A Tutorial on Silicon Heterogeneous Integrated Photonic Integrated Circuits: From Data Centers to Sensors

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International Photonics Conference
Nov. 14, 2023
Outline

• Economic drivers: high volume applications
• Laser integration platforms
• Narrow linewidth lasers
• Comb generation:
  • Mode locked lasers
  • Nonlinear combs
• Conclusions
The silicon photonic market

Silicon photonics 2019-2025 market by applications

Applications are mainly limited within communications!
The scope of silicon photonics is still quite small!
High Volume Silicon Photonic Applications

Datacom/Telecom

LIDAR

Optical Gyroscopes

AR/VR

Optical and Quantum Computing

Biosensors for glucose, oxygen,...
Lasers in telecommunications

Data traffic volume requirements are continuously rising.

Laser applications
- Datacenter optical interconnects
- Long-haul optical transceivers

Source: Ericsson traffic measurements (Q1 2022).
Note: Mobile network data traffic also includes traffic generated by fixed wireless access (FWA) services.

S. Mzekandaba, Itweb (2022), “Worldwide mobile data traffic growth doubles in two years.”

Image: Intel
Skybox, Prologis Plan Massive 600-Megawatt Data Center Campus in Austin

Skybox Datacenters and Prologis plan to build a massive 600-megawatt campus near Austin, Texas which will offer up to 4 million square feet of data center space.

175-hectare, 600MW data center campus proposed outside London in Havering
**RISING DEMAND FOR AI AND COMPUTE POWER**

Number of programs which use deep learning has *doubled* every 3.4 months, much faster than Moore’s Law.

Silicon Photonics can improve efficiency
Quantum Dot Lasers may be key for higher efficiency

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Mehonic et al., "Brain-inspired computing needs a master plan"

Switch bandwidth evolution
Economic Driver: Merging Photonics and Electronics

Co-packaged Optics – enabling lower power designs

3.2T CPO Optical Module

51T Switch + CPO Optics Assembly

3.2 Tps per module: Combs of many wavelengths required
The Path to Higher Capacity

Integration is key: N wavelength x P fibers = 3NP devices
8 wavelengths x 4 fibers x 3 = 96 devices

Higher signaling rates are achieved by using different modulation techniques to data rate. 25Gigabaud sampling may create 25Gb/s NRZ, 50 Gb/s PAM-4 or 100Gb/s Coherent lanes.
UCSB/AIM/AP/Ciena: 1 Tbps link with 0.5 pJ/bit efficiency

Key elements: 3D Integration Comb sources

Transmit
Data Mods

Receive
Data Filters

Passive Quantum Dot Mode Locked Lasers with Saturable Absorbers
60.0 GHz, 140 mW with -5 to -7 dBm/line

Advantage of Quantum dot mode locking:
1) Higher FWM allows better locking and even self mode locking (no saturable absorber)
2) Lower linewidth enhancement factor results in reduced reflection sensitivity (no isolator required)

- 2.5 dB Flatness
- 21 lines
- Exactly 60.0 GHz spacing
- 140 mW total electrical power

UCSB
100x FWM in QDs Drives Magic Mode Locking:

