Nonlinear Integrated Photonics for Quantum Communications and Computing

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Quantum Computing: Devices, Cryogenic Electronics and Packaging
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Outline

- ❑ Introduction
- ❑ Nonlinear Quantum Photonics
- ❑ AlGaAsOI
- ❑ Applications:
  - ❑ Path Encoding
  - ❑ Multi-photon Cluster State Generation
  - ❑ Frequency Bin Quantum Information Processing

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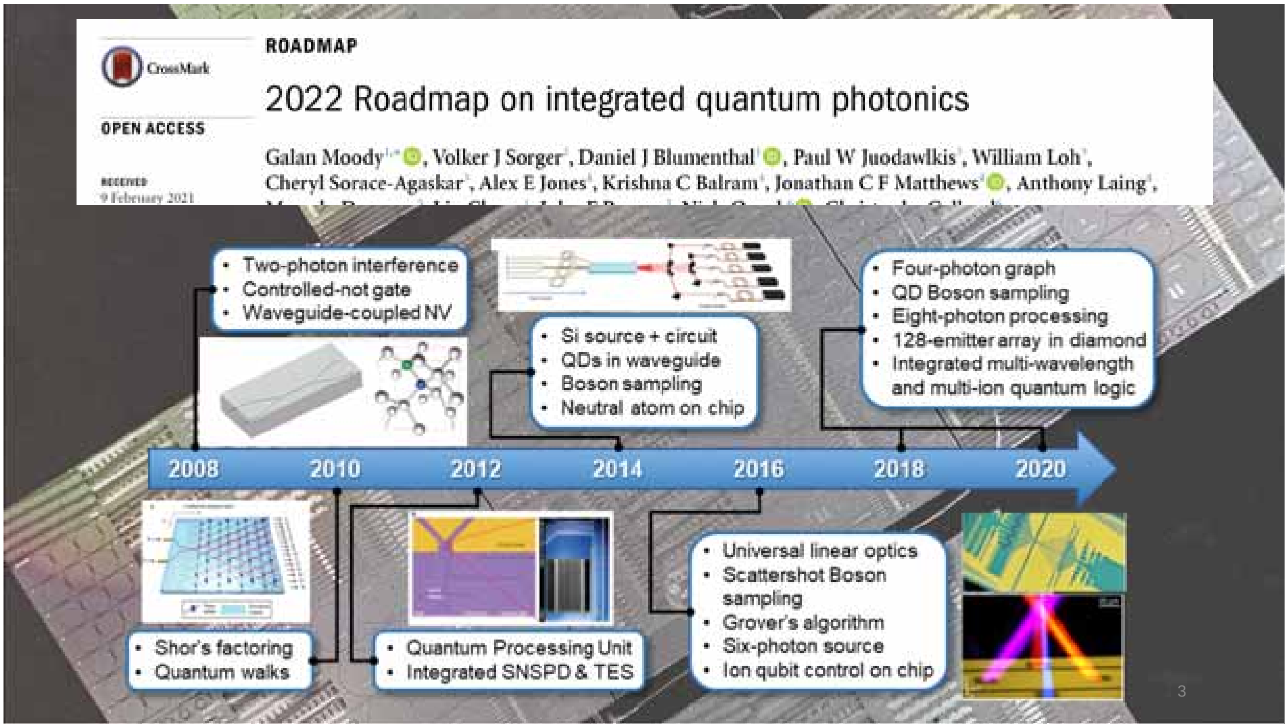
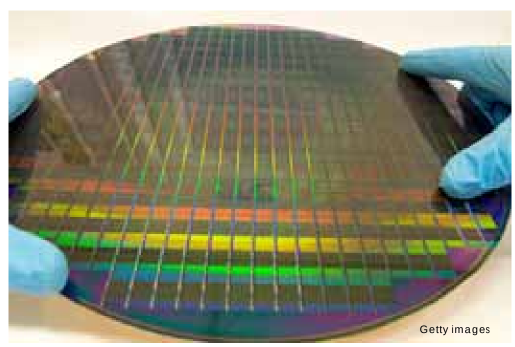
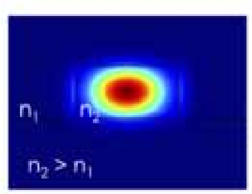
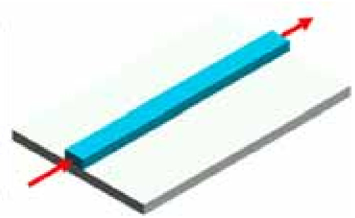


