The role of Nanostructures in Integrated Photonics

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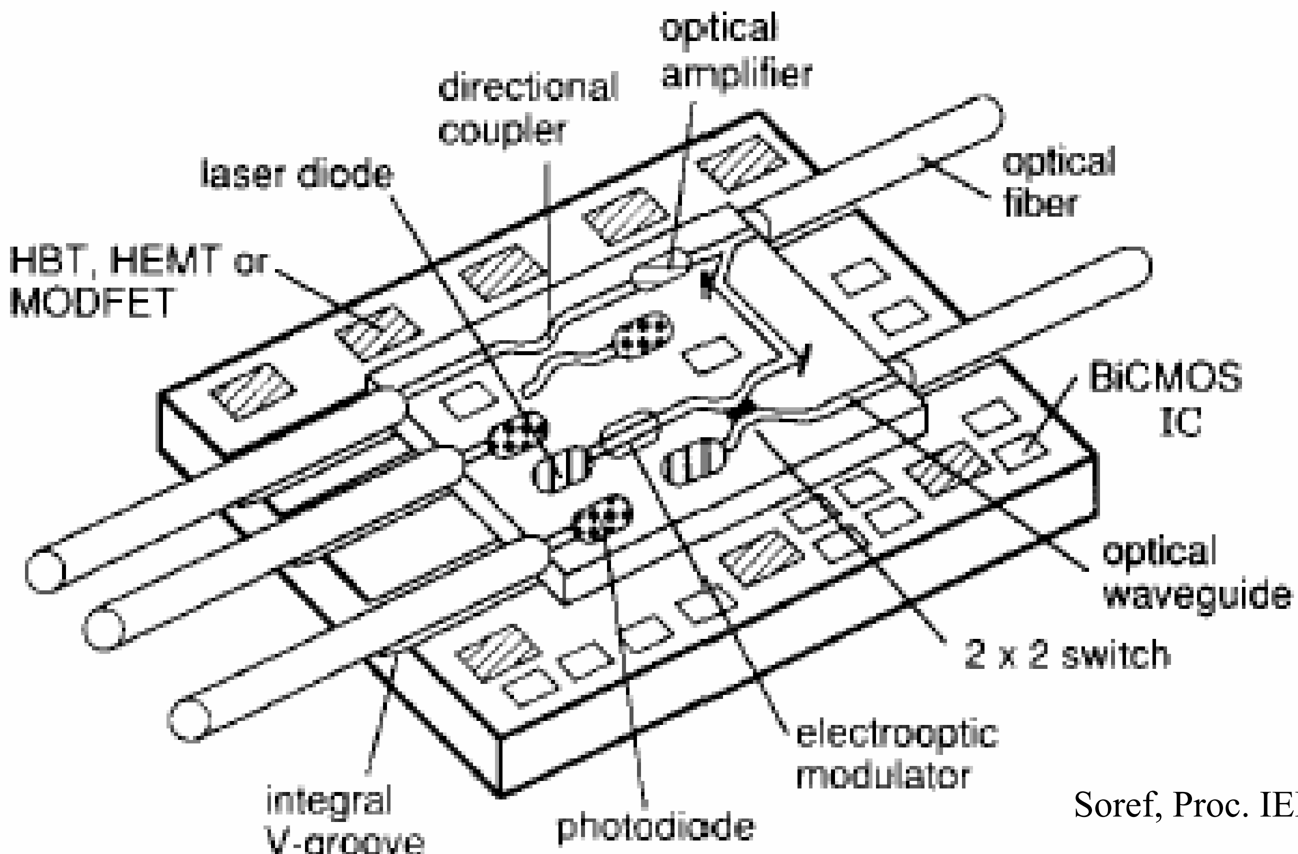
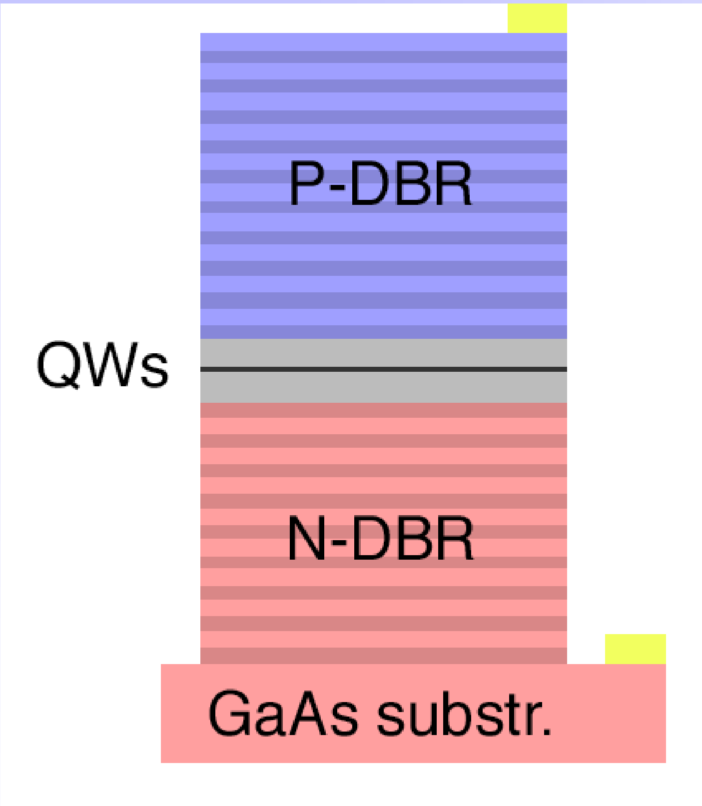
1993 Photonic Integrated Circuit

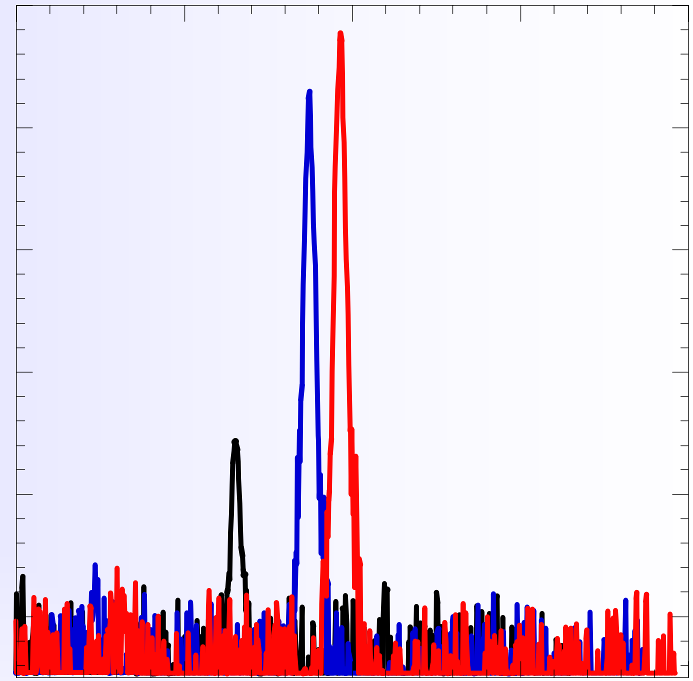


Soref, Proc. IEEE, 1687 (1993)

- Waveguide architecture with butt coupled fibers and edge emitting lasers
- Hybrid bonding (non-monolithic) of different structures
- Mostly III-V devices, very little electronics

