Silicon Photonics:

From Device Engineering to Large-Scale System Integration

Jie Sun

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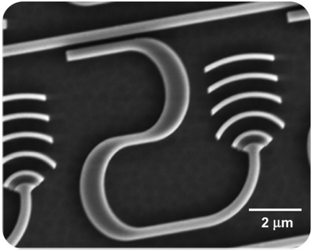
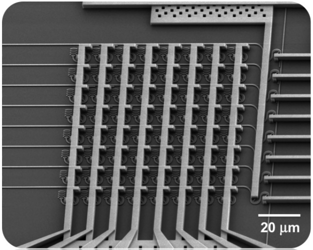
Massachusetts Institute of Technology
February 27, 2014





What is Silicon Photonics

Optical Technology

Silicon Chip

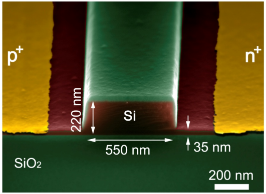


Image Courtesy of IBM

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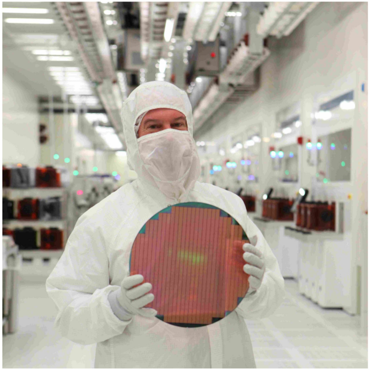
CMOS Fabrication Techniques



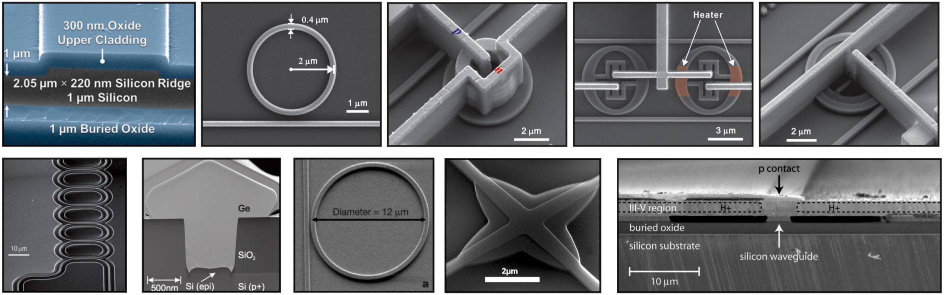
Images from Internet

Silicon Photonics

- Silicon (and other compatible materials) as the material for photonics
- Accessible to well-developed CMOS processing technology

Silicon Photonics: A Rich Device Library

Silicon Photonics Device Library

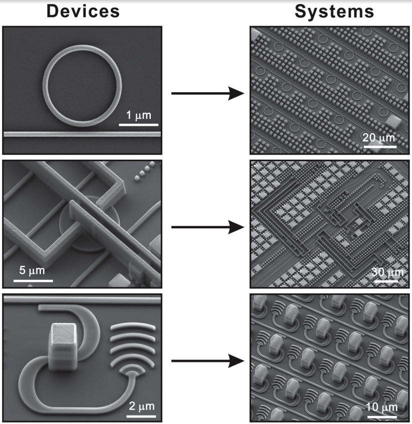


IBM Sandia Cornell IMEC UCSB

Silicon Photonic Devices

- **High-refractive-index contrast:** compact devices, integration
- **Electro/Thermo-optic effects:** active devices
- **Hybrid integration:** light sources

Silicon Photonics: From Devices to Systems

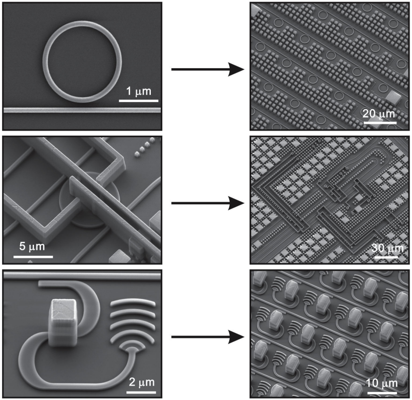


System Integration: A Unique Advantage of Si Photonics

- **CMOS Compatibility:** wafer-scale & nm-precision manufacturing; electronic-photonic integration; large scale (Moore's Law)

Silicon Photonics: From Devices to Systems

Devices | **Systems**



Si Photonic Moore's Law

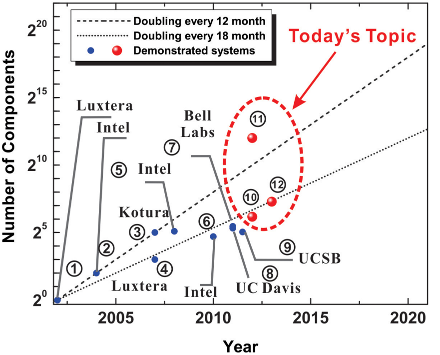


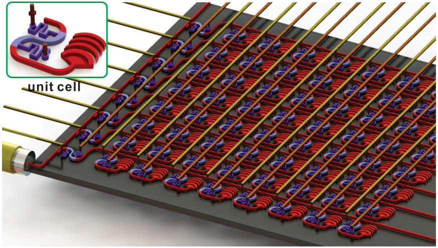
Image courtesy of Prof. M. Hochberg

System Integration: A Unique Advantage of Si Photonics

- **CMOS Compatibility:** wafer-scale & nm-precision manufacturing; electronic-photonic integration; large scale (Moore's Law)

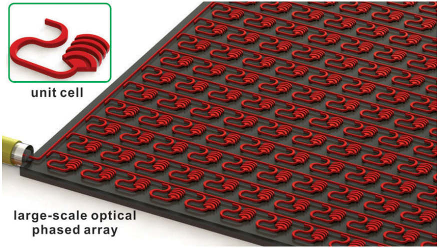
Integrated Optical Phased Array

- The ultra-compact unit cell
- Optical beam steering and manipulation



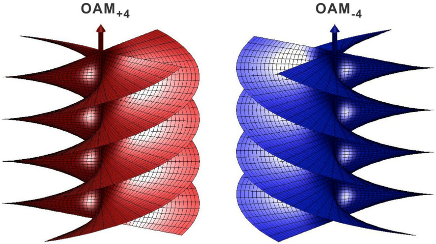
Large-Scale Phased Array

- Optical phased array w/ up to 4,096 antennas
- Largest silicon photonic circuit to date



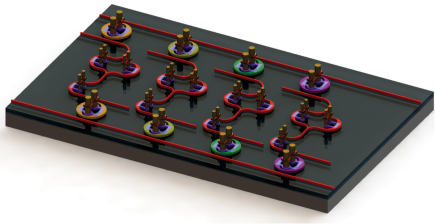
Arbitrary Beamform Generation

- Generating arbitrary beamforms: Gaussian, OAM, etc.



Applications & Future Work

- LADAR, signal processing, communication, sensing, etc.
- Devices and materials



Integrated Optical Phased Array

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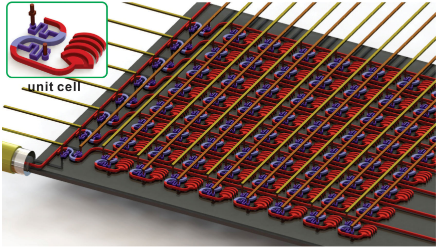

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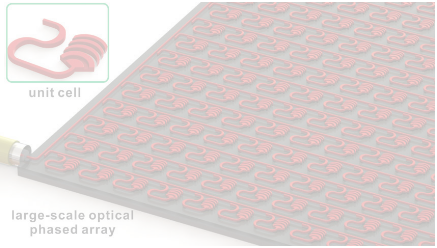

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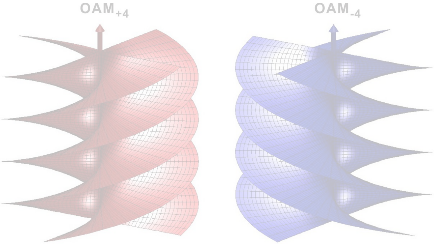

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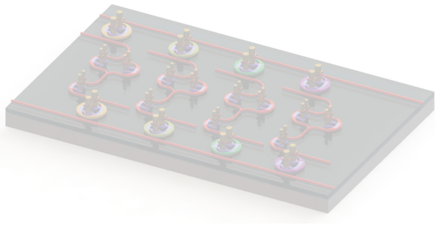
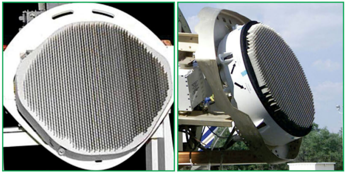
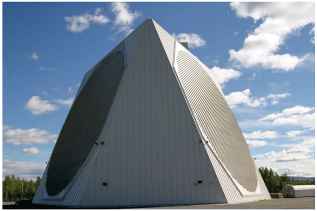


Phased Array: A Well-Known Technology

F22 Raptor



PAVE PAWS: ALASKA

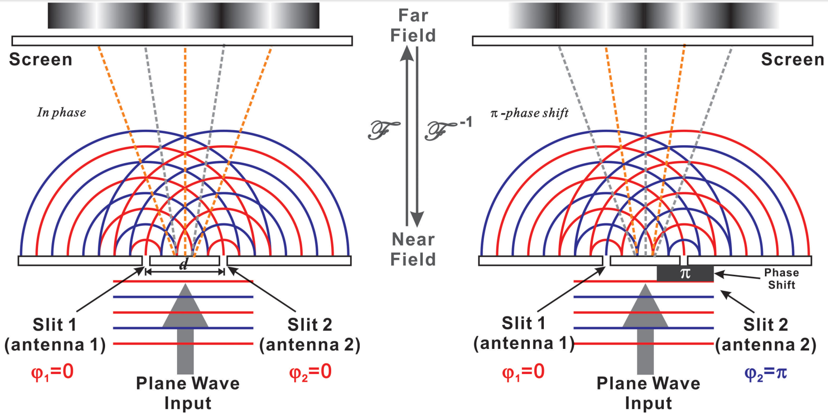


PAVE PAWS: CALIFORNIA

Phased Array: From Microwave to Lightwave

- **Phased Array:** beamshaping with an array of antennas
- **Optical Phased Array:** small $\lambda \rightarrow$ compact systems

Optical Phased Array: A Longer History

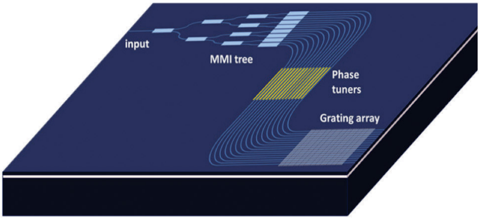


The Simplest Optical Phased Array

- **Principle:** interference & Fourier transform
- **Antenna spacing:** $d \sim \lambda \rightarrow$ opportunity for Si Photonics

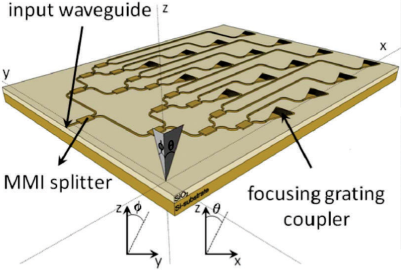
Integrated Optical Phased Array: Previous Work

1×16
Parallel Feeding



J. Doylend, et al, OE, 2011

4×4
Parallel Feeding

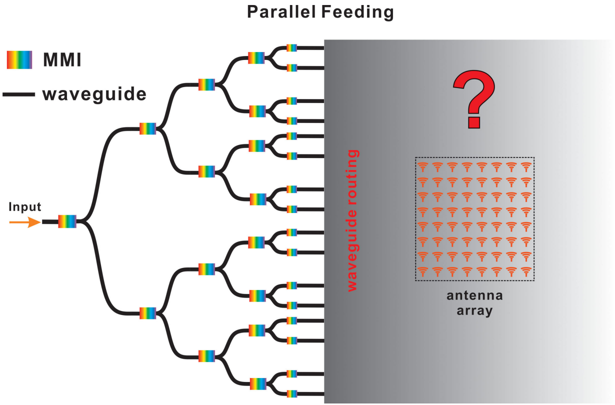


K. van Acoleyan, et al, OE, 2010

Our Goal

- **Large-Scale**: thousands ∼ millions of antenna
- **Two-Dimensional:** full control of the radiation field

Large-Scale Two-Dimensional Phased Array: Challenges

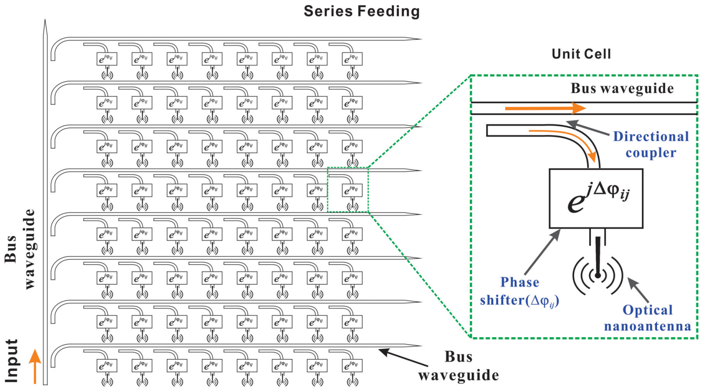


Break the Scaling-Up Limitation: Challenges

- **Architecture:** Parallel Feeding vs. Series Feeding

Jie Sun, et al, *Nature*, **493**, pp. 195-199 (2013)

Large-Scale Two-Dimensional Phased Array: Challenges

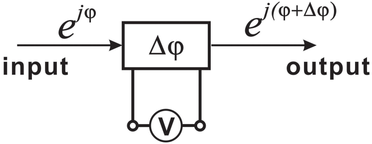


Break the Scaling-Up Limitation: Challenges

- **Architecture:** Parallel Feeding vs. Series Feeding
- **Ultra-Compact Unit Cell:** Tunable Phase Shifter, Antenna, and Coupler

Jie Sun, et al, *Nature*, **493**, pp. 195-199 (2013)