Mature Silicon Photonics Ecosystem







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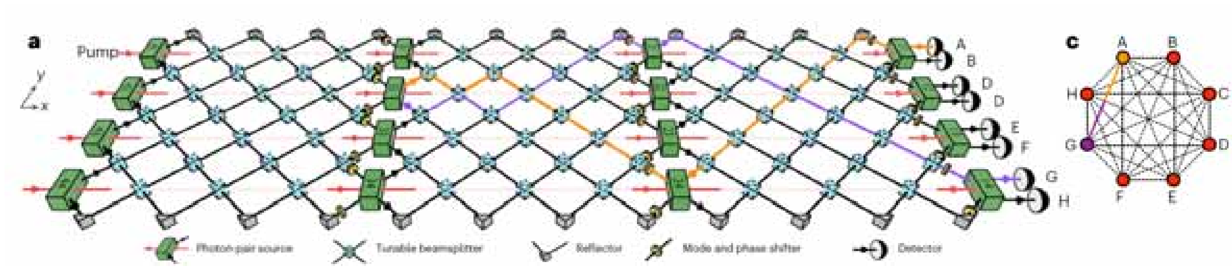

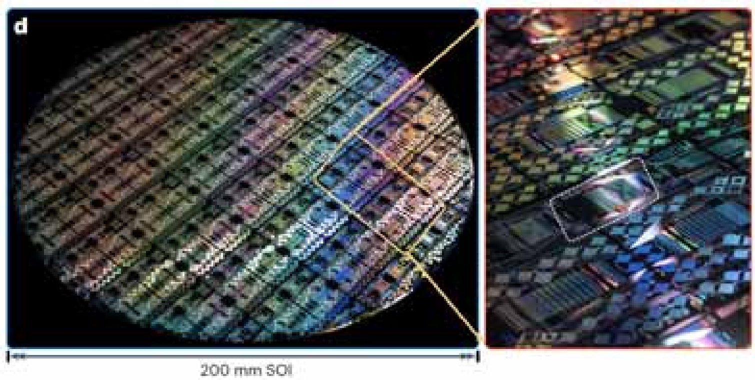

- Up to four-photon, 3-dimensional qudits
- Pulsed lasers + amplifiers to pump quantum light sources (~2-5 mW)
- ~20 mHz four-photon rates
- 4.5 dB chip-to-fiber coupling loss

Bristol/PsiQuantum/PKU, Nature Photonics (2023)

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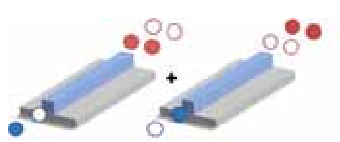
Photonic Qubits

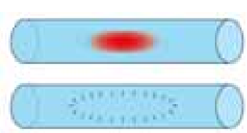
Discrete Variable

Time-Bin



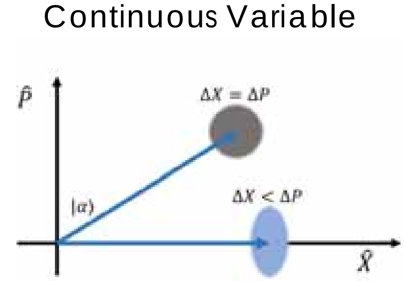
Moody, G. *et al. AVS Quantum Sci.* 2, 041702 (2020)