First Photonic Crystal Device

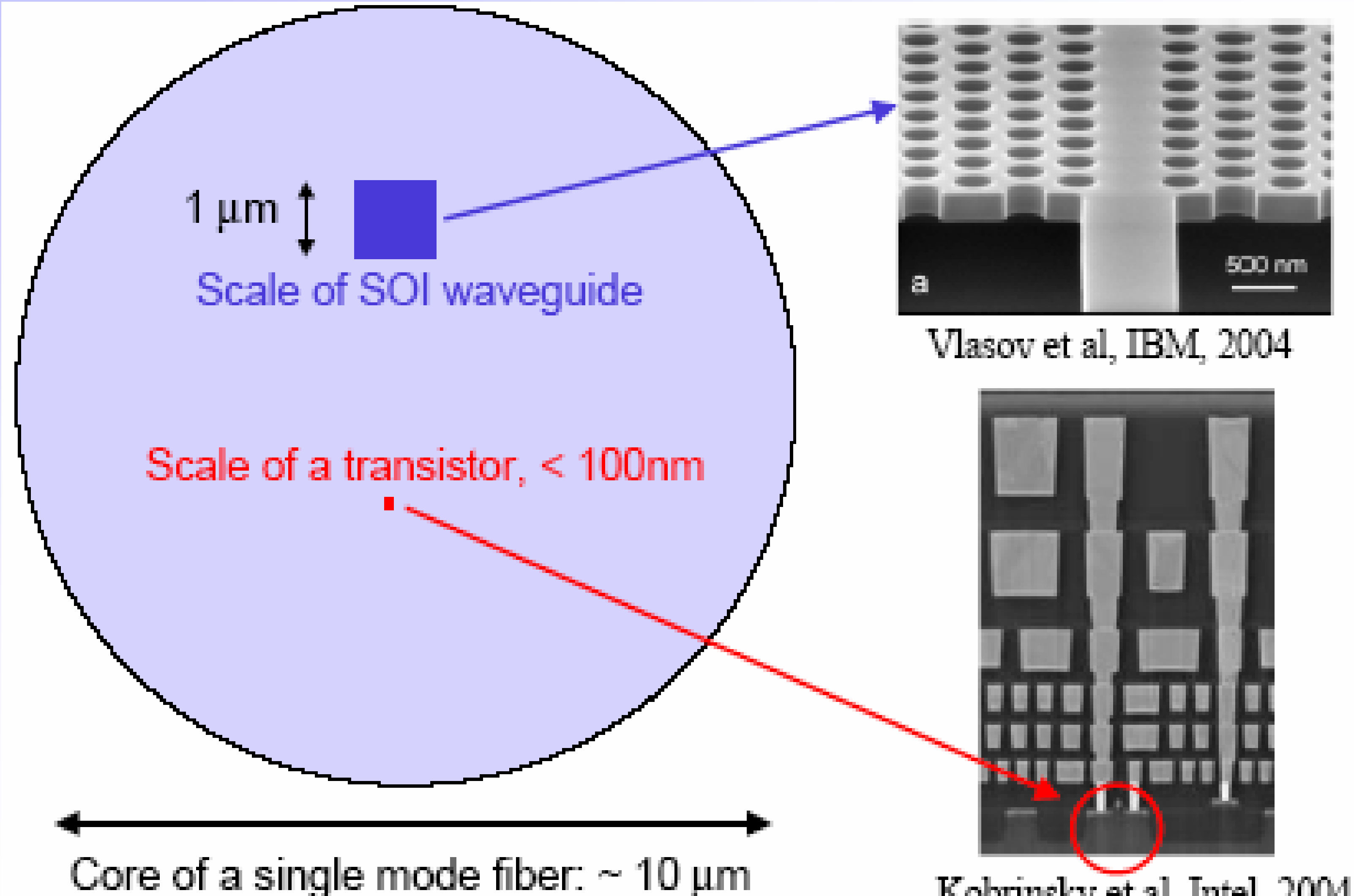




DBR (Distributed Bragg Reflector
- 20-40 quarter wavelength different index layers (~70 nm)
- One-dimensional photonic crystal

- Single longitudinal mode emission, independent of temperature and current injection
- Circular beam pattern
- Vertical emission--2-D array

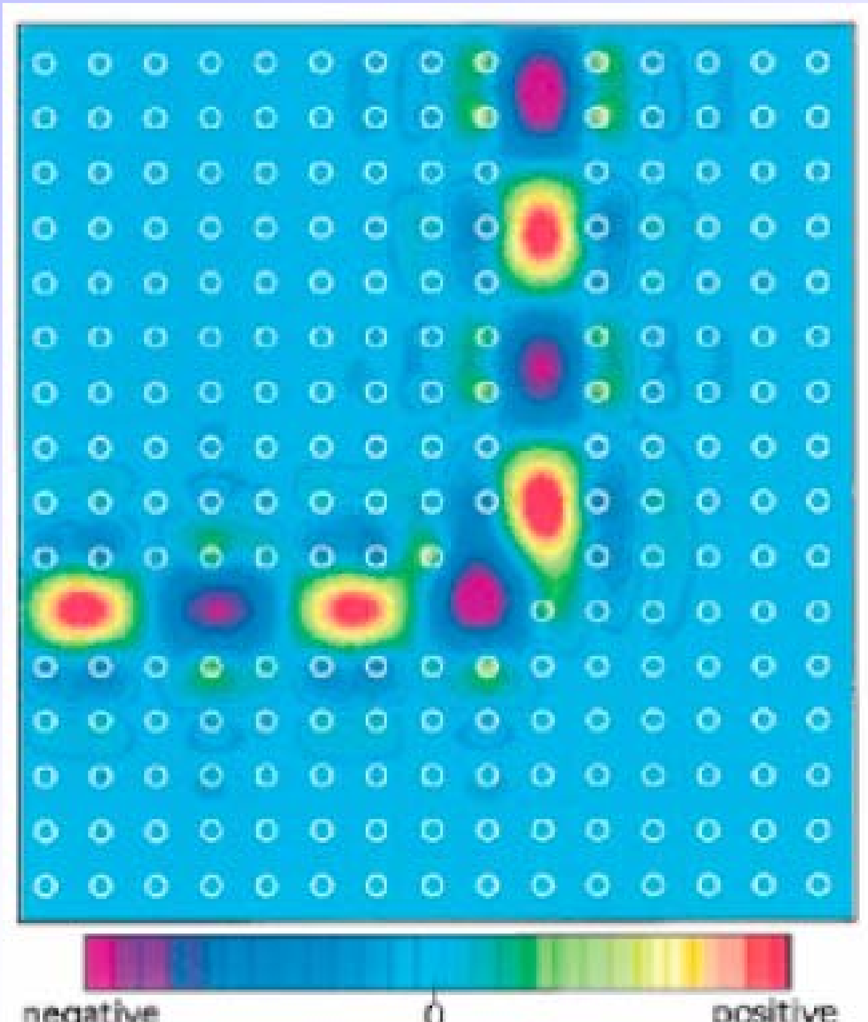
Dimensional Mismatch Between Optics and Electronics



