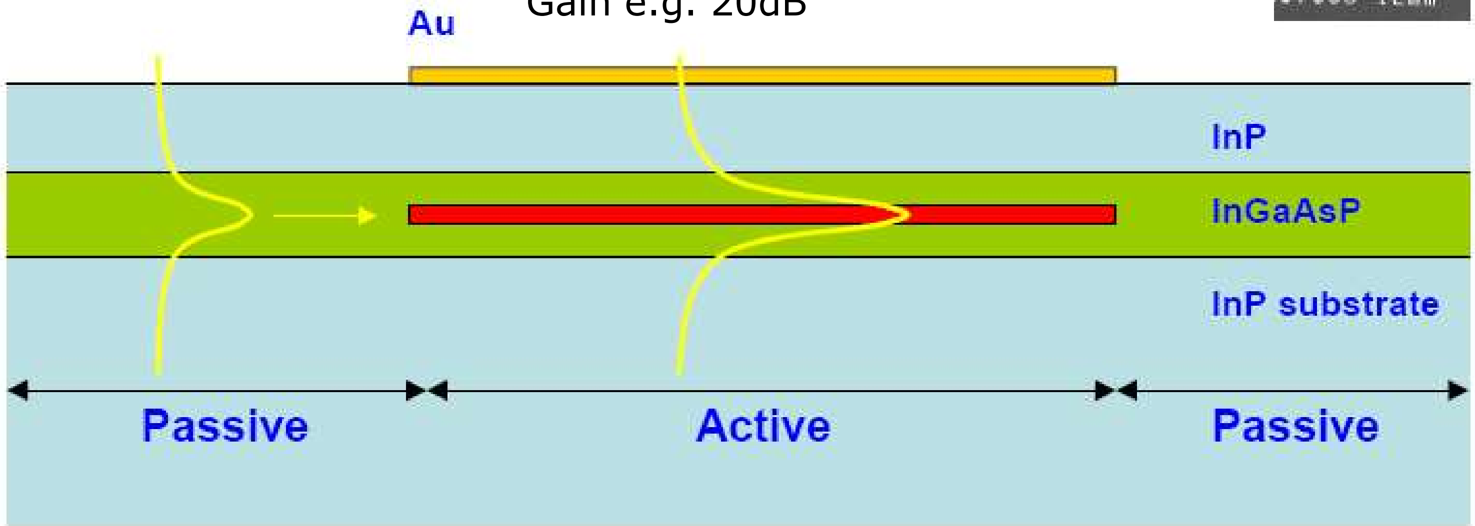



# Mode matching problem

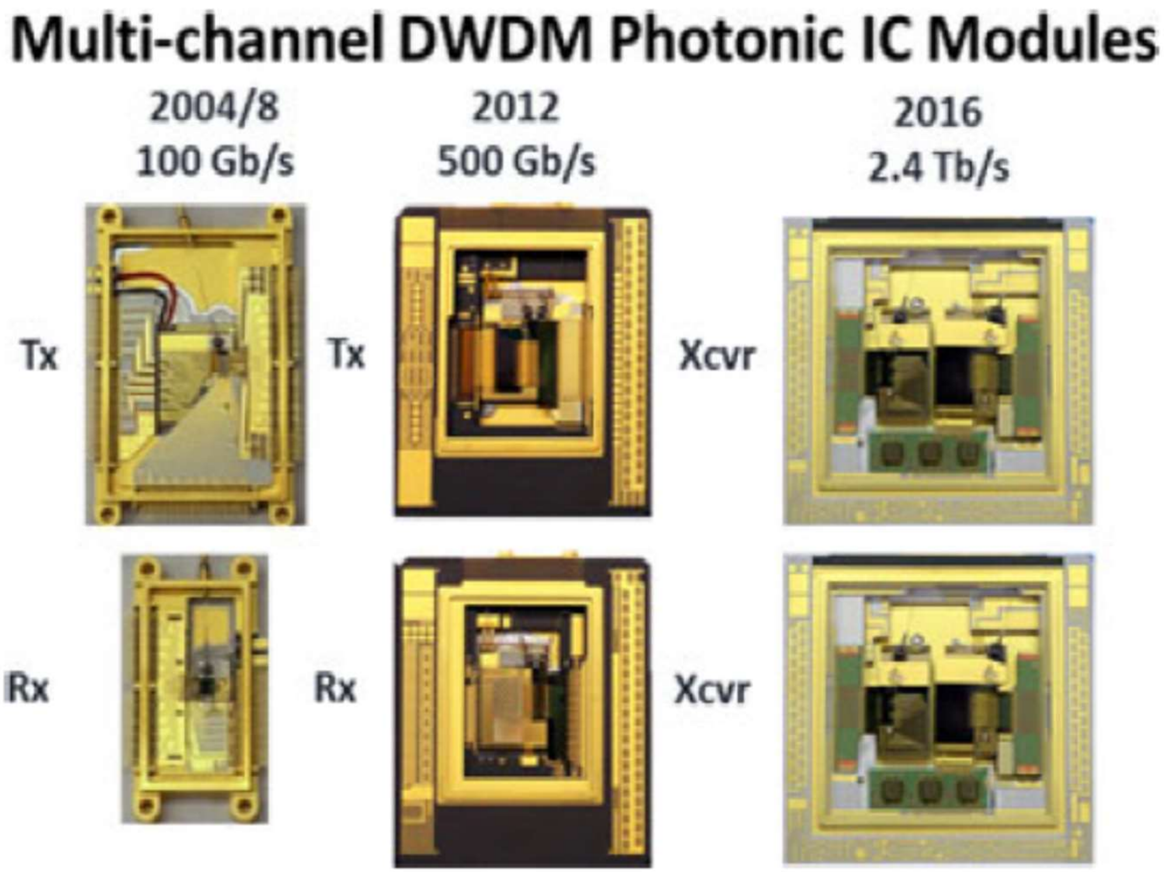
- Which is worse?
  - Loss
  - Reflections

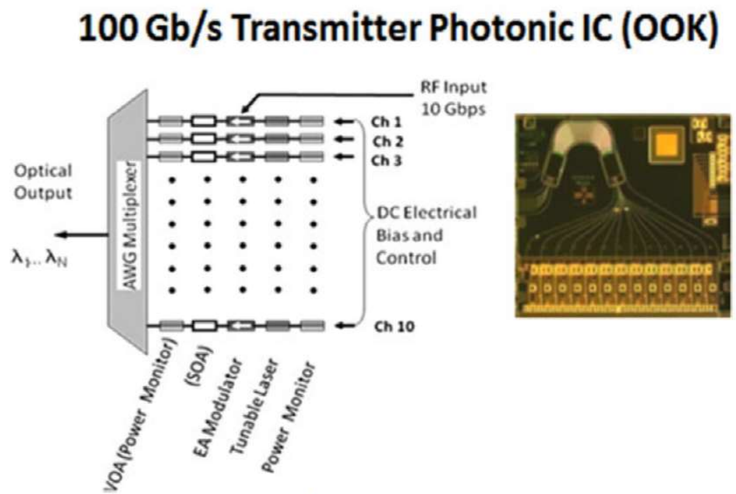
Semiconductor optical amplifier (SOA)

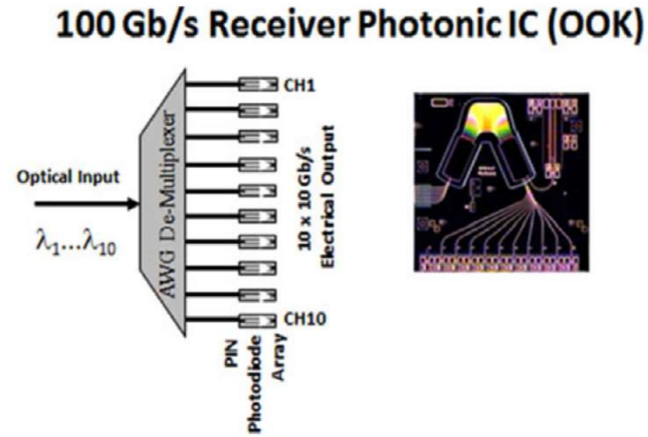
Gain e.g. 20dB



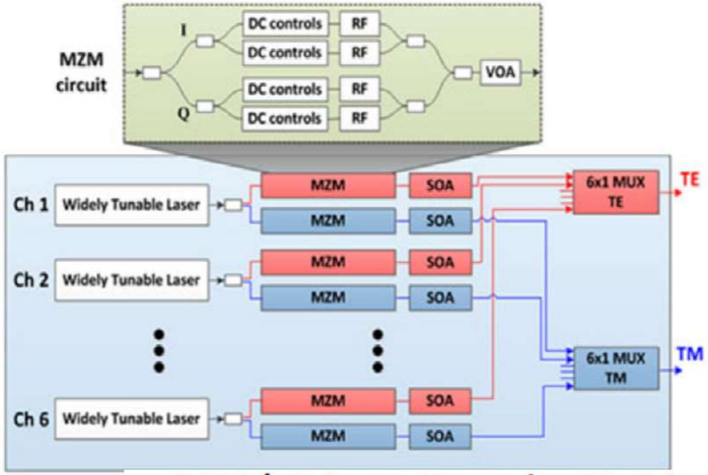
# First major commercial PIC (2004) Infinera (US) 10x10Gbit/s



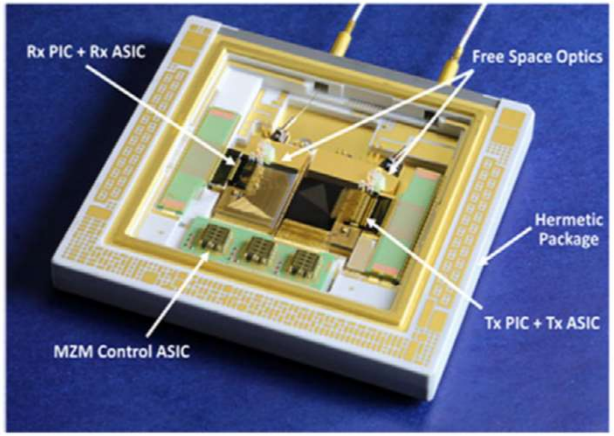



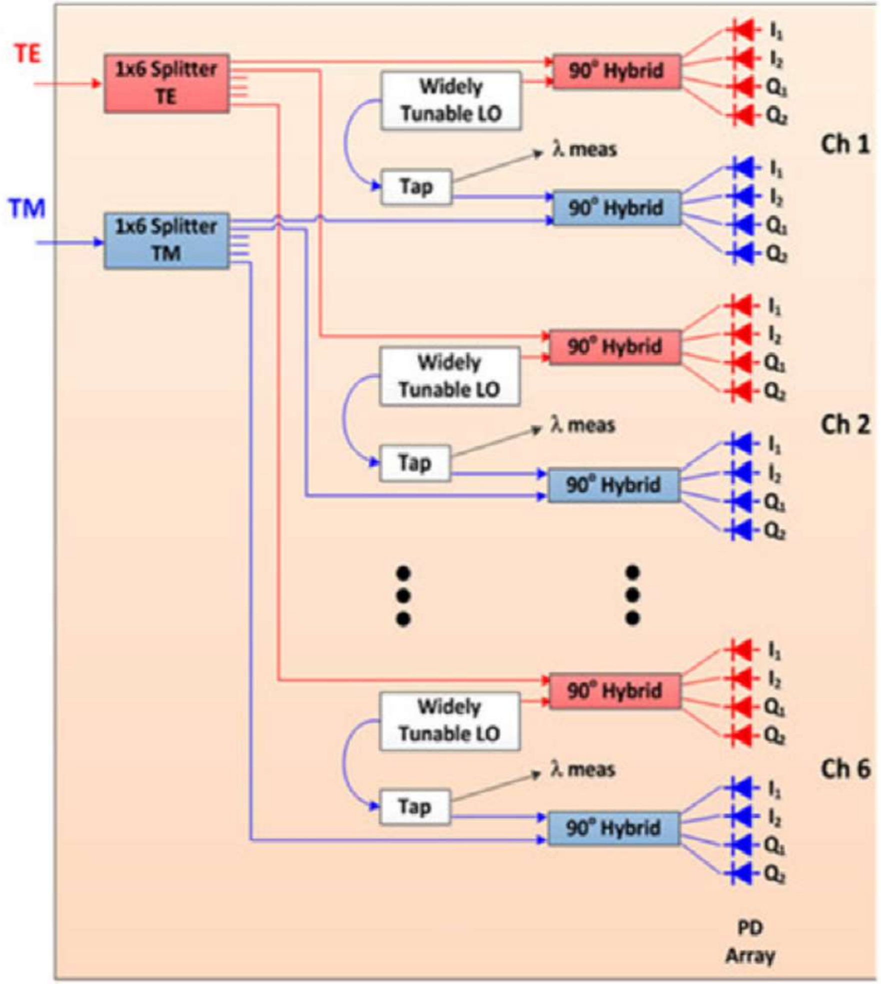
## 1.2 Tb/s Transmitter Photonic IC (PM 16-QAM)




1.2 Tb/s Coherent Transceiver Module
(6 channels x 200 Gb/s, PM 16-QAM)

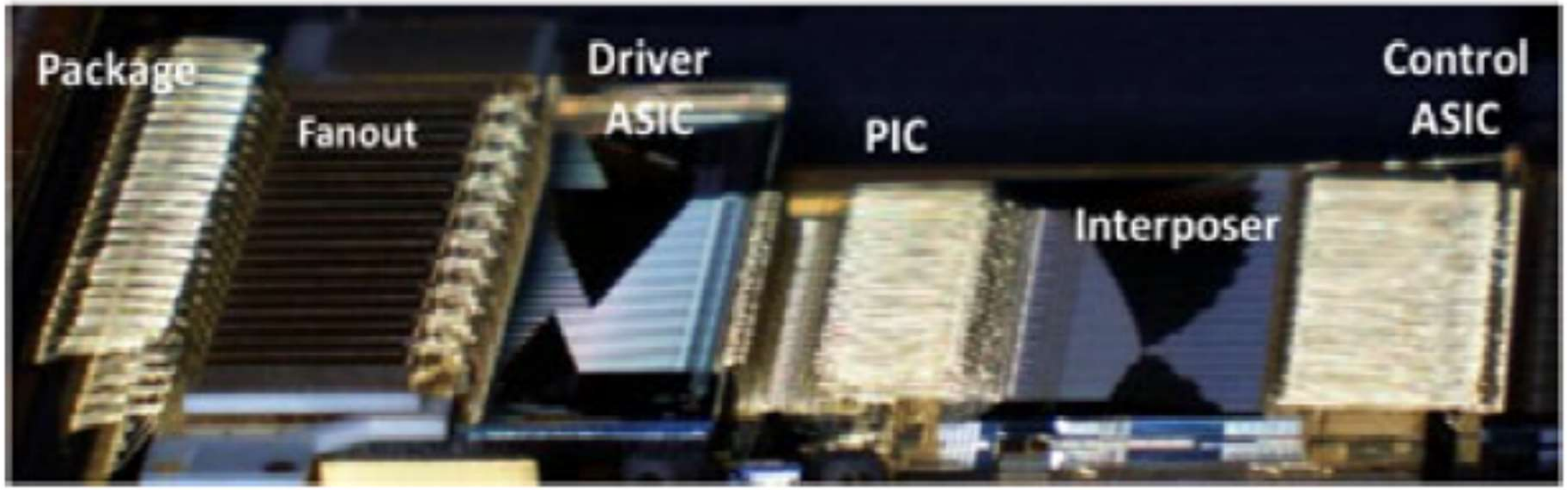



## 1.2 Tb/s Receiver Photonic IC (PM 16-QAM)



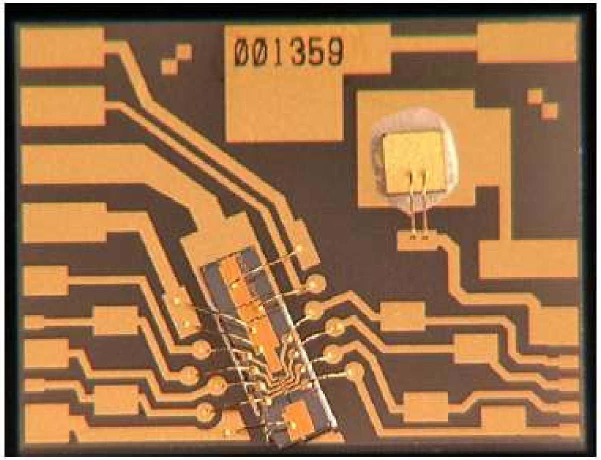
# Interfacing

## 500 Gb/s Multi-Channel PIC Transmitter Module



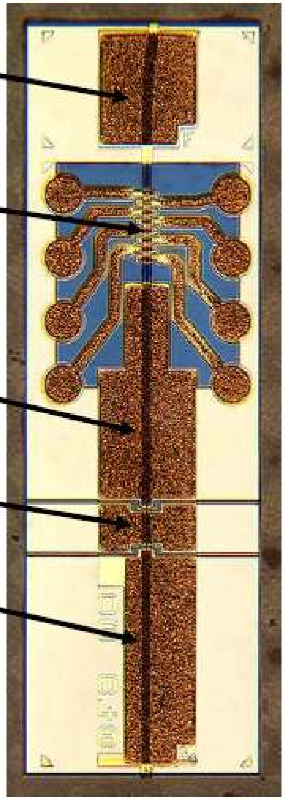

- 5 layers of DC interconnects !
- 40 modulators

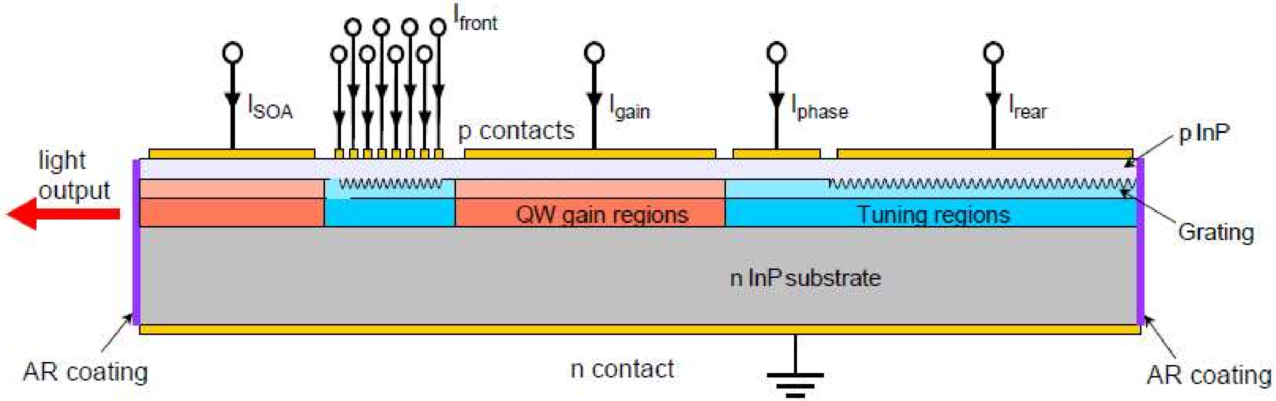
# DS-DBR laser overview




Chip-on-tile based solution for angled waveguide output

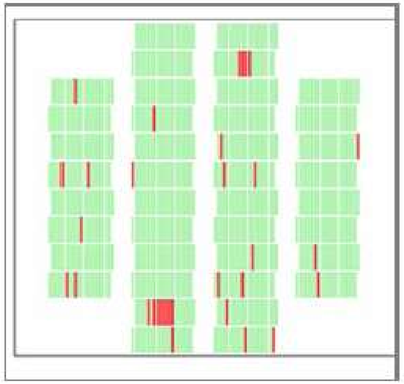
- SOA to boost o/p power, provide power control and shuttering
- Front chirped grating
  - Multiple contacts provide local reflection enhancement to select supermodes
- MQW gain section
  - Generates light inside cavity
- Phase section
  - Fine wavelength tuning
- Rear phase grating
  - Generates comb of 7 reflection peaks

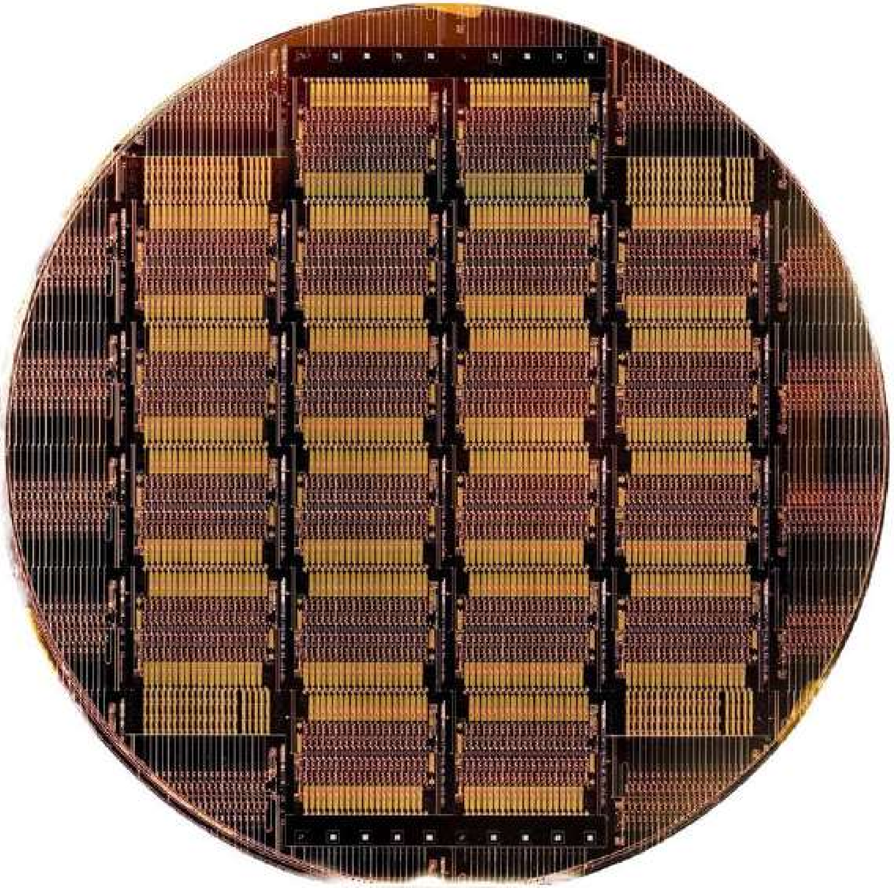




## Multifunction Photonic Integrated Circuits (PICs)

- Monolithic Laser + Modulator chip for Tunable XFP module
- ~1000 chips per wafer
- Batch processed
- 3” InP wafers
- On wafer tested
- Scalable





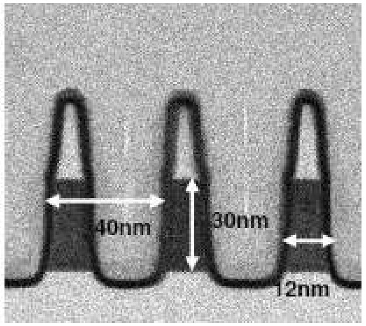
Oclaro’s photonic integration technology is built on work done over >20 years, supported in significant measure by collaborative programmes (EC, DTI/TSB)

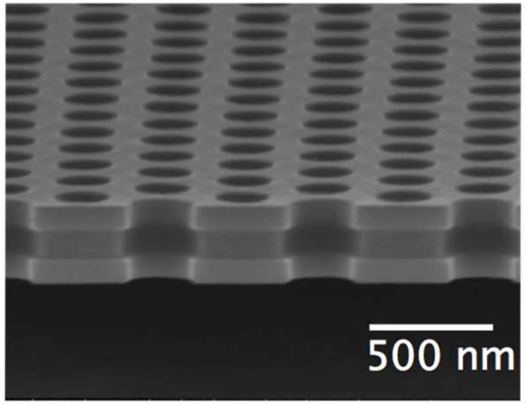
- Impressive yield, but not good enough for optical interconnects

# Silicon photonics

- Use depreciated CMOS fabs
- Large strong wafers 200-300mm diameter.
- Fully automated
- Extremely good lithography (small structure definition)
    - Optical structures are much bigger than electrical gates but require extreme precision (few nm).

| | |
|---|---|
| Vdd (V) | 0.9 |
| Lg (nm) | 20-30 |
| Gate Pitch (nm) | 80-100 |
| Fin Pitch (nm) | 40 |
| Dfin (nm) | 12 |
| Hfin (nm) | 30 |

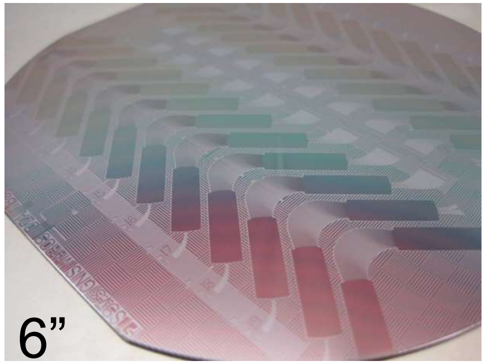



- Unfortunately silicon is not the ideal optical material.