- Removing saturable absorber increases the wall plug efficiency
- We have observed magic mode locking due to four wave mixing
- Theory for FWM in good agreement with measurements.
Magic mode locking: Single Section Mode Locking
## Comb Generation Using Nonlinear materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\chi^{(2)}$ [pm/V]</th>
<th>$\chi^{(3)}$ [cm$^2$/W] $n_2$</th>
<th>Refractive index @1550nm</th>
<th>Bandgap (nm)</th>
<th>Integration with active devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>26</td>
<td>$5.3 \times 10^{-15}$</td>
<td>~2.14</td>
<td>310</td>
<td>No</td>
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<tr>
<td>SiO$_2$</td>
<td>-</td>
<td>$2.2 \times 10^{-16}$</td>
<td>~1.44</td>
<td>137</td>
<td>No</td>
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<tr>
<td>Si$_3$N$_4$</td>
<td>-</td>
<td>$2.5 \times 10^{-15}$</td>
<td>~2</td>
<td>238</td>
<td>No</td>
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<tr>
<td>Ta$_2$O$_5$</td>
<td>-</td>
<td>$6.2 \times 10^{-15}$</td>
<td>~2</td>
<td>320</td>
<td>No</td>
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<tr>
<td>AlN</td>
<td>1</td>
<td>$2.3 \times 10^{-15}$</td>
<td>~2</td>
<td>205</td>
<td>No</td>
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<tr>
<td>SiC</td>
<td>12</td>
<td>$1 \times 10^{-14}$</td>
<td>~2.7</td>
<td>383</td>
<td>No</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>$6.5 \times 10^{-14}$</td>
<td>~3.4</td>
<td>1100</td>
<td>Indirect</td>
</tr>
<tr>
<td>GaAs (AlGaAs)</td>
<td>180</td>
<td>$2.6 \times 10^{-13}$</td>
<td>~3.4</td>
<td>570-873</td>
<td>Direct</td>
</tr>
<tr>
<td>InP</td>
<td>263</td>
<td>$1.1 \times 10^{-13}$</td>
<td>~3.2</td>
<td>922</td>
<td>Direct</td>
</tr>
</tbody>
</table>

### Why (Al)GaAs?

- High nonlinear coefficients
- High refractive index (~3.4)
- Compatible with active devices
- Tunable bandgap to avoid TPA at telecom bands
Comb Generation (Al)GaAs on insulator platform

(Al)GaAs on insulator platform
- High index contrast: footprint, power intensity, geometry tailoring
- Low loss
- Integration compatible and scalable

Q ~ 3.3 x 10^6
1 THz FSR
14 µm

Maximum Q > 3 x 10^6 achieved
Propagation loss < 0.2 dB/cm

Resonance split caused by scattering

E. Stanton, L. Chang...J. Bowers, R. Mirin, APL Photonics (2020)

Key: Passivation to reduce edge absorption
Low oval defect density, Scaling to 3”
Ultra-low threshold Kerr comb generation

\[
P_{th} \approx 1.54 \left( \frac{\pi}{2} \right) \frac{1}{\eta} \frac{n}{n_2} \frac{\omega}{D_1} \frac{A}{Q_T}
\]

Si$_3$N$_4$: $n_2 = \text{2.5} \times 10^{-15}$ cm$^2$/W, $A \sim 1.5$ µm$^2$

(Al)GaAsOI: $n_2 = \text{2.6} \times 10^{-13}$ cm$^2$/W, $A \sim 0.25$ µm$^2$

AlGaAsOI reduces the Power by 20 times!

\~20 µW threshold for 1 THz comb
- **100** times lower than previous III-V semiconductor platforms
- **10** times lower than state of the art dielectric platform

DWDM Comb Experiment

2 Tbps
20 wavelengths
PAM-4
50 Gbaud

H. Shu et al., “Microcomb-driven silicon photonic systems” Nature (2022)
Major Applications of Comb Sources

H. Shu et al., “Microcomb-driven silicon photonic systems” Nature (2022)
Si Quantum photonic integrated circuits

Quantum dots

Nonlinear devices

Atoms/Ions

Computation

Hybrid integration

Superconducting

Acoustic

SNSPD

NIST


MIT Lincoln lab

N. C. Narris, et al. Nat. Photonics 2017


E. Lucero, UCSB

Steiner, Moody Bowers, Optica 2023

Efficient photonic circuits, lasers, quantum sources, and detectors are key enabling technologies for future computers, networks, and communications.