Tunable Phase Shifter: Indirect *vs.* Direct Heating

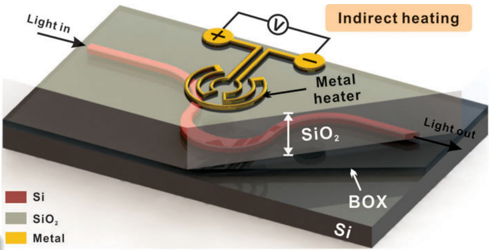


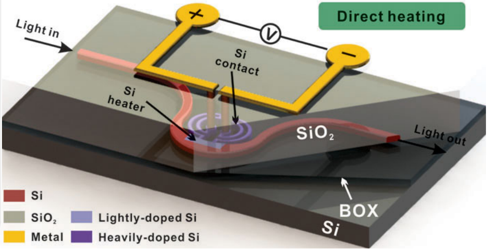
Thermooptic Phase Shifter

- **Less Power & Faster:**
  $FOM = P_\pi(\text{power}) \times \tau(\text{time const.})$
- **Minimize FOM:**
  $P_\pi = \Delta T_\pi \cdot G,\ \tau = H_c/G$

  $$\boxed{FOM \sim H_c \rightarrow min.\ \ H_c}$$

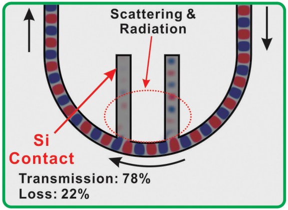
  * G & H_c: Heat Conductance & Capacity
- **Indirect vs. Direct Heating**





M. Watts, Jie Sun, et al, *Opt. Lett.*, **38**, pp. 733-35 (2013)

Adiabatic Bend: Low-Loss Silicon Contact

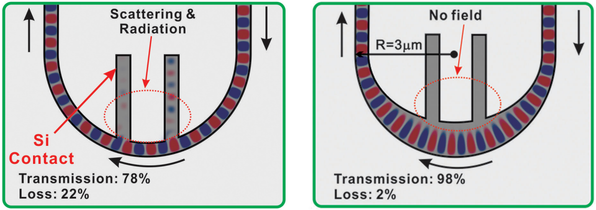


Direct contact

Low-loss silicon contact

- **Direct Contact:** scattering loss

Adiabatic Bend: Low-Loss Silicon Contact



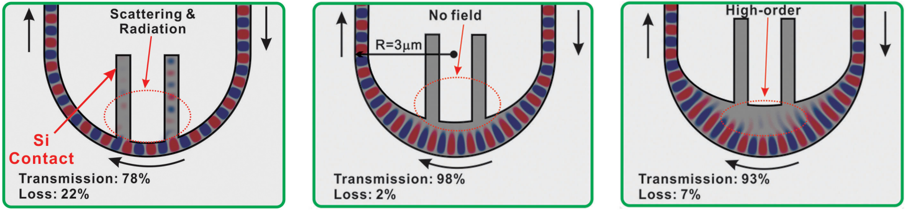
Direct contact

Adiabatic transition

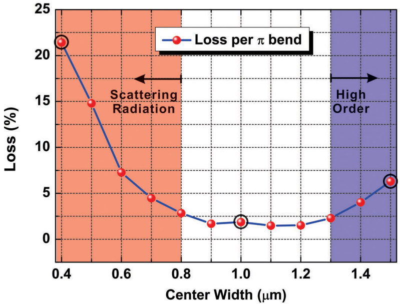
Low-loss silicon contact

- **Direct Contact:** scattering loss
- **Adiabatic:** low loss

Adiabatic Bend: Low-Loss Silicon Contact



Direct contact — Adiabatic transition — Non-adiabatic transition



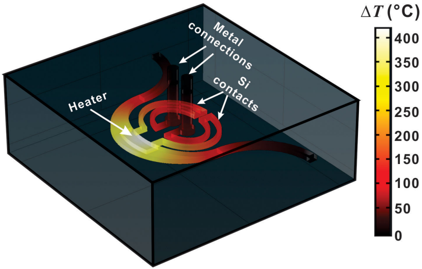
Low-loss silicon contact

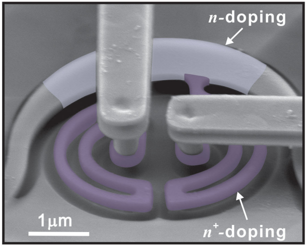
- **Direct Contact:** scattering loss
- **Adiabatic:** low loss
- **Non-adiabatic:** high-order mode

$$\kappa_{mn}(\theta) \sim \int \boldsymbol{e}_m^* \cdot \boldsymbol{e}_n \frac{d}{d\theta} \epsilon(\theta)\, dA$$

Tunable Phase Shifter: Power & Speed

COMSOL Thermal Model

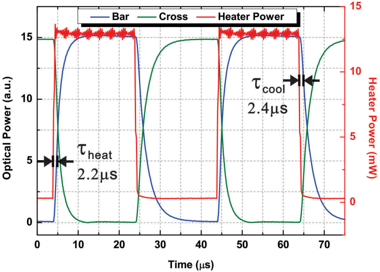




Power & Speed

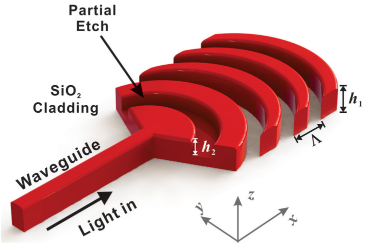
- **Heat:** Localized
- **Power:** $P_\pi = 12.7\text{mW}$
- **Speed:** $\tau = 2.4\mu\text{s}$
- **Impact:** Record $FOM = P_\pi \times \tau$

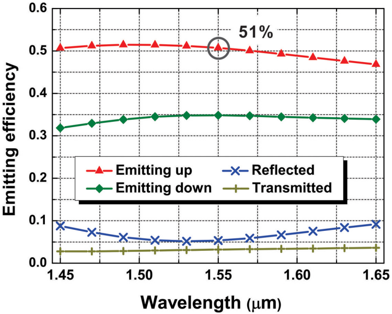
Measurement

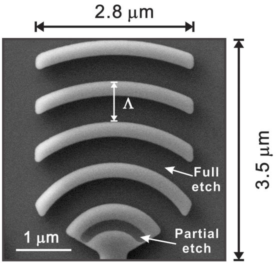


M. Watts, Jie Sun, et al, *Opt. Lett.*, **38**, pp. 733-35

High-Efficiency Optical Emitter





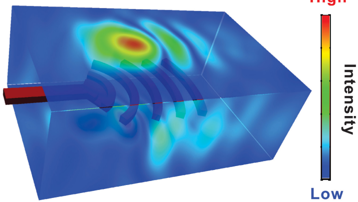


High-Efficiency Optical Emitter

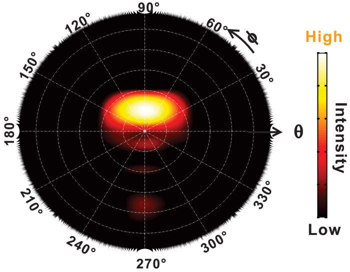
- **Compact:** $2.8\mu m \times 3.5\mu m \rightarrow$ Broadband
- **Directionality:** Partial-Etch$\rightarrow$ 51%$\uparrow$, 35% $\downarrow$
- **Anti-Reflection:** $\Lambda < \lambda$

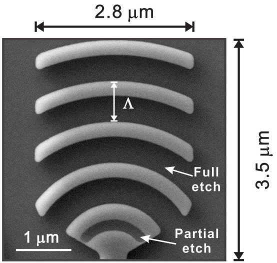
High-Efficiency Optical Emitter

Near Field



Far Field





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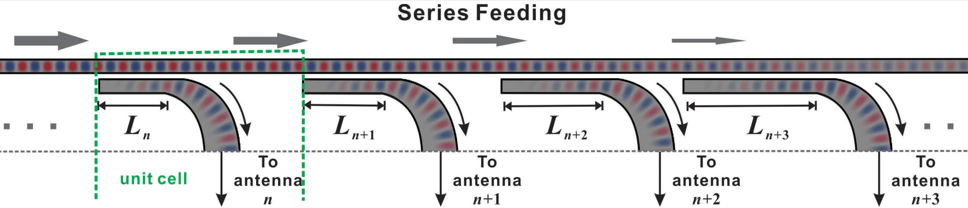
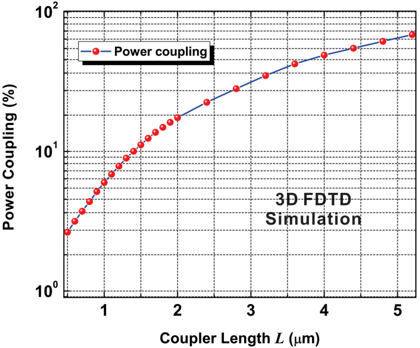
Directional Couplers



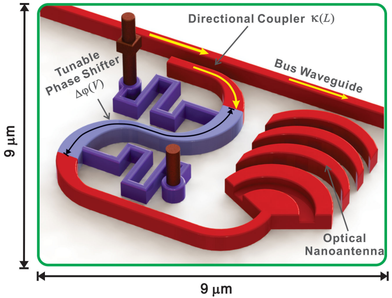


Directional Couplers

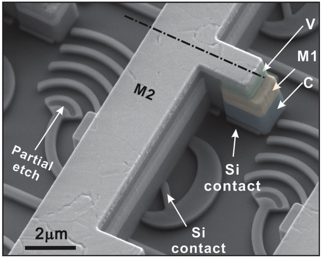
- Changing coupler length L_n
- Uniform or arbitrary power distribution

The Unit Cell

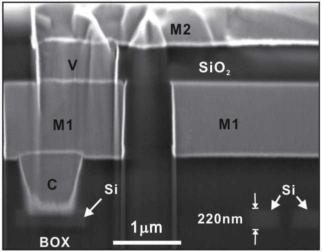
Unit Cell



Top View



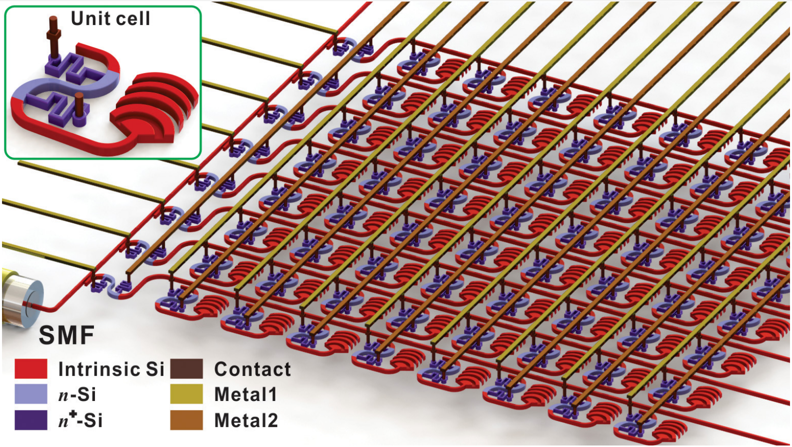
Cross Section



The Unit Cell

- **Size:** $9\mu m \times 9\mu m$
- **Fabrication:** 2 Dopings, 2 Metals

An 8×8 Phased Array

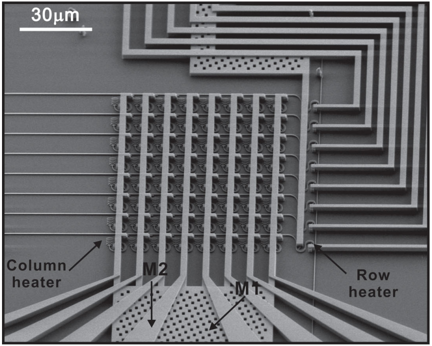


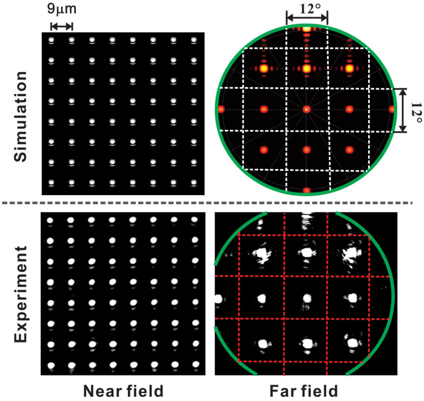
An 8×8 Phased Array

- **Electrical Connections:** 8×8 (Column)+8 (Row) $=$ 72 heaters

Jie Sun, et al, *Nature*, **493**, pp. 195-199 (2013)

Near- and Far-Field Measurement

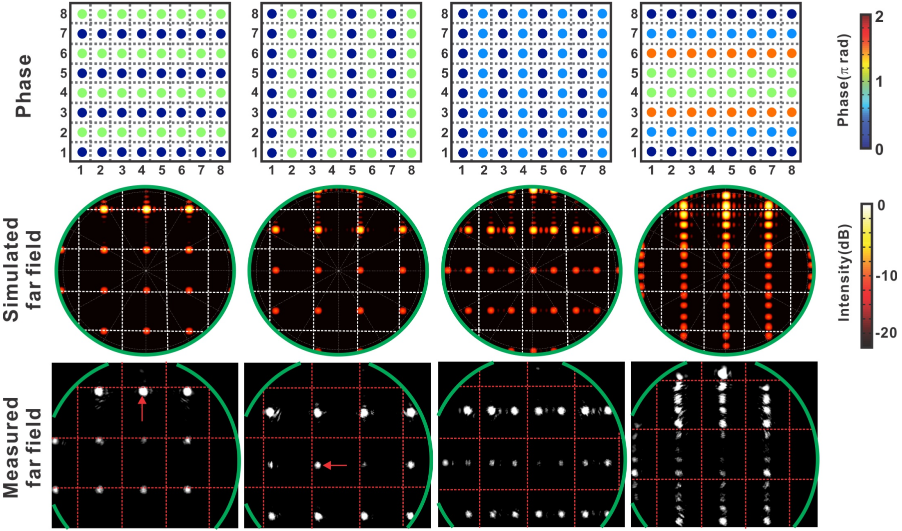




Near- and Far-Field Measurements

- **Multiple Order:** antenna spacing $d = 9\mu\text{m} \rightarrow 12^\circ$ order spacing

Optical Beam Shaping



Dynamic Optical Beam Shaping

Movie: Dynamic beam shaping

Optical Beam Shaping

- **Thermal Efficiency:** 8.5 mW per π phase shift per heater

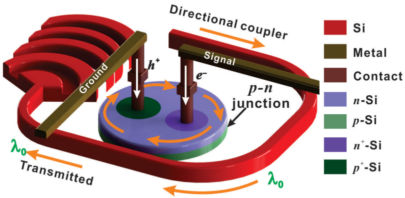
Next: Faster, and Less Energy Consumption

