Integrated Photonics Technologies

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February 2, 2018
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Outline

1. Amplitude
2. Polarization
3. Phase
4. Dispersion

\[ \mathbf{E}(\mathbf{r}, t) = \mathbf{A}(\mathbf{r}) e^{i \mathbf{k} \cdot \mathbf{r}} e^{-i \omega t} + \mathbf{A}(\mathbf{r})^* e^{-i \mathbf{k} \cdot \mathbf{r}} e^{i \omega t} \]
Reach of photonics technology

- Level (3) Communications (Century Link) is a global communications provider headquartered in Broomfield, Colorado
- Orange lines: fiber owned by multiple carriers or leased
- Red lines: fiber built and fully owned by Level (3)
- Circles indicate markets (internet services, private line, long distance services, managed routers, etc.)
- 180,000 miles of fiber - circles equator 7 times
- Data centers turn fiber into usable bandwidth (red and yellow squares) (red square is a data center with a metropolitan network)
- Bandwidth turned into internet service by installing routers and switches in key locations.

Global infrastructure for internet services as seen by Level (3) Comm (CenturyLink)

- Internet traffic includes: Email, voice calls, online video (Skype, Netflix, ...), online streaming services (Major League Baseball, ESPN, etc), banking, medical records, news, etc. and data traffic aggravators - social media (Facebook), cloud services (Google Drive), big data (Strava datasets), ...

http://maps.level3.com as of 2 September 2014
Growth of internet data traffic

- Performance requirements on data centers continues to steadily increase
- Similar trend observed for high-performance computers (HPC)

**GLOBAL DATA CENTER IP TRAFFIC**

- Plot: Global data center internet protocol (IP) traffic development (split by data center type).
- Statista 2018 projection: 9802 exabytes per year.
- 1 exabyte = $10^{18}$ bytes, 1 byte = 8 bits.

**PERFORMANCE DEVELOPMENT**

- Plot: "Top 500" most powerful supercomputers.
- Performance increased by factor of 10 every 4 years.
- 1 petaflop = $10^{15}$ flops.

- To meet projected requirements: communication bandwidth needs to scale exponentially.
- Scaling needed at all levels of a system (racks, backplanes, cards, carriers, and chip level).

Integrated photonics

- Analogous to integrated electronics; light guided on surface of optical chip by optical waveguides

Microelectronic integrated circuits

Fiber optics

- Advantages: Miniaturization (Size, Weight, Power, Portability), mechanical stability, economies of scale.
- Applications span interconnects, communications, and sensing
- Examples: data center signal routing, radio-over-fiber, imaging, signal processing (filtering), environmental monitoring, lab-on-a-chip, optical logic, spectroscopy, quantum optics, etc...
Optics on chip-scale
Integrated Optics

World-wide interest in academia, government, and industry

IBM

LUXTERA

CISCO

Battelle

NIST

Intel

NEC

ACACIA

KOTURA

Sandia National Laboratories

ORACLE

Alcatel-Lucent

Bell Labs
A Chip That Can Transfer Data Using Laser Light

By JOHN MARKOFF
Published: September 18, 2006

SAN FRANCISCO, Sept. 17 — Researchers plan to announce on Monday that they have created a silicon-based chip that can produce laser beams. The advance will make it possible to use laser light rather than wires to send data between chips, removing the most significant bottleneck in computer design.

As a result, chip makers may be able to put the high-speed data communications industry on the same curve of increased processing speed and diminishing costs — the phenomenon known as Moore’s law — that has driven the computer industry for the last four decades.

The development is a result of research at Intel, the world’s largest chip maker.

"Today, optics is a niche technology. Tomorrow it’s the mainstream of every chip we build."
- Patrick Gelsinger, Intel Sr. Vice President, 2006
FACT SHEET: President Obama Announces New Manufacturing Innovation Institute Competition

On National Manufacturing Day, The President and His Cabinet Will Visit Manufacturers Across the Country

U.S. manufacturing is central to the foundation of our economy, and the U.S. manufacturing sector is as competitive as it has been in decades for new jobs and investment. As the President said in his remarks at Northwestern University, "...with dedicated, persistent effort, we have been laying the cornerstones of this new foundation for growth and prosperity. The first cornerstone is new investments in the energy and technologies that make America a magnet for good, middle-class jobs."

As part of the effort to build on the progress made and highlight the need for continued investment in American manufacturing, the President is announcing today a new competition to award more than $200 million in public and private investment to create an Integrated Photonics Manufacturing Institute, led by the Department of Defense, and the second of four new institute competitions to be launched this year.