Looking Forward at the Next 5 to 10 Years

Some Predictions

- Space-based quantum networks with satellite-to-satellite and satellite-to-ground entanglement distribution (5 years)

- Useful quantum sensors for biology, space exploration, navigation (5 years)

- Useful quantum computing hardware (not universal) (10 years)
Photonic navigation

Incoherent
- Mode-locked laser
- Pulsed high-power laser
- Fast photodetector

Coherent
- Frequency-chirp DFB lasers
- Tunable lasers
- Narrow-linewidth lasers

Others
- Optical parametric oscillator
- Rayleigh/Raman scattering
- Absorption spectroscopy

LIDAR

TOF LIDAR

FMCW LIDAR

Berkeley
Silicon LIDAR

1D OPA

2009

III-V/Si beam scanner with lasers

2015

Monolithic OPA with independent control

2015

Coherent FMCW LiDAR

2019

FMCW LiDAR on-chip

2021

Large-scale 2D OPA

2013

High-resolution OPA

2016

III-V/Si phase shifter array-based OPA

2020

FMCW LiDAR with on-chip calibration

2021

Zhou et al, eLight 2023
On-chip coherent LIDAR system

R & D

Thales, Tyndall, IMEC 2018

Pointcloud, Southampton 2021

Berkley 2022

EPFL 2022

PKU, UCSB 2023

Commercialized

ANALOG PHOTONICS

LUMOTIVE

SOS L3B

TRILUMINA

Advancing Illumination to Sense Your World

Baraja
Photonic sensing technologies

Absorption spectroscopy

Emission, Absorption, Transmission, Detection

Raman spectroscopy

Key: Tunable laser

Surface plasmon resonance

Youtube, Francis Chong

wiki
Silicon photonic sensors

R & D

Ghent 2015

IBM 2017

IHP 2020

Commercialized

MIT 2017

Genalyte

SiPhox
300 mm Silicon Photonics

- Lower loss waveguides
- Cheap substrates
- Rapid scaling to high volume
- Most advanced CMOS processing
- Most advanced Packaging
- 3D EIC/PIC integration

Advanced Silicon Photonics
How to Integrate Lasers with Modulators, Photodetectors, Passives?

Off-Chip Laser

Hybrid Integration

Heterogeneous Integration

Monolithic Integration

Laser integration on Si
Heterogeneous Integration: Infrared to Visible

Passives: Si, SiN/SiON/SiO₂
Nonlinear: AlGaAsOI, LiNbO₃
Isolator/Circulator: Ce:YIG
Actives: Si, SiGe, InGaAsP
Gain: GaN, GaAs, InP

Intel: Si PIC failure rate 100x lower than InP PICs (based on >5 million Transceivers)
Why?
1) More integration is more reliable
2) No exposed III-V facets

- Technology developed through extensive device research at Intel Labs over the past 20 years

- Pluggable silicon photonics successfully scaled and shipping in volume to multiple cloud and networking equipment customers

- 2016 100G PSM4 release
- 2017 100G CWDM4 release
- 2018 2M units shipped
- 2019 1M units shipped
- 2020 4M units shipped
- 2020 400G release
- 2021 >5M units shipped
- 2022 >8M units shipped

Intel® Silicon Photonics – at scale
Heterogeneous Tunable Lasers Across O,E,S,C,L Bands

Wavelength by design across the entire low-loss fiber comm window on a single chip by bonding multiple different III-V gain material on low-loss Si waveguides.

Guo…Bowers., APL Photonics 8, 046114 (2023).
Waveguide? SOI (Si) or CSOI (GaAs) or Silicon nitride?