Free-Carrier Plasma Dispersion Effect

- **Pros:** Fast (ns) & less Energy
- **Cons:** Very small effect

Next: Faster, and Less Energy Consumption

Fast & Low-Energy Phase Shifter



Free-Carrier Plasma Dispersion Effect

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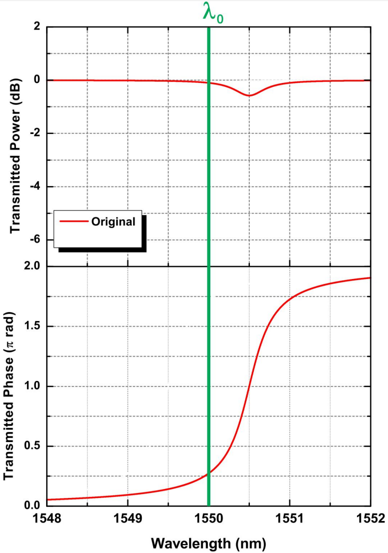
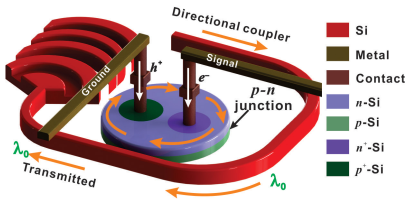
- **Solution:** Resonant structures



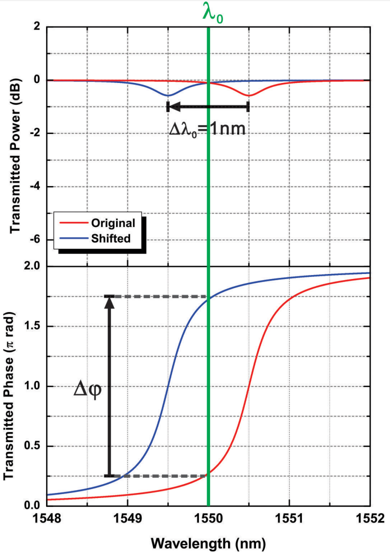
Next: Faster, and Less Energy Consumption

Fast & Low-Energy Phase Shifter



Free-Carrier Plasma Dispersion Effect

- **Pros:** Fast (ns) & less Energy
- **Cons:** Very small effect
- **Solution:** Resonant structures
- **Est. Power & Speed:**
  2.7 μW/GHz $\rightarrow$ 0.23 mW per π-shift
  Response time $\tau \sim 2.4$ ns
  (*Estimation based on M. R. Watts, et al, OE, 2011*)



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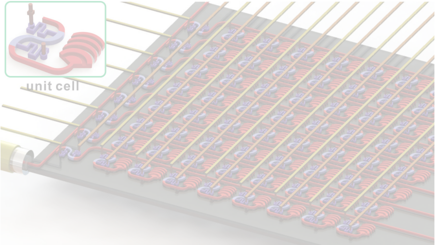

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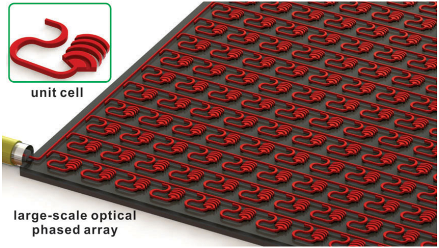

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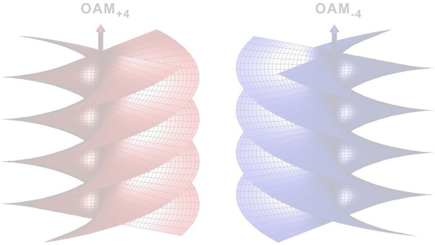

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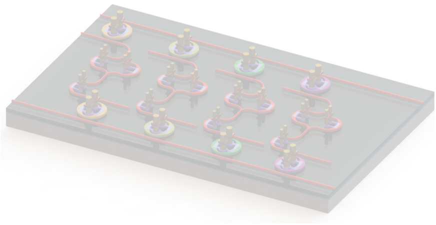
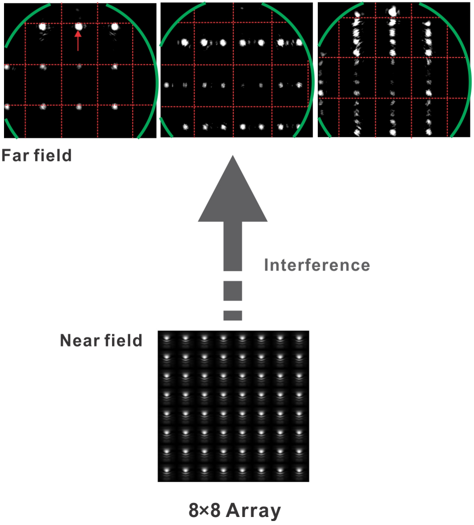
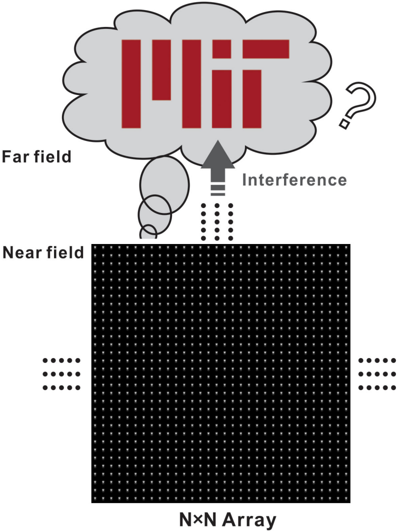
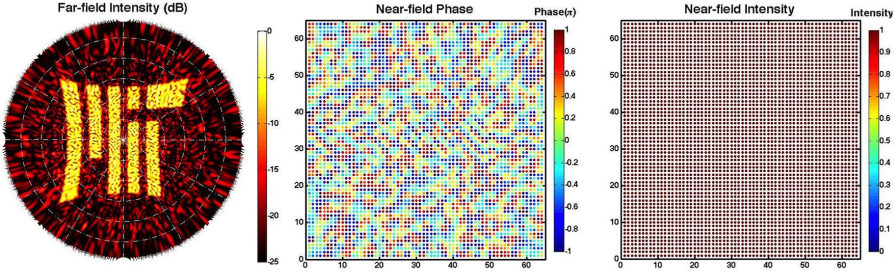


Large-Scale Phased Array: Motivation





Large-Scale Phased Array Synthesis



Large-Scale Phased Array Synthesis

- **Approach:** Fourier transform w/ a constraint (uniform near-field intensity)
- **Example:** 64×64
- **Performance:** fast convergence

Large-Scale Phased Array Synthesis

Movie: Large-Scale Phased Array Synthesis

Large-Scale Phased Array Synthesis

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- **Example:** 64×64
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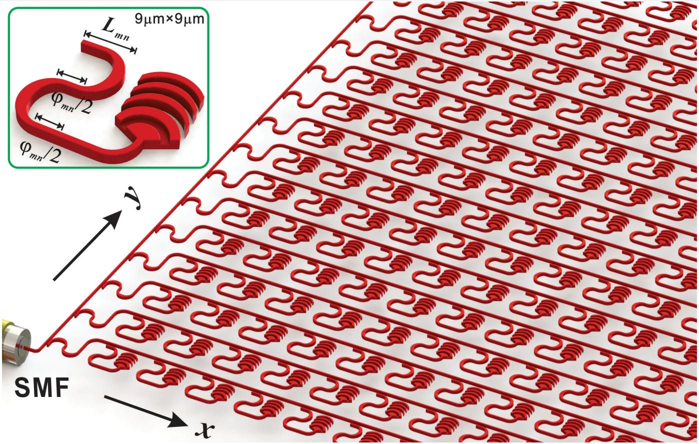
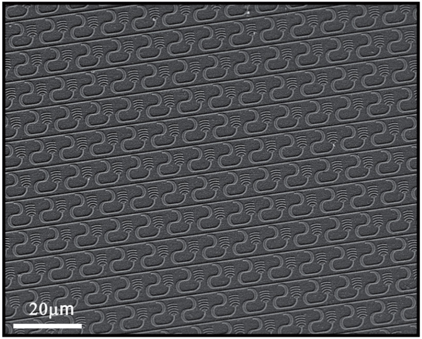
Implementation: A Large-Scale Si-Photonic PIC



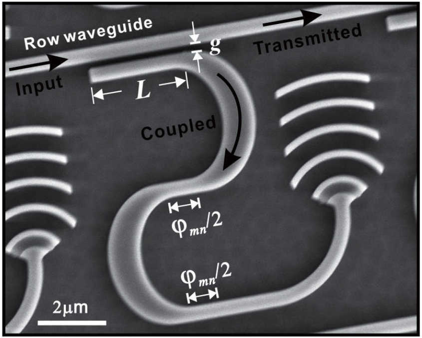
Large-Scale Optical Phased Array

- **Phase:** 'hard-coded' in the unit cell, φ_{mn}

Fabricated Large-Scale Optical Phased Array



Phased Array



Unit Cell

CMOS-Compatible Si Photonic Process

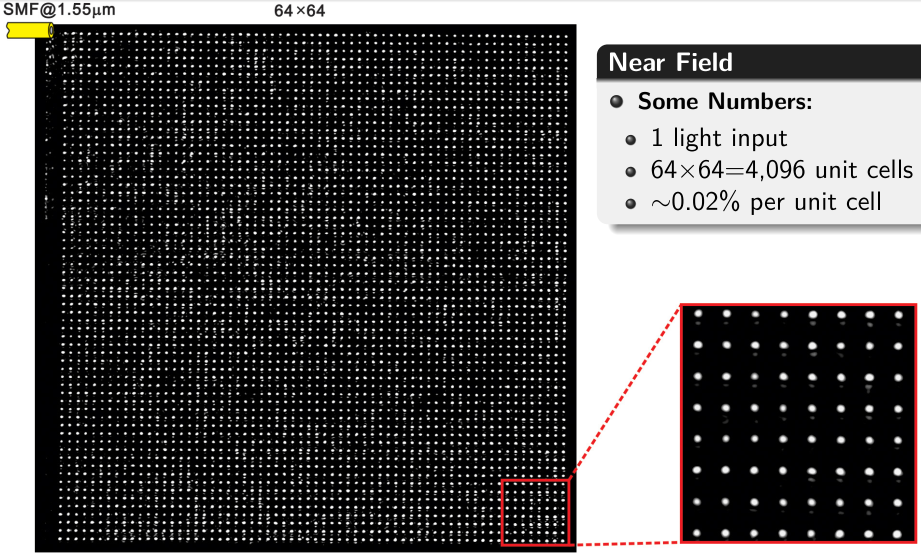
- **Unit Cell:** $9\mu m \times 9\mu m$ (multiple times of operating $\lambda = 1.55\mu m$)
- **Phased Array System:** $0.576mm \times 0.576mm$ (64×64)

Near Field Measurement

Near Field

- **Some Numbers:**
  - 1 light input
  - 64×64=4,096 unit cells
  - ~0.02% per unit cell

Near Field Measurement



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Near Field Measurement

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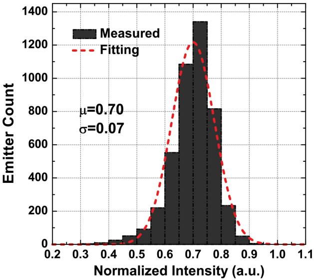
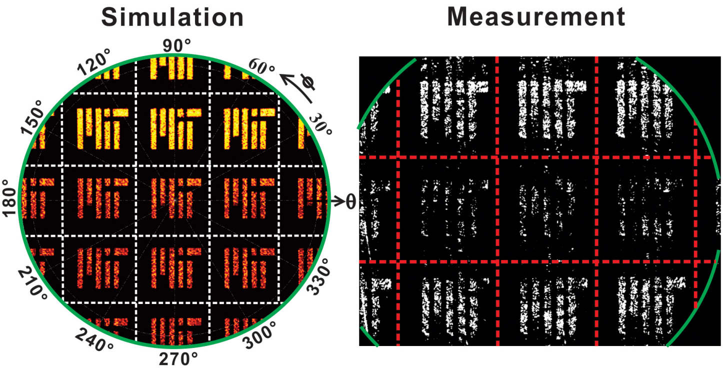


Far Field Measurement

Array 1: 64×64



Far Field

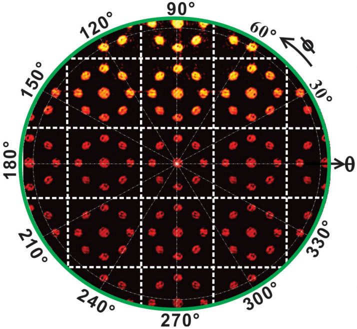
- **Result:** 4,096 unit cells, 12,288 Si-Photonic components
- **Impact:** Largest (Optical) Phased Array & Si PIC; Power of Si-Photonics

Jie Sun, et al, *Nature*, **493**, pp. 195-199 (2013)

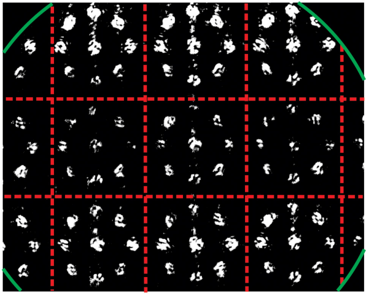
Far Field Measurement

Array 2: 32×32

Simulation



Measurement



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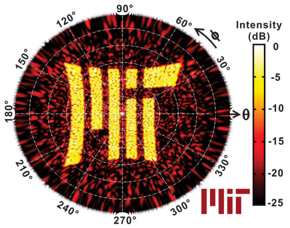
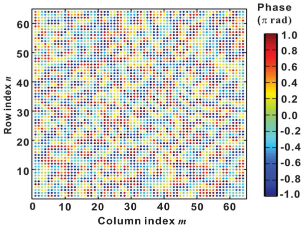
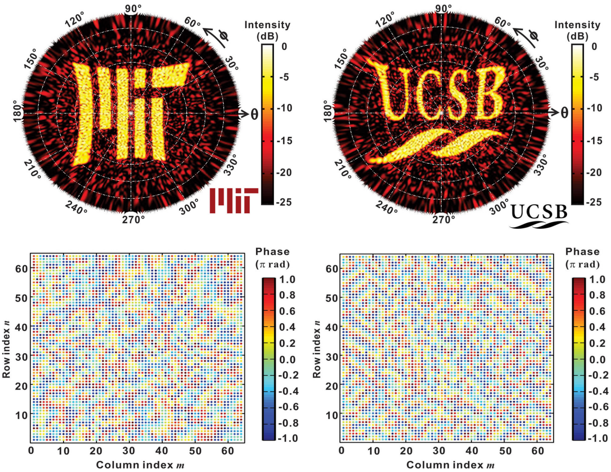
Toward Reconfigurable Large-Scale Optical Phased Array