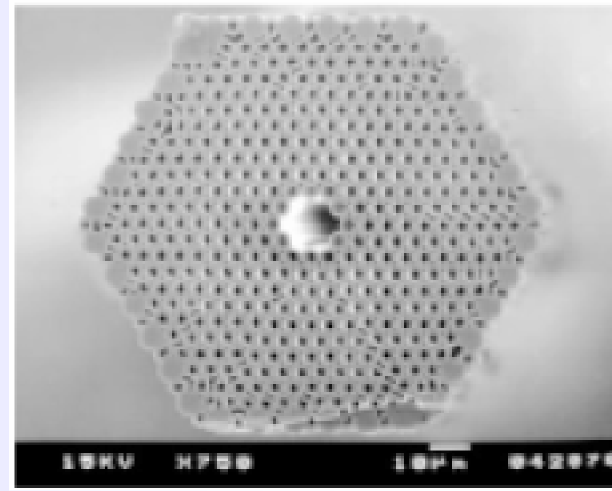
Vlasov et al, IBM, 2004

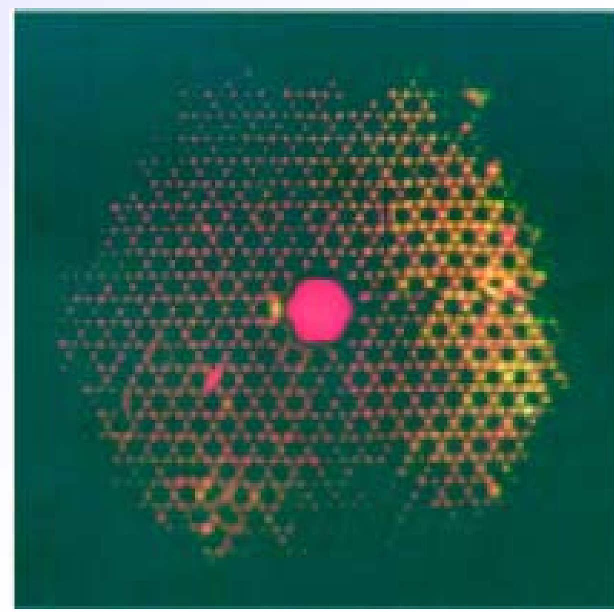
Kobrinsky et al, Intel, 2004

Unique Photonic Crystal Functionality

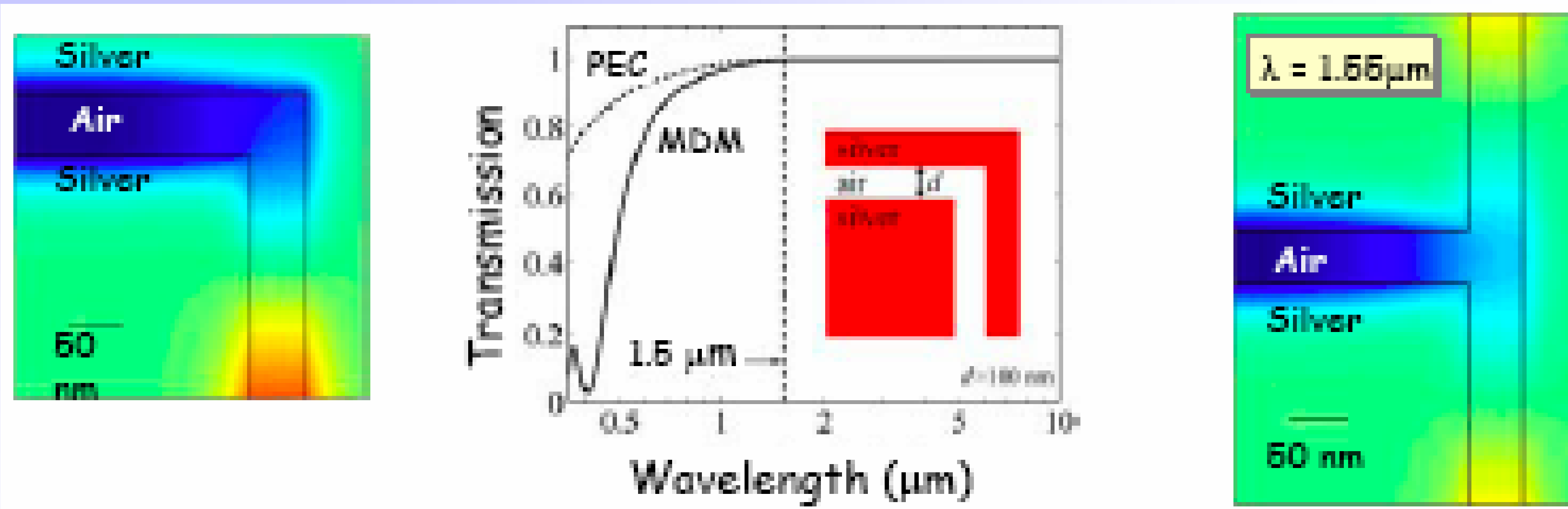


Electric Field Strength





Nanoscale Plasmonic Waveguides

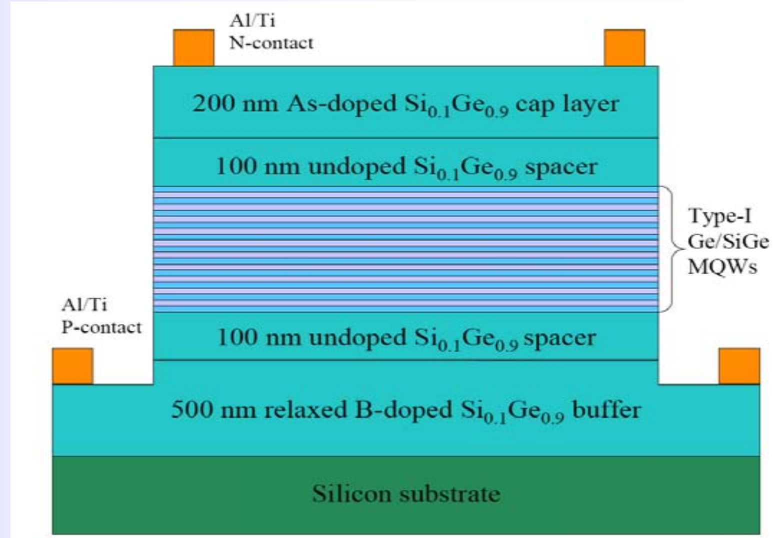


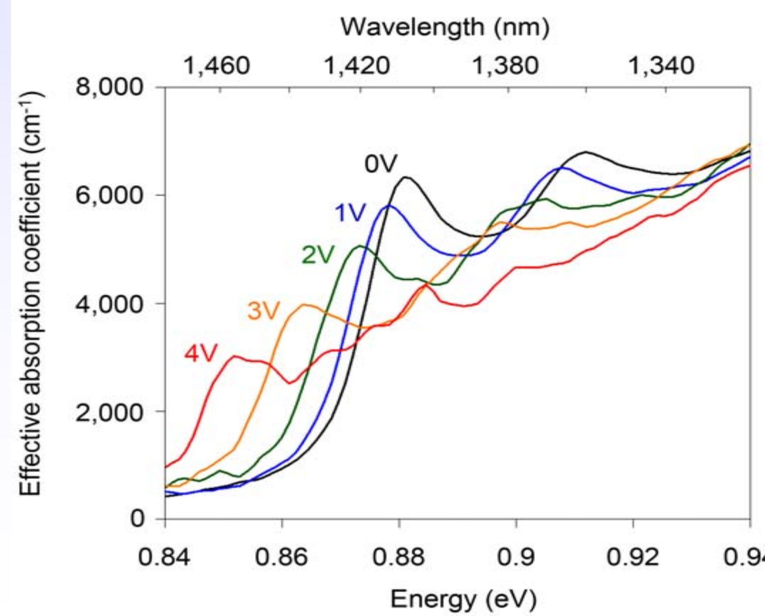
- 90° bends and splitters can be designed with 100% transmission from microwave to optical frequencies
- Provides bridge between dimensions of electronics and photonics
- Provides design flexibility for optoelectronic ICs

A New Si-Based Optical Modulator

Quantum-confined Stark effect (QCSE)

- Strongest high-speed optical modulation mechanism
  - Used today for high-speed, low power telecommunications optical modulators but in III-V semiconductors
- QCSE in germanium quantum wells on silicon substrates
- Fully compatible with CMOS fabrication
- **Surprises**
  - works in "indirect gap" semiconductor actually better than in III-V
  - higher speed (100 GHz) possible





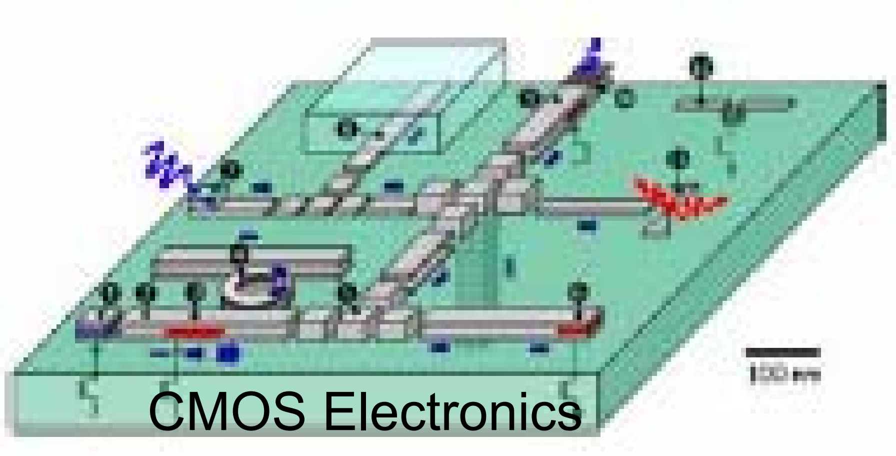
Y. H. Kuo, Y. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller & J. S. Harris, Nature **437**, 1334 (2005)