- Silicon Nitride Loss:
  - Si: 0.1 dB/cm
  - GaAs: 0.2 dB/cm
  - InP: >1 dB/cm

 Courtesy: M. Tran, Nexus
Narrow Linewidth Lasers
Si dominates narrow linewidth lasers because the loss of Si, SiO$_2$ and Si$_3$N$_4$ is so much lower than InP or GaAs waveguides.

\[ \Delta v_0 = \frac{q \omega^2 n_{sp}}{2 Q^2 (I - I_{th}) (1 + \alpha^2)} \]

We used to try to make Lasers on Si as good as native substrates. Now, they are better than native substrate lasers.
## Current status of integrated narrow linewidth lasers

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<thead>
<tr>
<th>Year</th>
<th>Instantaneous Linewidth</th>
<th>Band</th>
<th>Si Loss</th>
</tr>
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<tr>
<td>2013</td>
<td>348 kHz</td>
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<tr>
<td>2015</td>
<td>160 kHz</td>
<td>C+L</td>
<td>6 dB/cm</td>
</tr>
<tr>
<td>2015</td>
<td>50 kHz</td>
<td>O</td>
<td>2 dB/cm</td>
</tr>
<tr>
<td>2017</td>
<td>98 kHz</td>
<td>C+L</td>
<td>2 dB/cm</td>
</tr>
<tr>
<td>2017</td>
<td>148 kHz</td>
<td>C+L</td>
<td>6 dB/cm</td>
</tr>
<tr>
<td>2018</td>
<td>2 kHz</td>
<td>C+L</td>
<td>1 dB/cm</td>
</tr>
<tr>
<td>2019</td>
<td>120 Hz</td>
<td>S+C+L</td>
<td>0.15 dB/cm</td>
</tr>
<tr>
<td></td>
<td>95 Hz</td>
<td></td>
<td>120 nm</td>
</tr>
</tbody>
</table>
Laser Linewidth

White Noise Floor:
- Lorentzian Linewidth
- Fundamental Linewidth
- Instantaneous Linewidth
- Schawlow Townes Linewidth

Low Frequency fluctuations due to
- Thermorefractive noise (TRN)
- Photothermal noise (PTN)
- Acoustic noise
- Current noise
- Temperature fluctuations

Blumenthal, OFC 2022
Semiconductor Laser Linewidth and Reduction Strategies

Modified Schawlow Townes linewidth equation:

$$\Delta \nu_0 = \frac{q \omega^2 n_{sp}}{2Q^2 (I - I_{th})} \left(1 + \alpha^2\right)$$

- Increase $Q$ – cold cavity quality factor, governed by the internal loss
- Reduce $I_{th}$
- Reduce $n_{sp}$, $\alpha$

Extended Cavity Laser

$$\Delta \nu = \frac{\Delta \nu_0}{F^2}$$

$$F = 1 + A + B$$

$$A = \frac{1}{\tau_{in}} \frac{d\varphi_{eff}(\omega)}{d\omega}$$

$$B = \frac{\alpha_H}{\tau_{in}} \frac{d}{d\omega} \left(\ln |r_{eff}(\omega)|\right)$$

- Reduce $\Delta \nu_0$
- Increase $A$ - Extended cavity length/active length
- Increase $B$ - Negative feedback effect (detuned loading)

Vahala and Yariv, JQE, 1984 Kazarinov and Henry, JQE, 1987
Linewidth Reduction with Si/III-V Integration

\[ \Delta \nu_0 = \frac{q \omega^2 n_{sp}}{2Q^2 (I - I_{th})} \left( 1 + \alpha^2 \right) \]

- **Increase** $Q$: \( \frac{1}{Q} \rightarrow \frac{1}{Q_{in}} \)
- **Reduce** $I_{th}$: \( (I_{th} - I_{tr}) \sim \frac{1}{Q \Gamma_{qw}} \)

Si/III-V heterogeneous waveguide provides modal engineering capability to achieve lower loss cavity:

\[ \frac{1}{Q} = \frac{1}{Q_{ext}} + \frac{1}{\Gamma_{Si} Q_{Si}} + \frac{1}{\Gamma_{III-V} Q_{III-V}} \]

✓ Undoped waveguides

Linewidth Reduction with Si/III-V Integration

$$\Delta v = \frac{\Delta v_0}{F^2}$$

$$F = 1 + A + B$$

$$A = -\frac{1}{\tau_{\text{in}}} \frac{d \varphi_{\text{eff}}(\omega)}{d \omega}$$

$$B = \frac{\alpha_H}{\tau_{\text{in}}} \frac{d}{d \omega} \left( \ln |r_{\text{eff}}(\omega)| \right)$$