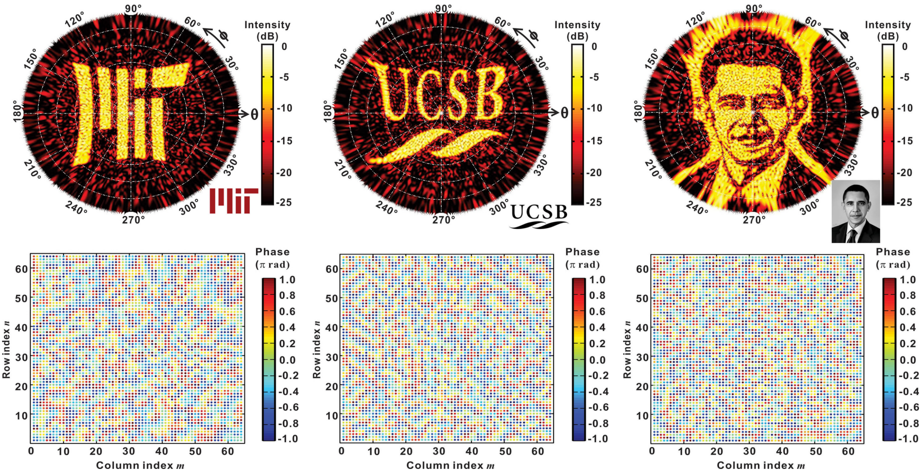




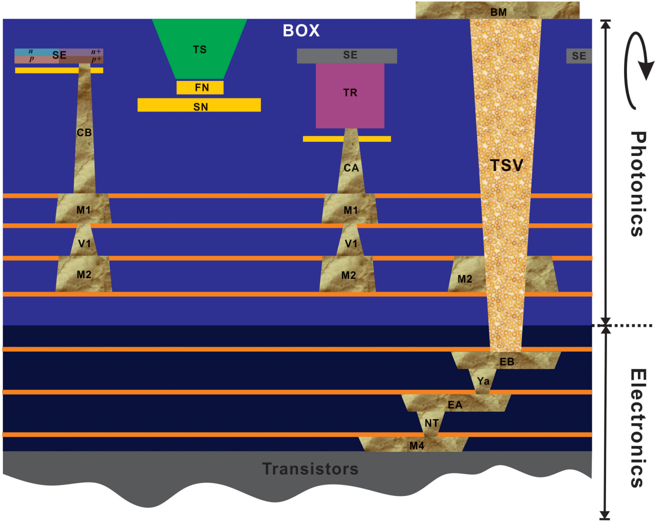
Toward Reconfigurable Large-Scale Optical Phased Array



Toward Reconfigurable Large-Scale Optical Phased Array



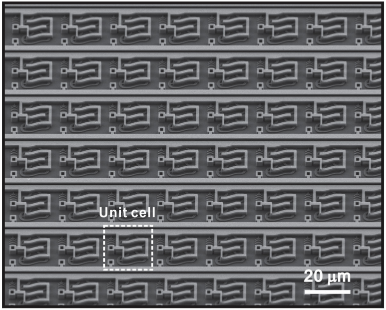
Electronic-Photonic 3D Integration



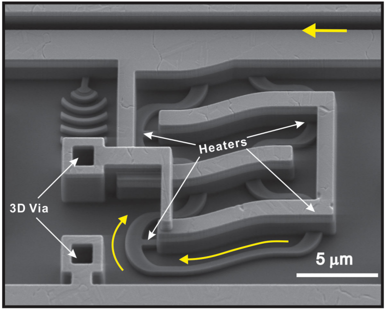
3D Integration

- **Photonics:** Photonic circuits, SOI
- **Electronics:** CMOS circuits
- **Integration:** flip-chip bonding w/ TSV

Fabricated Photonics



Phased Array



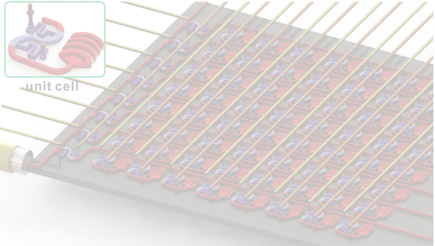
Unit Cell

Electronic-Photonic Integration

- **Photonics:** 32×32 phased array, 20μm unit cell size
- **Electronics:** Δ-Σ circuit (under development)
- **Integration:** Challenging, but promising

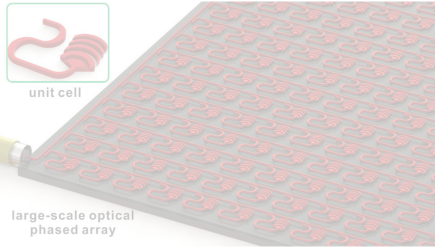
Integrated Optical Phased Array

- The ultra-compact unit cell
- Optical beam steering and manipulation



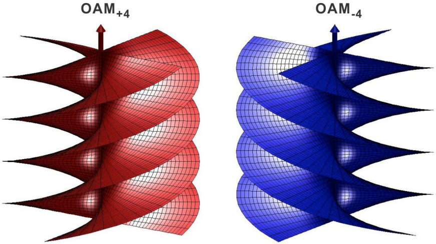
Large-Scale Phased Array

- Optical phased array w/ up to 4,096 antennas
- Largest silicon photonic circuit to date



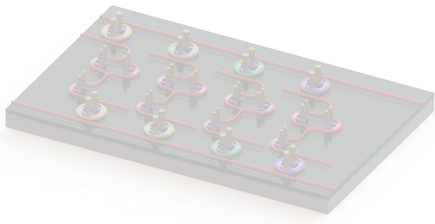
Arbitrary Beamform Generation

- Generating arbitrary beamforms: Gaussian, OAM, etc.

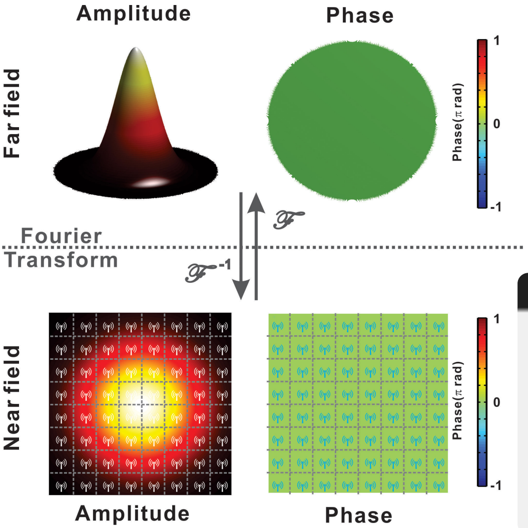


Applications & Future Work

- LADAR, signal processing, communication, sensing, etc.
- Devices and materials



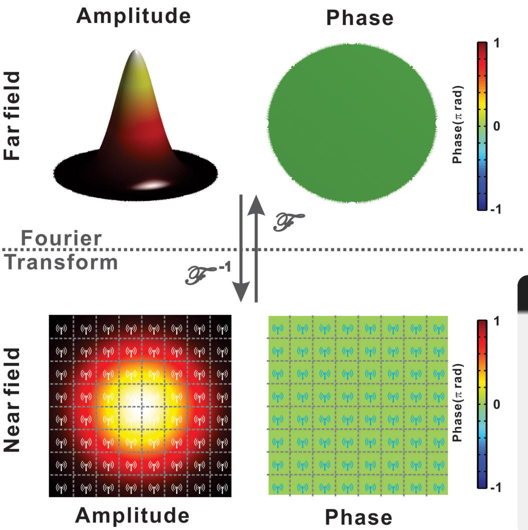
Arbitrary Beamform Generation: Principle

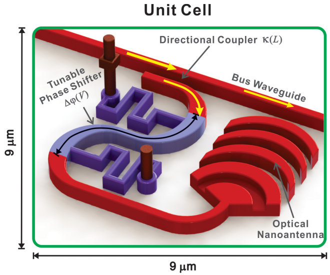


Arbitrary Beamforms

- **Far field (target beamform):** amplitude + phase
- **Near field:** controlling amplitude + phase

Arbitrary Beamform Generation: Principle

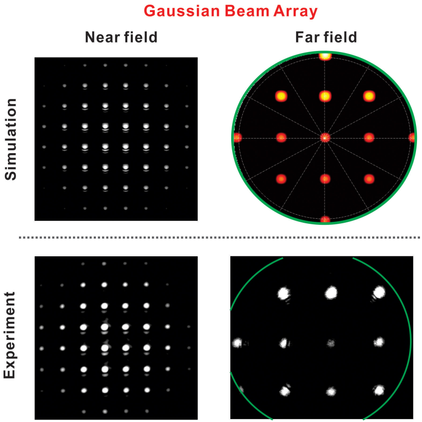


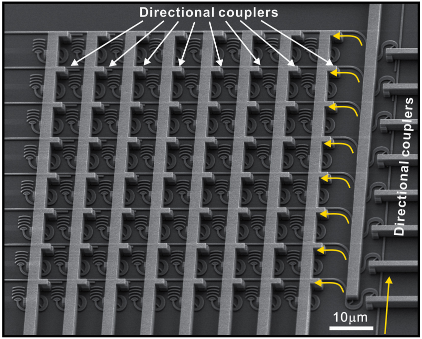


Arbitrary Beamforms

- **Far field (target beamform):** amplitude + phase
- **Near field:** controlling amplitude + phase
- **Antenna array:** phase→phase shifter amplitude→ directional coupler

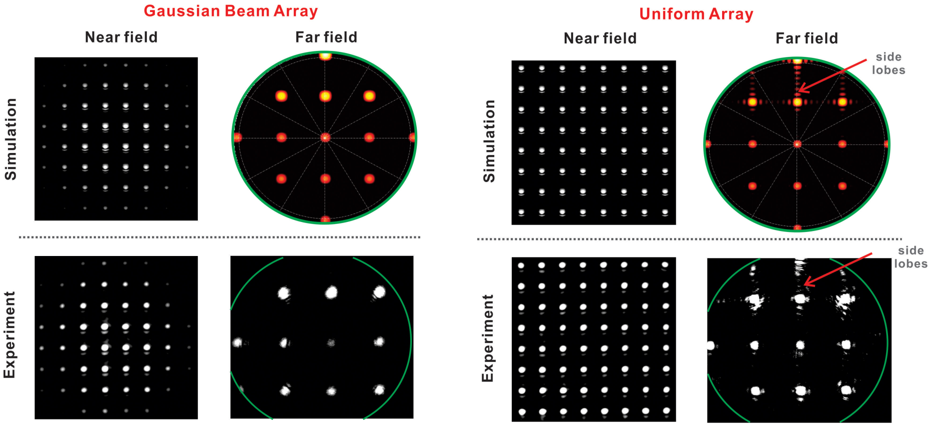
Example: Generating A Gaussian Beam





Jie Sun, et al, *CLEO Postdeadline*, San Jose, 2013

Example: Generating A Gaussian Beam



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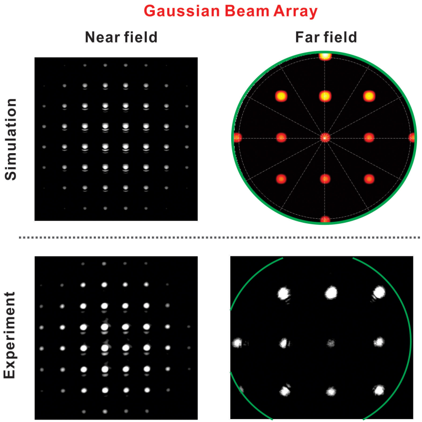
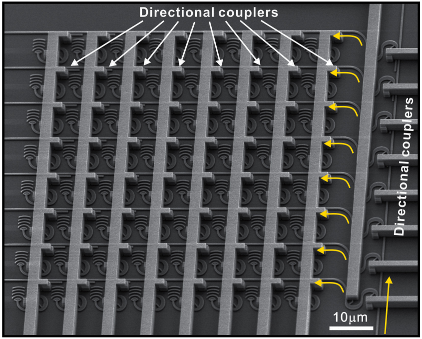
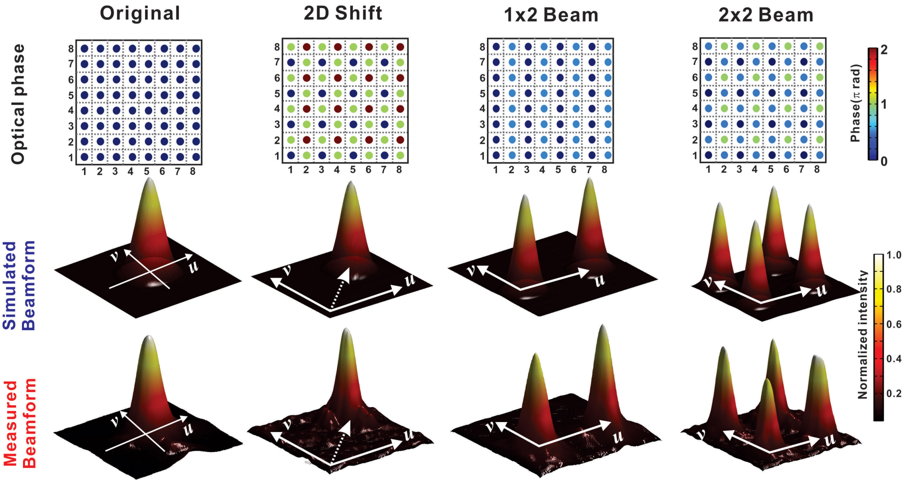


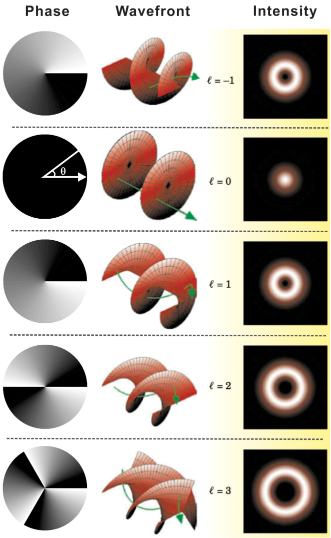


Jie Sun, et al, *CLEO Postdeadline*, San Jose, 2013

Dynamic Beam Manipulation



Optical Vortex Beam: A Twist of Light



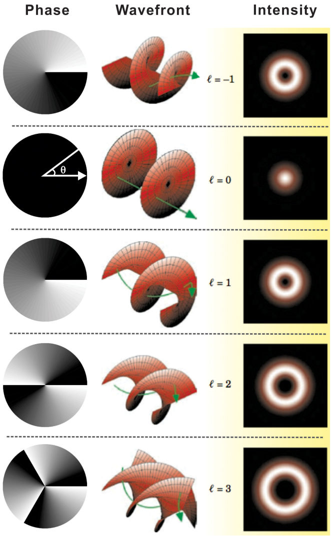
M. Padgett, et al, *Phys. Today*, **57**, 2004