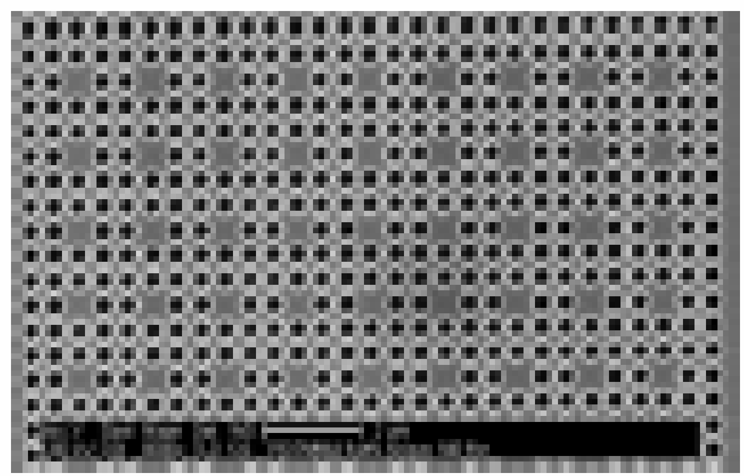
Integrated Optoelectronics on Si Platform Looks Feasible

- Silicon waveguides and integration with CMOS process now demonstrated
- Germanium-based detectors viable and integrable with CMOS
- Working modulators in silicon
  - carrier density index change modulators
- Quantum-confined Stark effect in Ge quantum wells on silicon demonstrated
  - much stronger absorption mechanism ➡ smaller devices, higher speed and lower power
- Many opportunities in nanophotonics for enhanced and new devices

Integrated Optoelectronics

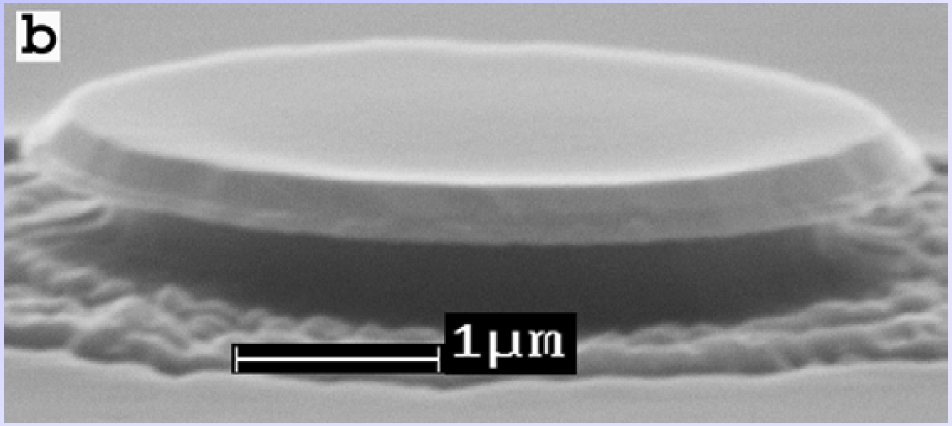
- **Mostly Electronics**, many "optical" functions done electronically--transistors are **FREE** (< 1µ¢ ea)
- Multi-layered nanometer deposition of compatible compatible high index of refraction materials
  - Si on Oxide (SOI)
  - GaAs/AlAs(AlO_x)
- Dielectric, semiconductor, and metal lithographic fabrication at deeply sub-wavelength scales
  - Silicon CMOS compatible processes
- Excellent quantum optoelectronic phenomena demonstrated in Si based devices
  - Ge quantum wells on silicon
- A platform, based on CMOS technology
  - Electronics
  - Optoelectronics
  - Optics

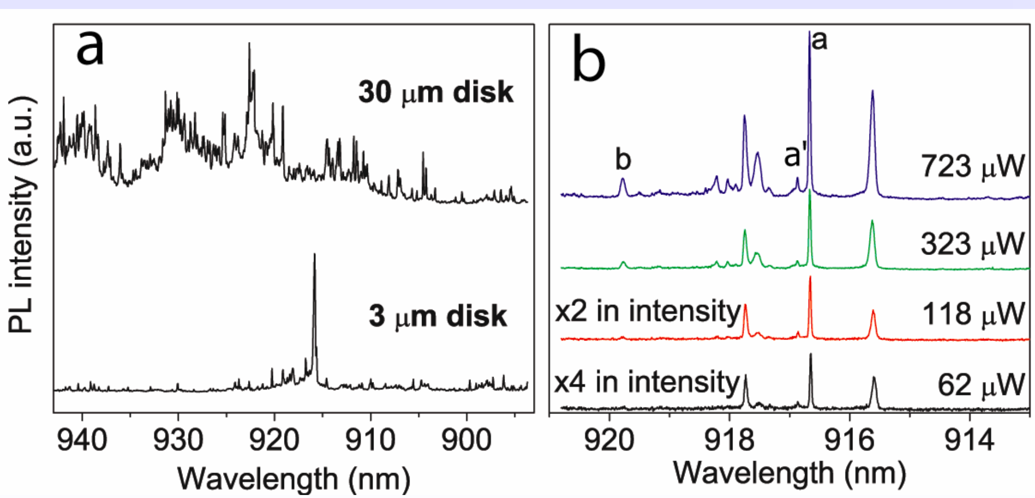


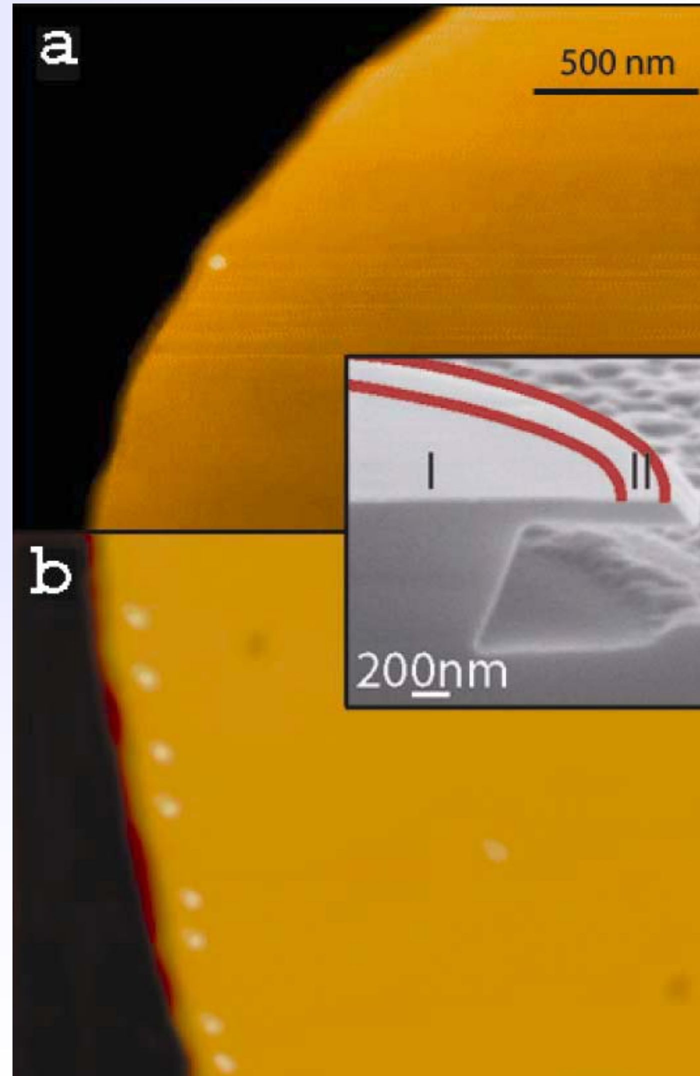


Photonic Crystal Passive elements
- waveguides
- resonators

Quantum Dot Microdisk Laser







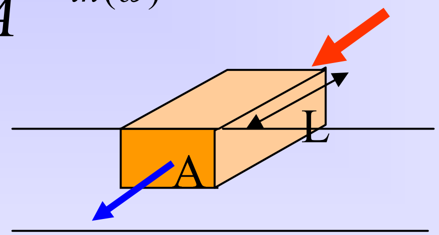
A ZERO threshold laser possible?