# Material platforms for planar photonics (commercial)

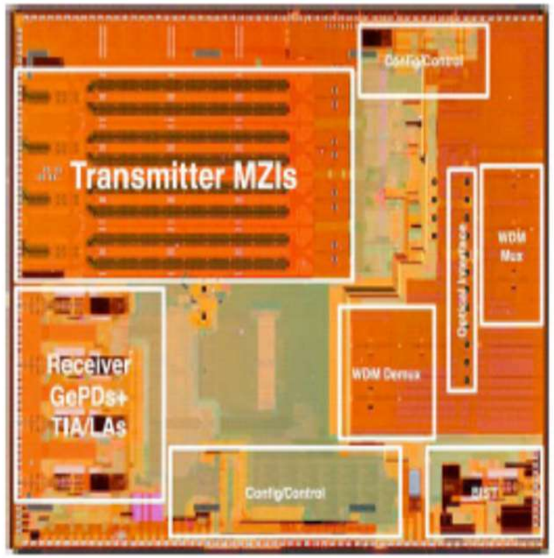
- Index contrast determines size of devices



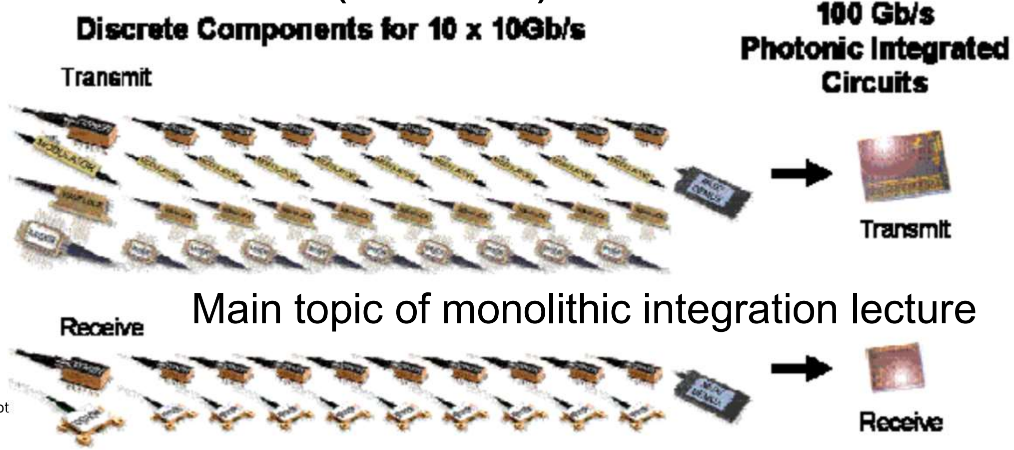

Silica (Accelink, Farum)
$\Delta n \sim 0.015$

(Lithium Niobate)

Silicon (Luxtera), $\Delta n \sim 2.5$



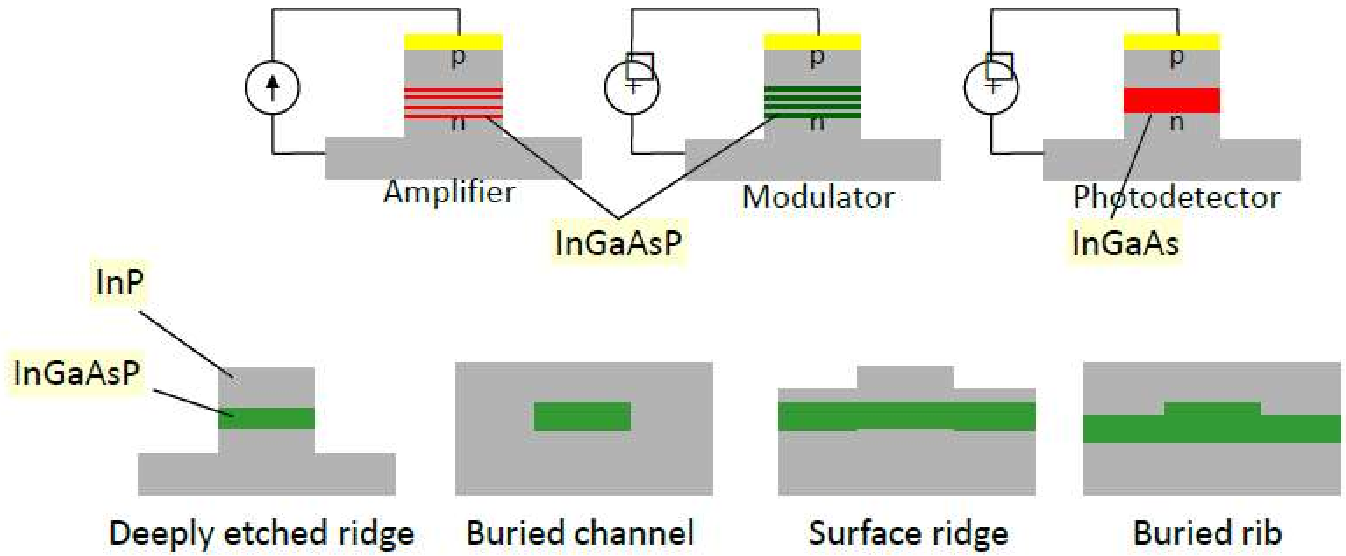

InP (Infinera), $\Delta n \sim 0.02\text{-}2.2$




Main topic of monolithic integration lecture

# InP family

www.acacia-inc.com




~1 dB/cm

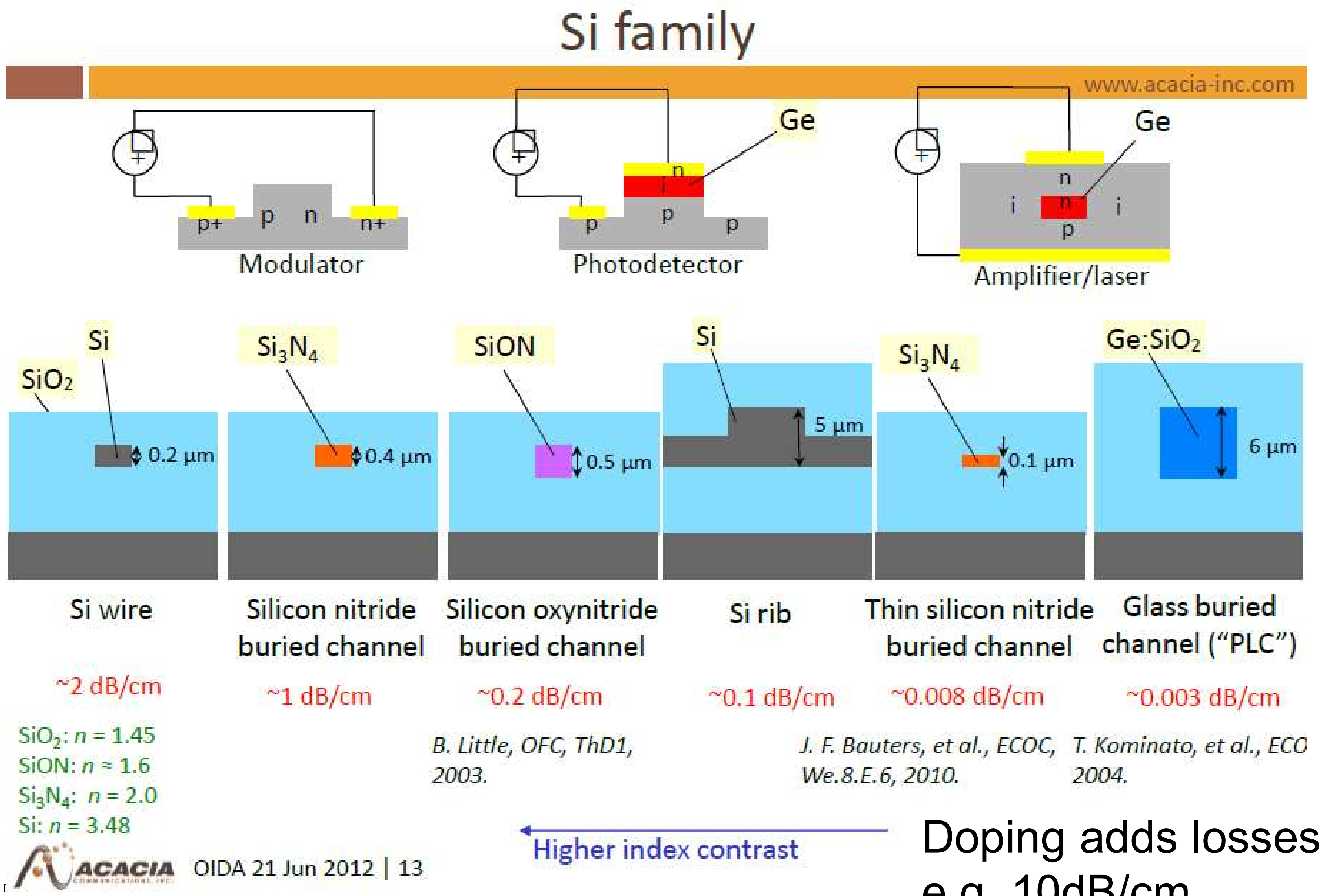
~0.2 dB/cm

InP: $n = 3.17$
InGaAsP: $n \approx 3.47$

Higher index contrast

Doping adds losses
e.g. 10dB/cm

ACACIA OIDA 21 Jun 2012 | 12



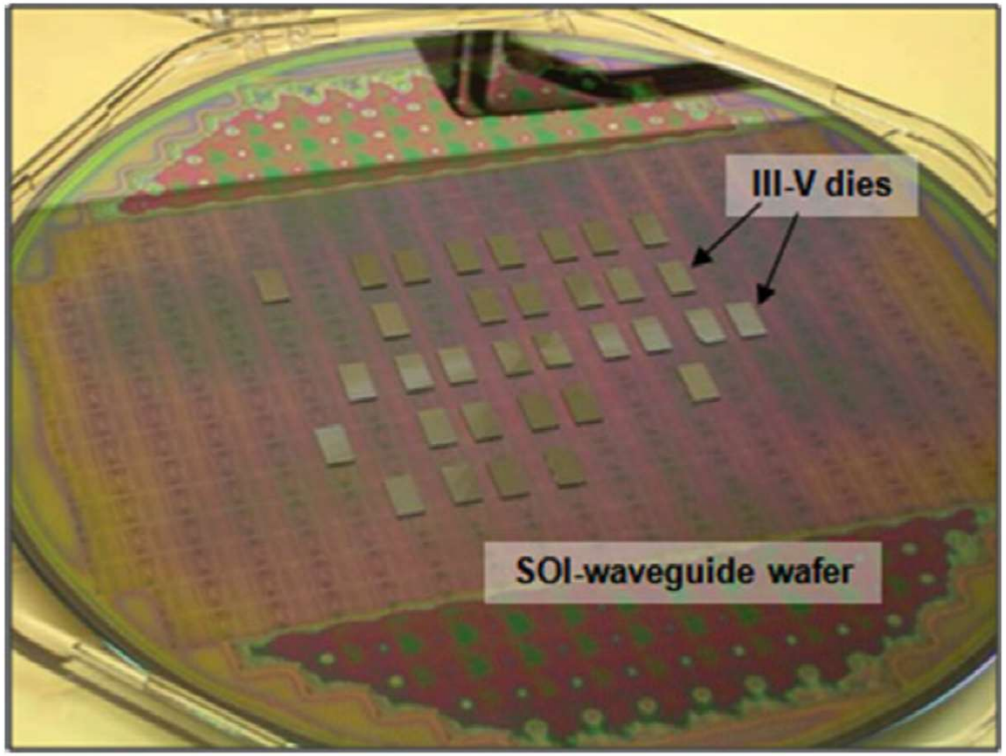

Doping adds losses
e.g. 10dB/cm

# Why silicon (on insulator)

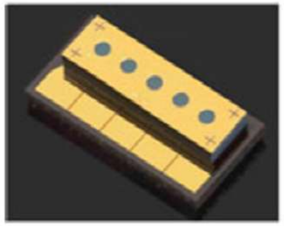
- ”CMOS compatible”
  - Use of existing manufacturing infrastructure
  - Large rigid wafers for automated wafer handling
- High index contrast
  - Very small components (bend radius <5μm)
  - SOI wafers with thin (100-400nm) Si layer can be purchased (easy etch)
  - “New possibilities”
- Many obstacles to overcome
  - Coupling
  - Polarization
  - Backscattering (unwanted reflections)
  - Weak interaction with light
    - New materials added: Ge, III-V
    - Resonant structures (rings, cavities,…)
      - Problem manufacturing tolerances, temperature
  - Manufactoring (Si photonics is sold as good for manufacturing, but the hybrid platforms are quite complicated structures)

# Heterogeneous integration

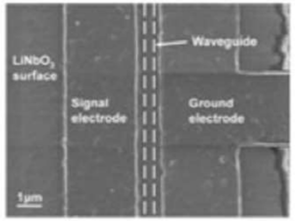
Add active only where needed (+ III-V wafers smaller than SOI)
Choose best material for application



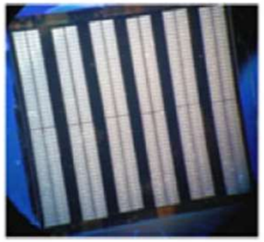

GaAs



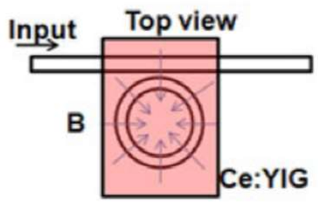
$LiNbO_3$



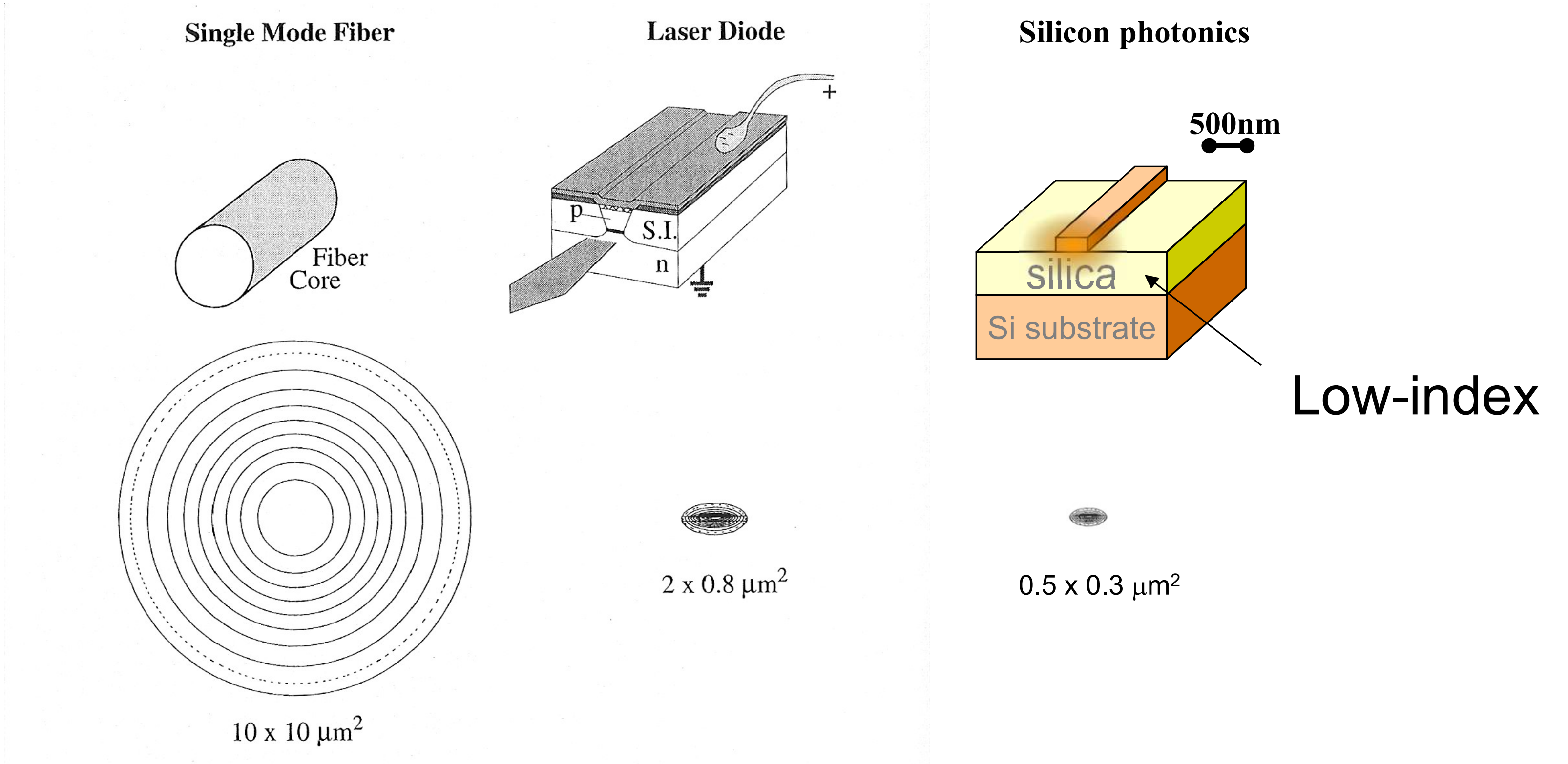

InP



Ce:YIG Isolator



# Silicon photonics: Mode-matching

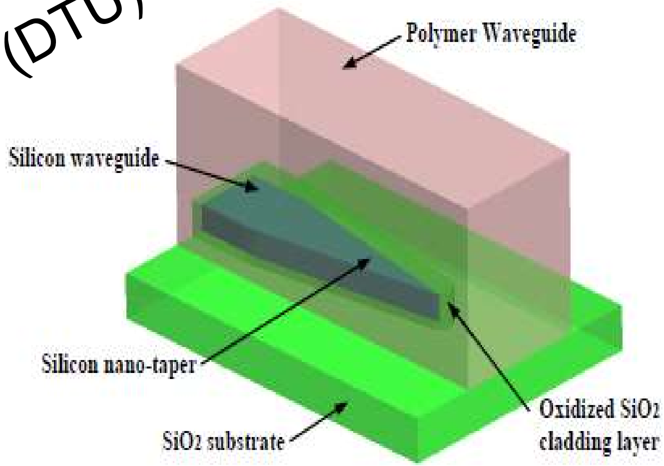



- Seems to be going the wrong way?