Path Encoded

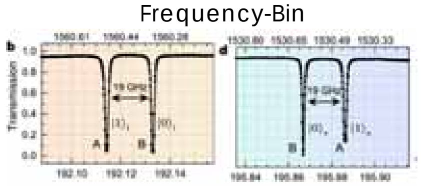


Wu, L. A. *et al. Sci. Rep.* 3, 1–6 (2013)

Continuous Variable

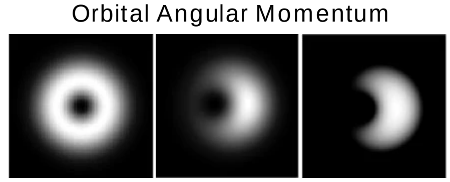


Frequency-Bin



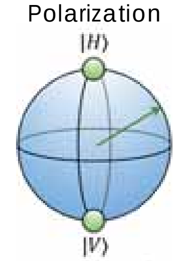
Clementi, M. *et al. Nat. Commun.* 14, (2023)

Orbital Angular Momentum



Mair, A. *et al. Nature* 412, 313–316 (2001)

Polarization



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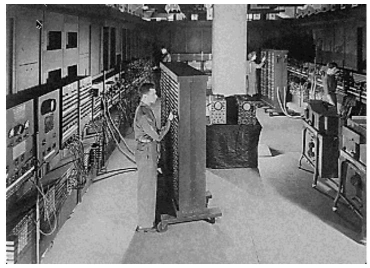
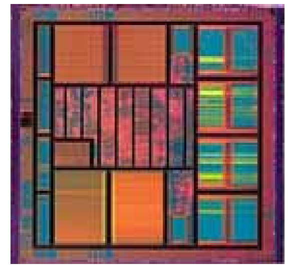
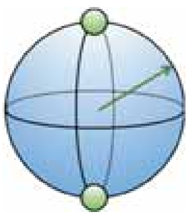
How do we go from a few qubits to a useful quantum computer?

ENIAC
(1946)

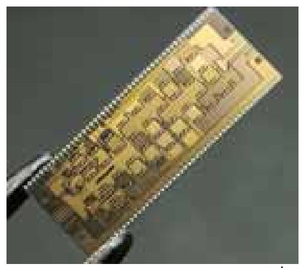


VLSI
(1980s)



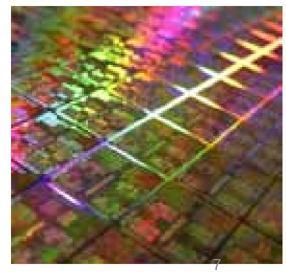


Quantum
Advantage
(2020s)



xanadu

Useful QC
(?)



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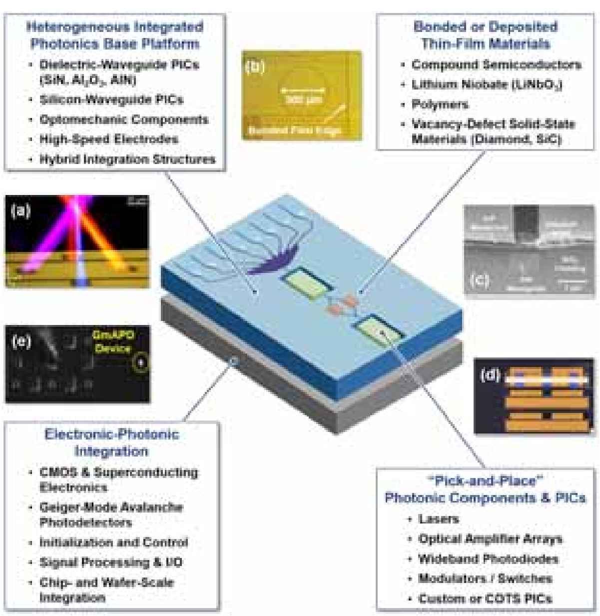
The Future of Integrated Quantum Photonics is Heterogeneous