Wavefront of an OAM_{+4} Beam

Optical Vortex/ Orbital Angular Momentum (OAM)

- **Definition:** $E \sim \exp(j \cdot l \cdot \theta)$
  $l \in \mathbb{Z}$: topological charge, OAM: $L = l\hbar$

Optical Vortex Beam: A Twist of Light



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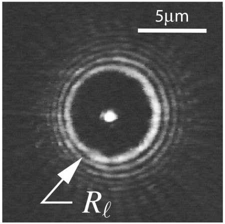

J. E. Curtis & D. G. Grier, *PRL*, **90**, 2003

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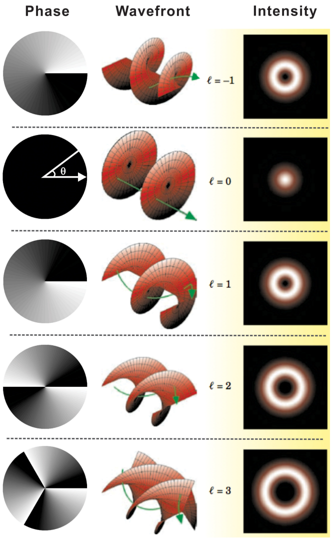

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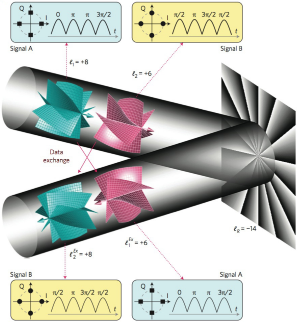

A. E. Willner, et al, *Nat. Photon.*, **6**, 488-96, 2012

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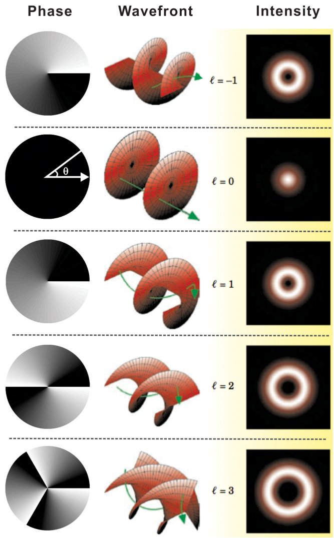

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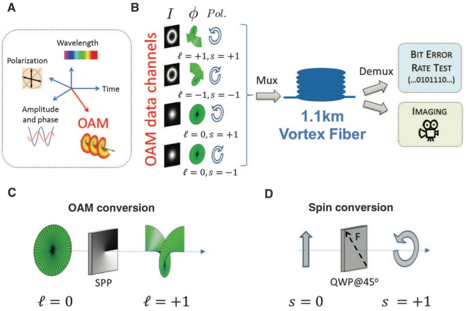

N. Bozinovic, et al, *Science*, **340**, 1545-48, 2013

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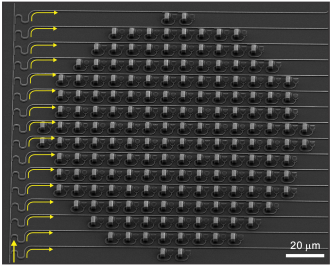
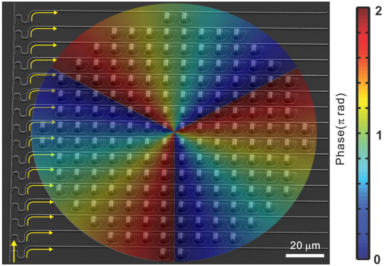
Generating OAM: An Integrated Silicon Photonic Solution



Generating OAM: An Integrated Silicon Photonic Solution



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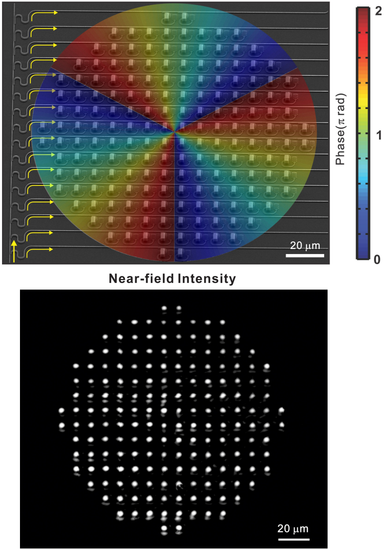

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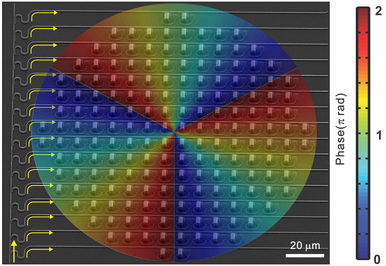
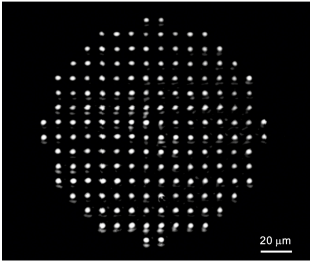
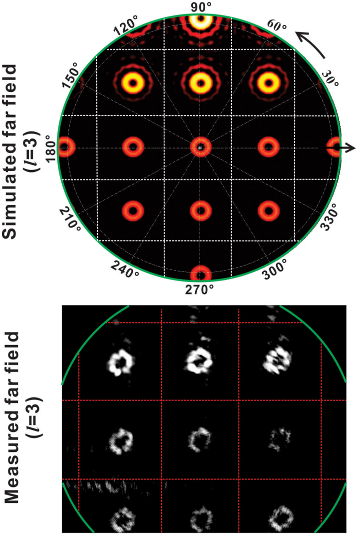


Near-field Intensity





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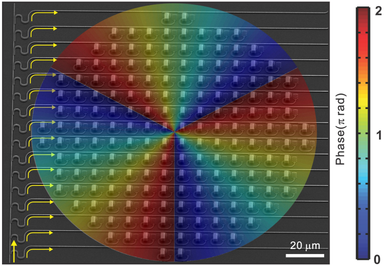

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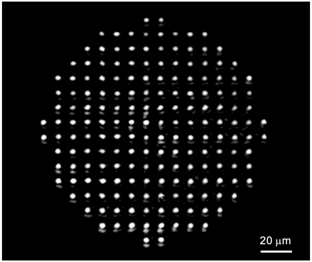

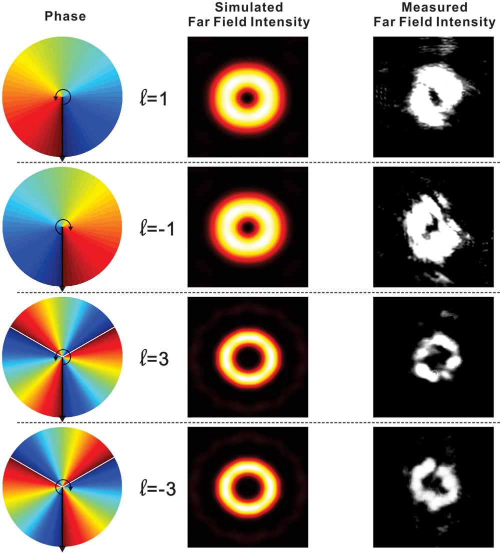

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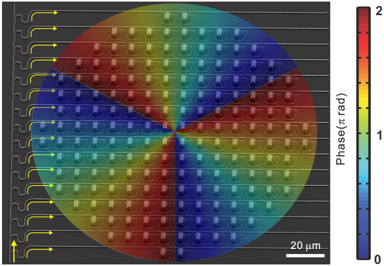

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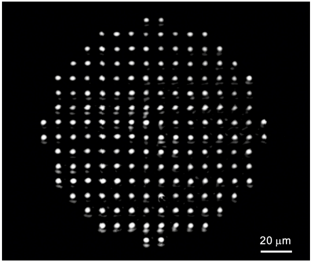
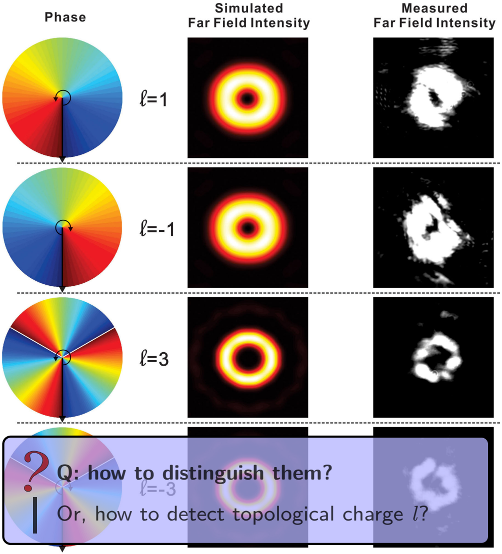


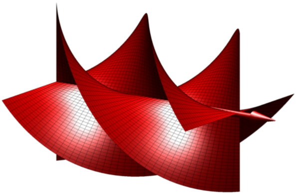


Q: how to distinguish them?

Or, how to detect topological charge l?

Detecting Topological Charge l

$\mathbf{OAM_{+4}}$



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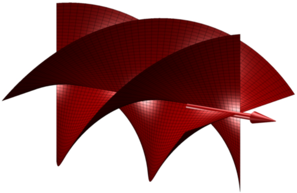
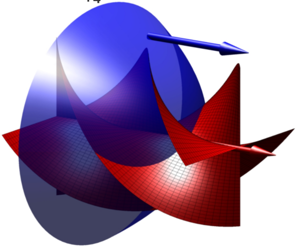
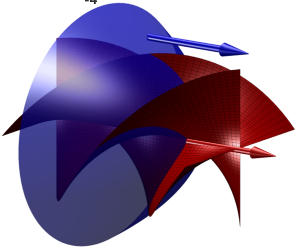


Detecting Topological Charge l

OAM_{+4}



OAM_{-4}



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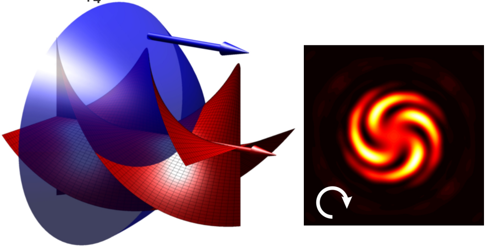
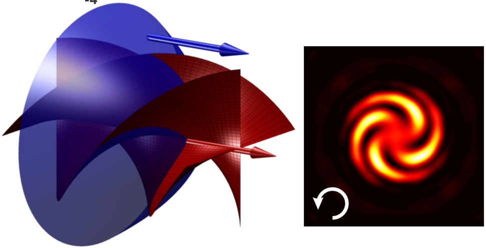


OAM_{-4}



Detecting Topological Charge l

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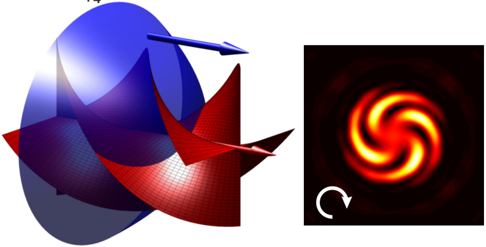

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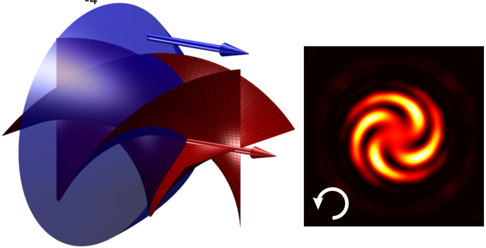
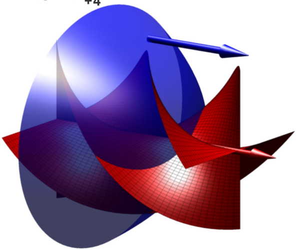
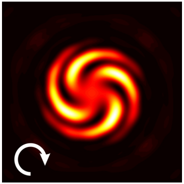


Q: How to interfere two beams?

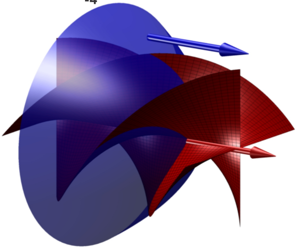
Detecting Topological Charge l

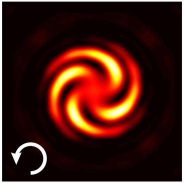
OAM_{+4}

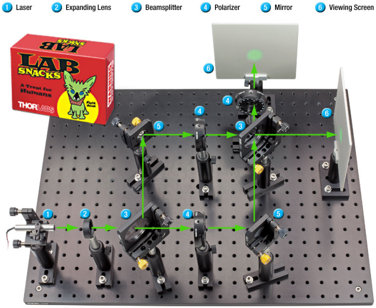




OAM_{-4}





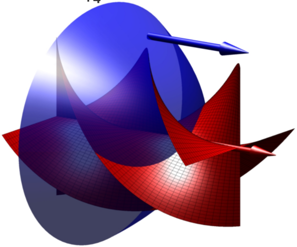


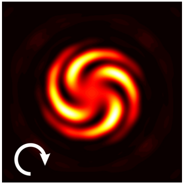
Q: How to interfere two beams?

- **Thorlabs Solution**: Free space . . .

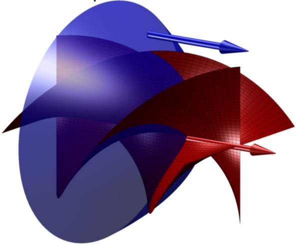
Detecting Topological Charge l

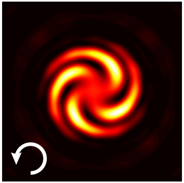
OAM_{+4}

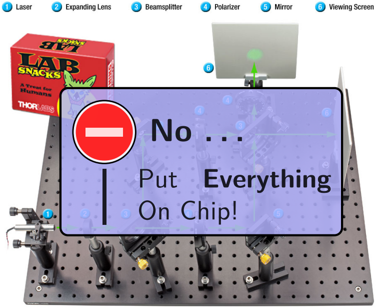




OAM_{-4}







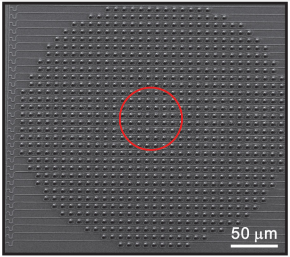
No . . .

Put **Everything** On Chip!