# Couplers to nanowires

- Inverse taper coupler

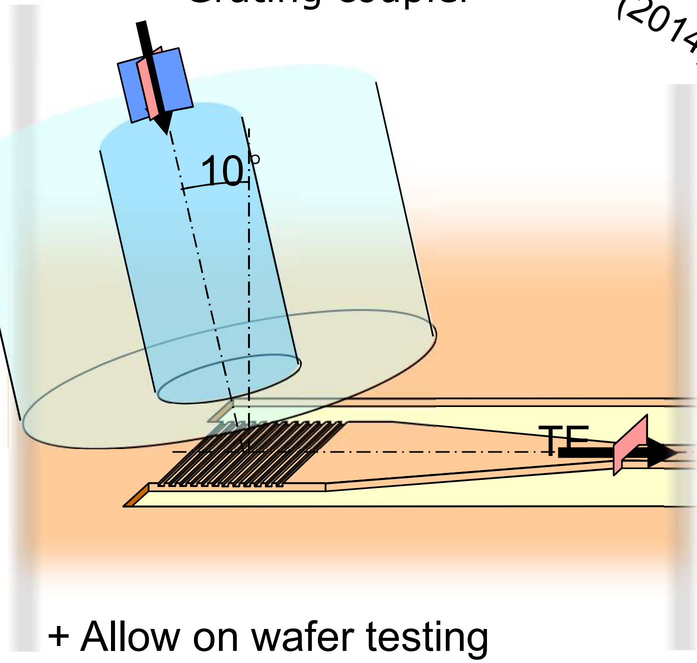
M. Pu (DTU)




+ Good performance >90% (TE&TM)
+ Low wavelength dependence
+ Low reflection
- To tapered fibres (~0.5dB extra loss)
- Extra processing
- Large e.g. 300um
- Has to be at edges of chip

Yunhong Ding (DTU)
>85% with single etch depth and bottom mirror (2014)

- Grating coupler

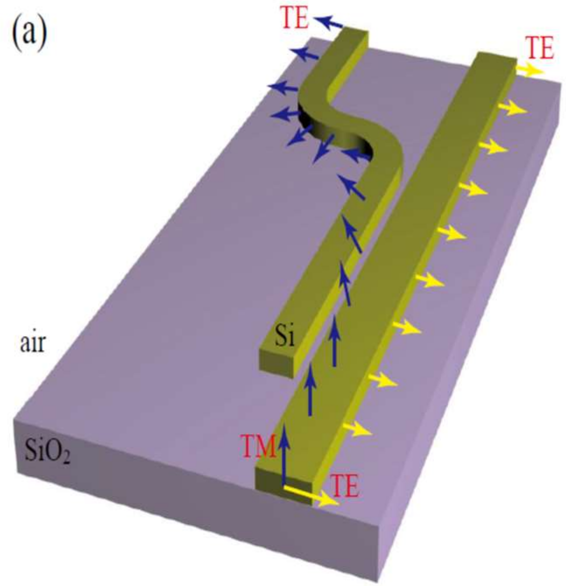


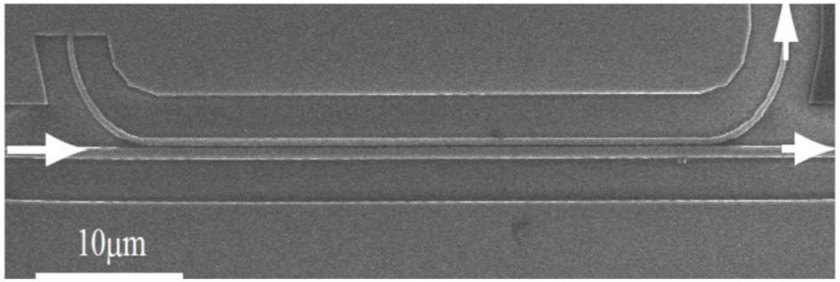

+ Allow on wafer testing
+ To cleaved fibers
- Extra processing for best performance

- Polarization dependent
- Limited bandwidth

# Polarization

- For asymmetric cladded waveguides it is possible to phasematch the TM mode in one waveguide with the TE in the adjacent waveguide
  - Polarization splitter and rotater in the same device
- Polarization diversity

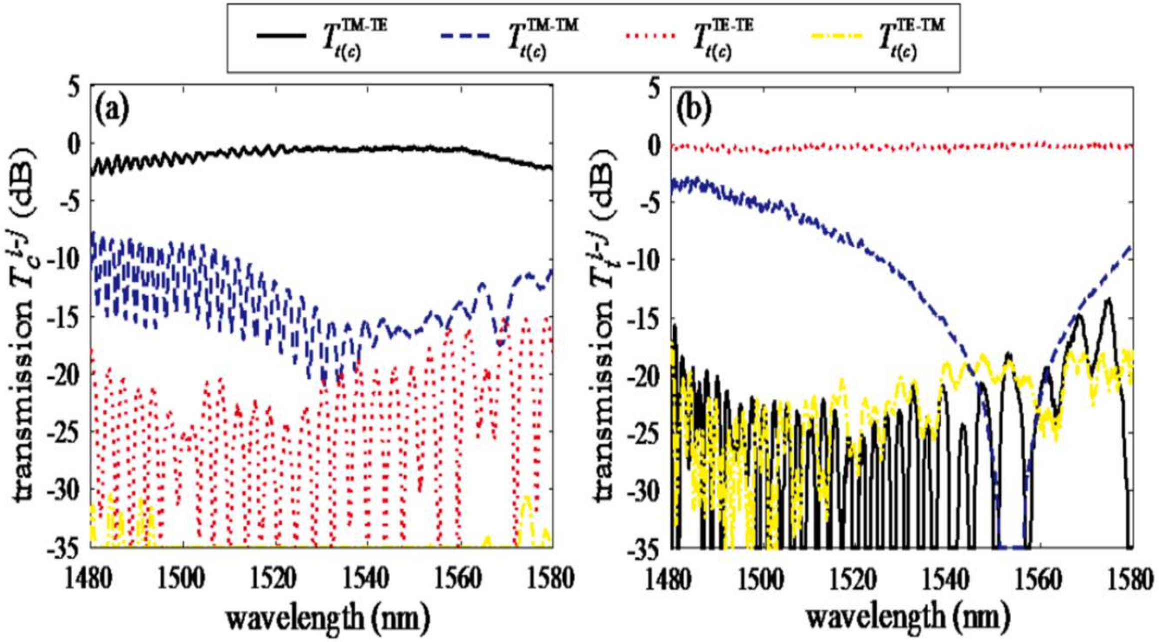



**Silicon-on-insulator polarization splitting and rotating device for polarization diversity circuits**

Liu Liu,[1,2,*] Yunhong Ding,[2,3] Kresten Yvind,[2] and Jørn M. Hvam[2]

20 June 2011 / Vol. 19, No. 13 / OPTICS EXPRESS 12646



# Time for break

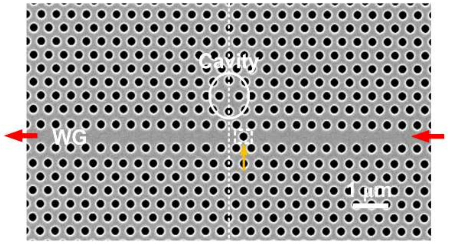
- Questions?

# Two basic research centers

NAnophotonics
for TErabit
Communications

VILLUM FONDEN

Jesper Mørk

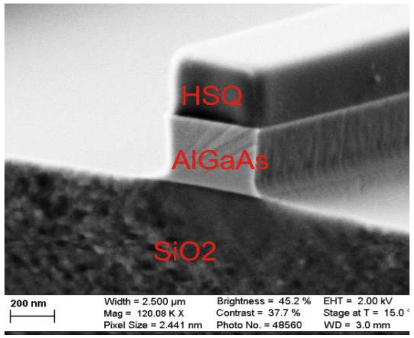



Photonic crystals for ultralow energy pr bit. ”new physics”.

Minimal footprint and energy

Danmarks Grundforskningsfond
Danish National Research Foundation

Leif Katsuo Oxenløwe



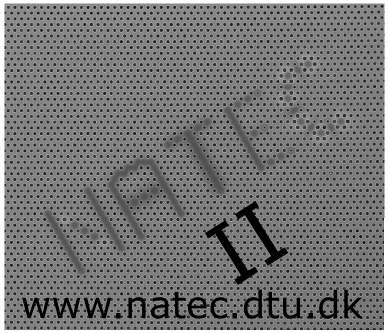

Photonic nanowires for ultrabroadband control and creation of optical data signals.

Maximal bandwidth pr. chip.

# InP membrane photonic crystal devices

Kresten Yvind, Yi Yu, Dagmawi Bekele, Thorsten S. Rasmussen, Aurimas Sakanas, Andrey Marchevsky, Kristoffer S. Mathiesen, Alexandra Lupi, Hitesh K. Sahoo, Luisa Ottaviano, Elizaveta Semenova, and Jesper Mørk

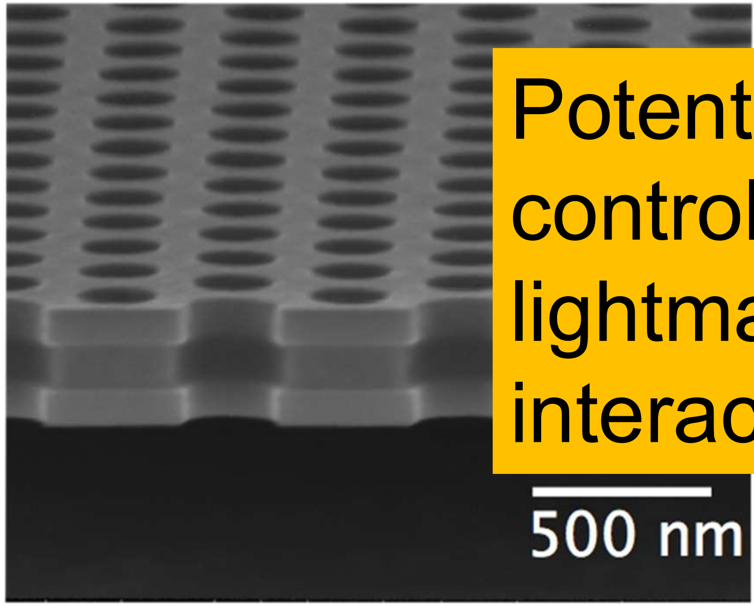
DTU Fotonik
Department of Photonics Engineering




VILLUM FONDEN

**Tools:**

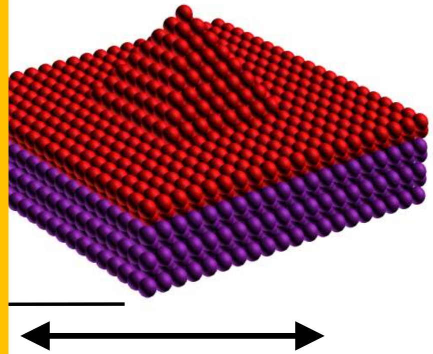
**Photonic crystal slabs**



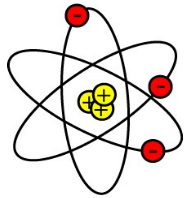

Potentially full control of lightmatter interaction

Allows confinement and control of the **light** (optical density of states)

**Quantum structures**

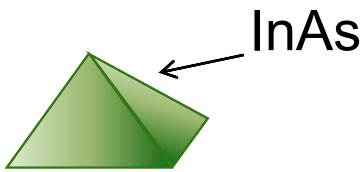



Allows confinement and control of **electronic states** (density of states and interaction)



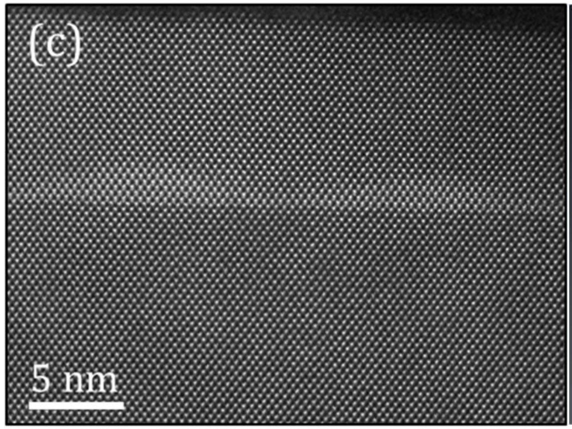
*www.natec.dtu.dk*

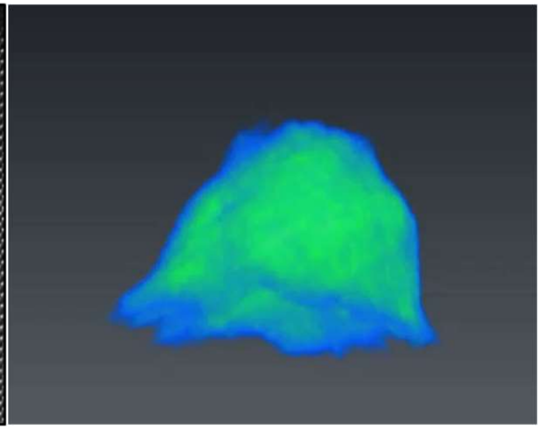
# Quantum dot shape manipulation (w. DTU CEN)

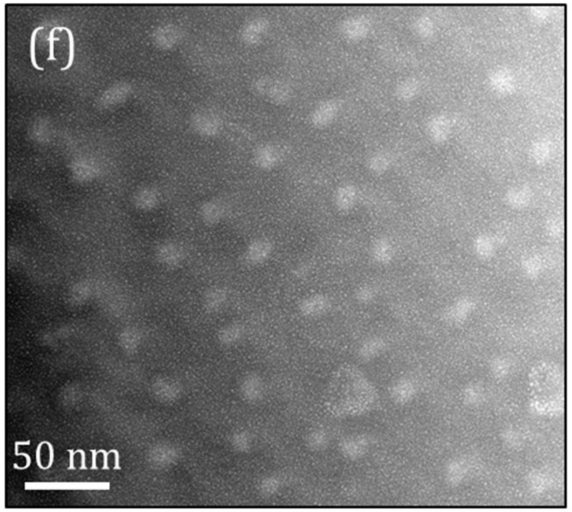



1.65ML InAs/InP

$T_{growth}$=485°C



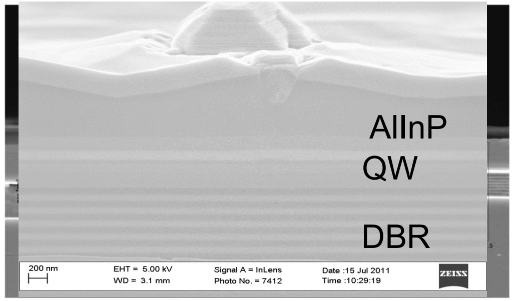





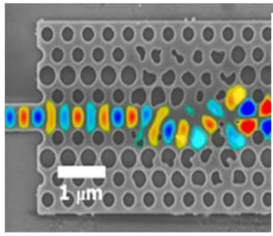

**Elizaveta Semenova, Kresten Yvind, Shima Kadkhodazadeh (CEN)**

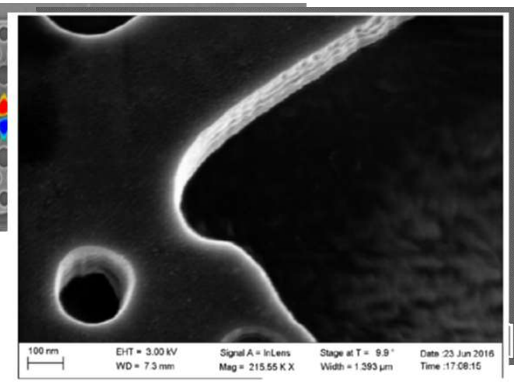
# Key technologies

- Materials growth

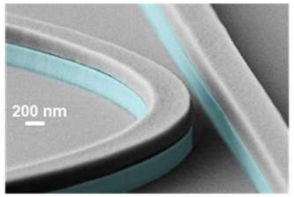



- E-beam lithography

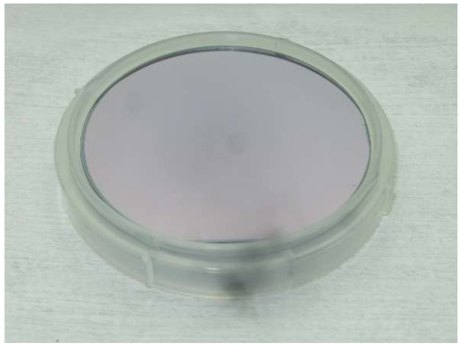


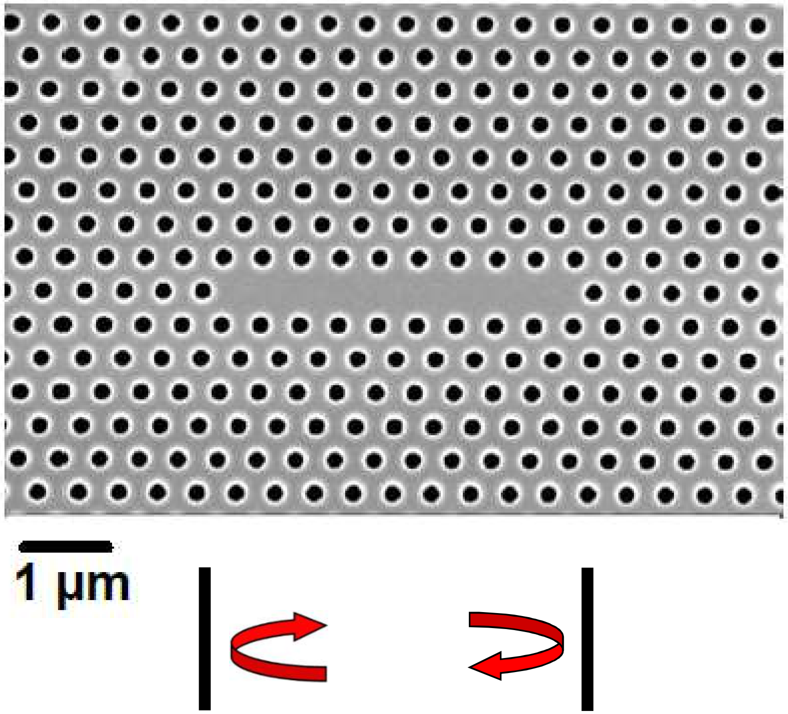

- Dry etching




- Wafer bonding



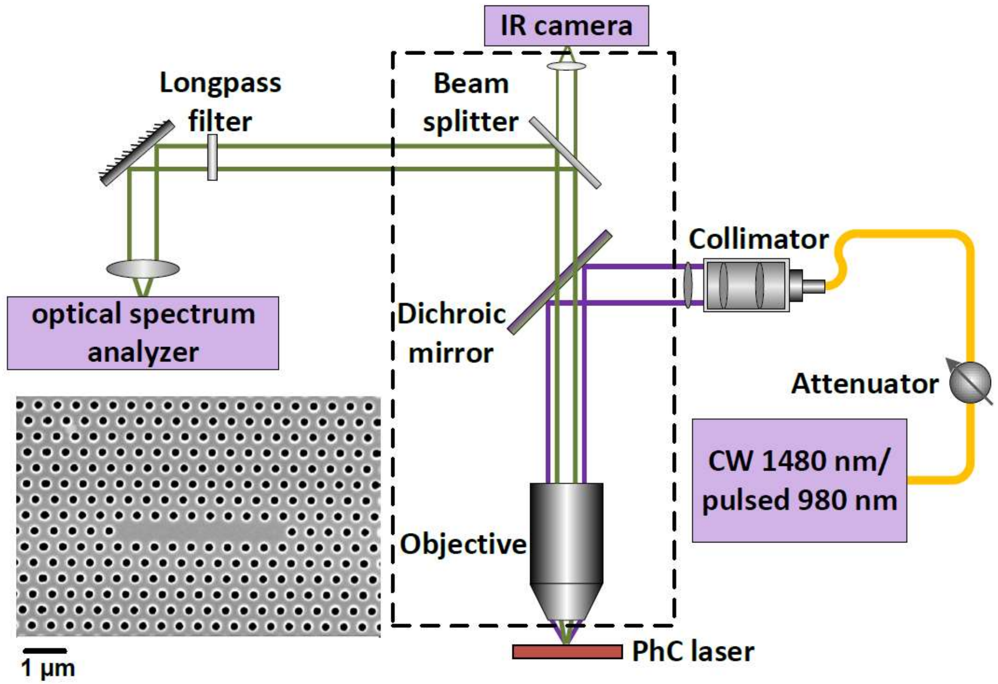
# Photonic crystal laser

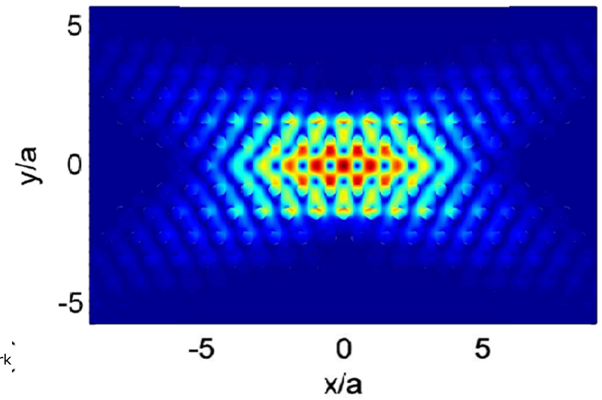


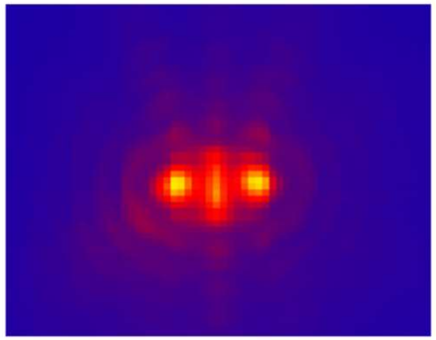

InP membrane,
3 layers of InAs
quantum dots

Can slow-light effects be used to decrease the threshold gain?