Extended Cavity Laser

Integrates Silicon Resonators Coupled Lasers

A. Resonance cavity length (\sim Q) enhancement

B. Negative optical feedback (detuned loading)

Laser Design – Double Ring Mirror Lasers

- Silicon waveguides
- Couplers
- Optical amplifier waveguides
- MMI 3dB splitters
- Multiring mirrors
- Gain Section
- Phase Tuner
- LRM
- HRM
- InP
- Pt/Au
- Passives
2-Ring Mirrors

![Diagram of 2-Ring Mirrors]

- $\kappa_c$
- $R_1, \alpha_1$
- $\kappa_1$
- $R_2, \alpha_2$
- $\kappa_2$

![Graphs showing Reflection vs. Wavelength]

Reflection (dB) vs. Wavelength (nm)
Laser Characterization

40 nm

LIV

Wavelength Tuning Map

2π

R1 Heater (mW)

R2 Heater (mW)

Current (mA)

Output Power (mW)

Voltage (V)
Mode Hopping

Cavity longitudinal mode hopping

Ring mode hopping

→ Cavity length ~4.7 mm
3 nm (375 GHz) Mode-Hop-Free Tuning with a Narrow Linewidth Integrated InP/Si Laser

- Tuning over 375 GHz (3nm)
- Improving the heater efficiency will make the tuning range above 1.25 THz (10 nm)
- Resistant to vibrations and shocks
- Reduction of Size, Weight, Power, Cost (SWaP-C)
- Ideal for LiDAR and OFDR

Paolo Pintus, Joel Guo, Warren Jin, Minh Tran, Jonathan Peters and John E. Bowers “Integrated mode-hop-free tunable heterogeneous laser” J. Lightwave Technology (2023) and CLEO 2022
Frequency Noise and Lorentzian Linewidth

- **Frequency Noise Spectrum**
  - Noise peaks originated from current sources
  - White noise level = 650 Hz

- **Lorentzian Linewidth across the Tuning Range**
  - Linewidths < 2.5 kHz across the tuning range

Fundamental linewidth = 2.1 kHz
Direct Observation of Negative Optical Feedback Effect

• Narrowest linewidth is NOT at the maximum power output
Direct Observation of Optical Negative Feedback Effect

- Linewidth/power vs frequency detuning

\[ \kappa_1 = \kappa_2 = 0.2; \ R_{\text{front}} = 0.5; \ P_0 = 15 \text{ mW} \]
\[ \alpha = 1 \text{ dB/cm}; \ n_{sp} = 1.5; \ \alpha_H = 4; \ \alpha_{\text{inernal}} = 6 \text{ cm}^{-1} \]

- Calculated/measured linewidth reduction factor

\[
F = 1 + A + B \\
A = \frac{1}{\tau_{in}} \frac{d\phi(\omega)}{d\omega} \\
B = \frac{\alpha_H}{\tau_{in}} \frac{d}{d\omega} \ln \left( |r_{\text{eff}}(\omega)| \right) \\
\Delta \nu = \frac{\Delta \nu_0}{F^2}
\]
Sub-kHz Linewidth Widely Tunable Lasers
Achievable Linewidths vs. Waveguide Loss

Need waveguides with lower propagation loss
→ How to achieve lower loss on Silicon?