"Heterogeneous Integrated Photonics for Quantum Information Science and Engineering"
Juodawlkis, Loh, Sorace-Agaskar, MIT Lincoln Lab

Current and Future Challenges
- ❑ Breadth of requirements
- ❑ Variety of materials needed
- ❑ Electronic-photonic integration
- ❑ Scaling prototypes to products

Advances in Science & Tech Needed
- ❑ Community-defined set of broad-wavelength platforms
- ❑ Heterogeneous integration techniques fabricated using silicon-foundry-compatible processes and open PDKs
- ❑ 3D integration to decouple photonic/electronic processes

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  - ❑ Frequency Bin Quantum Information Processing
  - ❑ Quantum Key Distribution

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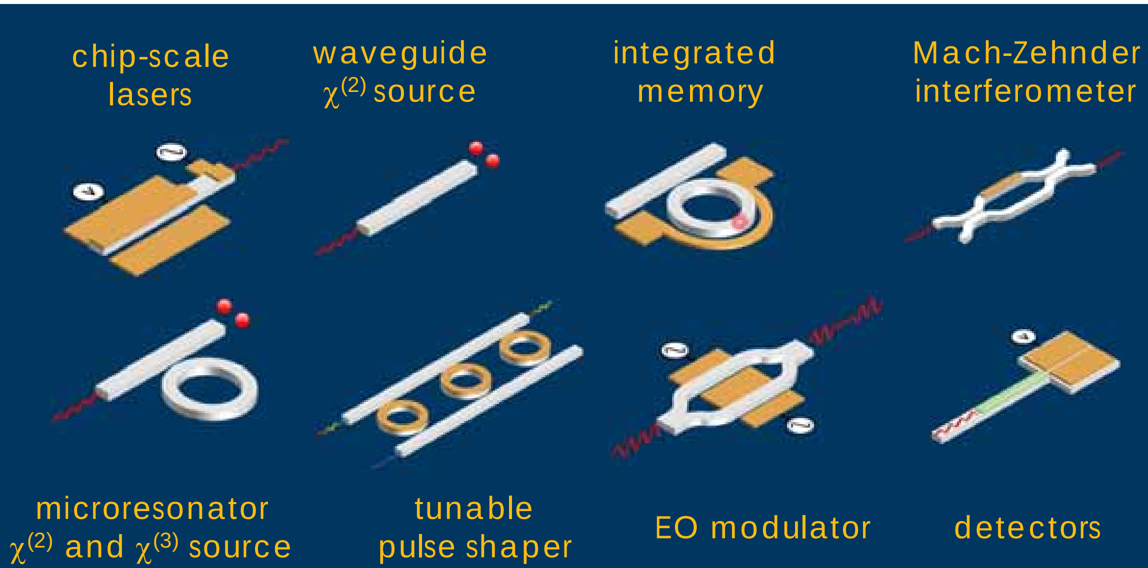

