The role of Nanostructures in Integrated Photonics

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3rd U.S.-Korea Forum on Nanotechnology
Seoul, Korea
April 3 & 4, 2006
1993 Photonic Integrated Circuit

- 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

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

DBR (Distributed Bragg Reflector)
- 20-40 quarter wavelength different index layers (~70 nm)
- One-dimensional photonic crystal
Dimensional Mismatch Between Optics and Electronics

Scale of SOI waveguide: 1 μm

Scale of a transistor, < 100 nm

Core of a single mode fiber: ~ 10 μm

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

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(AlOₓ)
- 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?

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

- 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

\[ \frac{P_{\text{out}}(2\omega)}{P_{\text{out}}(\omega)^2} \]

Internal Conversion efficiency [1/W]

- Sample length = 550 µm

\( \text{AlO}_x \text{AlAs conversion critical processing technology and unique to GaAs based systems} \)

\[ \Rightarrow \text{efficiency limited by SH loss} \Rightarrow \]

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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:

\[ w \ll \lambda \Rightarrow PT \propto \left( \frac{w}{\lambda} \right)^4 \]

C-aperture:

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

**Diagram:**
- Laser
- Detector

**Graph:**
- Power throughput vs. aperture size
- 1000x increase in power throughput

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Integrated Photonic Crystal Resonant Filter Sensor

Water in

Light from VCSEL

Water out

SiO₂

SiNx layer with PC

Thin bio-sensor layer

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

Operating Speed
- THz
- GHz
- MHz
- kHz

Critical Device Dimension
- 1 nm
- 10 nm
- 100 nm
- 1 µm
- 10 µm
- 100 µm
- 1 mm

Sub λ Diffraction Limit
RC Delay Limit

Plasmonics
Photonic Crystals
Electronics
The Past

Photonics
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?