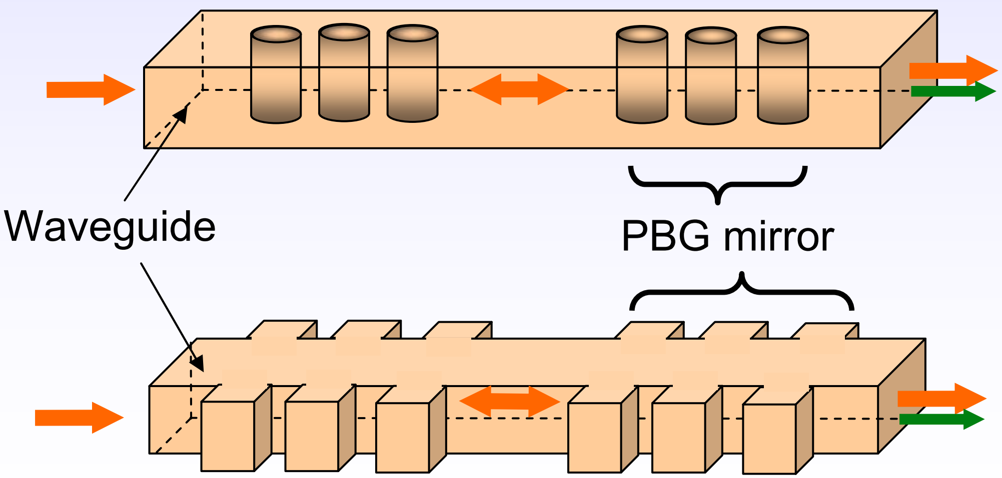
Nonlinear Optical Processes

How to increase the conversion efficiency?

$$\frac{P_{out(2\omega)}}{P_{in(\omega)}} \propto \frac{L^2}{A} P_{in(\omega)} F^2$$

$$F = Q\frac{\lambda}{L}$$



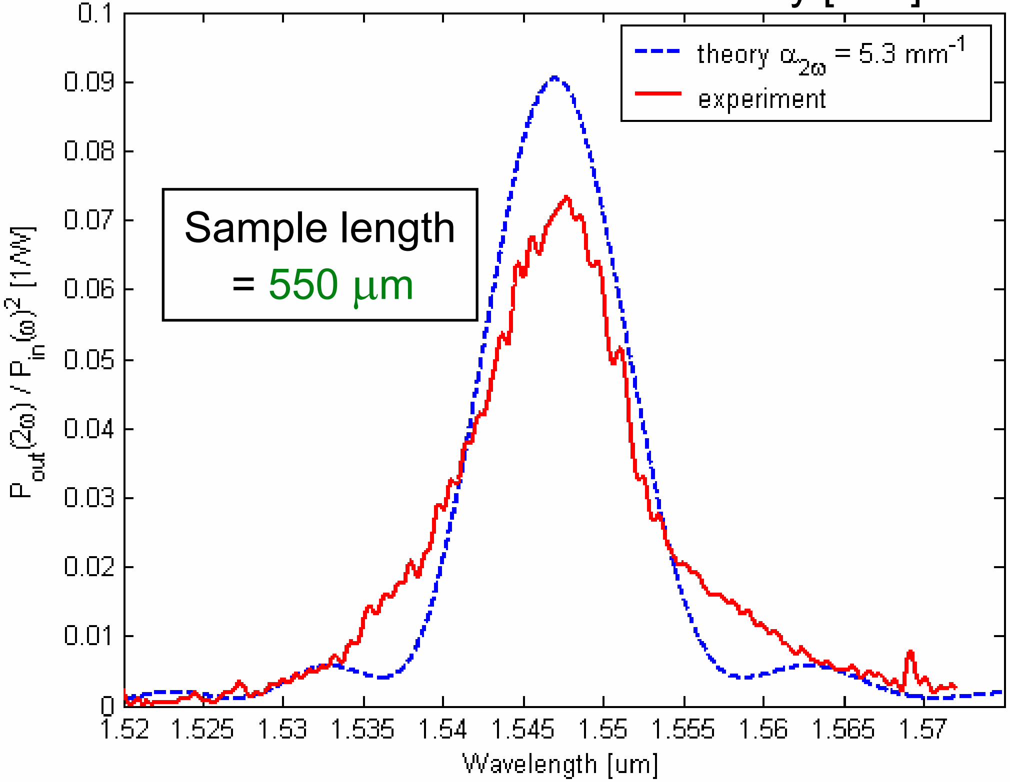


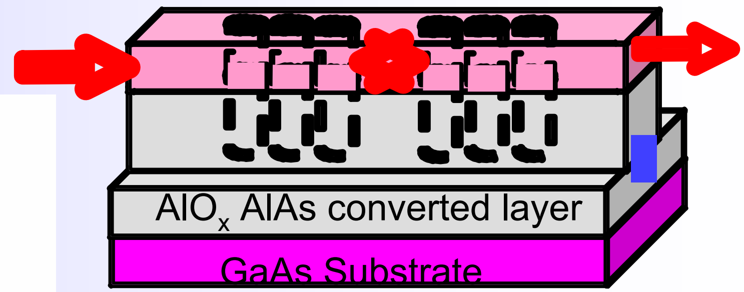
- Tightly confining waveguide
- High-Finesse (*F*) cavity, resonant at the fundamental frequency, increases the circulating power
- High-*F* cavity can be realized in tightly confining waveguides using photonic bandgap crystal (PBG) structures
- Cavity design Length ~ 200 μm Finesse ~ 60
  ➔ enhancement of a factor ~400
- Achievable internal conversion efficiency~ 4000 % / W (comparable to current 5-cm-long state-of-the-art PPLN waveguides)

Second Harmonic Generation

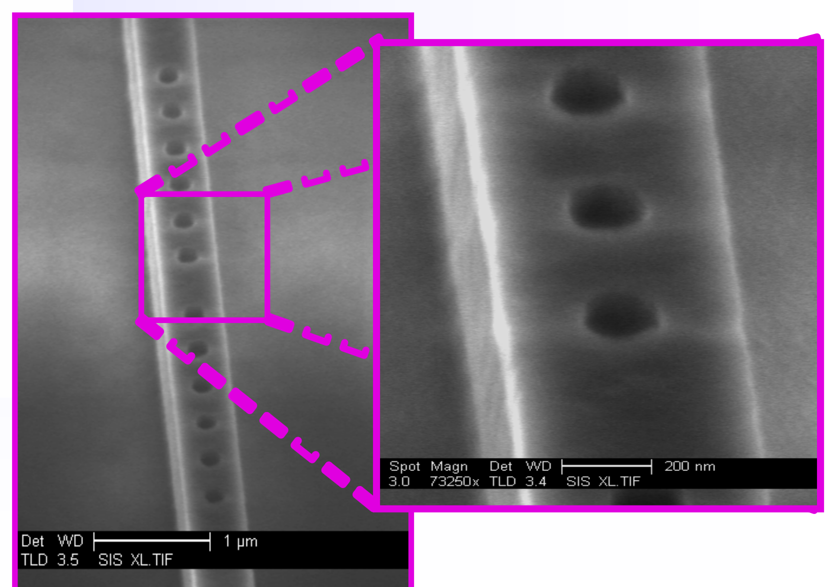
$P_{out}(2\omega) / P_{out}(\omega)^2$

Internal Conversion efficiency [1/W]