- ❑ **Low loss**
- ❑ **Wide bandgap**
- ❑ **High nonlinearities**
- ❑ **Gain**

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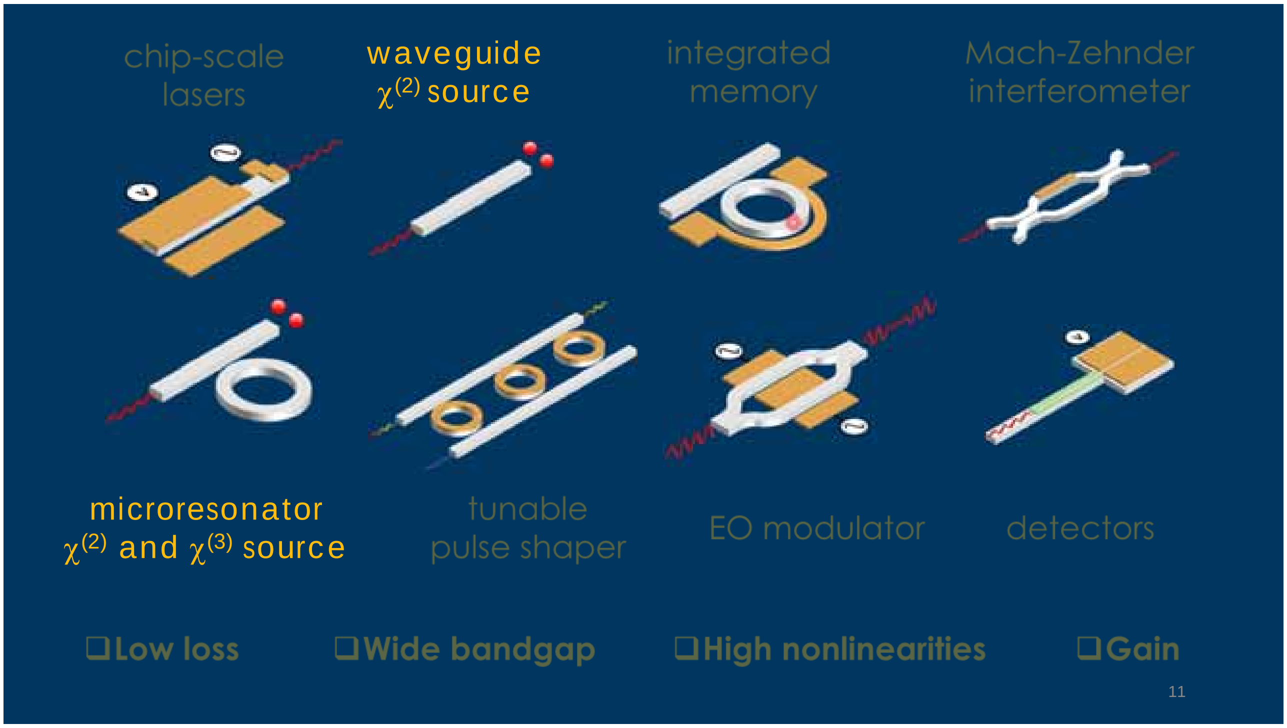
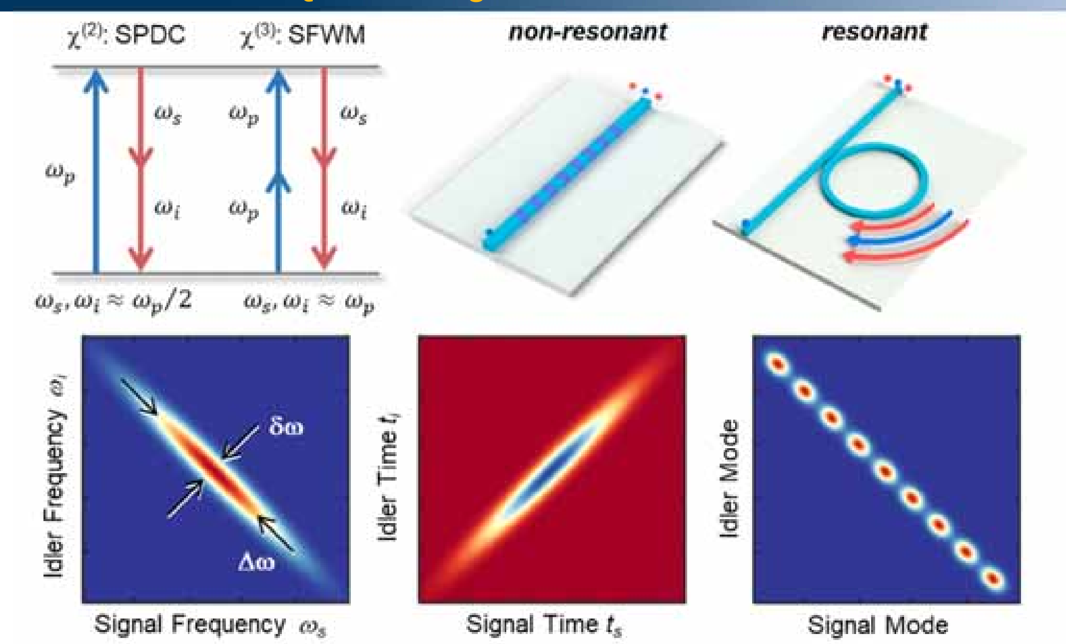