AIM Photonics (Photonics Media: $610 million in federal, state and private funds)
Silicon for optical interconnects

Optical links continue to replace electrical links at shorter link lengths

- Silicon photonics is particularly attractive:
  - Transparency at telecom wavelengths (optical networks at 1.3 µm and 1.55 µm)
  - High refractive index (high integration density, tight bends, confinement)
  - Materials compatible with CMOS and MEMS (o-e integration; low parasitics)
  - Large thermo-optic coefficient (∂n/∂T ~ 100 times glass)
  - Modulation via plasma dispersion effect
  - Large optical nonlinearities (χ(3) ~ 200 times glass)
  - Compatible with single mode technology for increasing bandwidth × length product (in contrast to 850 nm multi-mode optical link technology)
  - Challenge: electronics/photonics working together on same chip

Optical interconnects in HPC

- 2008: Optical transceivers in active optical cables used at board (i.e. card) level in IBM ROADRUNNER (1st PFlop system).
- 2011: Fiber-to-carrier; optical transceiver modules on carrier; IBM Power 775 supercomputer (~1 million optical fibers).
- 2015: On-carrier polymer waveguides & Si photonics chip on carrier (aiming at ≥1 Tbit/s off-carrier optical communication).

Silicon optical waveguides

Si strip waveguides: 450 nm x 250 nm
C-band: 2.5 dB/cm (TM), 2.38 dB/cm (TE)

RMS roughness: 2.12 nm

\[ \overline{E}(\vec{r}, t) = \overline{A}(\vec{r})e^{i\vec{k} \cdot \vec{r}} e^{-i\omega t} + \overline{A}(\vec{r})^* e^{-i\vec{k} \cdot \vec{r}} e^{i\omega t} \]

1. Amplitude
2. Polarization
3. Phase
4. Dispersion
Fiber-to-chip coupling
Fiber-to-chip coupling

Large coupling losses are the result of:

1. Effective index mismatch

- Corning SMF-28 optical fiber
  - Core diameter: 8.2 μm
  - Core refractive index: 1.464
  - Cladding diameter: 125 μm
  - Cladding refractive index: 1.458
  - TE $n_e = 1.461$ at $\lambda = 1.55 \mu m$

- Silicon strip waveguide
  - Core width: 450 nm
  - Core height: 250 nm
  - Core refractive index: 3.48
  - Cladding refractive index: 1.45
  - TE $n_e = 2.509$ at $\lambda = 1.55 \mu m$

2. Mode size mismatch (~3 orders x-section difference)

- SMF-28
- Si strip waveguide

3. Mode distribution mismatch

- Si strip (zoomed-in)
Fiber-to-chip coupling

Taper the fiber and inverse taper the waveguide

- Comparable MFDs with tapered fiber and inverse width tapers (low coupling loss and large bandwidth)
- Problem: Limited to edge coupling


Fiber-to-chip coupling

Alternative: Employ grating couplers

Grating couplers exploit diffracted light for out-of-plane coupling

- Grating coupler advantages:
  - no need to cleave or dice the chips
  - can couple light anywhere on chip surface
  - allows wafer scale testing

- Problem: efficiency-bandwidth tradeoff

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L. Vivien, et al., J. Lightwave Technol. 24, 2006 (Grating)
G. Masanovic, et al., Opt. Express 13, 2005 (Dual grating assisted directional coupler (DGADC))

A. Mekis, JSTQE, 2011.
Our work: Cantilever couplers

- Solution: Utilize cantilevers to enable out-of-plane coupling with silicon inverse width tapers
- Idea is to embed a silicon inverse width taper within an oxide bilayer cantilever that deflects out of plane because of residual stress; bilayer consists of PECVD oxide and BOX

Advantages:
- Exploits the bandwidth and efficiency of inverse width tapers
- Avoids dicing or cleaving chip
- Allows light to be coupled anywhere on chip surface

P. Sun and R. M. Reano, Optics Express, 17, 4565-4574 (2009).
Cantilever couplers

Cantilever couplers

- Avg C-band (1530 nm to 1565 nm) coupling efficiency: 0.62 dB (0.87) (TE), 0.50 dB (0.89) (TM)
- Avg coupling efficiency over measurement range < 1 dB (0.79).