Origins of Optical Loss in Silicon Waveguides

- **Scattering (dominant source)**
  - Line-edge/sidewall roughness introduced during lithography and etching processes

- **Bulk absorption:**
  - Free-carrier absorption

\[ \Delta \alpha = 8.5 \cdot 10^{-18} \Delta N + 6.0 \cdot 10^{-18} \Delta P \]

- **Surface absorption:**
  - Surface defects, dangling bonds
  → Perfect in Silicon thanks to the long investment and research in the electronics industry
Waveguide Scattering Loss Modeling

Measured Data on 231 nm Etched WG

Modeled Curves and Measured Data

n_w model approximation

\[ A(\sigma, L_c, n_{eff}) \cdot \left( \frac{\partial n_{eff}}{\partial w} + \frac{\partial n_{eff}}{\partial h} \right) \]

\( \sigma \): sidewall roughness rms

\( L_c \): the roughness correlation length

\( n_{eff} \): is the effective index of mode

\( w \): width of the waveguide

\( h \): rib height of the waveguide
Waveguide Loss OBR Measurements

Measured OBR trace of 1.8 um waveguide

Extracted loss vs. wavelength

Deposited SiO₂
Si
Thermal SiO₂
Si Substrate

0.18 dB/cm
Waveguide Loss with Ring Resonators

Single mode Si ring resonator response with Lorentzian fitted $Q_{\text{int}} = 4.1$ million

- FWHM = 91.3 MHz
- $Q_{\text{loaded}} = 2.1$ mil.

Intrinsic Q (million)

Frequency (MHz)

normalized Intensity

Single mode Si ring resonators with varying radii

Bend loss dominant regime

- 0.244 dB/cm
- 0.18 dB/cm
- 0.171 dB/cm
- 0.16 dB/cm
- 0.72 dB/cm
- 1.60 dB/cm

Radius (μm)

$Q_{\text{int}} = \frac{2 \cdot Q_{\text{loaded}}}{1 \pm \sqrt{T_0}}$

$\alpha_{wg} = \frac{2\pi n_g}{Q_{\text{int}} \lambda_{\text{resonance}}}$
Completed Suite of Optical Waveguides

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Strip waveguide</th>
<th>Rib waveguide</th>
<th>Ultralow loss waveguide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Si</strong></td>
<td>400 - 800 nm</td>
<td>600 - 1000 nm</td>
<td>1.8 um - 8 um</td>
</tr>
<tr>
<td><strong>Si</strong></td>
<td>231 nm</td>
<td>500 nm</td>
<td>500 nm</td>
</tr>
<tr>
<td><strong>Si</strong></td>
<td>500 nm</td>
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</tr>
</tbody>
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| Bend Radius | 2-5 um          | 30-55 um       | 400-700 um             |

<table>
<thead>
<tr>
<th>Waveguide Loss</th>
<th>2.5 dB – 8 dB/cm</th>
<th>0.7 dB – 1.2 dB/cm</th>
<th>0.04 dB – 0.15 dB/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polarization independent designs</td>
<td>Single mode operations</td>
<td>Ultralow loss, high-Q components</td>
</tr>
<tr>
<td></td>
<td>Very compact components</td>
<td>Compact functional components</td>
<td>High power handling</td>
</tr>
</tbody>
</table>
Double Ring Mirror Design

With ring radii ~ 600 um of ultralow loss Silicon waveguides

Side mode suppression ratio becomes too small with 600 um bend radii

→ High Q requires extra filtering element
Three Ring Mirror Design

The first two primary rings set the Vernier FSR.
The third ring suppresses the side modes.
Laser Construction

Compact Silicon Waveguides

Ultralow Loss Silicon Waveguides

(i) GAIN

(ii) TR/PHASE

(iii) RING

InP

Pt/Au

SiO₂

Si
Silicon Inter-waveguide Transitions

- Flexibility to use various types of waveguides for their optimal functionalities on the same chip
  - Compact waveguides for waveguide splitters, loop mirrors
  - Ultralow loss waveguide for high Q components

3 Ring Widely Tunable Laser with 95 Hz Linewidth

118 nm wavelength tuning covering S-, C- and L-bands

RIN: -155 dBc/Hz

Lorentzian linewidth <100 Hz

## Current status of integrated narrow linewidth lasers

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<td>O</td>
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<td>98 kHz</td>
<td>C+L</td>
<td>2 dB/cm</td>
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**Si Loss**