Nonlinear Photonics for Quantum Light Generation



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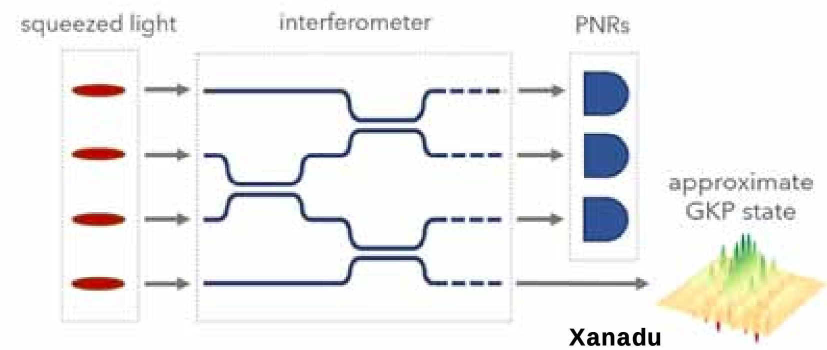
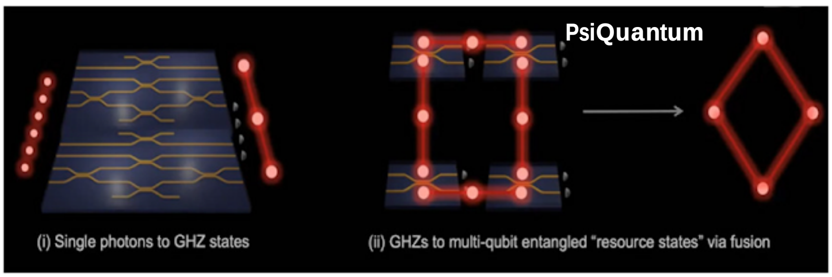
Moody, G. *et al. AVS Quantum Sci.* 2, 041702 (2020)

Nonlinear Photonics for Quantum Light Generation



Continuous Variable (CV)

- On-demand entanglement through two-mode or single-mode squeezing
- Computing via MZIs + PNRs + feed-forward



Discrete Variable (DV)

- Probabilistic entanglement via photon-pair generation
- Heralding, high-speed switching, fusion gates
- Fiber loop memory

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Comparison of Photonic Materials

Material	$\chi^{(2)}$ [pm/V]	$\chi^{(3)}$ [cm^2/W]	Refractive Index @ 1550 nm	Bandgap [nm]	Scalability [mm]	Functionality
SOI	-	6.5×10^{-14}	~3.4	1100	300	passives, manufacturability
SiNOI	-	2.5×10^{-15}	~2	238	300	passives, conversion, sources, visible
LNOI	26	5.3×10^{-15}	~2.14	310	150	sources, modulators, conversion, visible
AlGaAsOI	180	2.6×10^{-13}	~3.4	625	200	sources, modulators, conversion, gain
GaNOI	9	1.2×10^{-14}	~2.3	365	-	sources, modulators, conversion, gain
InGaPOI	263	1.1×10^{-13}	~3.2	650	200	sources, modulators, conversion, gain
Ta_2O_5	-	6.2×10^{-15}	~2	320	100	passives, conversion, sources, visible
AlN-OI	1	2.3×10^{-15}	~2	205	300	passives, sources, visible
SiC-OI	12	1×10^{-14}	~2.7	383	100	sources, modulators, visible