- Cantilever confinement and inverse width taper contribute to mode conversion → headroom for reduced coupling loss in optimized designs

90° cantilever couplers

- Deflection angle of as-fabricated 100 µm long cantilevers is 28°
- High temperature annealing used to increase deflection angle to 90°

- At high temperature, PECVD SiO₂ exhibits impurity release / network reconstruction
- Film thickness decreases, bilayer stress increases, deflection angle increases

Chip-to-chip coupling

Schematic of measurement setup

Angled-view optical image

$\overline{E}(\vec{r}, t) = \overline{A}(\vec{r}) e^{i \vec{k} \cdot \vec{r}} e^{-i\omega t} + \overline{A}(\vec{r})^* e^{-i \vec{k} \cdot \vec{r}} e^{i\omega t}$

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Background: Polarization rotation

- Current methods to rotate optical polarization include:

  - Off-axis double core [1]
  - Cut corner triangular core [2]

Drawbacks of current methods:
- Rotation is fixed once fabricated
- Impedance mismatch is large resulting in degradation of insertion loss
- Bandwidth is limited due to structures based on periodicity or mode coupling

Our approach: Berry's Phase

- In optics, Berry's phase manifests as optical polarization rotation.
- Amount of rotation depends on path traced by light in wavevector $\bar{k}$ space.

For non-planar paths, polarization rotation is equal to solid angle enclosed by path.
- Berry's phase is a global topological effect (Gaussian curvature of a sphere is $1/r^2$).
- Change in wavelength produces change in radius but solid angle constant $\rightarrow$ broadband.

Berry's phase on a silicon chip

- Mode at 1550 nm for deflection angle equal to 0°, 15°, 30°, and 45° in sequence.
Voltage control of optical polarization

- Challenging to achieve large deflection in compact bends (generally: 1 \( \mu m \) deflection for 20 \( \mu m \) bend radius)
- Solution: implement out-of-plane waveguide in ring resonator

Dynamic control of optical polarization

- Input polarization is TE only
- \( \text{PER} = \frac{P_{\text{TM}}}{P_{\text{TE}}} \)
- Results demonstrate a topological approach for voltage control of optical polarization on chip

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Phase control

- Phase control enables optical switching.
- Optical communications networks utilize switches for routing, reconfiguration, and restoration.

Switch: building block

1 to 4 multiplexer

- Desirable properties: small footprint, low power consumption, low insertion loss

Optical switching

- Optical switches based on silicon are particularly attractive
  - Highly confined optical modes; dense integration; tight waveguide bends
  - Large thermo-optic coefficient of silicon, $\frac{\partial n}{\partial T} = 1.86 \times 10^{-4} \text{ /K}$ at 300 K ($\text{SiO}_2 \sim 10^{-5} \text{ /K}$)
  - High thermal conductivity $\{W/(m \text{ K})\}$: 148 for Si, 1.4 for $\text{SiO}_2$, 0.026 for air

- Enables Mach-Zehnder interferometer (MZI) thermo-optic switches with:
  - Arm lengths as short as hundreds of micrometers
  - Switching powers as low as tens of milliwatts
  - Switching times as fast as microseconds

\[ \Delta \phi = \frac{2\pi}{\lambda} \left( \frac{\partial n_e}{\partial T} \right) (\Delta T)L \]

G. V. Treyz, Electron. Lett. 27 (1991)
$P_\pi = 75 \text{ mW}, T = 50 \mu\text{s}, \lambda = 1.3 \mu\text{m}; \ 1\times1 \text{ switch}; \ rib \ waveguides \ on \ 1.1 \mu\text{m} \ Si, \ W=10 \mu\text{m}, \ D=0.25 \mu\text{m}; \ L = 500 \mu\text{m}$

$P_\pi = 50 \text{ mW}, T = 3.5 \mu\text{s}, \lambda = 1.55 \mu\text{m}; \ 1\times1 \text{ switch}; \ strip \ waveguides, \ 0.6 \mu\text{m} \times 0.26 \mu\text{m}; \ L = 700 \mu\text{m}$
Free-standing waveguide MZI

- Submicrometer squared x-section and thermal isolation enhance temperature increase.
- Heating power from resistive heaters contributes to the thermo-optic effect more efficiently.

Cross-sectional dimensions of the silicon waveguide core are 450 nm × 250 nm
(w = 2.5 μm, h = 2.1 μm, g is 4 μm; interferometer arm length L is 100 μm)

P. Sun and R. M. Reano, Optics Express 18 (2010).
Free-standing waveguide MZI

P. Sun and R. M. Reano, Optics Express 18 (2010).
Free-standing waveguide MZI

- $\lambda = 1550$ nm; polarization is TE
- Switching power is $P_\pi = 540 \ \mu W$
- Extinction ratio of 25 dB
- Insertion loss $\sim 2.8$ dB
- $\Delta n = 7.7 \times 10^{-3}$ and $\Delta T = 41.7$ K
- Footprint: 320 $\mu m \times 28 \ \mu m$
- 10% - 90% switching rise time is 141 $\mu s$
- Unreleased version: 31 mW, 39 $\mu s$
- First submilliwallt demonstration

P. Sun and R. M. Reano, Optics Express 18 (2010).
Plasma dispersion effect

- Challenges: (1) Absorption accompanies phase shift; (2) DC tuning consumes power.