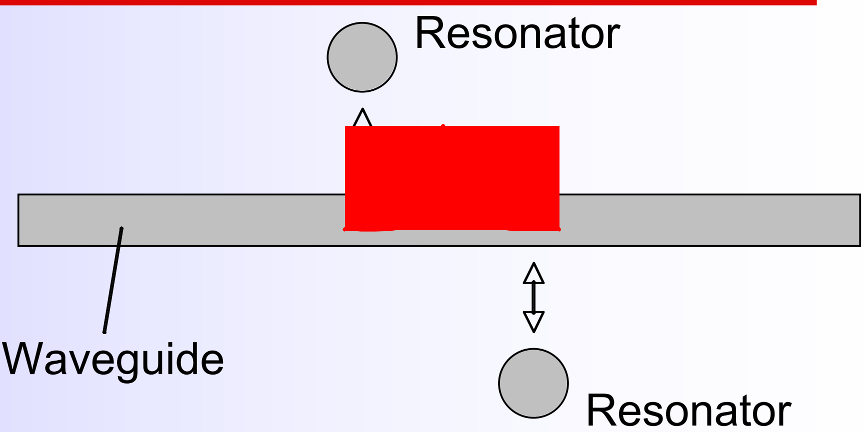
AlO_x AlAs conversion critical processing technology and unique to GaAs based systems



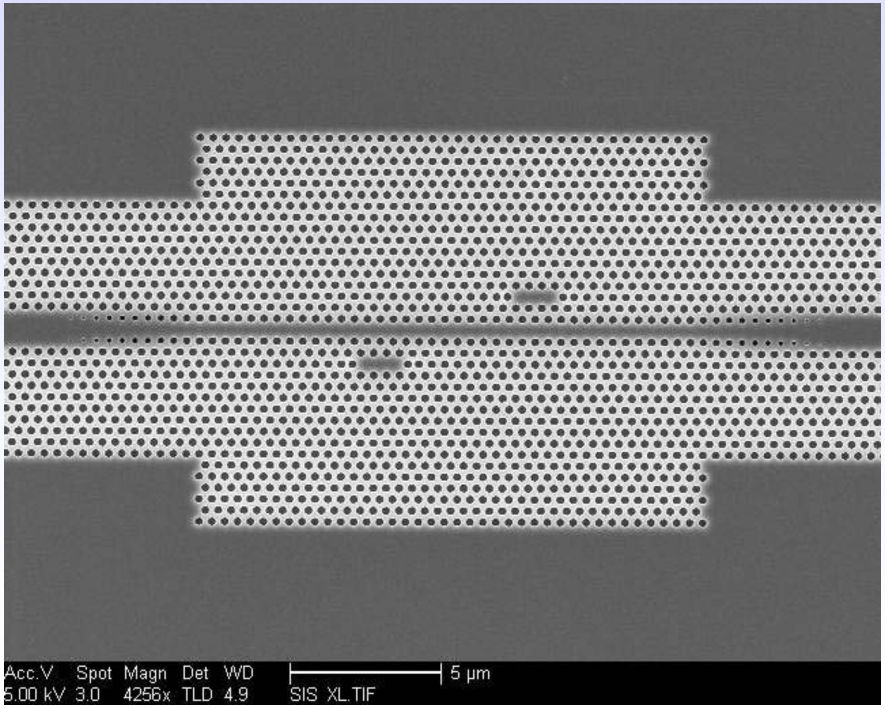
→**efficiency limited by SH loss** ←

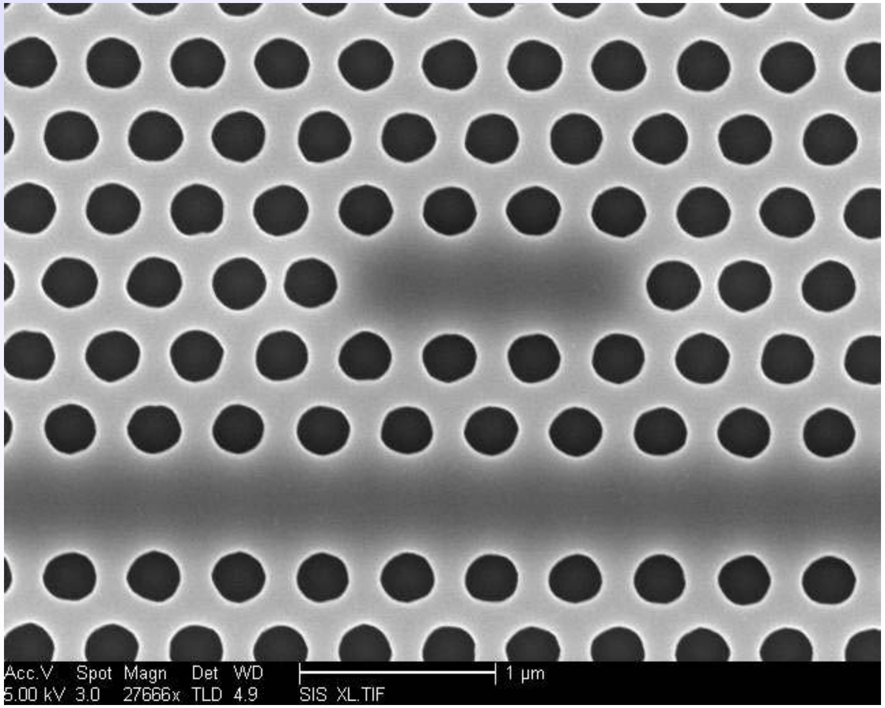
Stopping Light All-Optically

Light pulses can be **stopped** and **stored** coherently using a system of coupled waveguide and high-Q cavities.