See: Moody, Chang, Steiner, Bowers, AVS Quantum Science **2**, 041702 (2020)
Moody *et al.*, Roadmap on Integrated Quantum Photonics, J. Phys. Photonics **4**, 012501 (2022)

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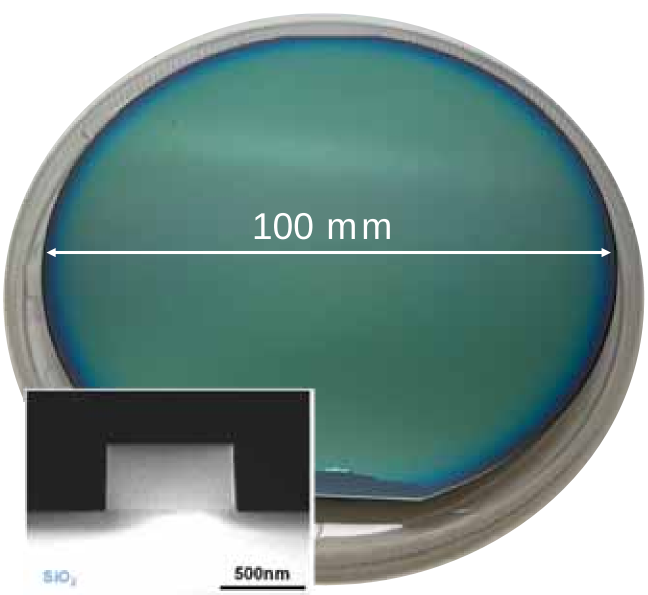
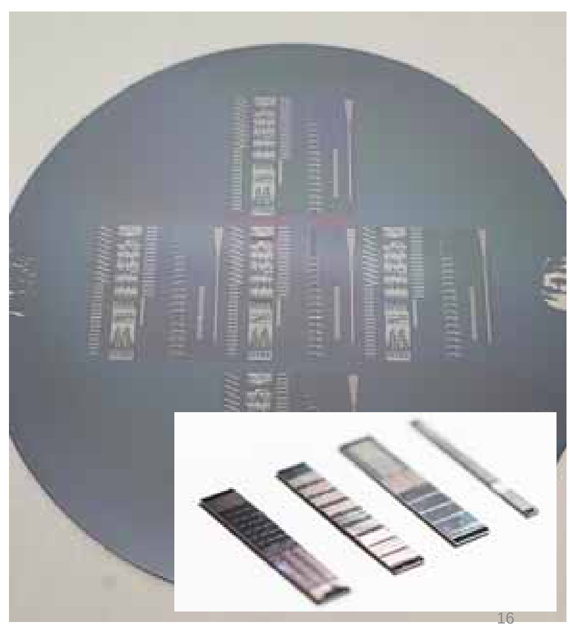
Compound Semiconductor-on-Insulator (CSOI)