- 6 dB/cm
- 6 dB/cm
- 2 dB/cm
- 2 dB/cm
- 6 dB/cm
- 1 dB/cm
- 0.15 dB/cm
Beyond telecom: visible integrated photonics

Extending the wavelength range of silicon photonics to visible

Silicon Nitride waveguide

- CMOS compatible
- Ultralow waveguide loss
- Highly uniform
- High power handling
- Low thermal noise
InGaAs/Silicon nitride Narrow linewidth laser at short wavelength

- High temperature lasing (185°C)
- 2 kHz fundamental linewidth
- Wide tuning range (> 20 nm)

Silicon Nitride: Low loss and high Q at blue and violet

- Record-high Q (6M, ~0.1 dB/cm) at blue (453 nm)
- Record-low loss (< 1 dB/cm) at violet (405 nm)

T. Morin, L. Chang... J. Bowers, Optica(2021)
Nexus Foundry Process for Heterogeneous GaAs lasers and PICs: 780, 980 nm
Heterogeneous GaAs lasers and PICs

Foundry process:
- High yield (99%)
- High uniformity
- High functionality
- More than just a laser!

Nature 2022, Optica 2023
Self Injection Locking

Narrow linewidth lasers
Comb Generation
Coupling to low loss SiN Cavities

• SiN resonators with $Q > 250$ M
• Commercial 200 mm foundry

Self Injection Locking Using $\Si_3\text{N}_4$ resonator direct pumping

High Q SiN resonator

High power DFB

Strong noise reduction by self-injection locking

Self Injection Locked DFB Lasers

- Ultra-low-loss CMOS SiN platform: 0.1 dB/m
- High Q Resonators: \( Q > 270 \) M
- > 70 dB noise reduction (thermorefractive noise limited)
- 40 MHz fundamental linewidth demonstrated
- Laser noise performance exceeds state-of-the-art-fiber laser

Comparison between SIL and fiber laser

TRN limiting the linewidth from high-Q resonators

- TRN scales with mode volume
- Noise reduction factor from high-Q limited by TRN

Heterogeneously-Integrated III-V/Si/Si$_3$N$_4$ laser

- Heterogeneously-integrated SiN laser with high-output power (> 30 mW)
- Narrow fundamental linewidth (<100 Hz, extended to Hz-level with self-injection locking to ultra-high-Q SiN)
- 10 pm/C temperature sensitivity (10-100x more stable than InP or Si)

This eliminates the need for CWDM! SiN AWGs and Lasers are temperature stable.

Self Injection Locked Heterogeneously-Integrated III-V/Si/Si$_3$N$_4$ laser

- 30 GHz FSR SiN resonator
- Normal dispersion
- 3 Hz Lorentzian linewidth
- Stable dark pulses observed

Xiang...Bowers, ‘High-performance lasers for fully integrated silicon nitride photonics’, Nature Communications 2021
Locking to Bulk Resonators to Achieve 1 Hz Integrated Linewidth

- PDH-lock SIL laser to vacuum-gap μ-FP cavity
- AOM provides frequency and intensity actuation for the PDH and RIN locks, respectively.
- The frequency noise, RF spectrum, and Allan deviation are measured via heterodyne with a stabilized frequency comb (for FN, two independently stabilized combs for cross correlation and greater measurement sensitivity)

UCSB, NIST, Caltech, Yale,
A Chip-Based, 1 Hz Integrated Linewidth Laser

- Integrated self-injection locked (SIL) laser PDH-locked to a microfabricated vacuum gap FP cavity
- 1.1 Hz FWHM measured via RF heterodyne beat
  - Hz-level integrated linewidth confirmed with FN Beta-separation line and $1/\pi$-integration estimations
- Frequency noise follows cavity thermal noise floor to $10^{-3}$ Hz$^2$/Hz at kHz offset frequencies
- Sub-$10^{-14}$ Allan deviation out to 1 second