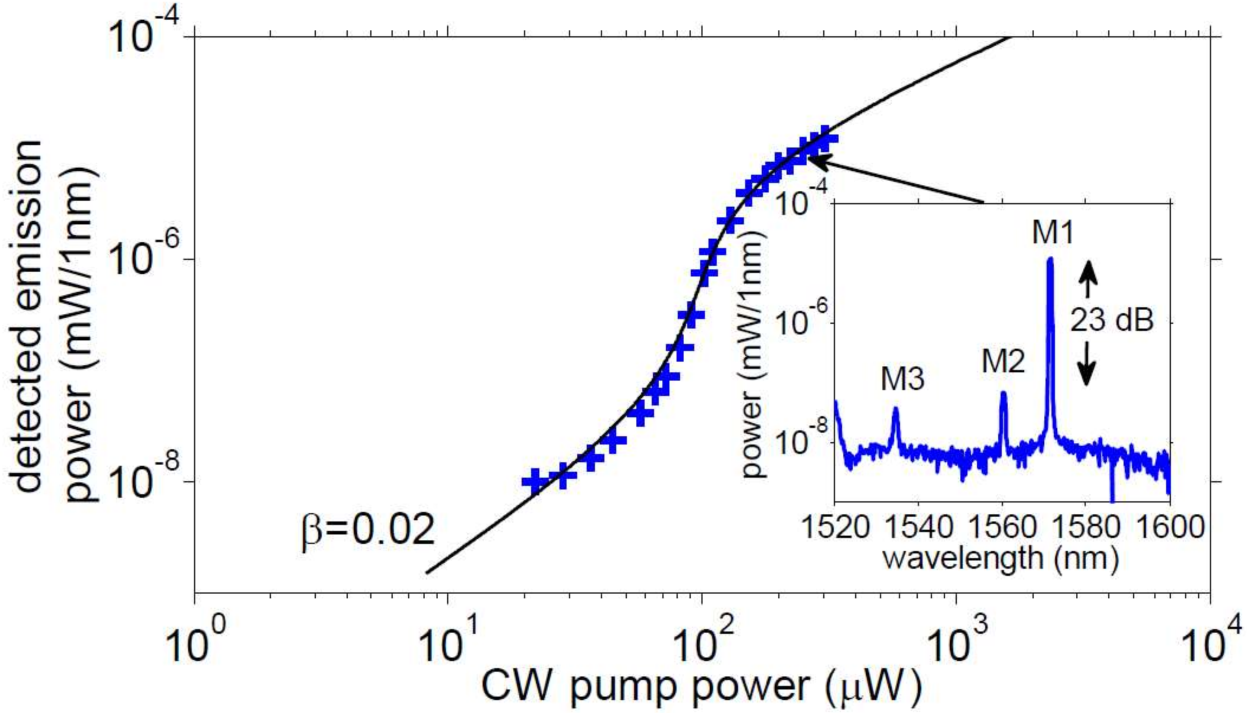
# Experimental set-up



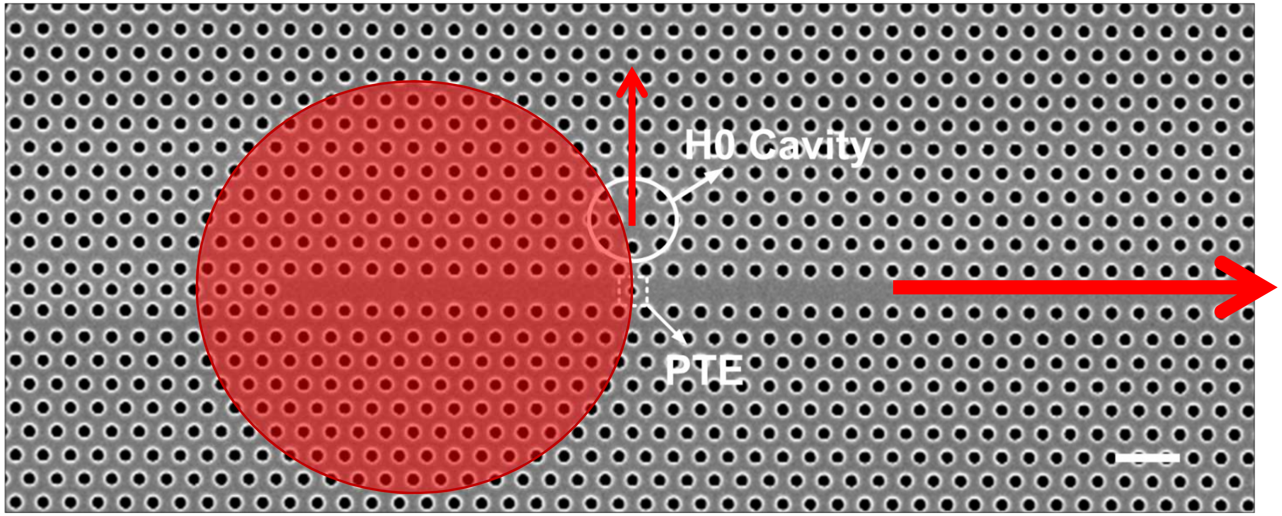



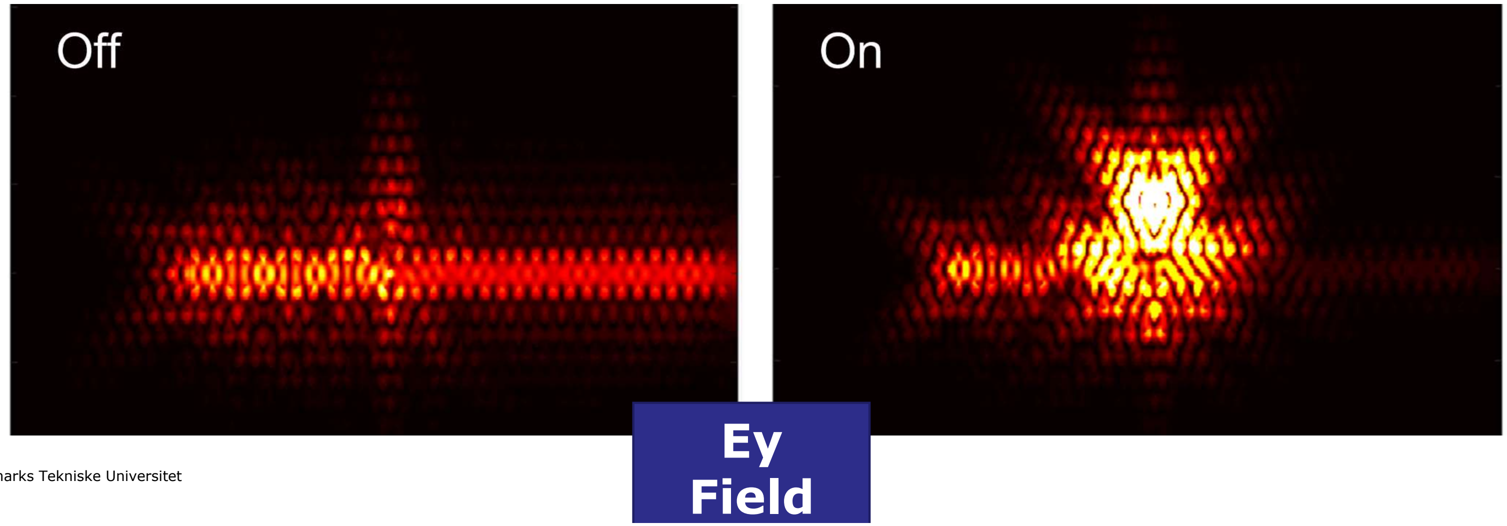
# Lasing characteristics



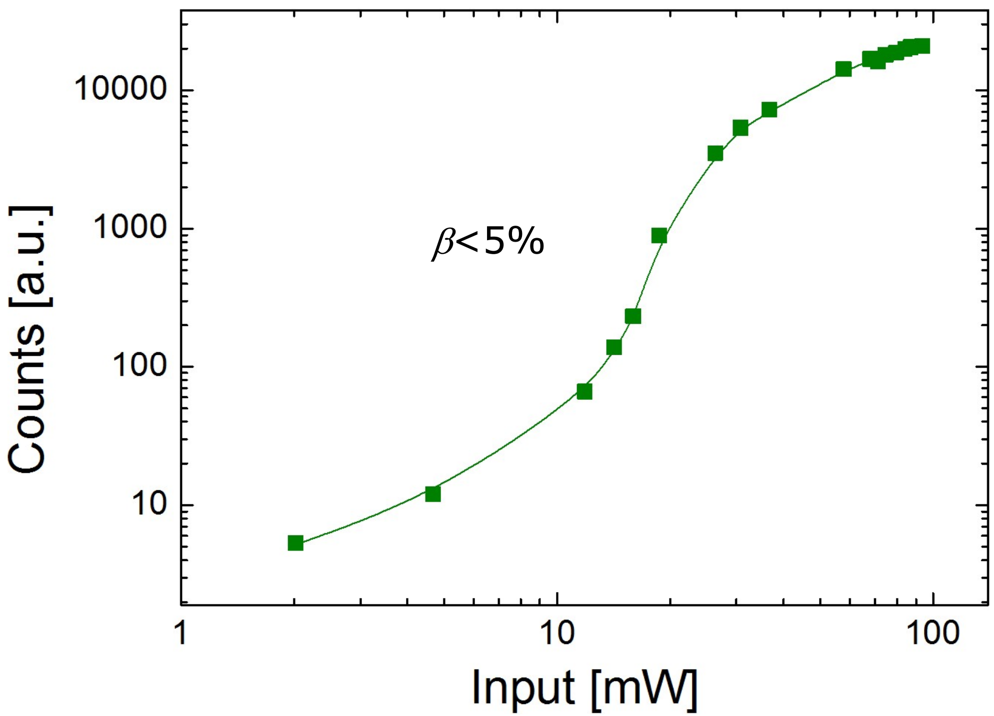

- Clear onset of lasing
- Several competing longitudinal modes

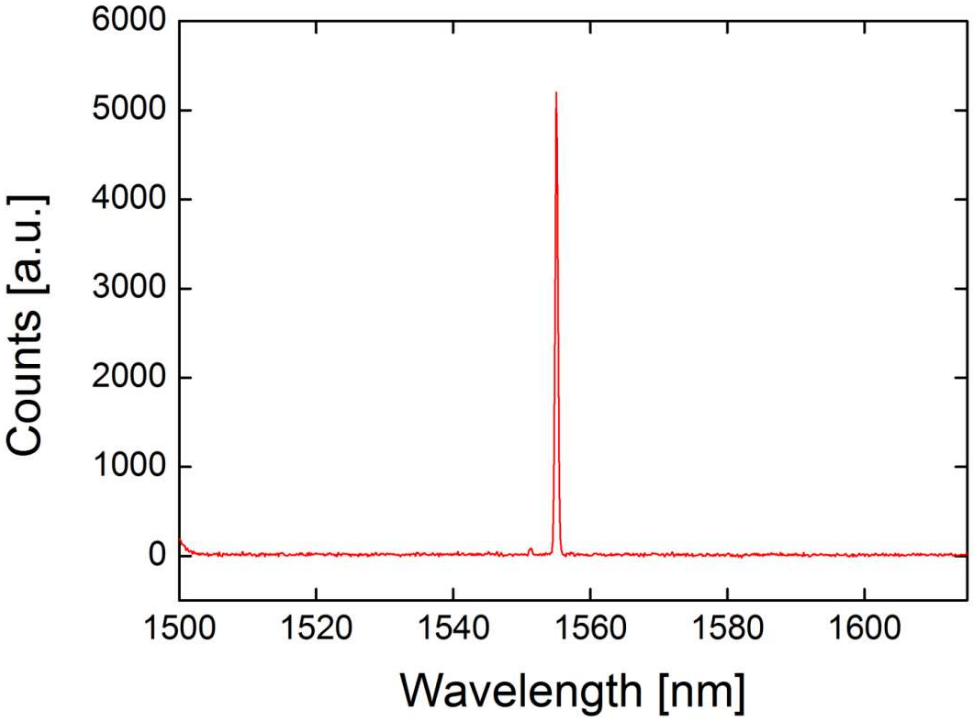
# ”Fano laser” geometry



# Lasing at room temperature

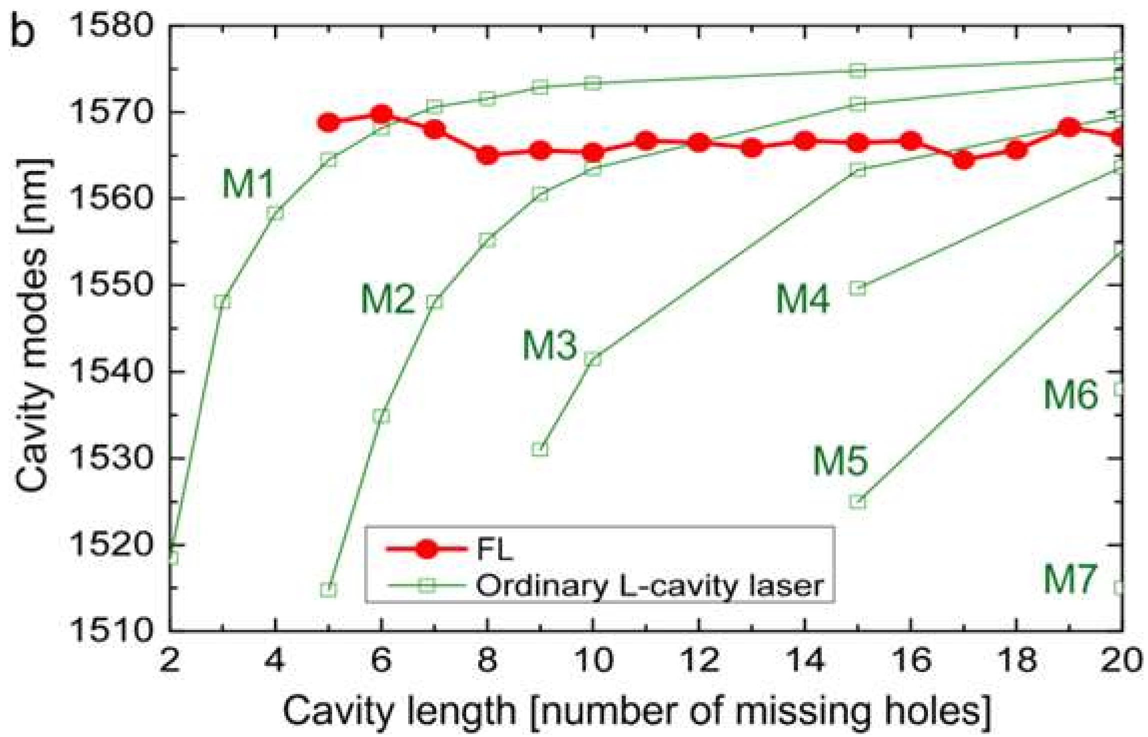


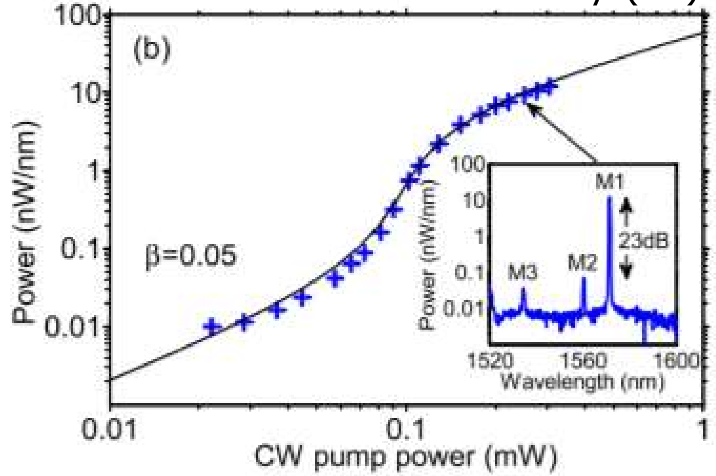

CW optical pump @ 1480 nm

*Yu et al.*, Nature Photon. **11**, 81 (2017)

# Mode variation with cavity length




Standard line defect cavity (L5)




**Fano laser:** Only a single mode, frequency determined by nanocavity, independently of length:, Yu, Y. et al. Nature Photonics, 11(2), 81-84 (2017)

**Ordinary PhC laser:** Several modes, mode frequencies change with cavity length:, *Xue et al.,* PRL **116**, 063901 (2016).

VILLUM FONDEN

# Buried-Heterostructure Technology for Photonic Crystal Lasers

Aurimas Sakanas, Yi Yu, Kristoffer S. Mathiesen, Elizaveta Semenova,
Luisa Ottaviano, Jesper Mørk, Kresten Yvind

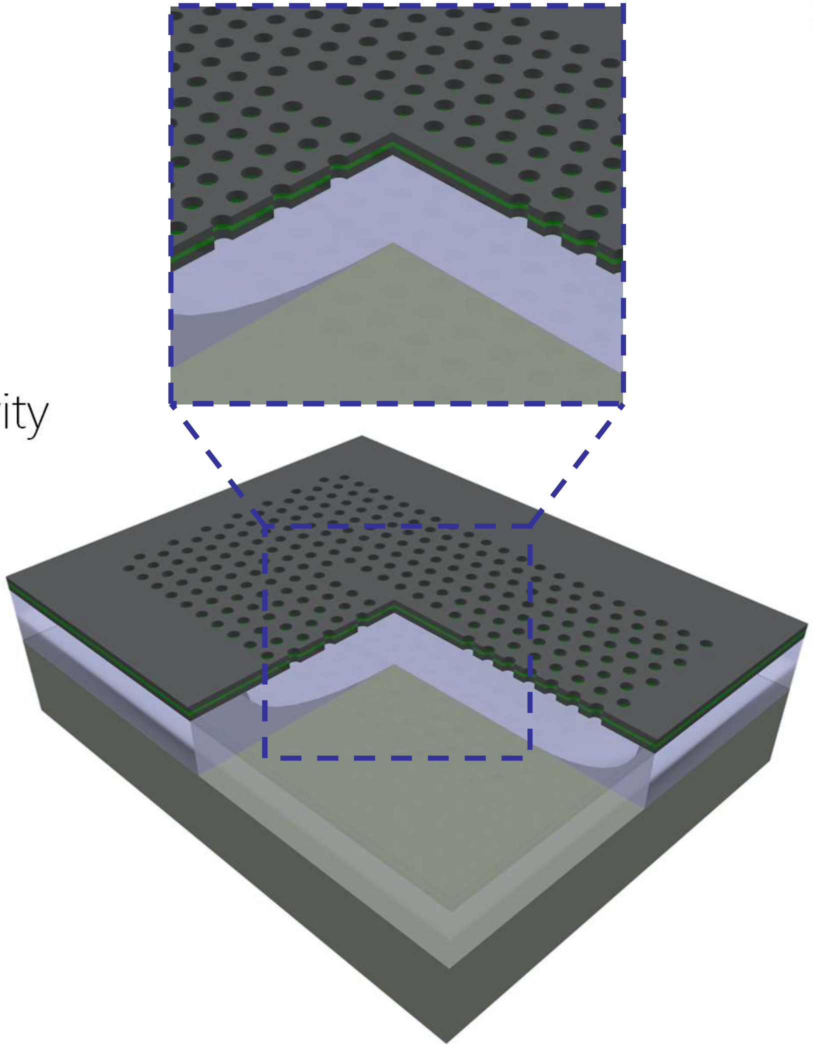
DTU Fotonik
Institut for Fotonik

# OUTLINE

- ❖Barriers for photonic crystal lasers
- ❖Fabrication process overview
- ❖Laser demonstrations
- ❖Room for further improvements
- ❖Summary and future directions

# BARRIERS FOR PHOTONIC CRYSTAL LASERS

- Non-radiative surface recombination in holes
- Pumping efficiency and carrier confinement to the cavity
- Heat generation and heat sinking



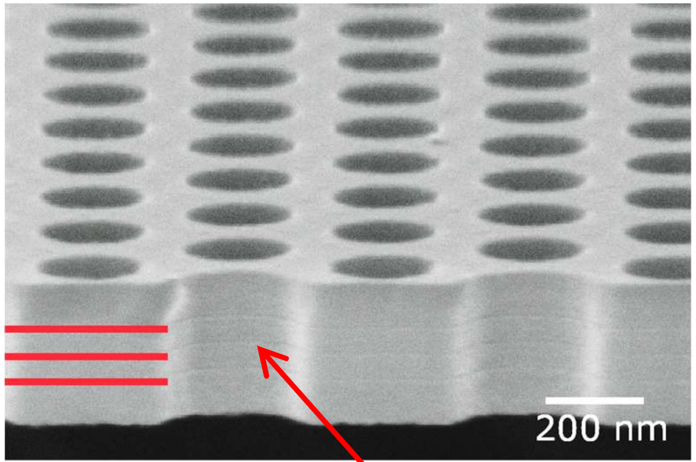
**Representative photonic crystal laser**

# NON-RADIATIVE SURFACE RECOMBINATION

- Recombination velocities *S*

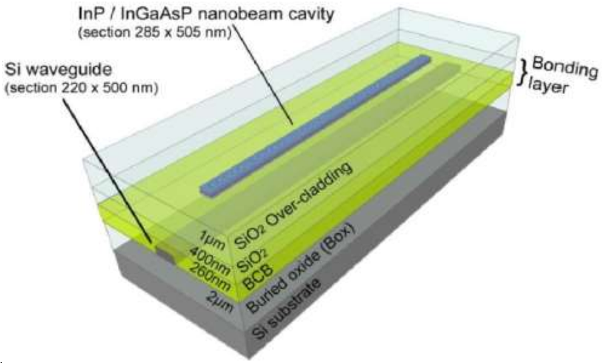
| | *S* (cm/s) |
|---|---|
| Si | **0.1 - 100** |
| GaAs | **$10^5$ - $10^6$** |
| InP | **$10^3$ - $10^5$** |
| InGaAs/GaAs QWs | **$5x10^5$** |
| InAs/GaAs QDs | **$5x10^4$** |

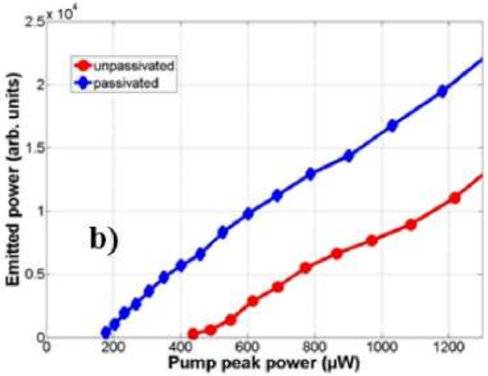
- Passivation:
  - Damaged material removal (etch)
  - Deoxidation and termination of dangling bonds
  - Encapsulation




Ek, PhD Thesis (2012)

**Air-exposed active material surface in holes**



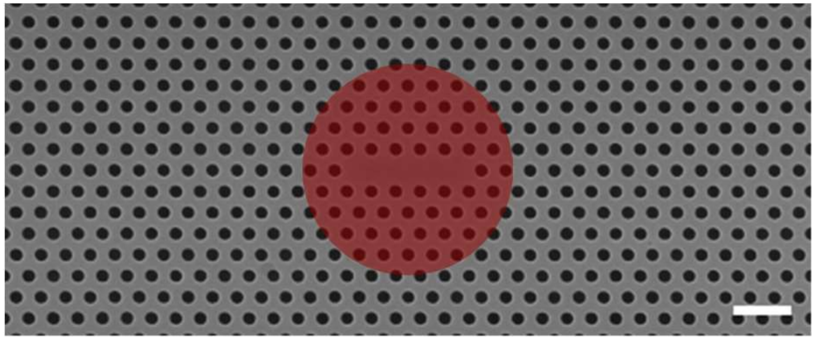



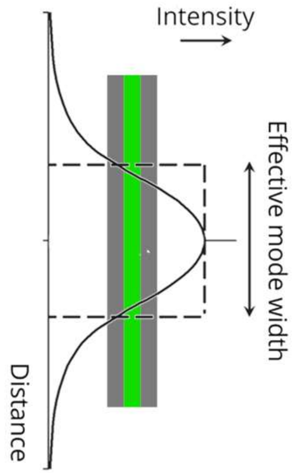

Crosnier, Opt. Express (2015)