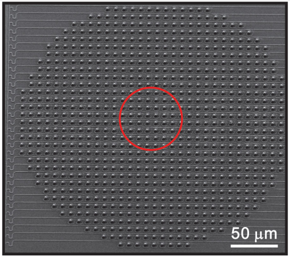
Q: How to interfere two beams?

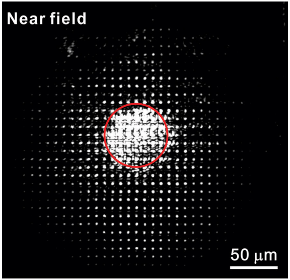
- **Thorlabs Solution**: Free space . . .
- **Our Solution**: Silicon photonics!

Detecting Topological Charge l: On-Chip Solution

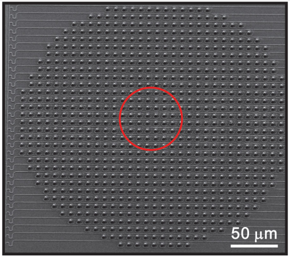


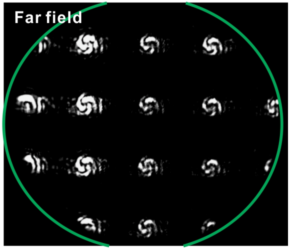
Detecting Topological Charge l: On-Chip Solution



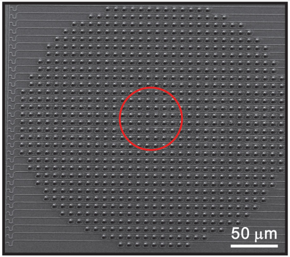


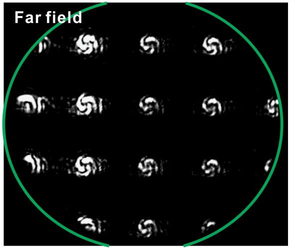
Detecting Topological Charge l: On-Chip Solution

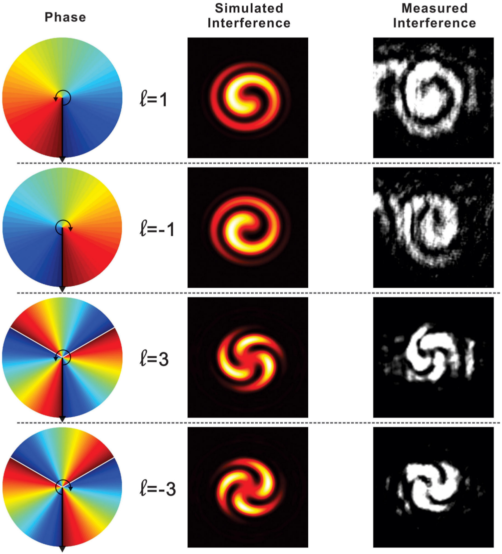




Detecting Topological Charge l: On-Chip Solution

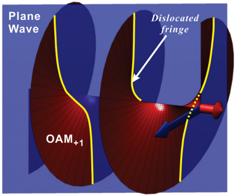


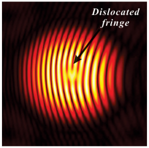


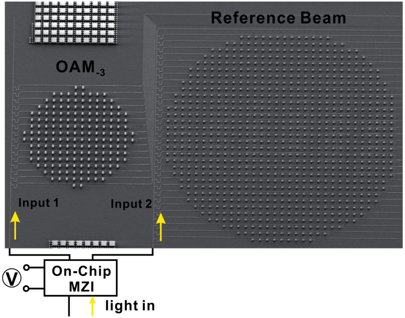


Interference at An Angle

Interference w/ an angle

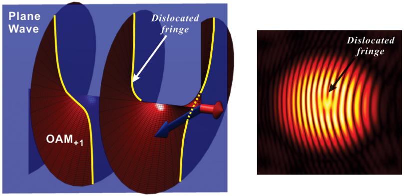


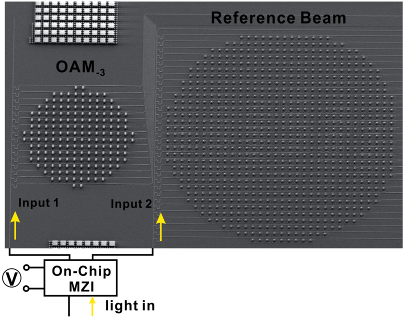


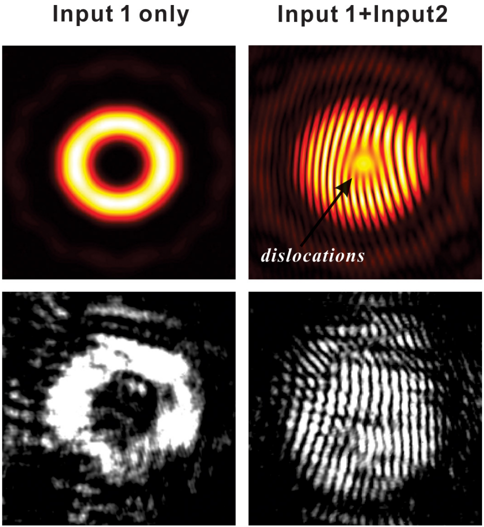


Interference at An Angle

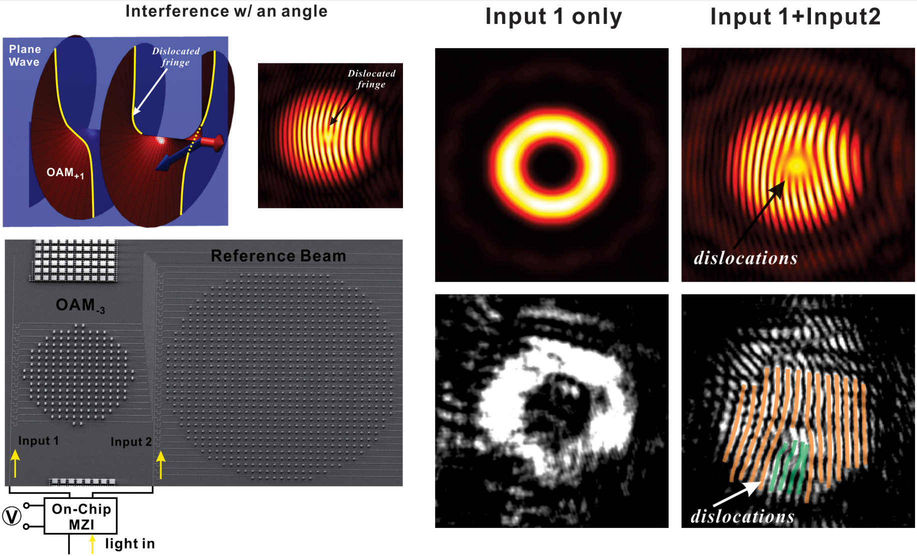
Interference w/ an angle



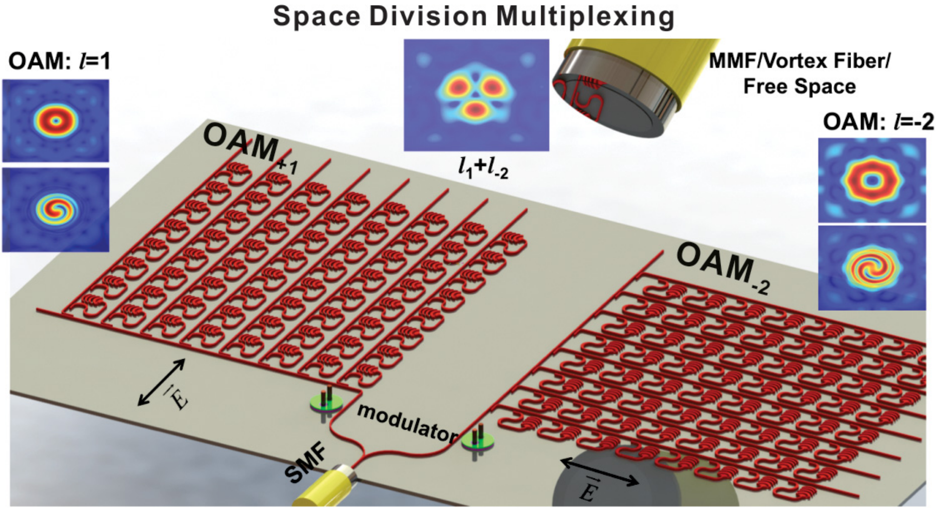




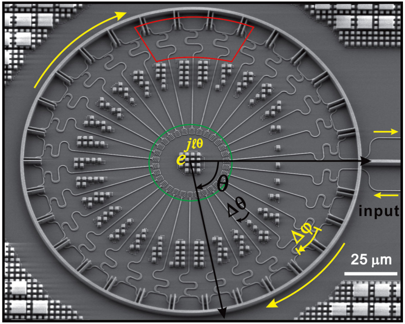
Interference at An Angle



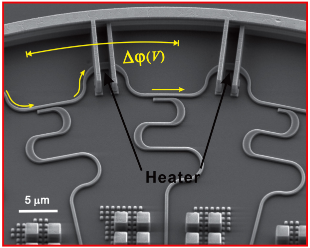
Application: Space Division Multiplexing



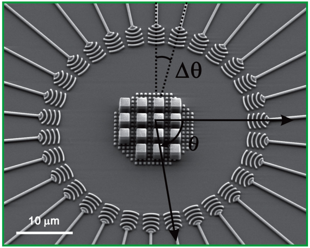
Next: Toward OAM w/ Reconfigurable Topological Charge l



Tunable Phase Shifter



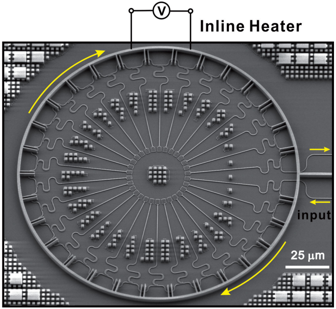
Circular Antenna Array



Tunable OAM

- **Motivation:** Space division multiplexing, etc.
- **Circular Array:** $\theta = m \cdot \Delta\theta$
- **Tunable Phase Shifter:** $\Delta\varphi(V)$
- **Emitting Field:** $E \sim e^{j \cdot m\Delta\varphi(V)}$
  when $\Delta\varphi(V) = l \cdot \Delta\theta \rightarrow E \sim e^{j \cdot l(m\Delta\theta)} = e^{j \cdot l\theta}$

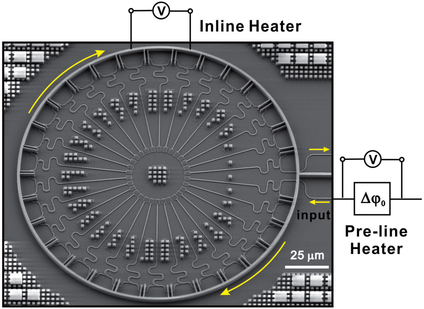
Reconfigurable OAM: Simulation



Reconfigurable OAM

- **Inline Heater:** to change topological charge $l = \frac{\Delta\varphi(V)}{\Delta\theta}$

Reconfigurable OAM: Simulation

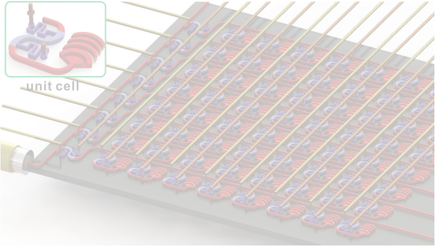


Reconfigurable OAM

- **Inline Heater:** to change topological charge $l = \frac{\Delta\varphi(V)}{\Delta\theta}$
- **Pre-Line Heater:** to visualize the spiral wavefront

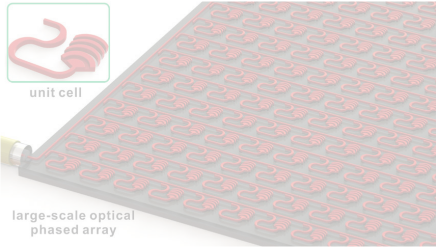
Integrated Optical Phased Array

- The ultra-compact unit cell
- Optical beam steering and manipulation



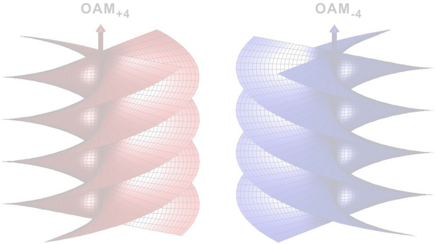
Large-Scale Phased Array

- Optical phased array w/ up to 4,096 antennas
- Largest silicon photonic circuit to date



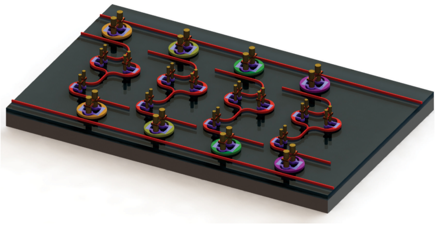
Arbitrary Beamform Generation

- Generating arbitrary beamforms: Gaussian, OAM, etc.



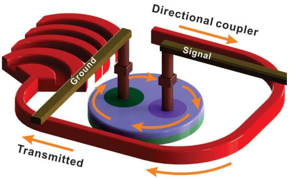
Applications & Future Work

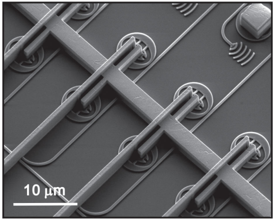
- LADAR, signal processing, communication, sensing, etc.
- Devices and materials



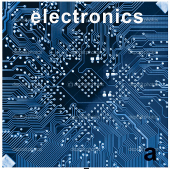
Optical Phased Array

Faster & Lower Power





Larger & More Controllable



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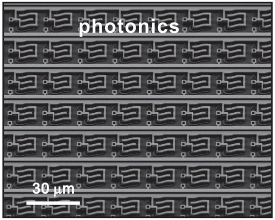
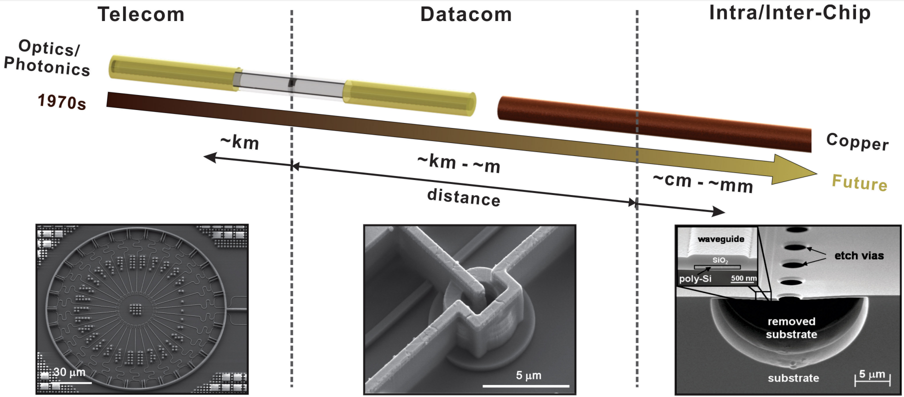


Applications

Images *a*, *b*, and *c* from Internet

Telecom→Datacom→Intrachip



E. Timurdogan, et al, MIT

C. Holzwarth, et al, MIT

Telecom

- **Advanced Modulation Format:** DQPSK, Space Devision, . . .
- **Complex Systems:** switch matrix, . . .