**RF Heterodyne Beat**

**Frequency Noise**

**Allan Deviation**

3D Optoelectronics: Towards Higher Performance PICs

- 3D Heterogeneous integration of III-V, Silicon, **two** SiN waveguides,
- 3D Heterogeneous integration of III-V laser, SiN resonator, modulators, PDs

Xiang...Bowers, Nature, 2023
3D integration for ultra-low-noise lasers

- 5 Hz fundamental linewidth for 30 GHz ring resonator
- FN limited by thermorefractive noise
- FN=250 Hz²/Hz @ 10 kHz offset

Laser isolator-free operation

• 26 dB and >34 dB improvement for SIL through and drop port in Regime 1 boundary
• Unaffected laser FN under on-chip feedback as high as -6.9 dB (limited by coupling loss in testing)

TFLN: Self injection locked to LN resonators with SHG output

- A second-harmonic linewidth of 31kHz
- 4 x pump linewidth in SHG process

**TFLN: Integrated Pockels laser: Gain plus LiNbO3**

- III-V gain + Lithium niobate based external cavity
  - Record Fast frequency modulation (chirping), $2 \times 10^{18}$ Hz/s
  - Fast wavelength switch (50 MHz)
  - Dual-wavelength lasing (telecom + visible)
  - Narrow linewidth maintained (~ 10 Hz)

Comb Generation

Mode Locked Lasers
Nonlinear Combs
Turnkey Direct pumping (self-injection locking) for microcombs

**Turnkey microcomb generation**

**20 GHz Microwave comb**

- Frequency (MHz) + 19.787 GHz
- Power (dBm)

**1 THz comb**

- Frequency (THz)
- Power (dBm)
- 35-40 mW pump

**Turnkey soliton generation, no tuning required**

Dark pulse generation by self-injection locking

- Self-injection locking enables dark soliton generation under normal dispersion
- Get rid of the SiN thickness requirement for dispersion engineering
- Turnkey operation enabled for soliton generation

First CMOS-foundry-based microcomb production!

Demonstrated by Bowers group and Vahala group at 2021
Heterogeneously integrated laser soliton microcomb

- Output single soliton (100 GHz repetition rate) and soliton crystal state
- Fully electrical current initiated and controlled
- Wafer-scale heterogeneous process

Xiang, Liu, ..., Kippenberg, Bowers, 'Laser soliton microcombs heterogeneously integrated on silicon', Science 2021
Heterogeneously integrated laser soliton microcomb

• Current initiated and controlled soliton generation
• Soliton states dependent on the laser-resonance detuning, controlled by laser current and phase tuner current
• Manually tuned into soliton states, without feedback or sweep
• Very stable soliton without feedback, hours operation in lab environment
Soliton generation in AlGaAsOI resonator

**Challenges:**

- Soliton step observed
- Thermal optic effect too large at room temperature


Soliton comb at cryostat

AlGaAsO1 dark pulse generation

- Operating at blue detuning side of resonance (thermally stable)
- Record low threshold of coherent comb generation (< 1 mW)
- High conversion efficiency (> 15% at 10 mW)
- Wide access window (> 11 GHz at 10 mW)

H. Shu, L. Chang... X. Wang, J. Bowers, Arxiv: 2112.08904
Noise measurement of free running comb

Coherency is good enough for many applications

Great long-term stability (> 7 hours, power variation due to the drift of lensed fiber)

H. Shu, L. Chang... X. Wang, J. Bowers, Arxiv: 2112.08904
DWDM Comb Experiment

2 Tbps
20 wavelengths
PAM-4
50 Gbaud

H. Shu et al., “Microcomb-driven silicon photonic systems” Nature (2022)
There is a silicon photonics revolution happening!

Complicated, high performance PICs are being commercialized on silicon substrates (Intel, Cisco, Broadcom, Juniper Networks, ...) in high volume.