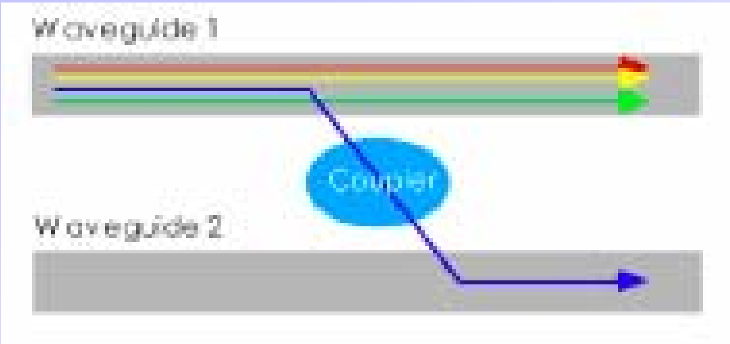


Suspended Si waveguide on SOI



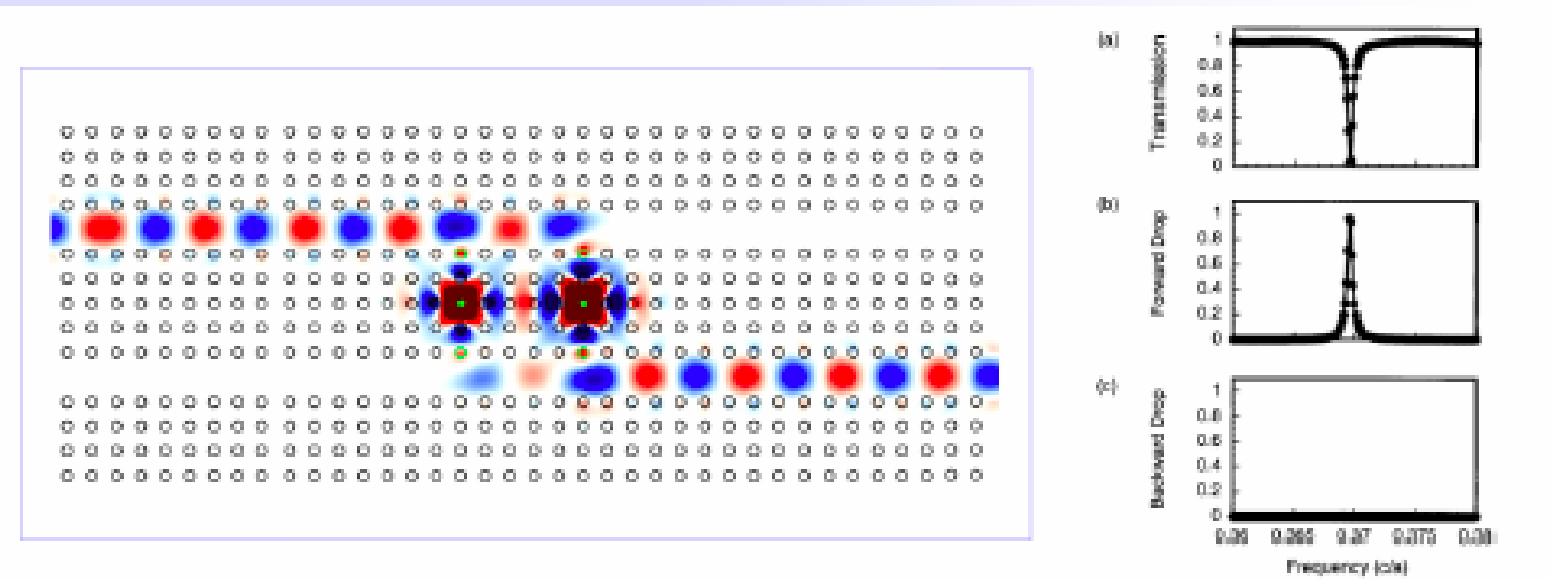


Photonic Crystal Add/Drop Filter



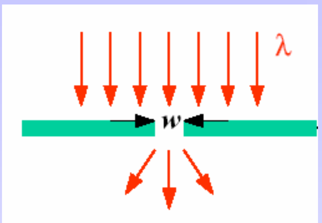
Two resonant modes with even and odd symmetry.

- Modes must be degenerate.
- Must have the same decay rate.



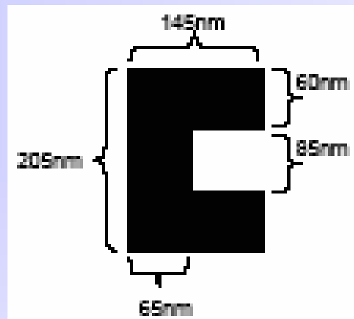
Nanometallic Enhancement of Photodiodes and Lasers

In a conventional aperture



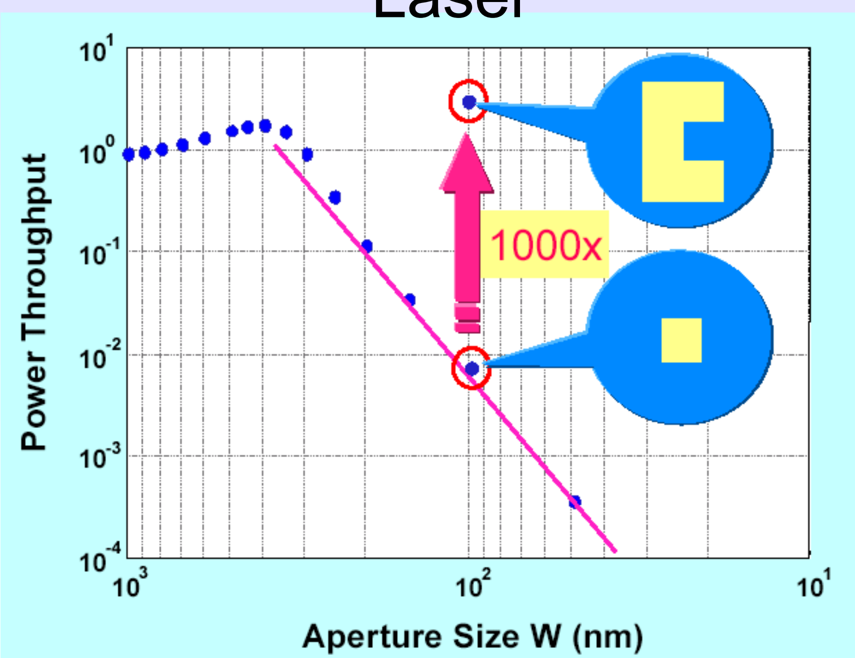
$$w << \lambda \Rightarrow PT \propto \left(\frac{w}{\lambda}\right)^4$$

C-aperture

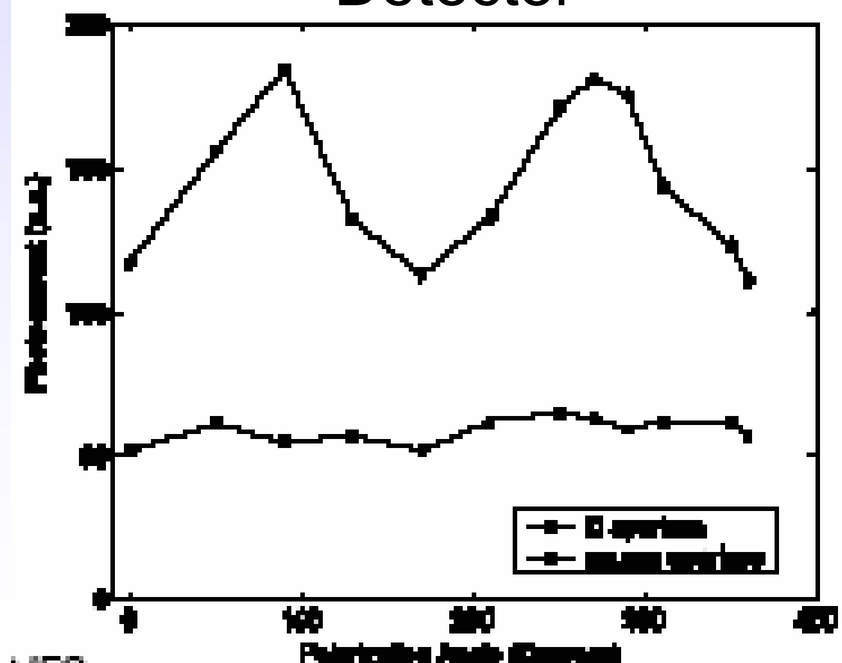


- Sub-wavelength (0.01 λ^2) C-shaped gold apertures
- Reduced device area
  - lower capacitance
  - higher speed
  - lower power