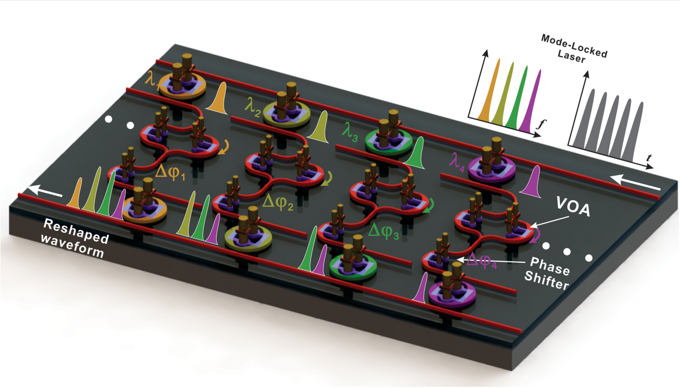
Datacom

- **Energy:** fJ/bit
- **Integration:** with lasers and circuits

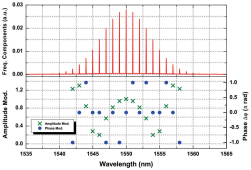
Intra/Inter-chip

- **Process:** Zero-change CMOS process

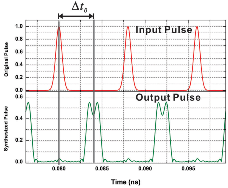
Optical Arbitrary Waveform Generation & Microwave Photonics



Frequency domain



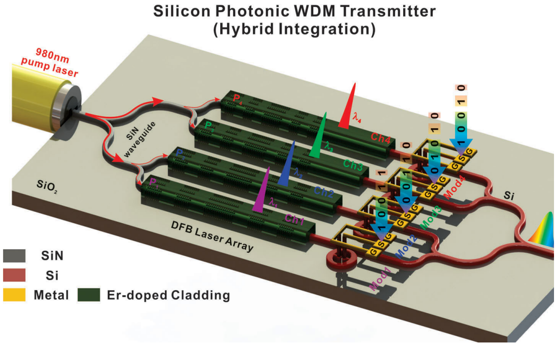
Time domain

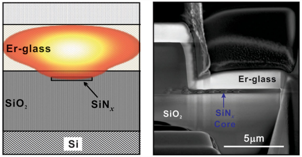


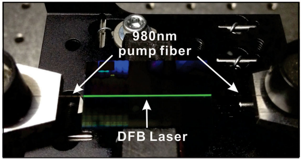
Optical/Microwave Signal Processing

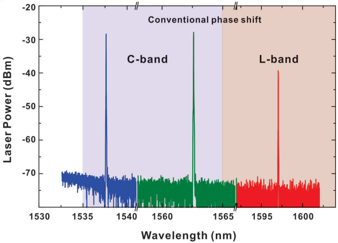
- **Optical AWG:** delay and/or reshape optical pulses
- **Microwave Photonics:** generation and manipulation of RF signals using integrated photonics

Backbones of Silicon Photonics: Materials & Devices







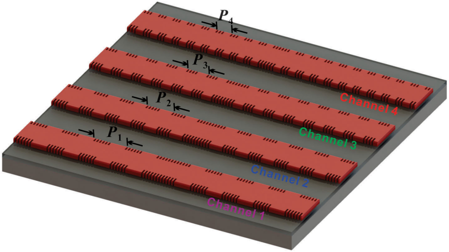


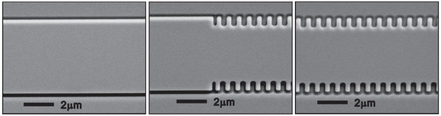
Optically Pumped DFB Laser

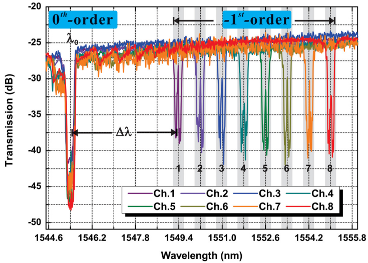
- **Laser**: C+L band, single pump (980nm)
- **Hybrid integration**: Deposited Er^{3+}

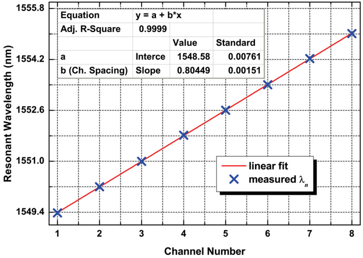
Purnawirman, Jie Sun, et al, *Opt. Lett.*, **38**, pp. 1760-62 (2013)

Bragg Grating Array with Highly-Uniform Channel Spacing









$\lambda/4$-Shifted Grating Array

- Uniform channel spacing
- Integration with III-V gain for WDM

Jie Sun, et al, *Opt. Lett.*, **38**, pp. 4002-04 (2013)

Bright Future of Silicon Photonics

Optical Technology

Silicon Chip

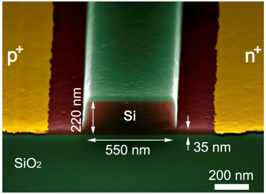


Image Courtesy of IBM

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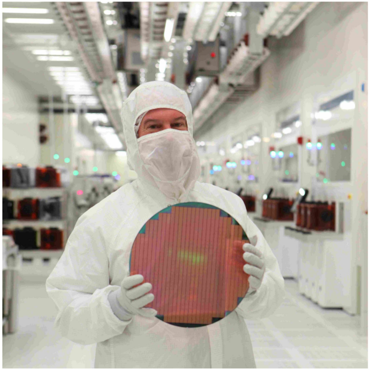
CMOS Fabrication Techniques



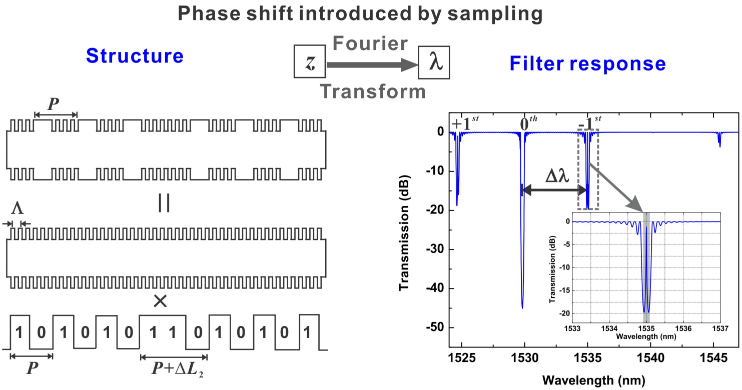
Images from Internet

Silicon Photonics

- Silicon (and other compatible materials) as the material for photonics
- Accessible to well-developed CMOS processing technology

Backup Slides

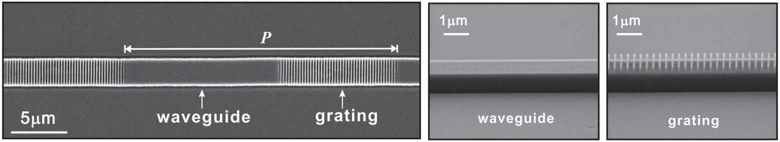
$\lambda/4$-Shifted Bragg Grating Enabled by Sampling

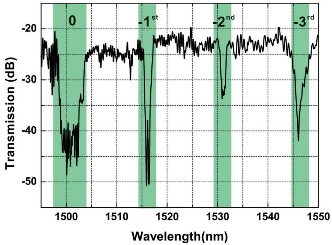


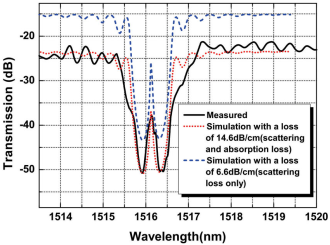
$\lambda/4$-shifted Bragg grating enabled by sampling

- **Phase shift:** $\Delta\phi = 2\pi\frac{\Delta L_2}{P}$ (Quarter-Wave: $\Delta\phi = \pi \rightarrow \Delta L_2 = \frac{P}{2}$)
- $P \sim 100\mu\text{m}$, $\Delta L_2 \sim 50\mu\text{m} \rightarrow$ Easy fabrication!

$\lambda/4$-shifted Bragg Grating Enabled by Sampling





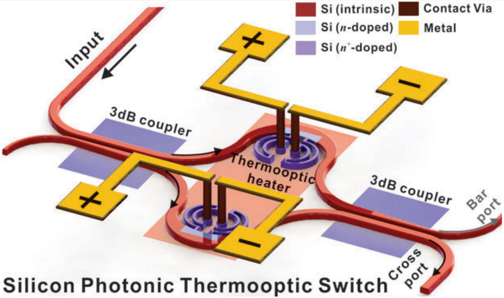


Relaxed fabrication requirement yet improved accuracy

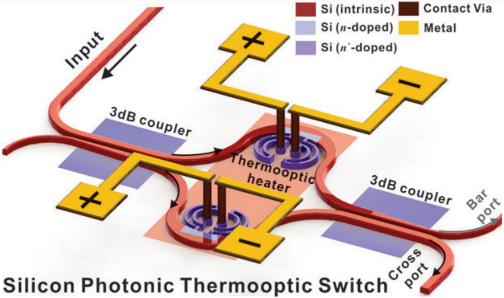
- Interference lithography + contact lithography (1µm-resolution)

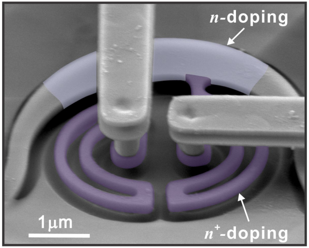
Jie Sun, C. W. Holzwarth, and H. I. Smith, *IEEE PTL*, **24**, pp. 25-27 (2012)

An Optical Switch (Power Consumption P_π)



An Optical Switch (Power Consumption P_π)

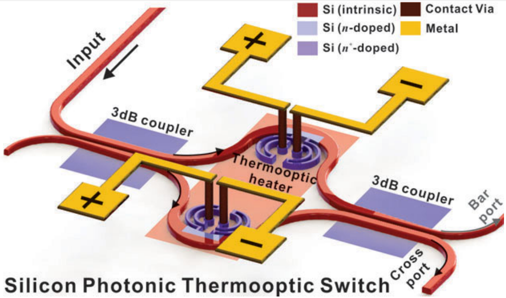


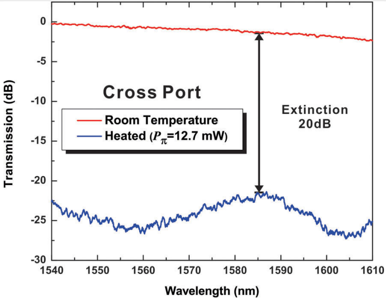


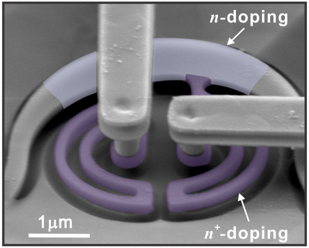
An optical switch enabled by tunable phase shifter

- **Light-doping:** large resistance, low optical loss
- **Heavy-doping:** small resistance
- **Long contact line:** thermal isolation

An Optical Switch (Power Consumption P_π)







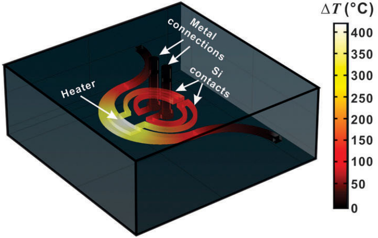
An optical switch enabled by tunable phase shifter

- **Light-doping:** large resistance, low optical loss
- **Heavy-doping:** small resistance
- **Long contact line:** thermal isolation
- **Performance:**

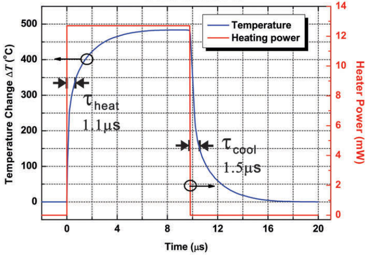
P_π	Extinction	Bandwidth
12.7 mW	20 dB	70 nm

An Optical Switch (Response Time τ)

COMSOL Thermal Model



Simulation

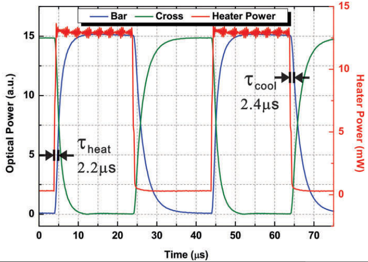


An optical switch

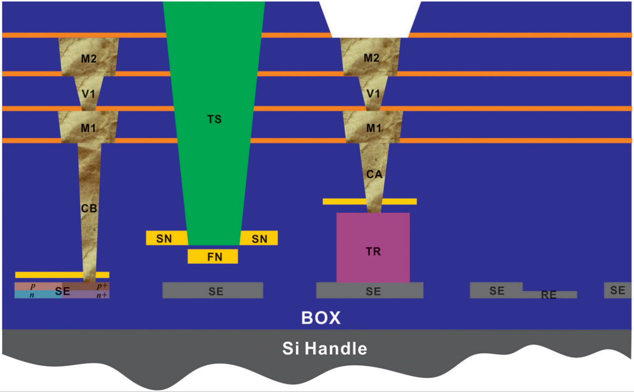
- **Simulation:** direct heating, localized heat
- **Measured τ:** $\tau_{heat} = 2.2\mu s$, $\tau_{cool} = 2.4\mu s$
- **Impact:** record FOM→faster & less power $P_\pi \cdot \tau = 30.5(\mathrm{mW} \cdot \mu s)$
- **Applications:** tunable filters, phased arrays, etc.