# PUMPING EFFICIENCY AND CARRIER CONFINEMENT

**Active material across the entire device**

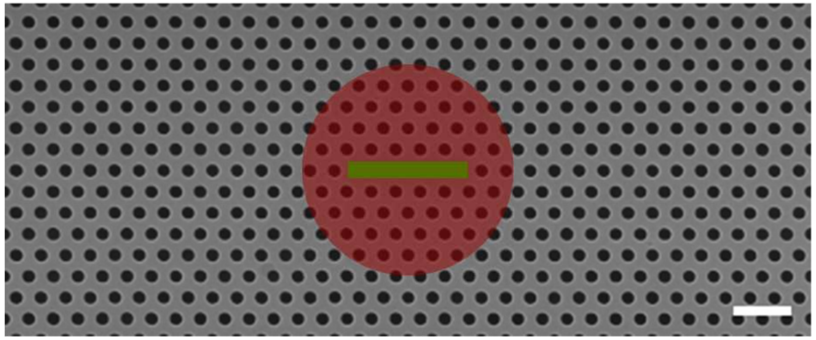
- Carriers generated everywhere across the pump beam spot
- Carriers not confined

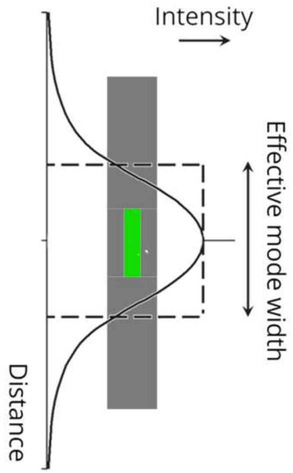





**Active material only in the cavity**

- Carriers generated only in the cavity
- Carriers confined to the cavity region
- + Index guiding





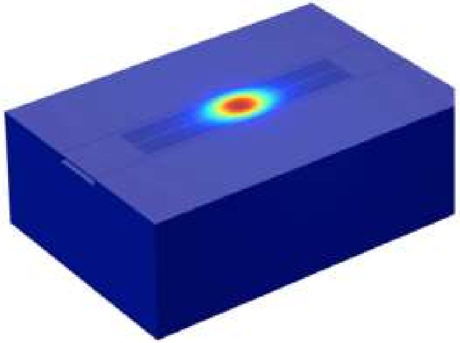


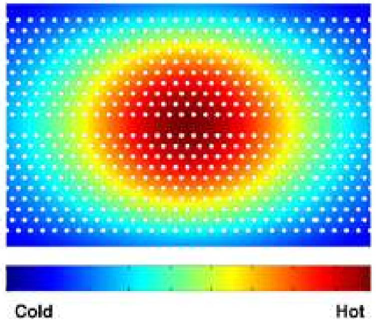
**– pump laser beam spot**

# HEAT GENERATION AND HEAT SINKING

- Thermal conductivity $k$

| | $k$ (W/m·K @ 300K) |
|---|---|
| Si | **130** |
| GaAs | **52** |
| InP | **68** |
| InGaAsP | **6.8** |
| InAs | **27** |
| $SiO_2$ | **1 - 1.4** |
| Air | **0.027** |

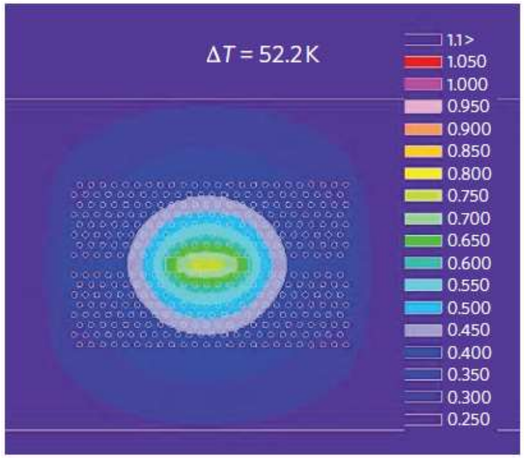


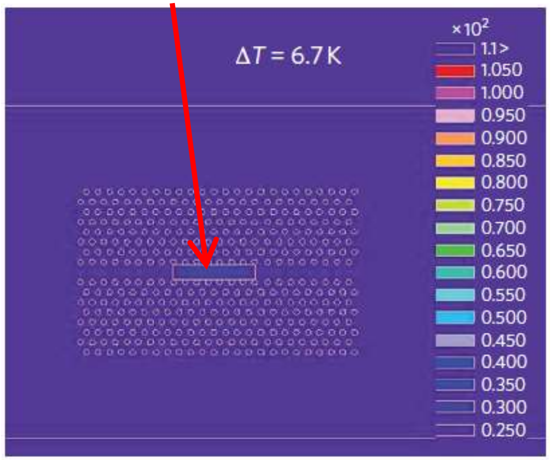



Xue, Opt. Express (2015)

- Thermal simulations:

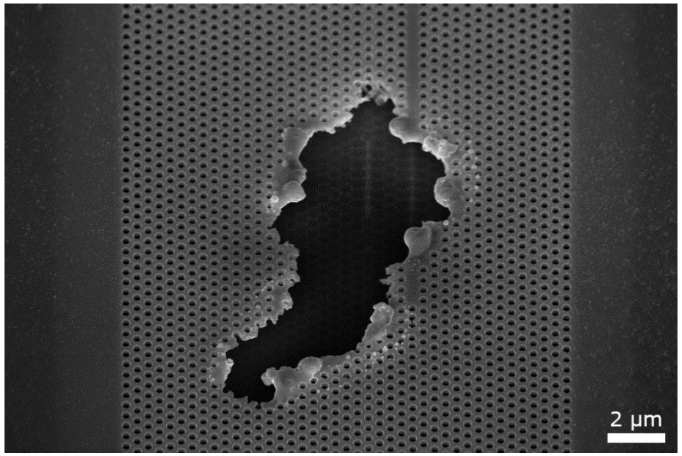
**Active material only in the cavity**



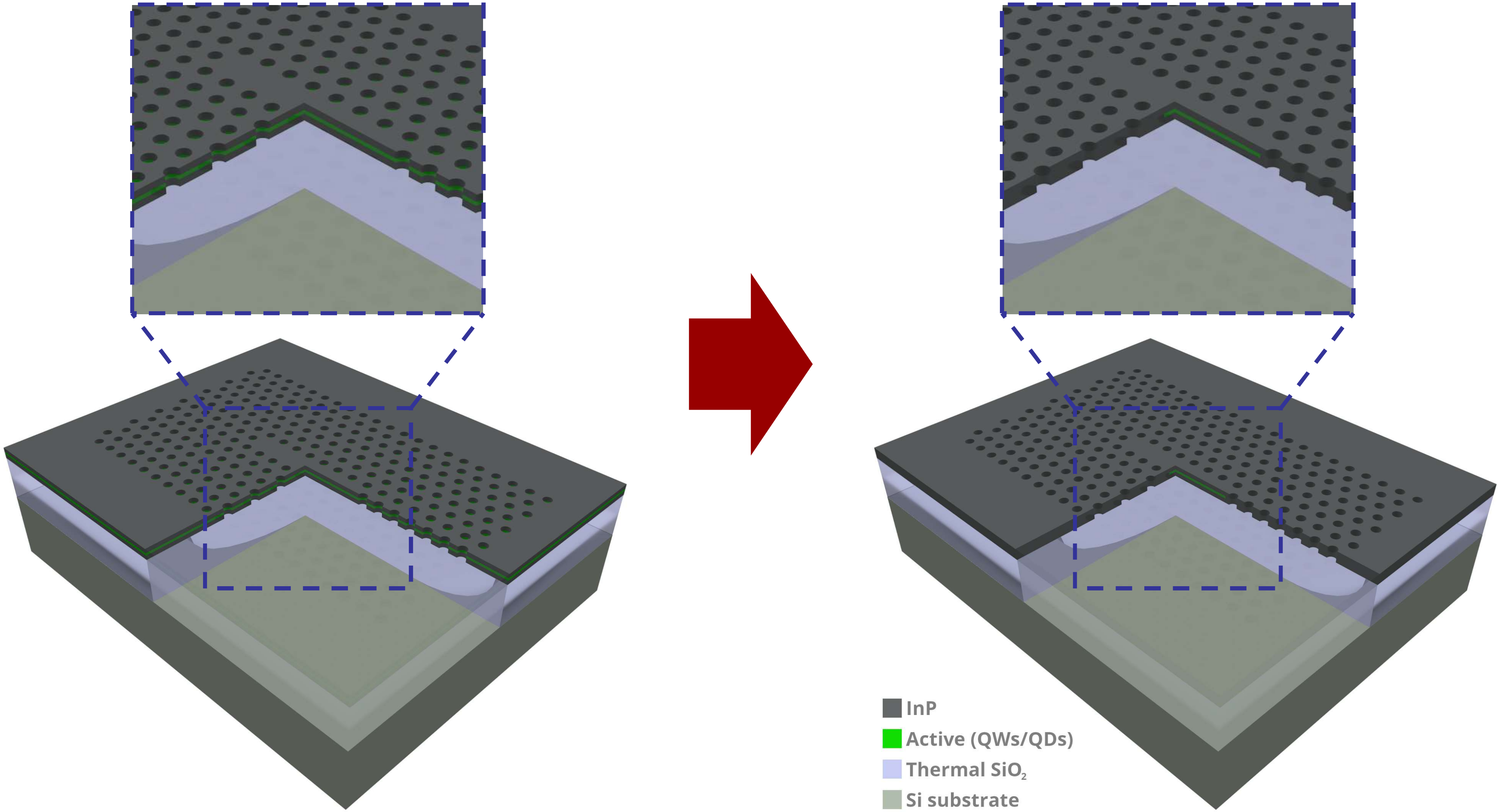




Matsuo, Nat. Photonics (2010)

**Too much heating...**

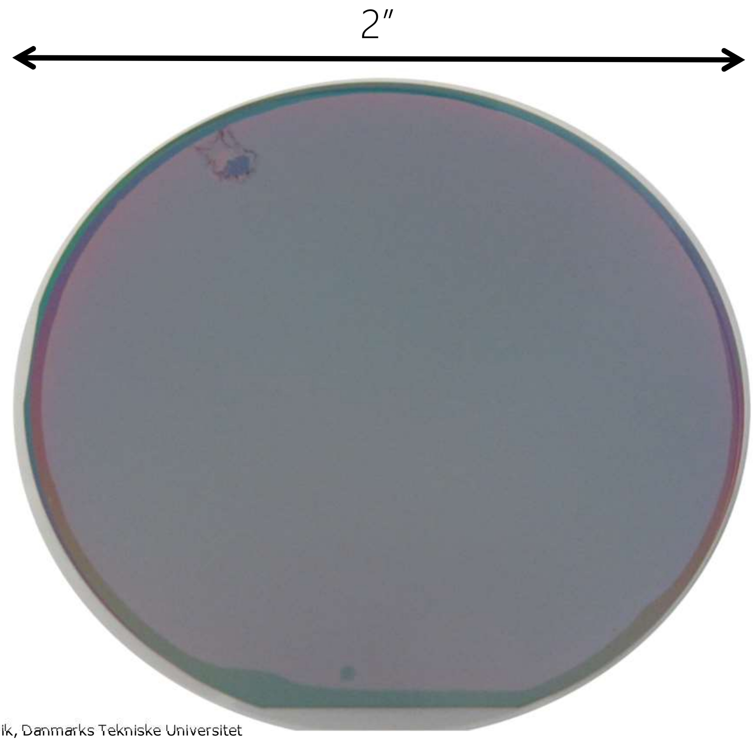


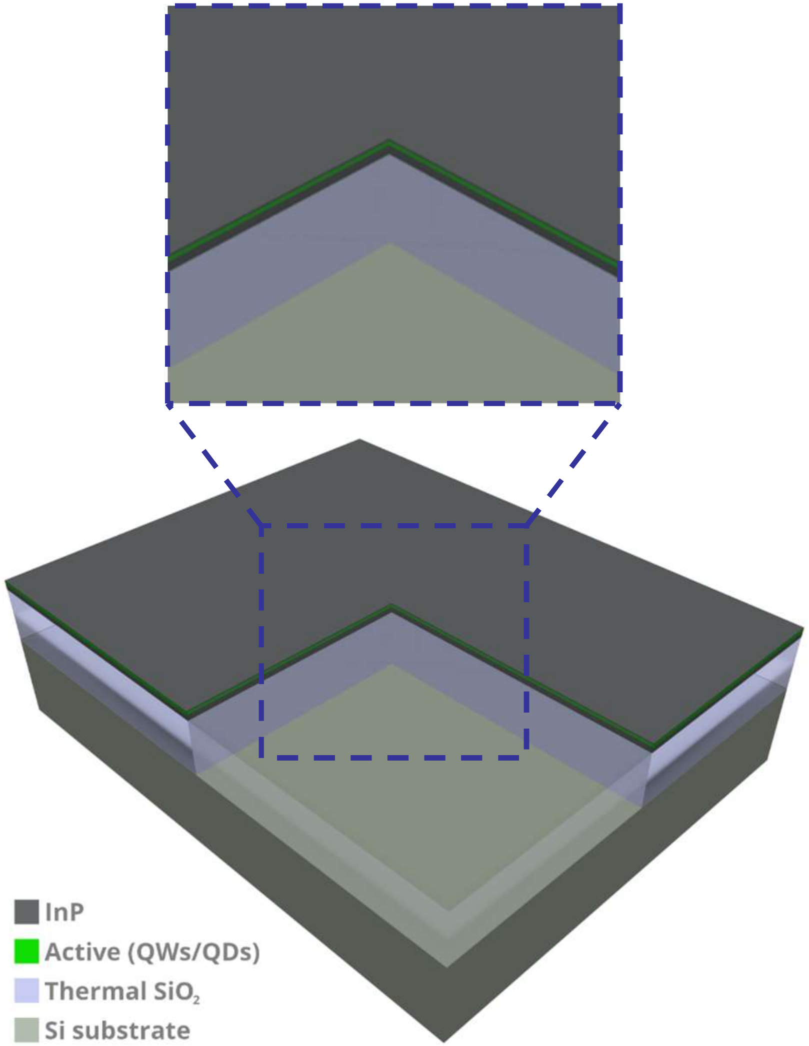
# SOLUTION – BURIED HETEROSTRUCTURE PHOTONIC CRYSTAL LASER



# FABRICATION |1|

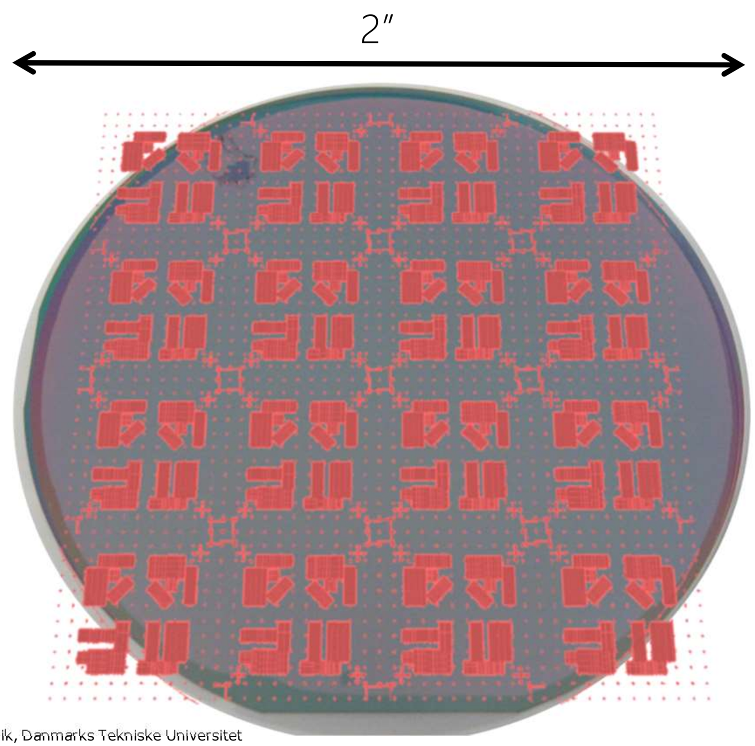
- Direct wafer bonding to Si
- Few nm intermediate $Al_2O_3$ ALD-deposited layer

