Enabling Nanophotonics with Plasmonics and Metamaterials

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OUTLINE

- Why NANOPHOTONICS?
- Si nanophotonics
- Why metamaterials/plasmonics?
- Future of nanophotonics with metamaterials
- All begins with materials/nanofabrication

Thanks go to A. Boltasseva, M. Brongersma, S. Bozhevolniyi, and Y. Vlasov for slide materials
Nanophotonics ≠ Nano-optics

Electronics
Electrons
Wires

Nanophotonics
Photons
Waveguides

$\bar{e} \quad \rightarrow \quad \rightarrow \quad \rightarrow$

$f \sim 10^{10} \text{ Hz}$

$f \sim 10^{15} \text{ Hz}$
NANOPHOTONICS

- Photonics vs. Electronics
- Fiber Optics: Transmitting Information
- Integrated Optics: Processing Information
- New Paradigms:
  - Plasmonics
  - Metamaterials
The operating speed of data transporting and processing systems is increasing due to the ever-increasing need for faster information processing and transport. Electronic components are running out of steam due to issues with RC-delay times. This has led to the rise of alternative technologies such as Photonics and Plasmonics. Photonics uses structures in the micrometer scale (~1 µm), while Plasmonics uses structures in the nanometer scale (~1 nm). Future advancements in communication networks will likely involve the integration of these technologies, particularly Plasmonics, to further increase operating speeds.
SYSTEM INTERCONNECT HIERARCHY

Inter-chip: millimeters
Inter-board: centimeters
Inter-shelf: ≤ meters
Inter-rack: meters
Inter-site: kilometers
Long-haul: 10-10^3 kilometers
Network Element
Network Elements
Central office

Slide credit to Vlasov
Si NANOPHOTONICS

1989

Concept:
Deep scaling of optics (materials with high refractive index – but still diffraction limited!)

CMOS compatible
Materials
Processing

R. Soref et al
Silicon Integrated Nanophotonics

Slide credit to Vlasov
Top 500 most powerful supercomputers

www.top500.org

1EFlops
100PFlops
10PFlops
1PFlops
100TFlops
10TFlops
100GFlops
10GFlops

www.top500.org

94 96 98 00 02 04 06 08 10 12 14 16 18

Slide credit to Vlasov
IBM HPC systems

MareNostrum
2006

10,240 PowerPC970 processors, 90 TFlops

IBM P775 system
2011

256 P7 processors, 90 TFlops

Slide credit to Vlasov
FROM 5K TO 1M FIBER LINKS

2006
MareNostrum
~5K fiber cables

2011
P775 system
~500K fiber cables

Slide credit to Vlasov
## COST AND POWER PER BIT

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak Performance</th>
<th>number of optical channels</th>
<th>Optics Power Consumption</th>
<th>Optics Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>1PF</td>
<td>48,000 (@ 5Gb/s)</td>
<td>50mW/Gb/s (50pJ/bit)</td>
<td>$10,000 per Tb/s</td>
</tr>
<tr>
<td>2012</td>
<td>10PF</td>
<td>2x10^6 (@ 10Gb/s)</td>
<td>25mW/Gb/s</td>
<td>$1,100 per Tb/s</td>
</tr>
<tr>
<td>2016</td>
<td>100PF</td>
<td>4x10^7 (@ 14-25 Gb/s)</td>
<td>5mW/Gb/s</td>
<td>$170 per Tb/s</td>
</tr>
<tr>
<td>2020</td>
<td>1000PF (1EF)</td>
<td>8x10^8 (@ 25 Gb/s)</td>
<td>1mW/Gb/s</td>
<td>$25 per Tb/s</td>
</tr>
</tbody>
</table>

Acknowledgment: A. Benner, J.Kash

Slide credit to Vlasov
OFF-CHIP NP INTERCONNECTS

Goal: Integrate Ultra-dense Nanophotonics Circuits with CMOS chip
MAP OF THE ROAD

Circa 2015

Circa 2020

“Technologies for Exascale systems”, P. Coteus, J.Knickerbocker, C. Lam, and Y. Vlasov
IBM Journ. R&D, 55, No.5, 2011
IBM Silicon Integrated NP Technology

IBM 90nm Silicon Integrated Nanophotonics:
Integrated photodetector (red feature)
Modulator (blue feature)
Silicon transistors (red sparks)

IBM chip:
BLUE optical waveguides and
YELLOW copper wires

“After More Than a Decade of Research, Silicon Nanophotonics is Ready for Development of Commercial Applications.”

IBM Press release, December 10, 2012
Cloud and Big Data Applications

*Release: 12 May 2015, Yorktown Heights, N.Y.*
Cassette carrying several hundreds chips intended for 100Gb/s transceivers
Plasmonic (Metal) Antennae as Electrical Metamaterials: Focusing Light to Nanoscale

Coupling Light to Nanoscale via Surface Plasmons

Surface plasmon = Collective oscillation of the conduction electrons

Localized SURFACE PLASMON resonance = Optical NANO-ANTENNA

Plasmon Slot Waveguide can squeeze the optical signal by shrinking its wavelength by a factor of 10 or more.
Integration of plasmonic elements onto Si-based microphotonic chips
SEM images are of actual photonic devices

Courtesy of Y. Vlasov (IBM)
Unleashing the full potential of HYBRID nanophotonic components for on-chip optical communication by leveraging the ability of METALS to perform simultaneous electronic and optical functions

Courtesy of M. Brongersma
PLASMONICS/METAMATERIALS

- Interconnects
  - Optical processing of data
  - Subwavelength confinement
  - Electrodes are in place
  - Coupling to other on-chip devices
  - Combination of guiding, detection, modulation, sensing
  - Usage of field enhancement for nonlinear optics
  - Integration with optoelectronics, lab-on-a-chip, solar cells

- Nano-imaging & spectroscopy

- Data recording and storage

- Sensing, SERS

- Sub-\(\lambda\) photodetectors

- Medical applications