Ferroelectrics on Si

- Bonding thin films of lithium niobate to silicon waveguides using BCB

**Advantages:**
- Enables field effect structures based on second order susceptibility
- Potential advantages in speed, linearity, and power consumption.

Ion slicing LiNbO$_3$

(a) 1 mm thick Z-cut LiNbO$_3$ wafer
(b) Ion implantation with helium ions
(c) Rapid thermal annealing at 250$^\circ$ C
(d) Hydrofluoric acid (HF) etch

Fabrication process

(a) Silicon waveguide patterning
(b) Spin coat BCB
(c) LiNbO$_3$ bonding
(d) PECVD SiO$_2$ deposition and etch
(e) Electrode deposition
(f) SEM cross-section
Fabrication results

- Si strip waveguide: 550 nm by 170 nm; X-cut LiNbO$_3$ thickness: 1 µm
- Racetrack radius: 10 µm; Racetrack straight section length: 50 µm
- 25% optical power confinement in LiNbO$_3$
- TE mode accesses the $r_{33}$ EO coefficient (31 pm/V in bulk LiNbO$_3$) in the straight sections
Measurements

- Quality factor of 14,400, FSR of 4.05 nm, tunability of 5.3 pm/V, $V_{πL}$ of 6 V cm
- Footprint 3 orders of magnitude smaller than LiNbO$_3$ MZI

L. Chen and R. M. Reano, Optics Express 20, 4032-4038 (2012). (RF photonic E-field sensor)
Hybrid Si/LiNbO$_3$ platform

Electrically tunable optical filters, switches, and modulators; E-field sensors; $\chi^{(2)}$ nonlinear optics on-chip

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Dispersion for miniaturization

- **Defect mode resonators**
  - Defect created in PhC lattice
  - Operate inside band gap
  - Often high, but fixed Q (>10⁶)
  - Tightly confined modes
    - Small interaction volume
    - Less volume for gain media
  - Similar total footprint

- **Transmission mode resonators**
  - Terminated PhC lattice
    - Operate at band edge
  - Q scales with number of periods
  - Large, disturbed electric fields
    - Increased interaction volume
    - Larger volume for gain media
  - Similar total footprint


(light emitters, low power switches, high sensitivity sensors, compact footprint)
Transmission mode cavities

• Regular Band Edge (RBE)
  - $(\omega - \omega_0) \sim (k - k_0)^2$
  - Q-factor $\sim N^3$

• Degenerate Band Edge (DBE)
  - $(\omega - \omega_0) \sim (k - k_0)^4$
  - Q-factor $\sim N^5$

• Advantages of DBE
  - Finite length periodic structures can be used to realize compact resonators
  - Internal field scales as number of periods $N$ in RBE and $N^2$ in DBE
  - DBE with $N$ periods performs as RBE with $N^2$ periods
    (significant difference with respect to miniaturization)
Proposed DBE realizations

• **1D anisotropic layered structures**
  • Need high contrast artificial birefringence
  • Bulk realization


• **Optical fibers with multiple gratings**
  • Precise control of period and grating amplitudes required
  • Control of mode coupling for high transmission challenging

DBE in silicon photonics

- **Coupling-gap DBE (cgDBE)**

- **Zero-coupling-gap DBE (zcgDBE)**

DBE in Si photonics: Experiment

SEM of fabricated zcgDBE resonator in silicon photonics for operation in infrared

DBE mode decomposition

- Transmission response of zcgDBE structure with 30 periods

DBE electro-optics

• PIN diodes used to create carrier injection DBE voltage controlled switch
• Experimentally demonstrated 7.09 nm/V DC tunability
• Digital transmission: 91 aJ/bit at 100 Mb/s with 3 dB ER and 108 μW DC power

Summary and Outlook

\[ \overline{E}(\vec{r}, t) = \overline{A}(\vec{r}) e^{i\vec{k} \cdot \vec{r}} e^{-i\omega t} + \overline{A}(\vec{r})^* e^{-i\vec{k} \cdot \vec{r}} e^{i\omega t} \]

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5. Frequency

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