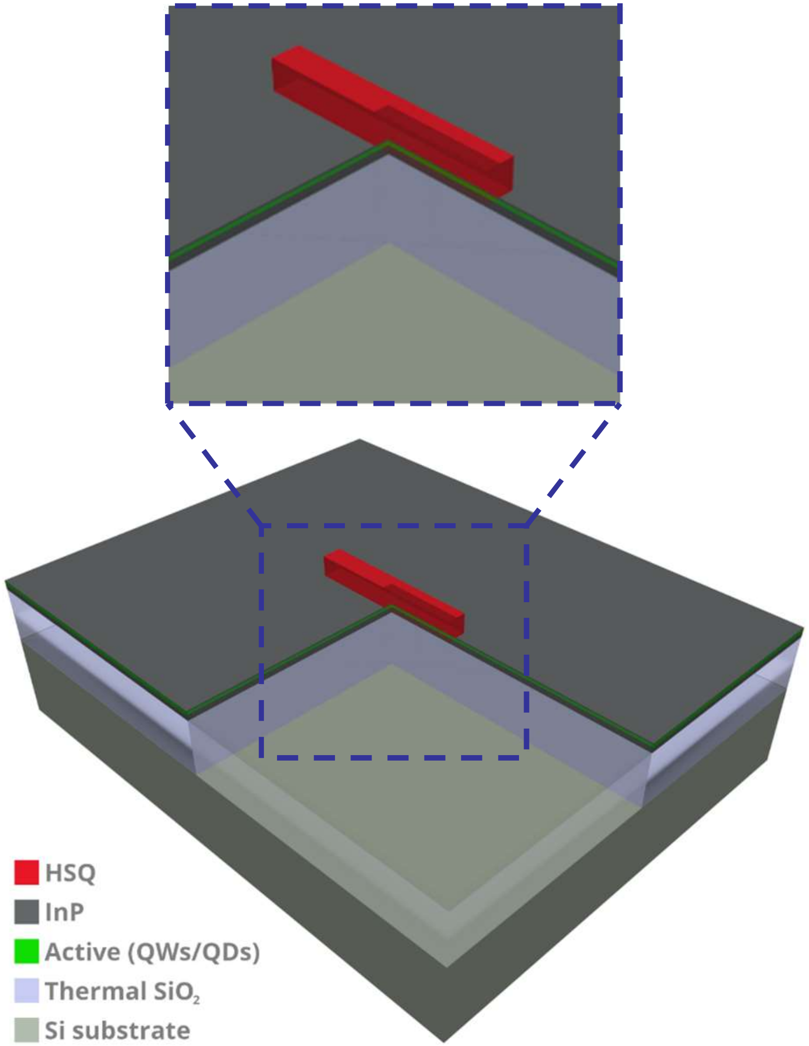


# FABRICATION |2|

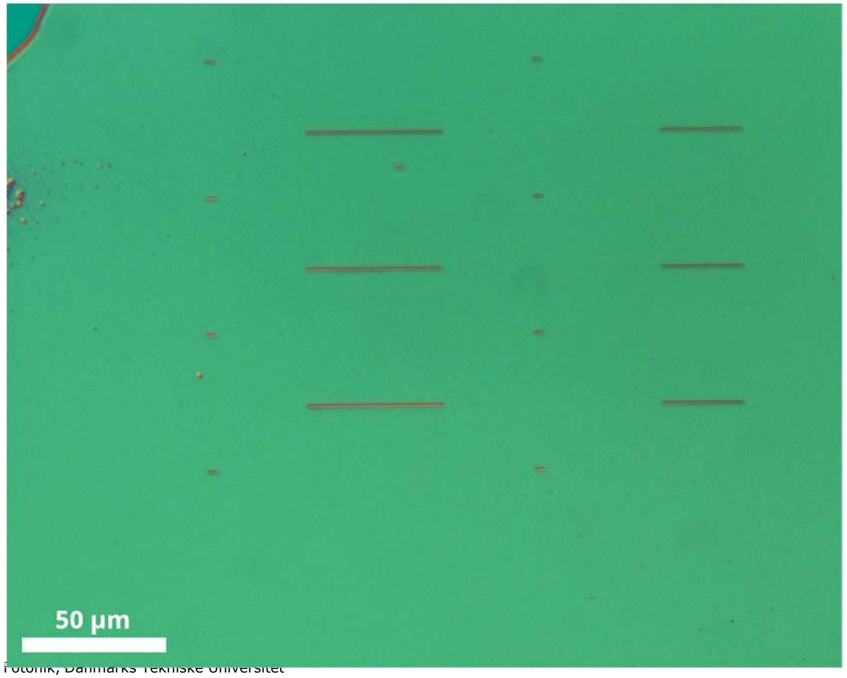
- E-beam BH mask pattern exposure

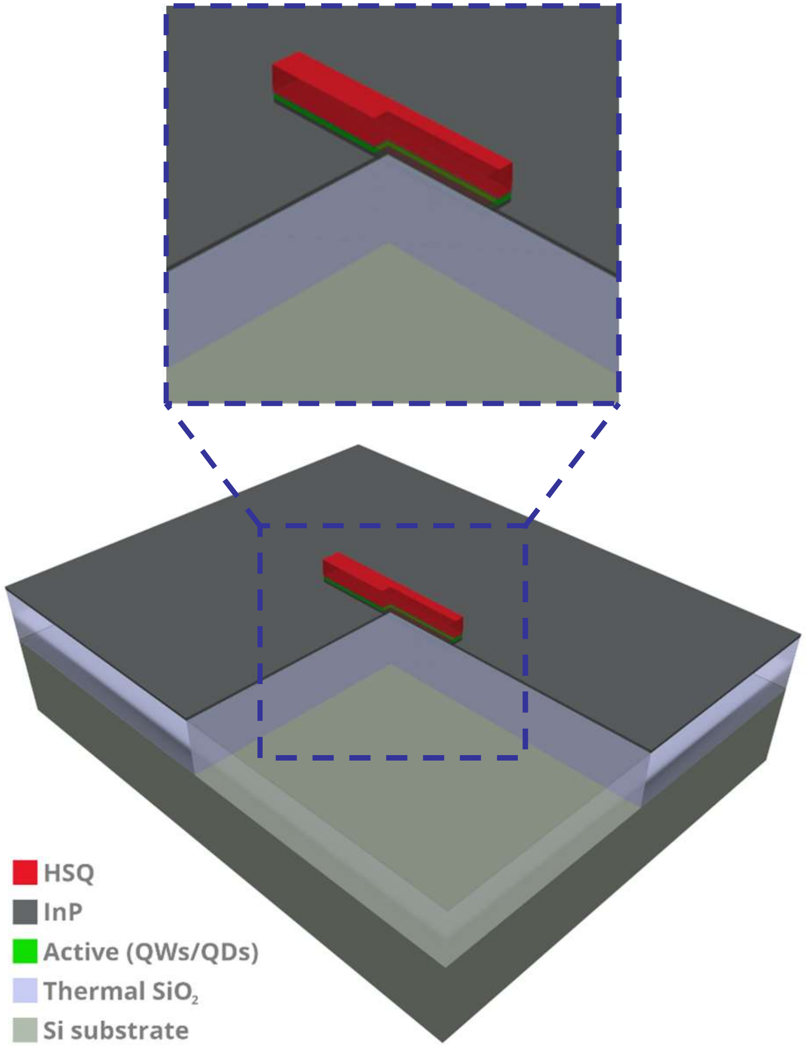


# FABRICATION |3|

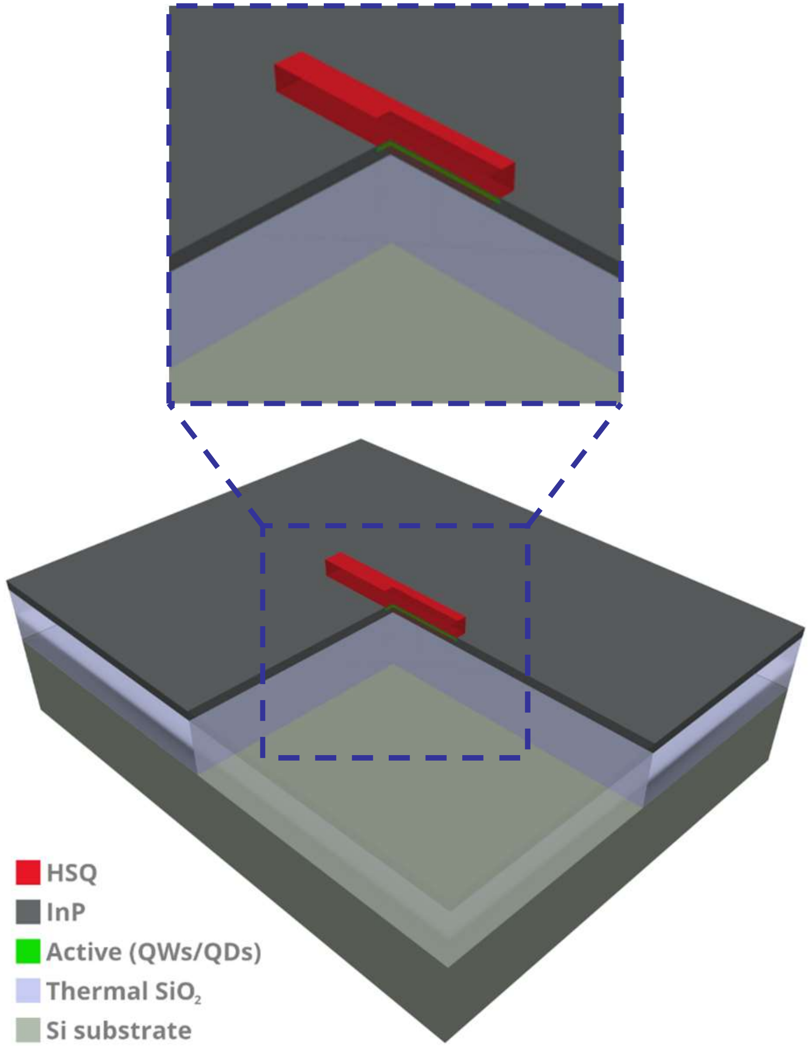
- Pattern BH pattern etching



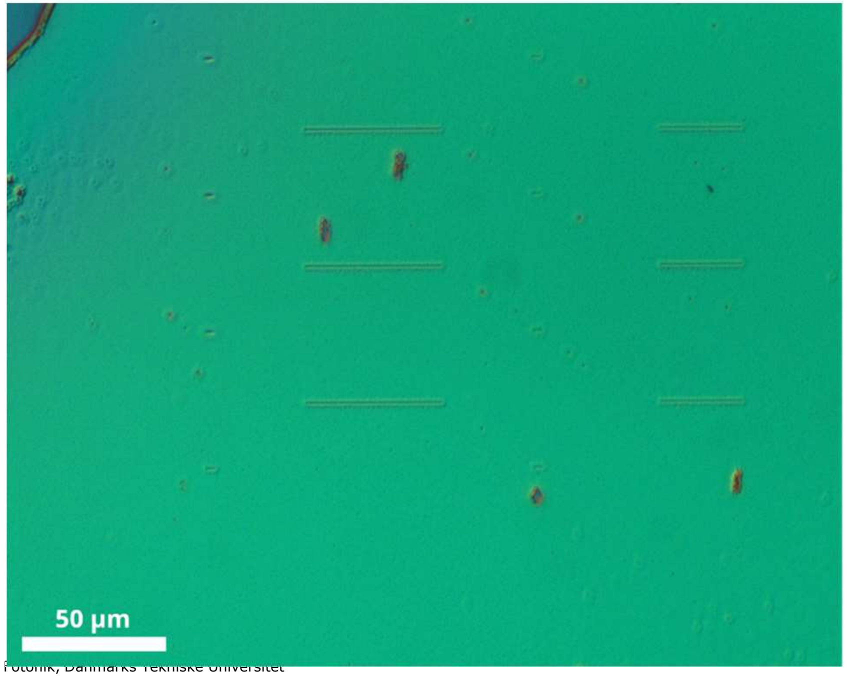
# FABRICATION |4|

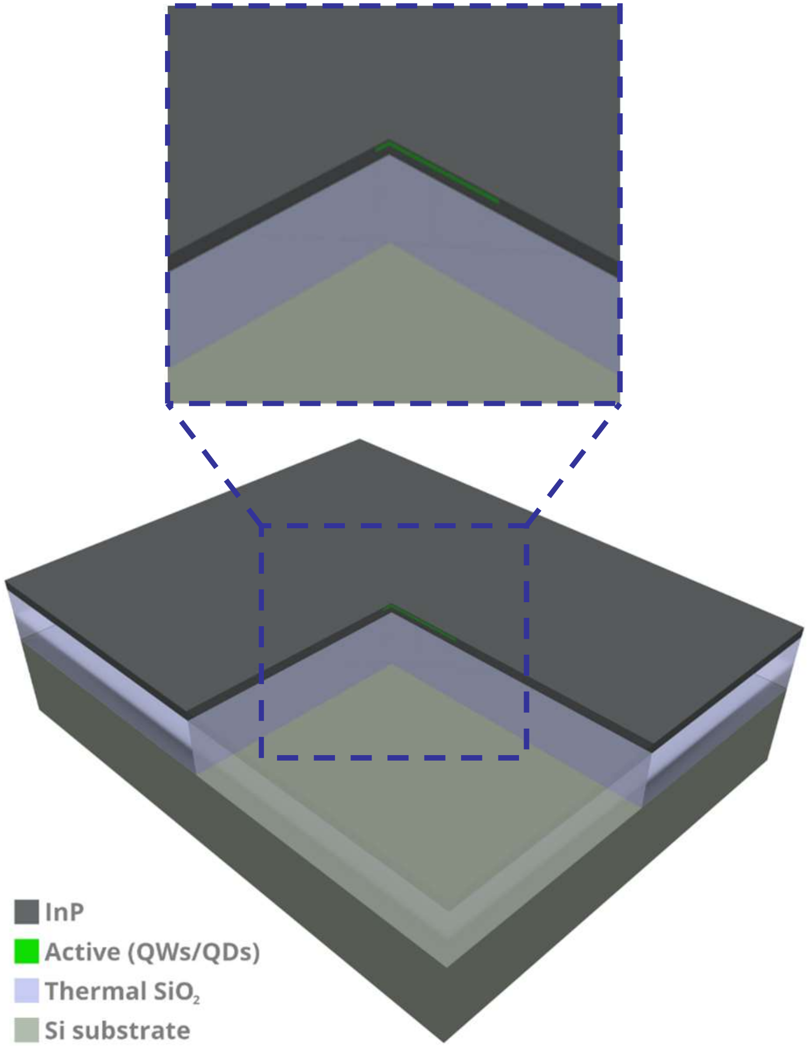
- 1st re-growth (selective-area growth)

# FABRICATION |4.1|

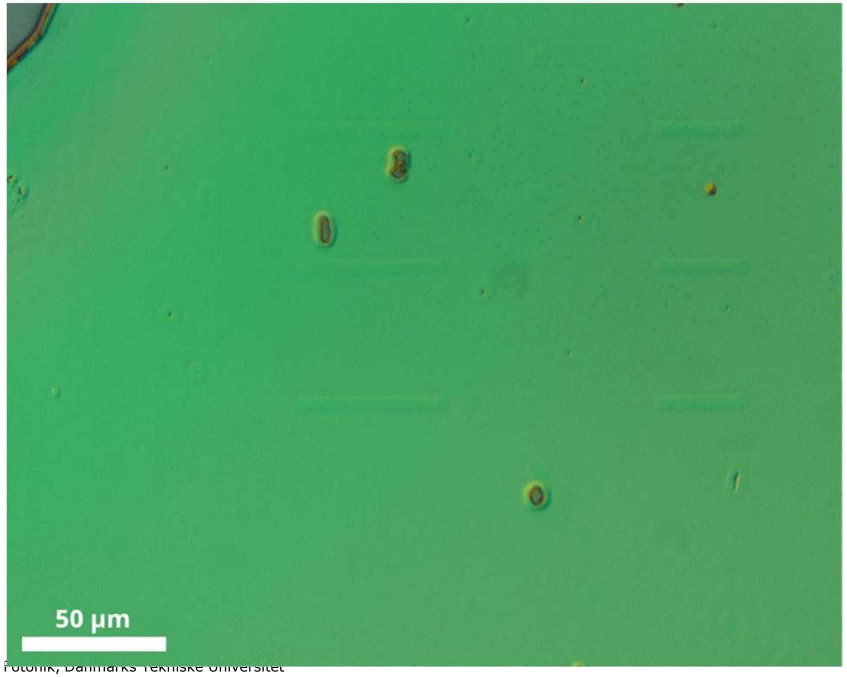
- BH mask removal

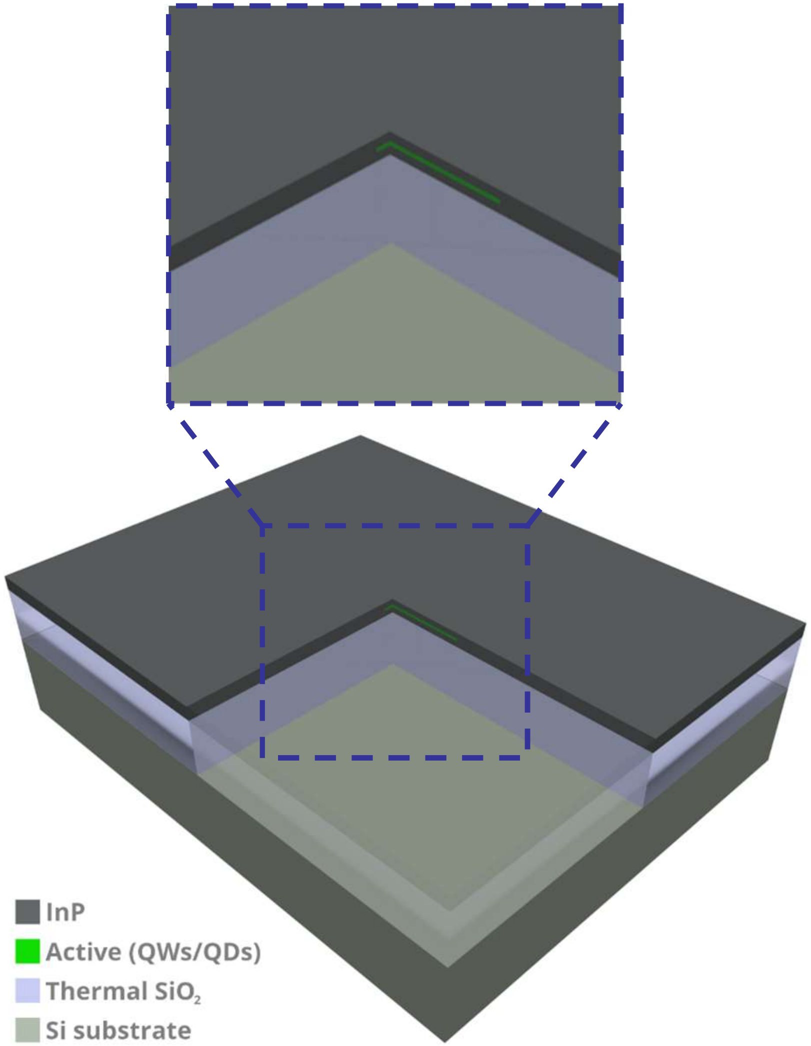


# FABRICATION |5|

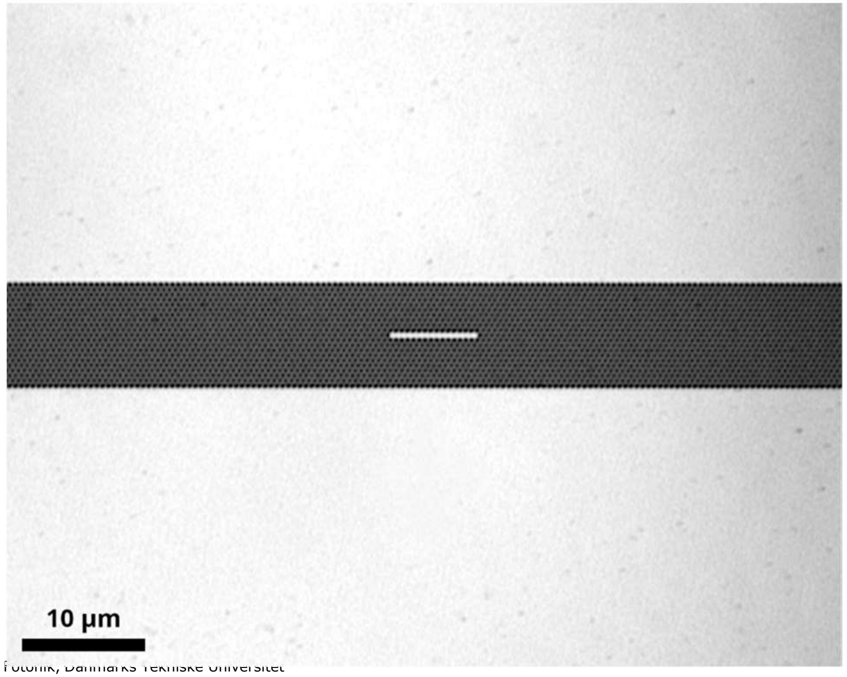
- 2nd re-growth (surface planarization)
- Final membrane thickness ~250 nm

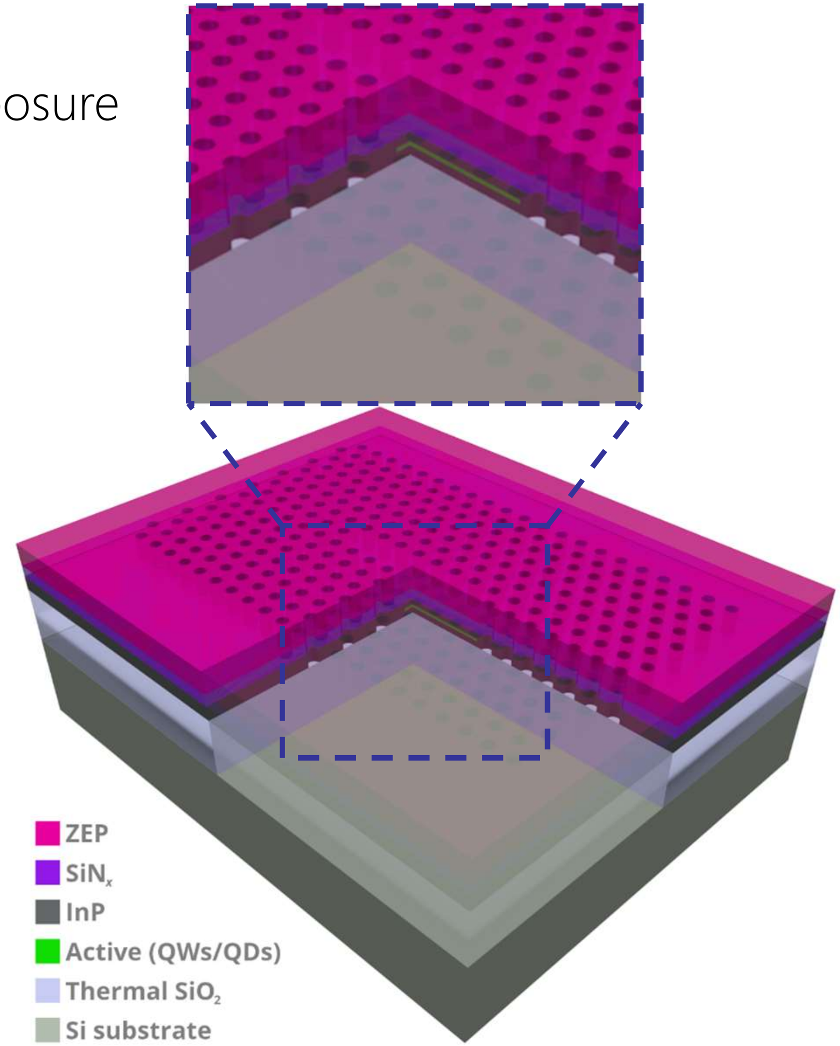


# FABRICATION |6|

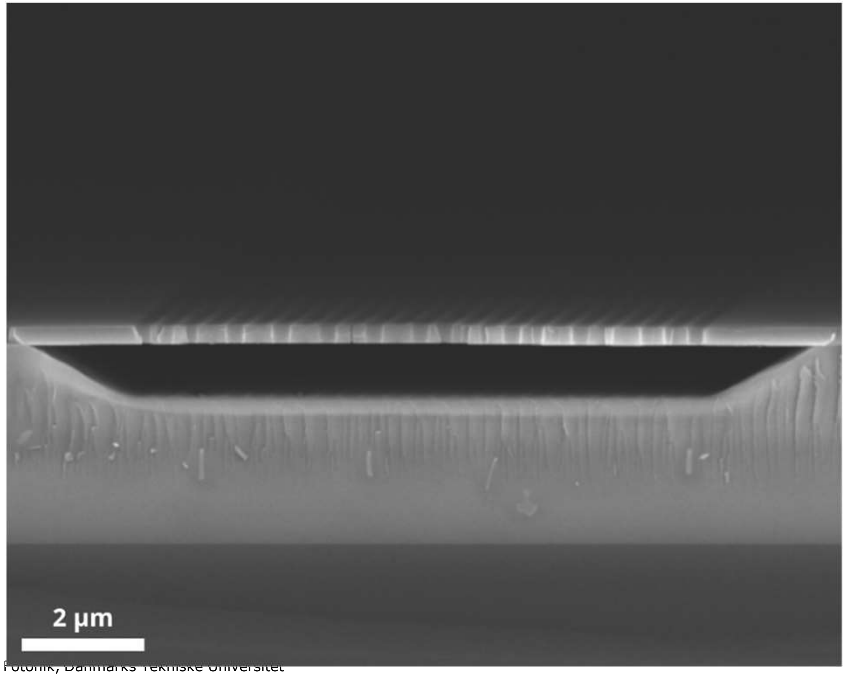
- E-beam alignment and photonic crystal mask exposure
- Photonic crystal holes etching