M. Watts, Jie Sun, et al, *Opt. Lett.*, **38**, pp. 733-35 (2013)

Measurement



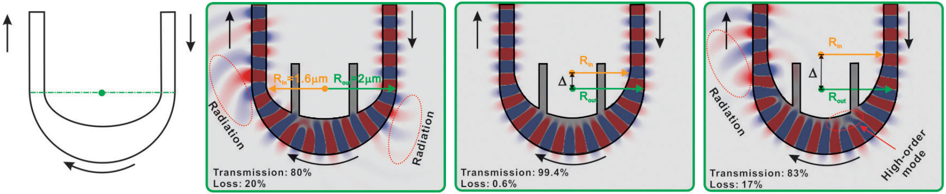
Fabrication: The CMOS-Compatible Si-Photonic Process



A customized CMOS-compatible Si-photonic process

- 300-mm SOI (220nm Si, 2µm BOX) line at 65-nm node using 193-nm optical immersion lithography
- Si (2 etches, 4 doping levels), 2 metal interconnections, Ge, SiNx, Er^{3+} (back-end processing)

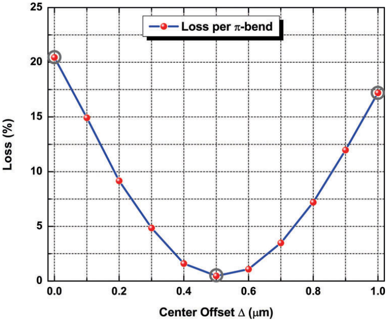
A Ultra-Small Bend (2 μm)



Δ=0, high loss

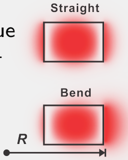
Δ=0.5μm, low loss

Δ=1.0μm, high loss

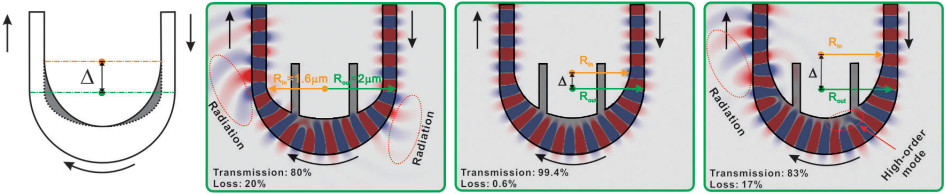


Ultra-compact bend ($R_{out} = 2\mu m$)

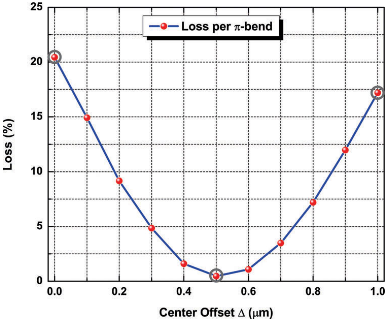
- **No center offset:** high loss due to straight-to-bend mode mismatch
- **Medium offset** ($\Delta = 0.5\mu m$): low loss
- **Large offset** ($\Delta = 1.0\mu m$): high loss due to high-order mode excitation



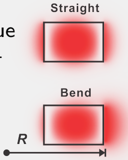
A Ultra-Small Bend (2 μm)



Δ=0, high loss | Δ=0.5μm, low loss | Δ=1.0μm, high loss



Ultra-compact bend ($R_{out} = 2\mu m$)



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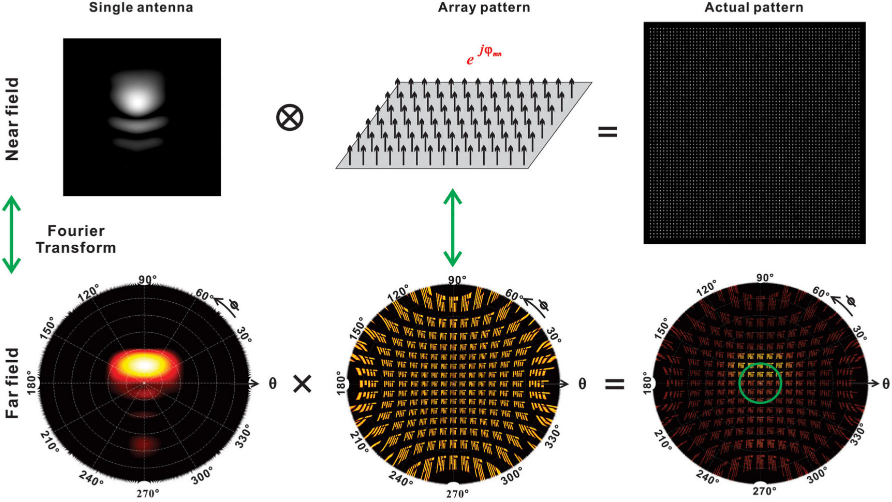
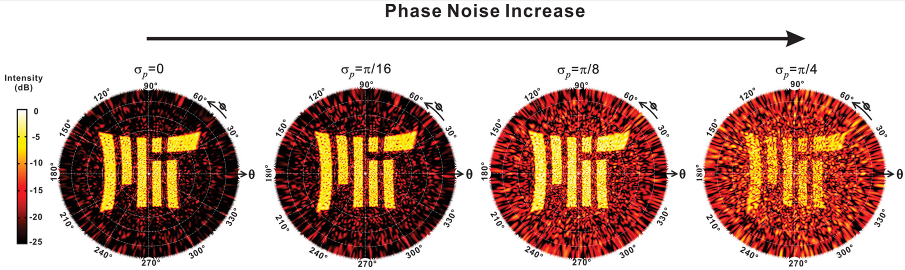
High-Order Interference



Jie Sun, et al, *IEEE JSTQE*, **20**(4), 2014

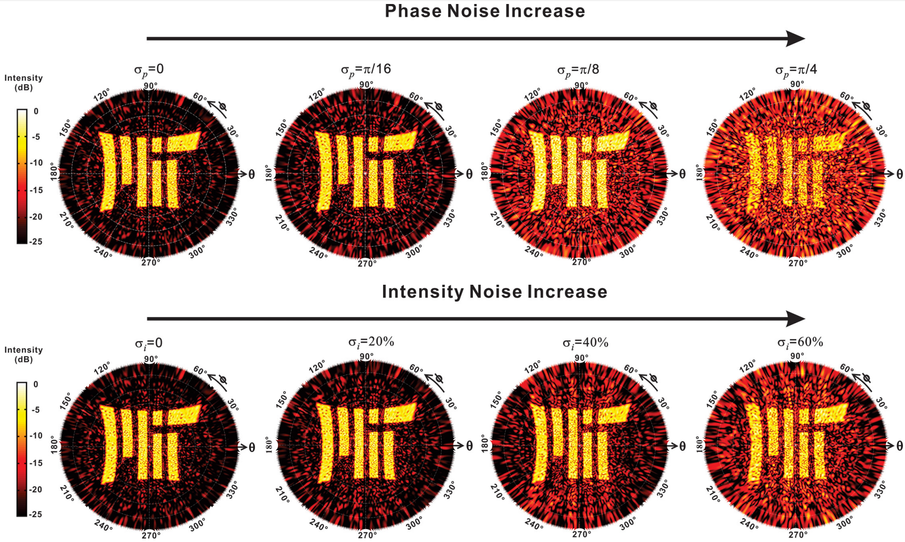
Phase/Intensity Noise Tolerance

Phase/Intensity Noise Tolerance



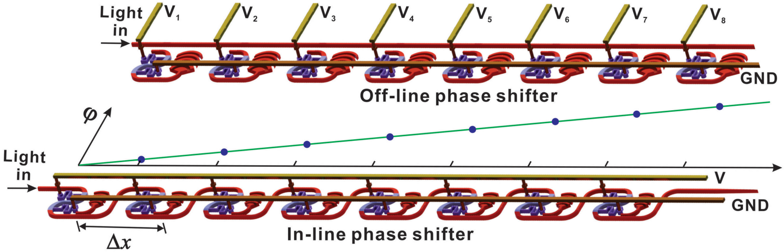
Jie Sun, et al, *IEEE JSTQE*, **20**(4), 2014

Phase/Intensity Noise Tolerance



Jie Sun, et al, *IEEE JSTQE*, **20**(4), 2014

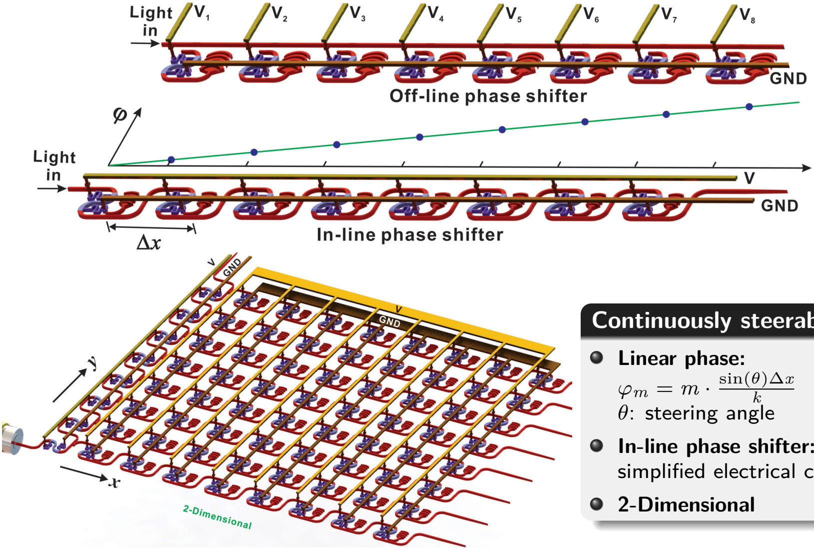
Continuously Steerable Phased Array



Continuously steerable

- **Linear phase:**
  $\varphi_m = m \cdot \frac{\sin(\theta)\Delta x}{k}$
  θ: steering angle
- **In-line phase shifter:**
  simplified electrical control

Continuously Steerable Phased Array

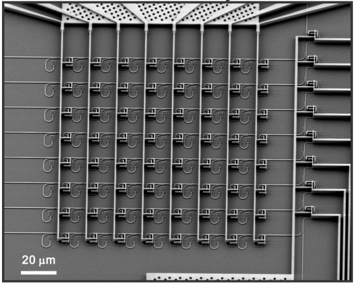


Continuously steerable

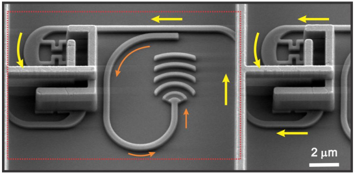
- **Linear phase:**
  $\varphi_m = m \cdot \frac{\sin(\theta)\Delta x}{k}$
  θ: steering angle
- **In-line phase shifter:** simplified electrical control
- **2-Dimensional**

Fabricated Continuously Steerable Phased Array

Continuously Tunable Phased Array



Unit Cell

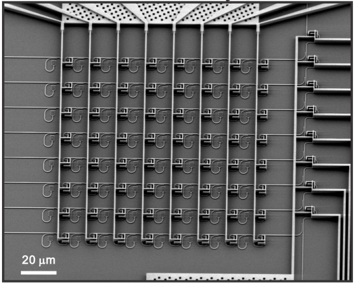


Continuously steerable array w/ inline heaters

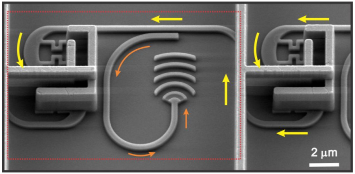
- **Unit cell:** 16μm×16μm (5.6°, can be improved)

Fabricated Continuously Steerable Phased Array

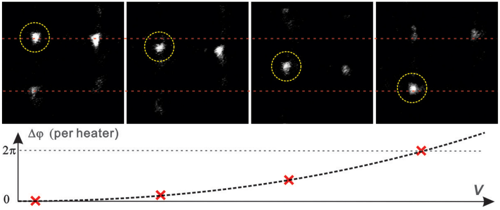
Continuously Tunable Phased Array



Unit Cell



Continueous Beam Steering

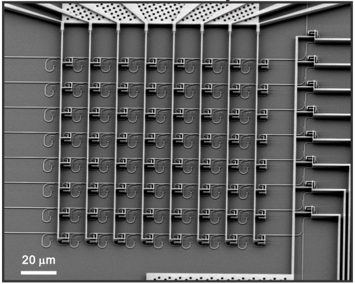


Continuously steerable array w/ inline heaters

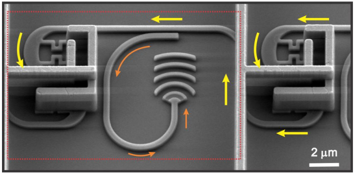
- **Unit cell:** 16μm×16μm (5.6°, can be improved)
- **Efficiency:** 16.9mW per 2π phase shift per heater

Fabricated Continuously Steerable Phased Array

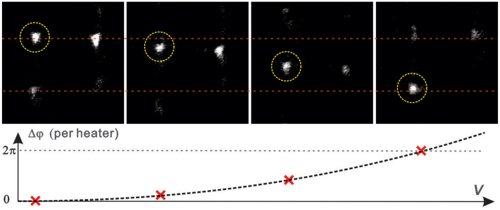
Continuously Tunable Phased Array



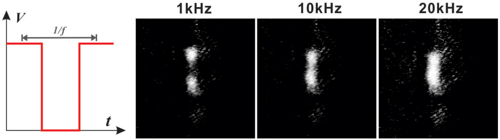
Unit Cell



Continueous Beam Steering



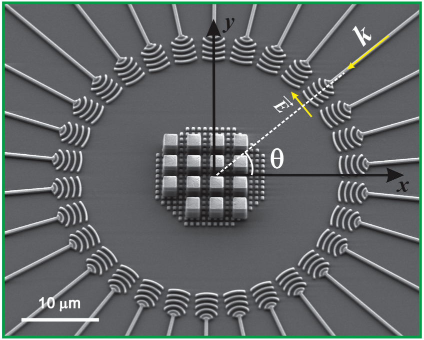
Beam Steering Speed



Continuously steerable array w/ inline heaters

- **Unit cell:** 16µm×16µm (5.6°, can be improved)
- **Efficiency:** 16.9mW per 2π phase shift per heater
- **Speed:** several tens of µs

Polarization of Circular Array



Polarization of The Antenna Emission

- $\vec{E} = \begin{pmatrix} -\sin\theta \\ \cos\theta \end{pmatrix} \cdot e^{j \cdot l\theta} = \frac{-j}{2}\left(e^{j(l-1)\theta} \cdot \begin{pmatrix} 1 \\ j \end{pmatrix} + e^{j(l+1)\theta} \cdot \begin{pmatrix} 1 \\ -j \end{pmatrix}\right)$
- LHCP $(l-1)$ + RHCP $(l+1)$