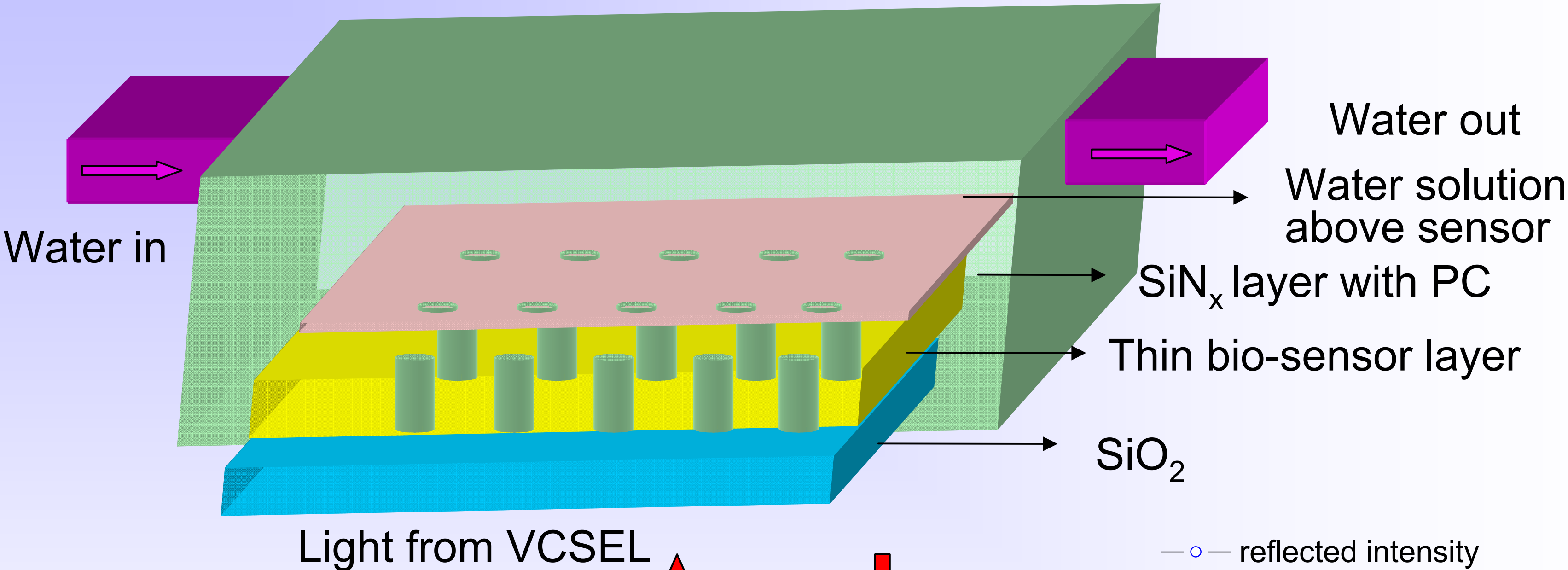
Laser



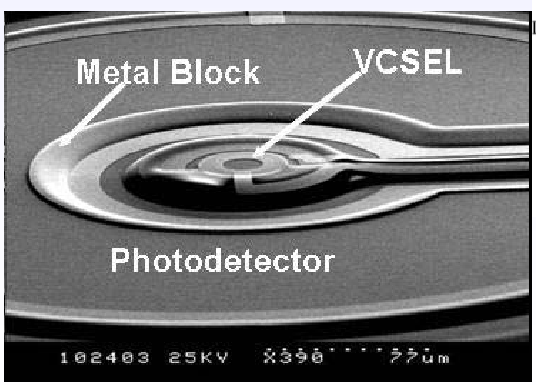
Detector

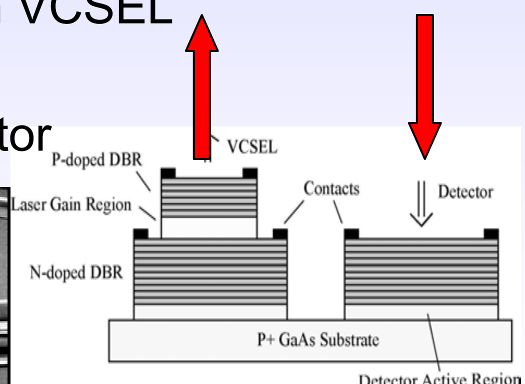


Integrated Photonic Crystal Resonant Filter Sensor



Integrated VCSEL/Detector

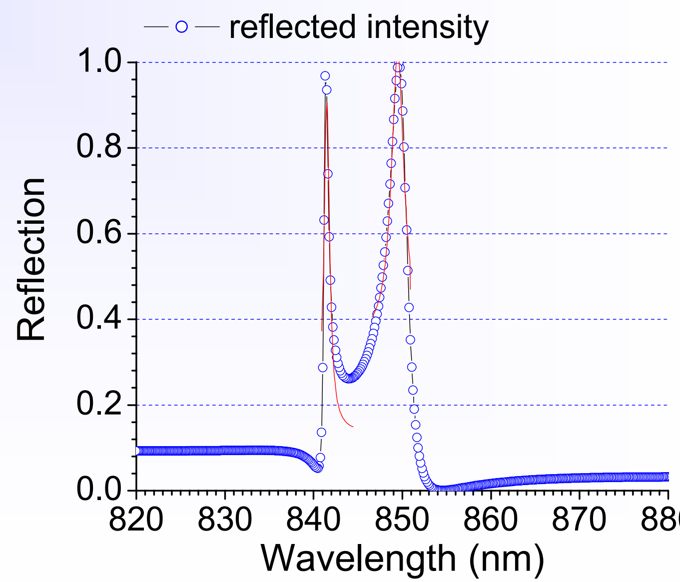




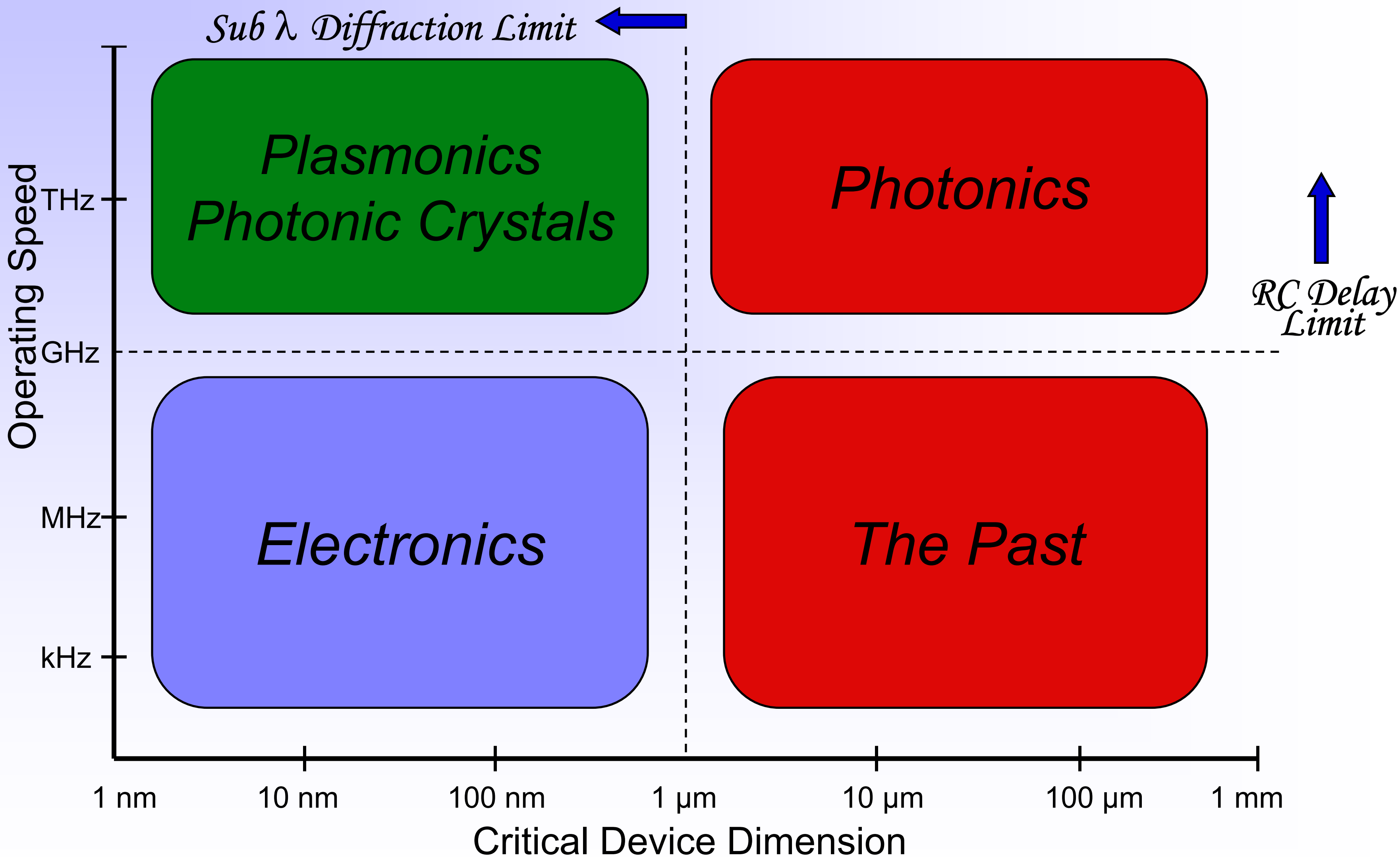
Peak width [FWHM]

at 850 nm = 2.7 nm Q= 314

at 841.3 nm = 0.8 nm Q= 1078



New Wave of Chip Scale Technologies



Opportunities for Nanophotonics

- Compact, highly functional components
  - Control and separate optical modes
    - Wavelength and space
- Deep sub-wavelength field concentration
  - very small photodetectors with high efficiency
  - match optical wave and electronic device sizes
- Very high Q/V cavities
  - enhance emission, optical nonlinear response
- Slow light
- Negative refractive index
  - metal-dielectric-metal structures
- Integrated quantum information processing?