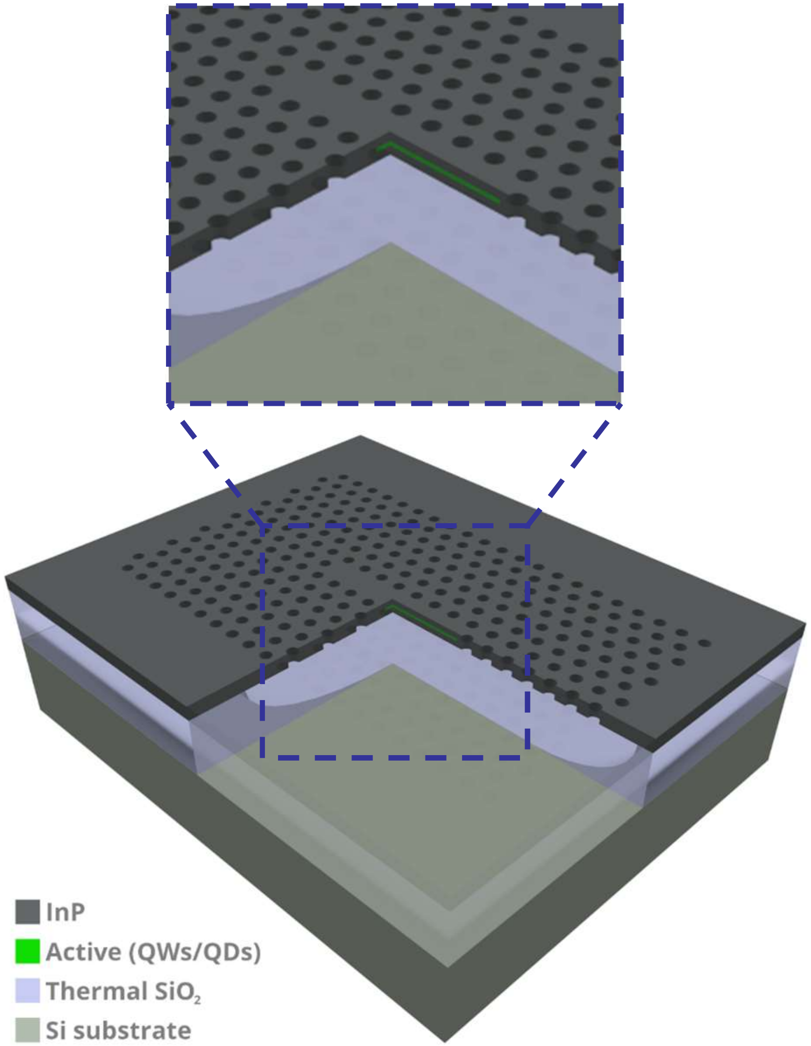


# FABRICATION |7|

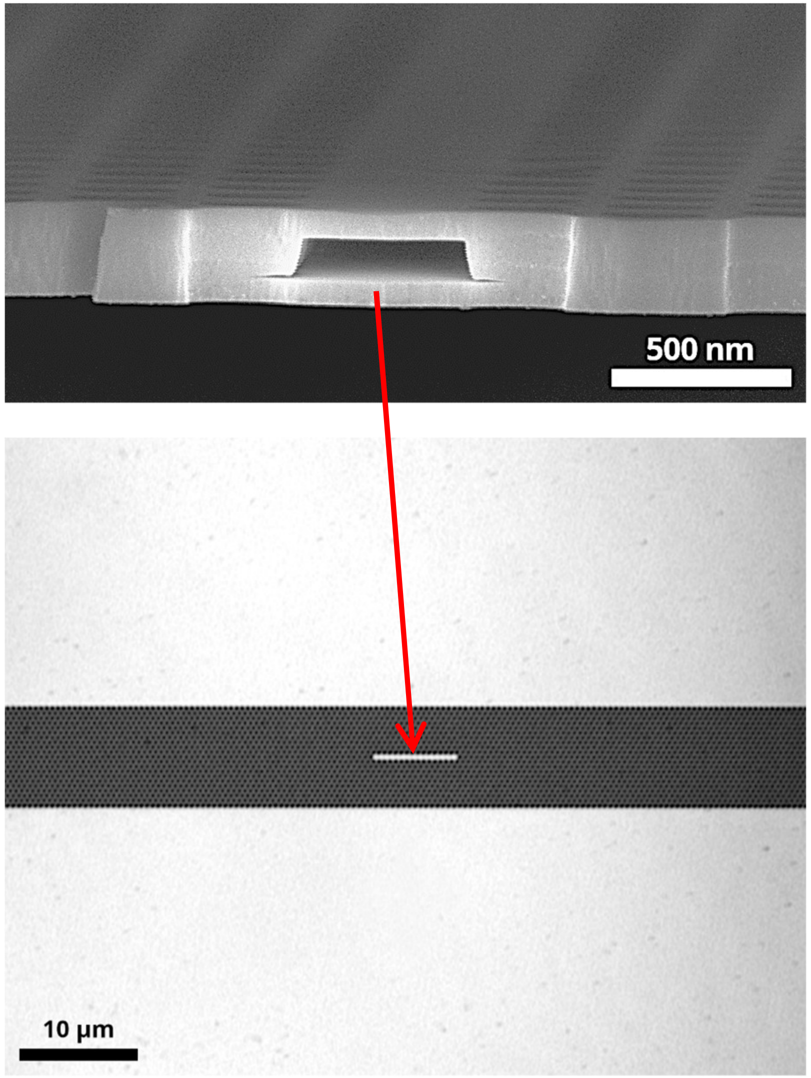
- Membranization



Pros:

- Avoided non-radiative surface recombination
- Optimized optical pumping efficiency
- Carriers confined to the cavity region
- Improved thermal properties (InP membrane)

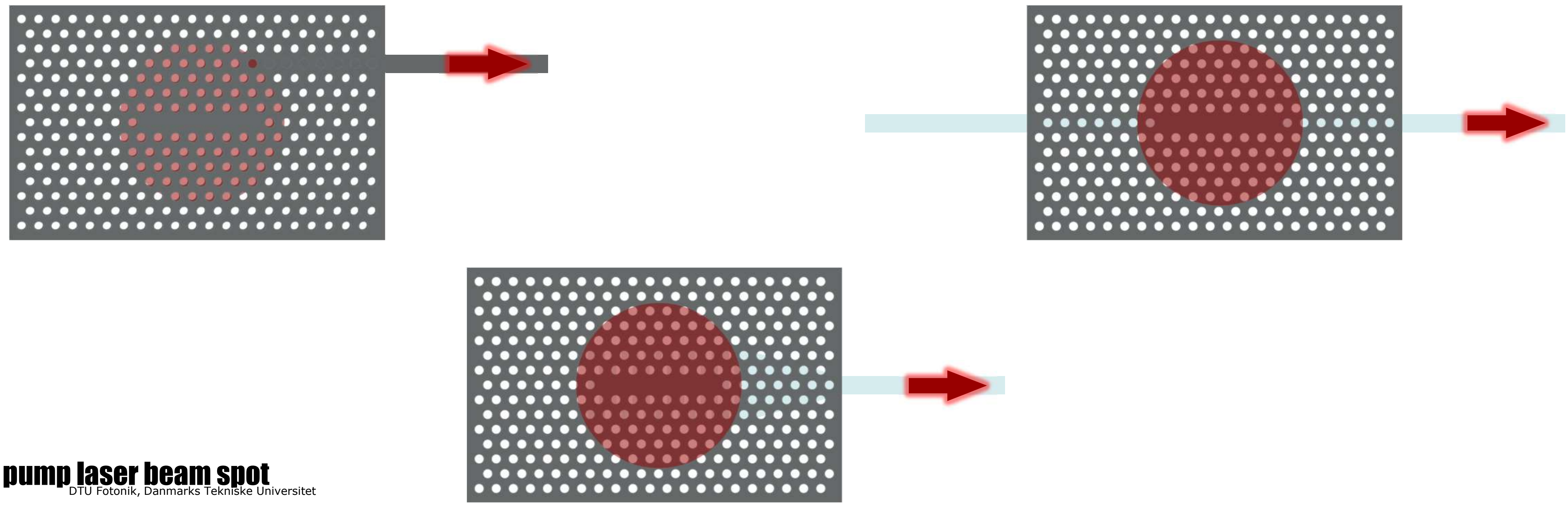



Cons:

- Increased complexity in the fabrication process
- Required very precise active material positioning in the cavity region

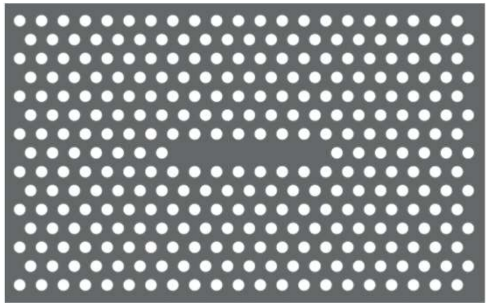
## LINE-DEFECT LASERS

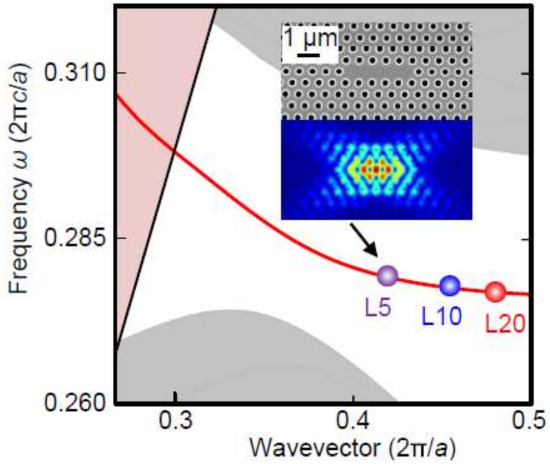
- Simplest photonic crystal laser design
- Insight into the disorder effects/mechanisms (inherent to photonic crystals)
- In-plane coupling possible for more "practical" applications



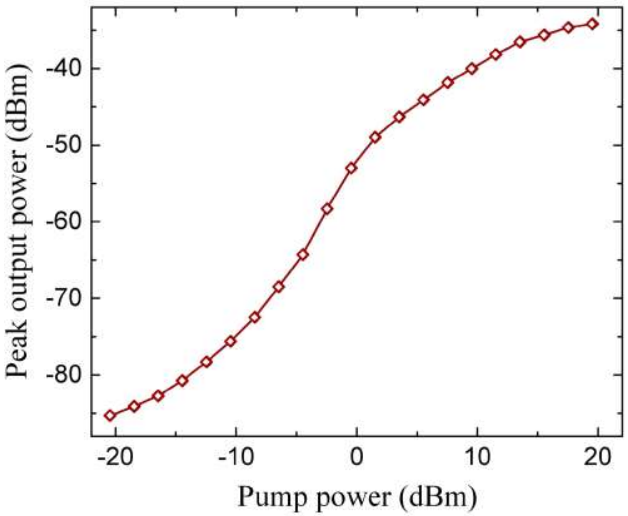
– pump laser beam spot

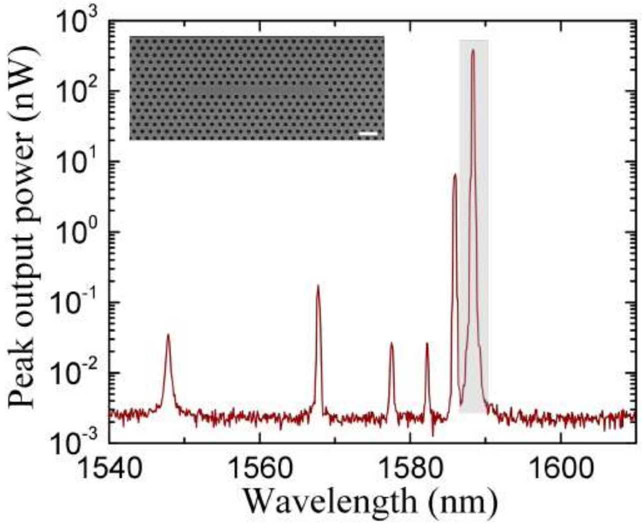
# L-DEFECT LASER DEMONSTRATIONS

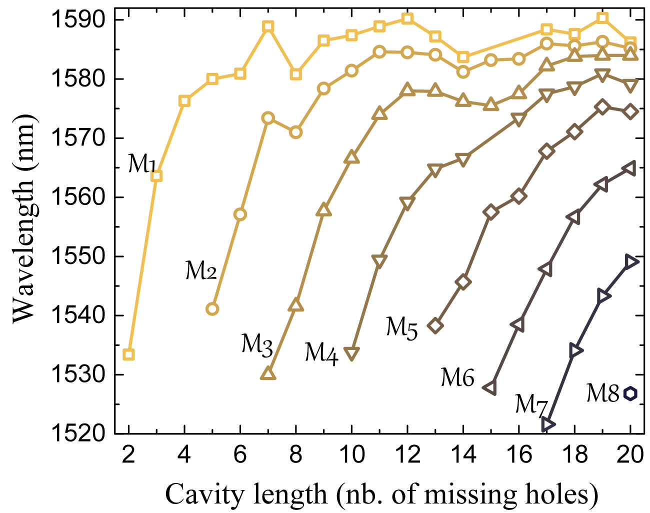





Xue, Phys. Rev. Lett. (2016)

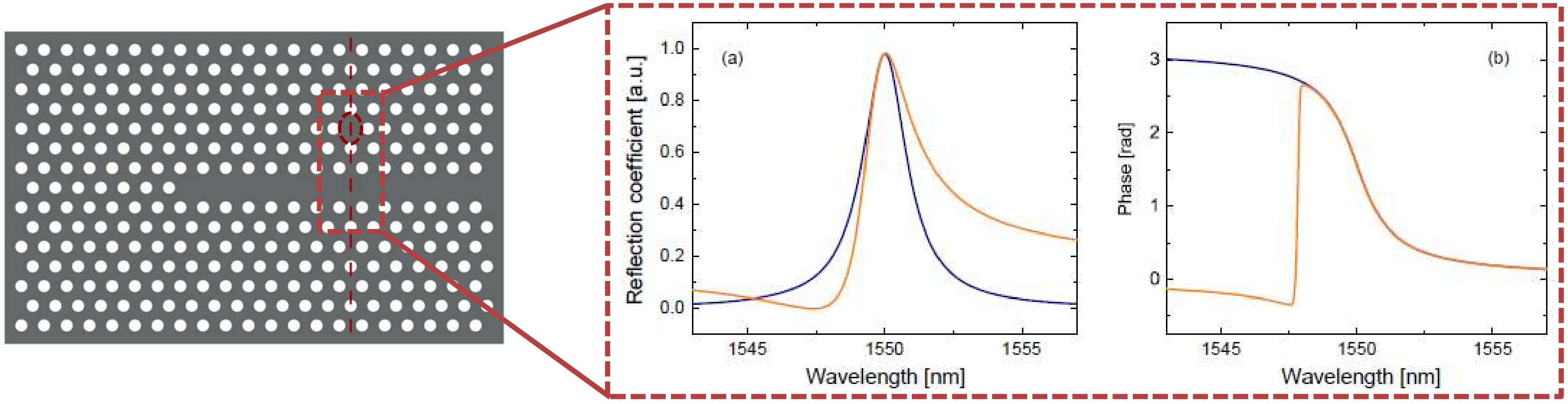


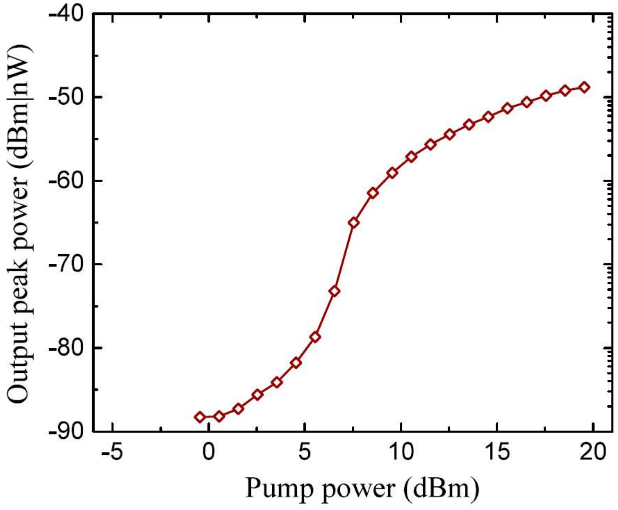
## FANO LASERS

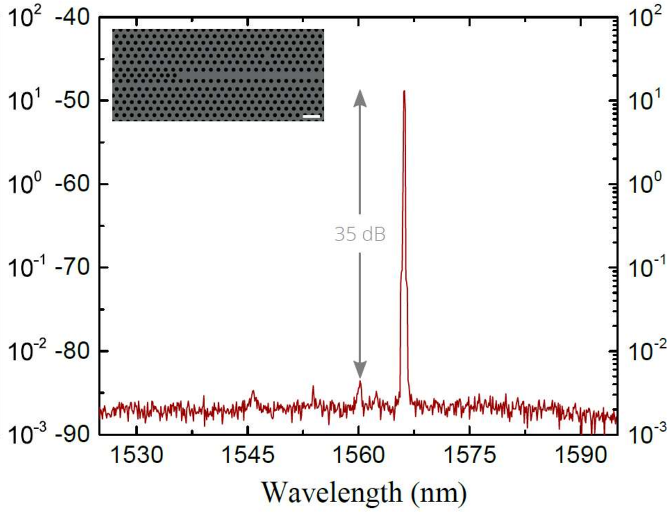
- Unique characteristics
- Novel (others cannot do!)
- Very sensitive to design and fabrication

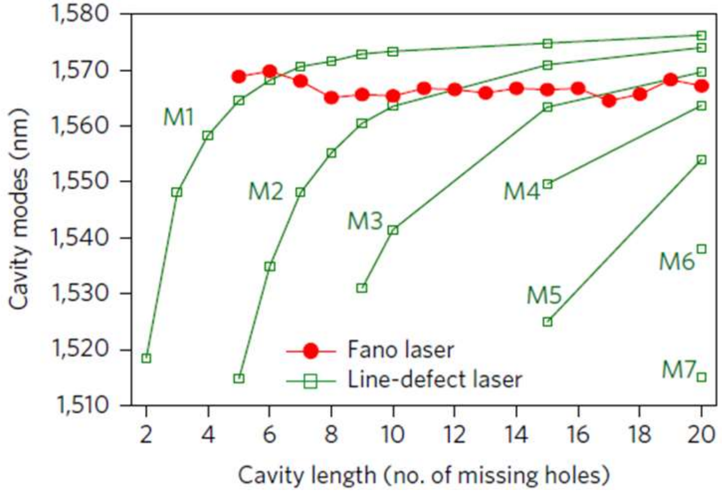


# FANO LASER DEMONSTRATIONS

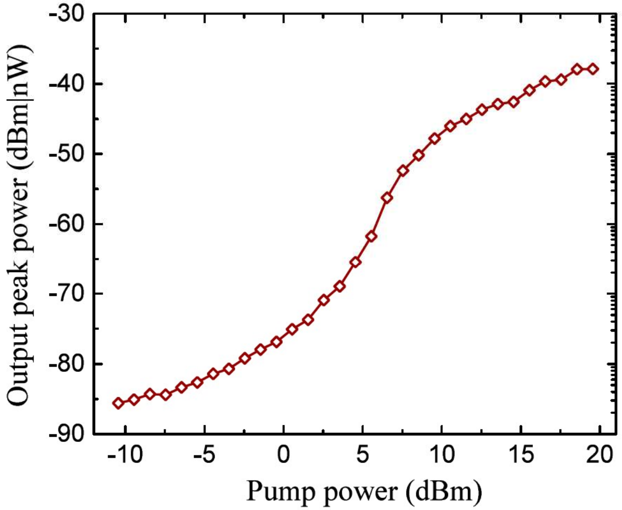
DTU

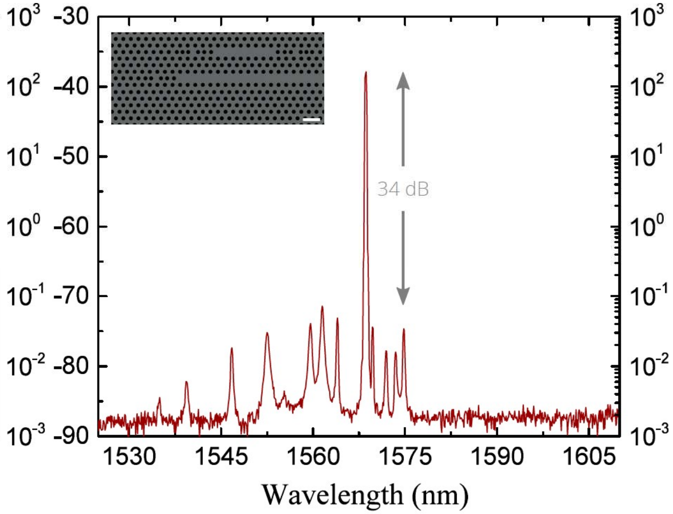


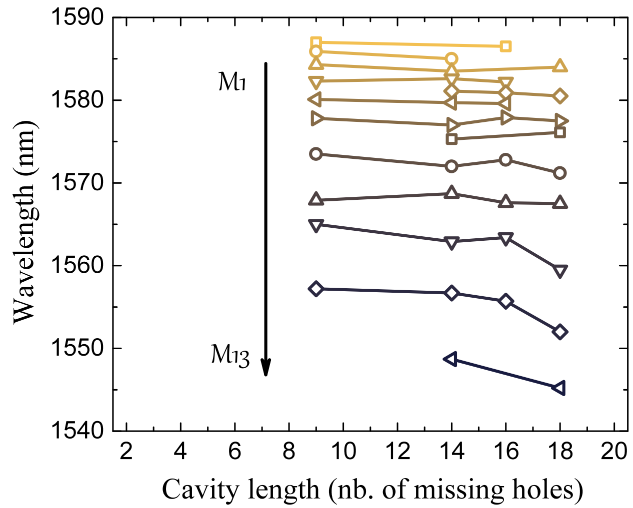



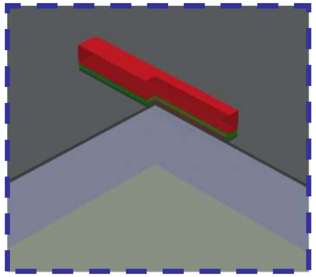

Yu, Nat. Photonics (2016)

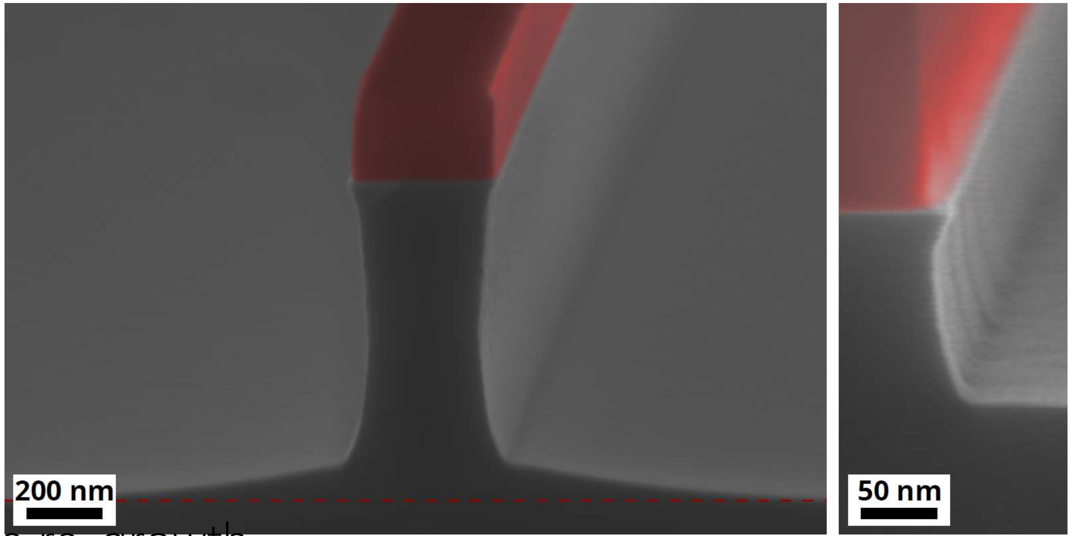


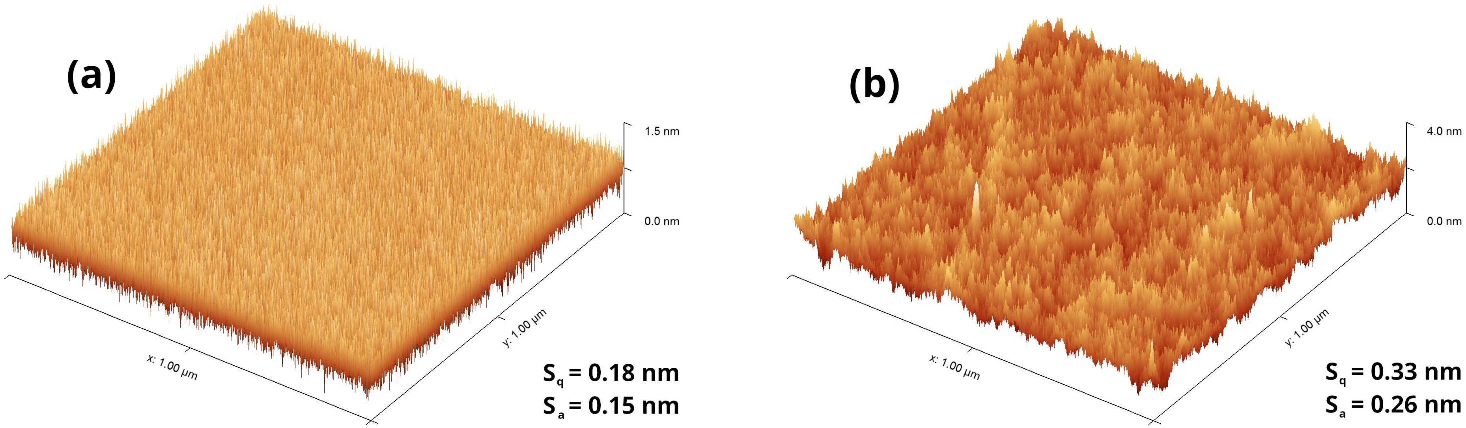



# BURIED HETEROSTRUCTURE INTERFACES AND SURFACE (|3|)

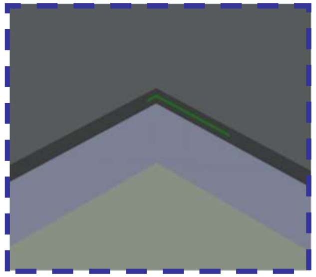


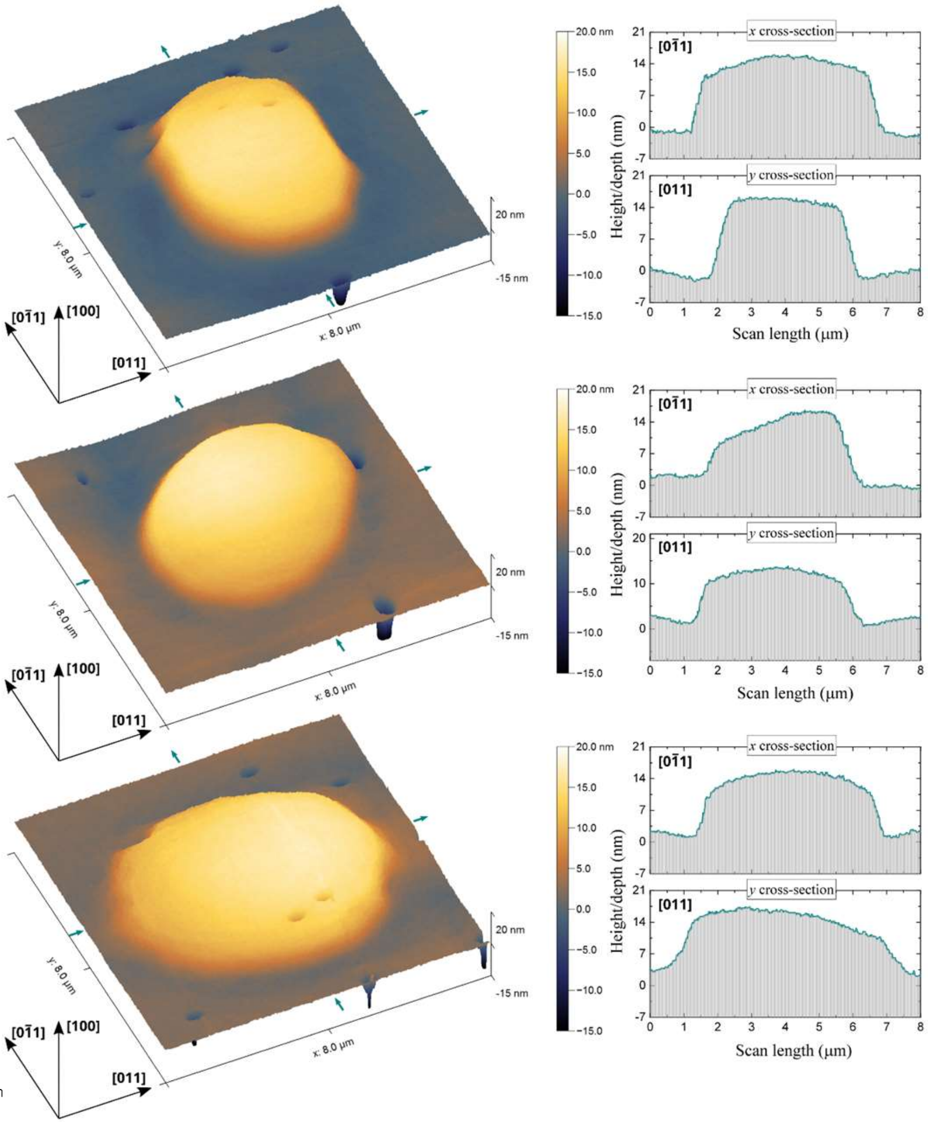


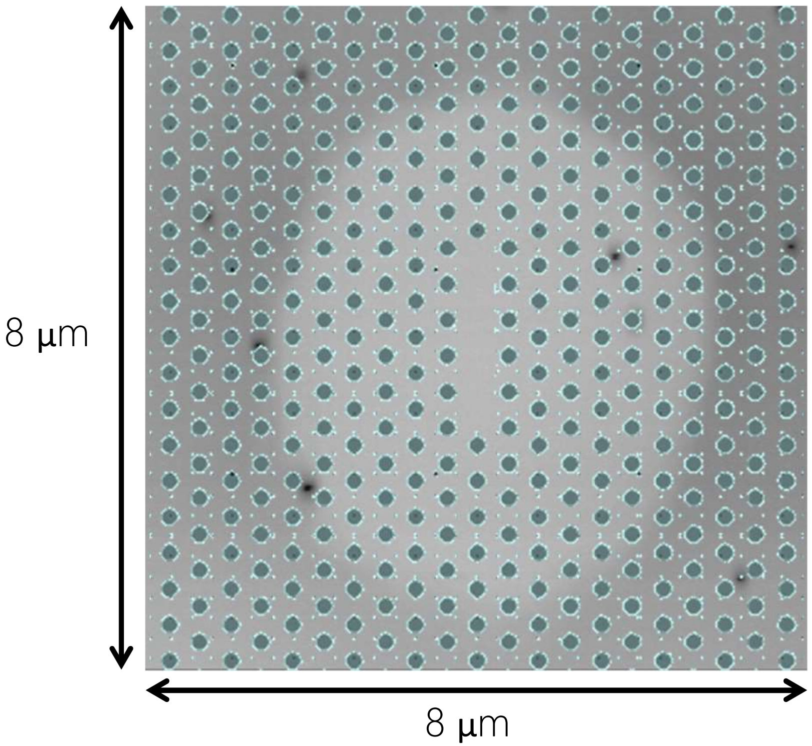

- HBr-based etching
- Surface quality critical for the re-growth



# BURIED HETEROSTRUCTURE INTERFACES AND SURFACE (|5|)

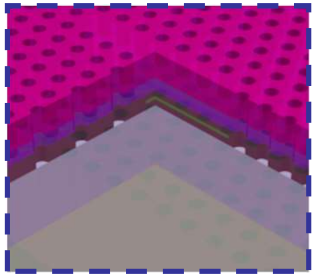




# WAFER DISTORTION AND E-BEAM METROLOGY METHOD (|6|)

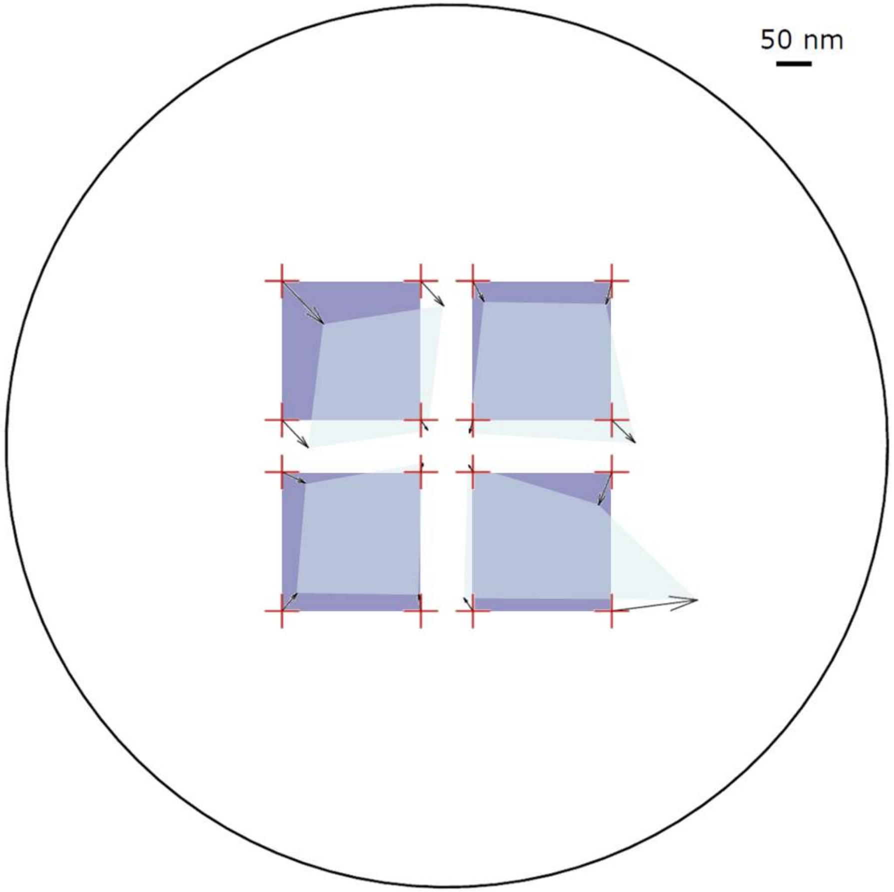
DTU



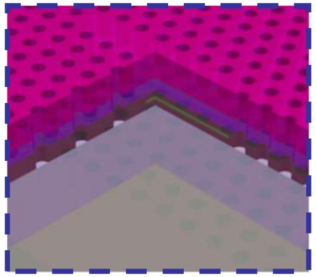
- Thermal expansion coefficients $\alpha$

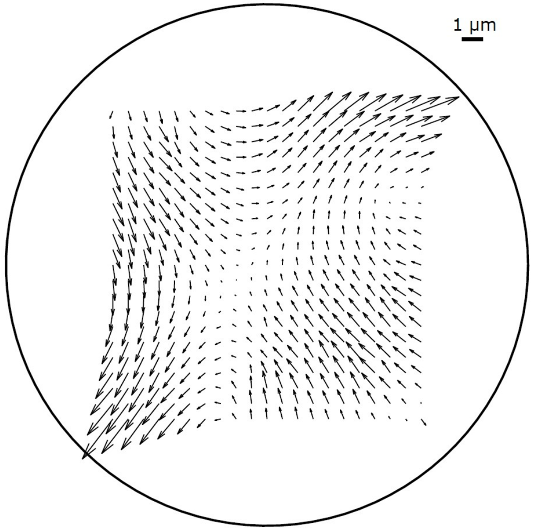
| | $\alpha$ ($10^{-6}$/K @ 300K) |
|---|---|
| Si | **2.56** |
| GaAs | **5.8** |
| InP | **4.6** |
| $SiO_2$ | **0.5 - 0.75** |

- Bonding-induced wafer deformations
- Processing-induced wafer deformations

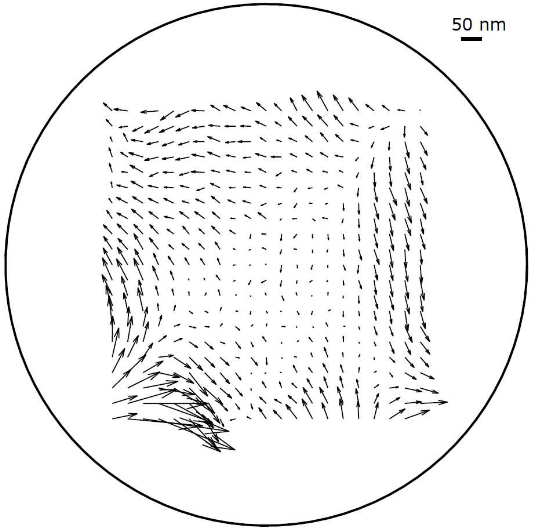


# WAFER DISTORTION AND E-BEAM METROLOGY METHOD ([6])

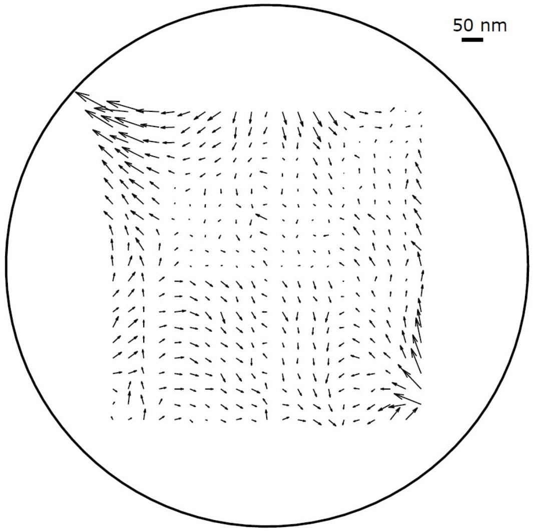




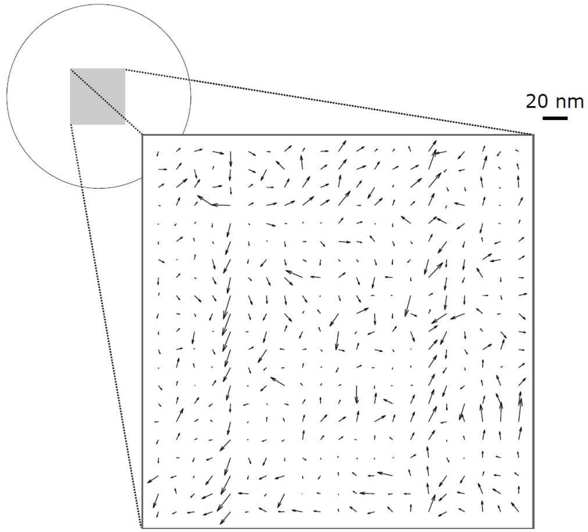

BCB to direct bonding



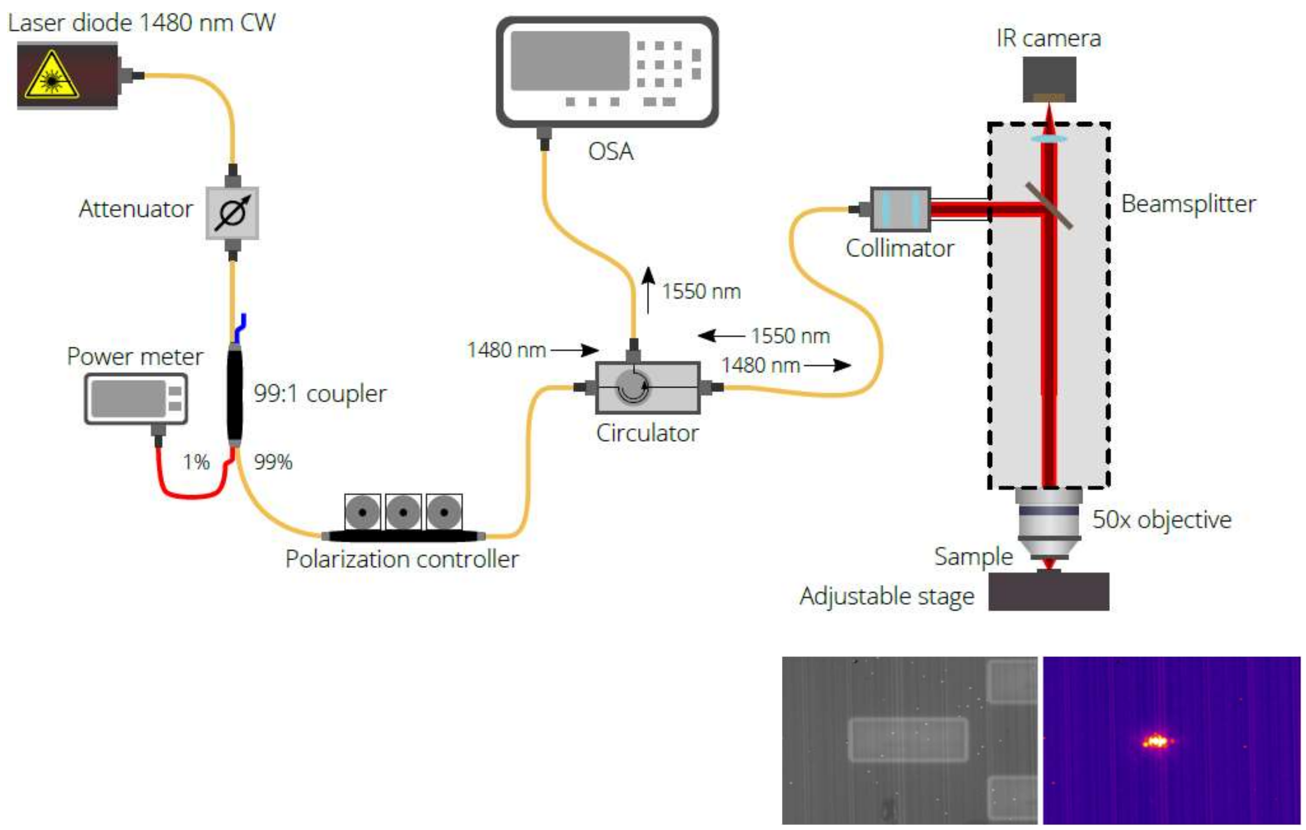

Sakanas, Microelectron. Eng. (2019)



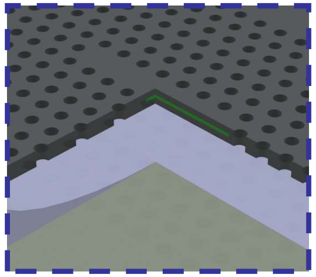

2" to 4" bonding

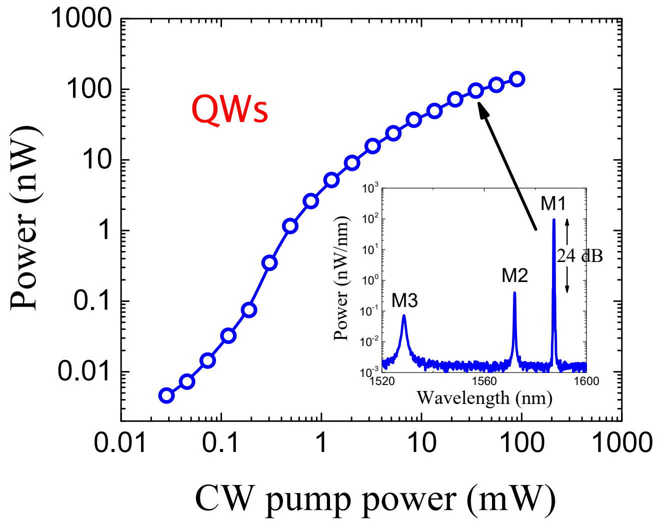


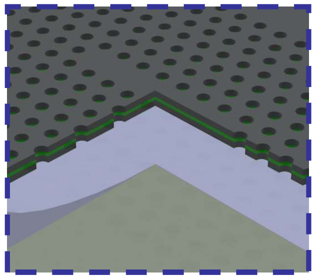
# EXPERIMENTAL SETUP

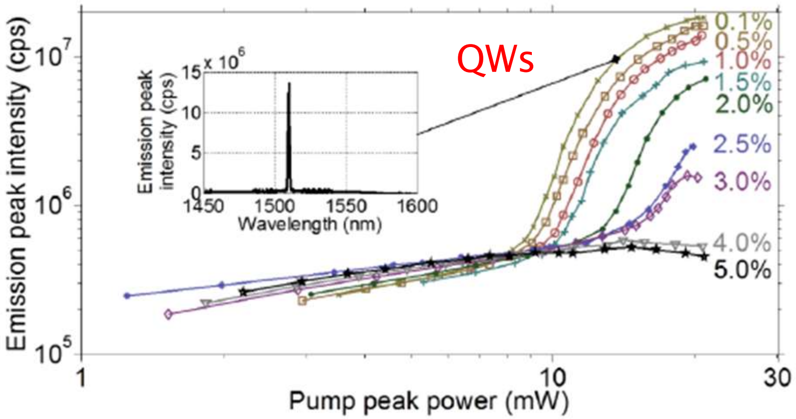


# BURIED HETEROSTRUCTURE LASING PERFORMANCE IMPROVEMENT

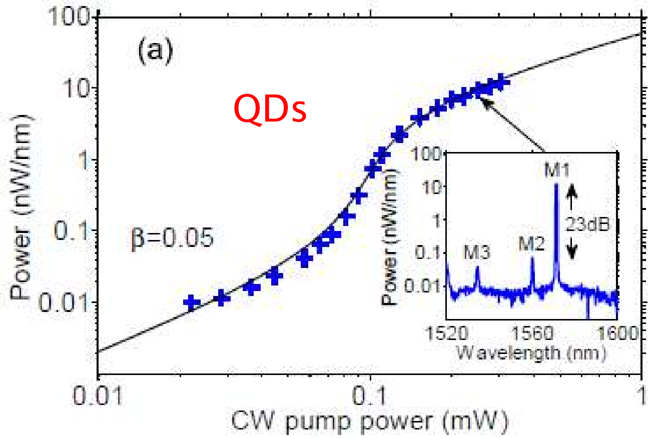







Xue, Opt. Express (2015)




Xue, Phys. Rev. Lett. (2016)

# SUMMARY AND FUTURE DIRECTIONS

- Buried heterostructure approach – effective solution for photonic crystal lasers

- Performance enhancement justifies increased fabrication complexity

- Optically pumped devices – necessary stepping stone to electrically pumped devices

# Summary

- Optical connects will get an increased penetration and allow the future development of the internet and computers
- ”Quantum” photonics may be an enabler.

- Technology is difficult….

- Questions.