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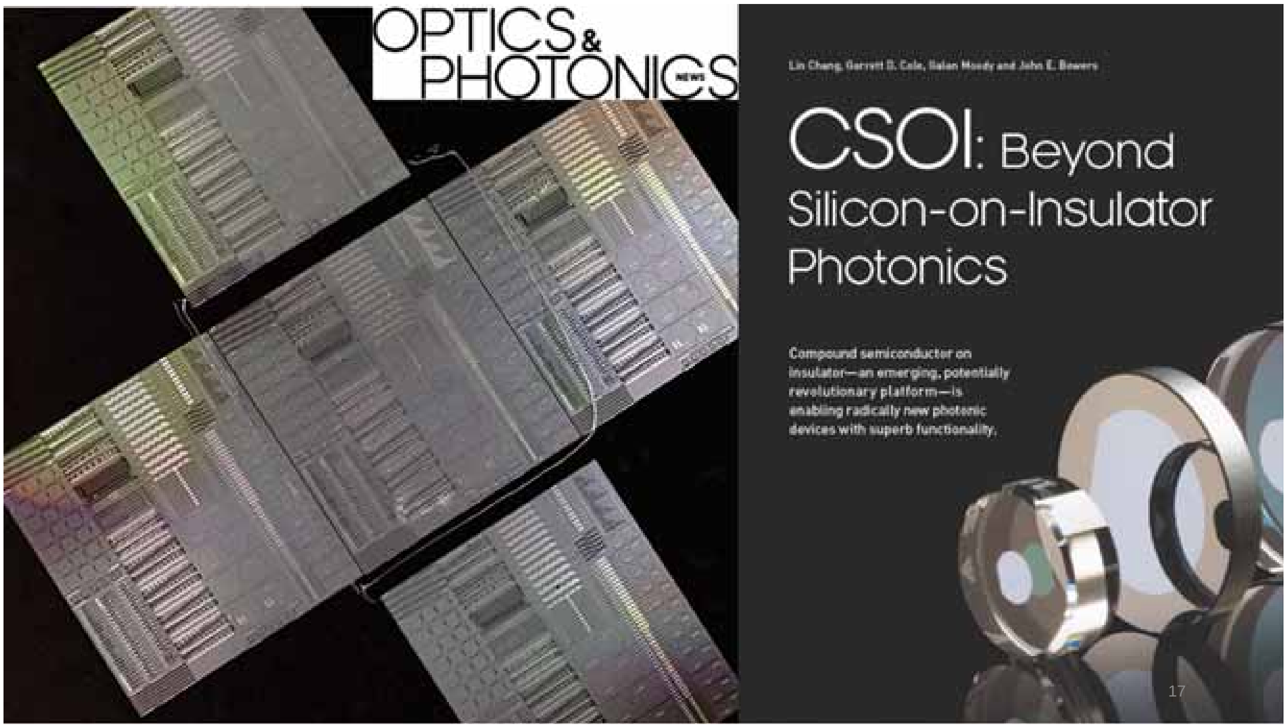
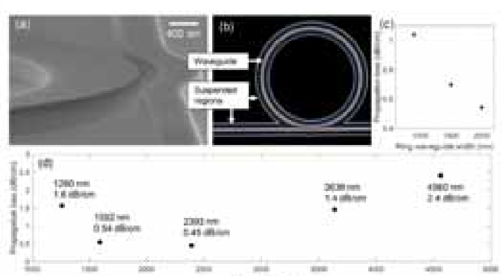
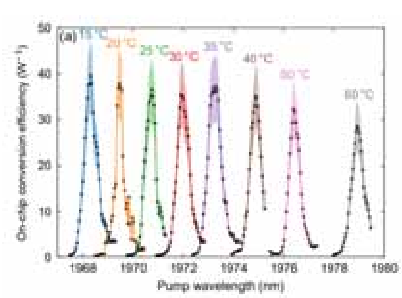


Nonlinear Photonics with III-V Materials



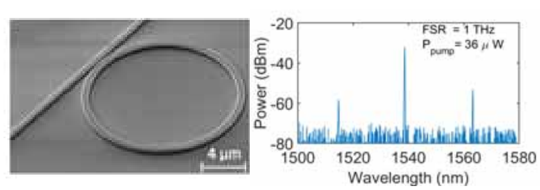
Multi-functional integrated photonics in the mid-infrared with suspended AlGaAs on silicon

Chiles, ..., Moody *et al.*, Optica **6**, 1246 (2019)



Record-high second-harmonic generation efficiency on chip

Stanton, ..., Moody *et al.*, Optics Express **28**, 9521 (2020)



Ultralow threshold frequency comb generation

Bowers group, Nature Communications **11**, 1331(2020)

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AlGaAsOI for Quantum Light Generation

PRX QUANTUM 2, 010337 (2021)

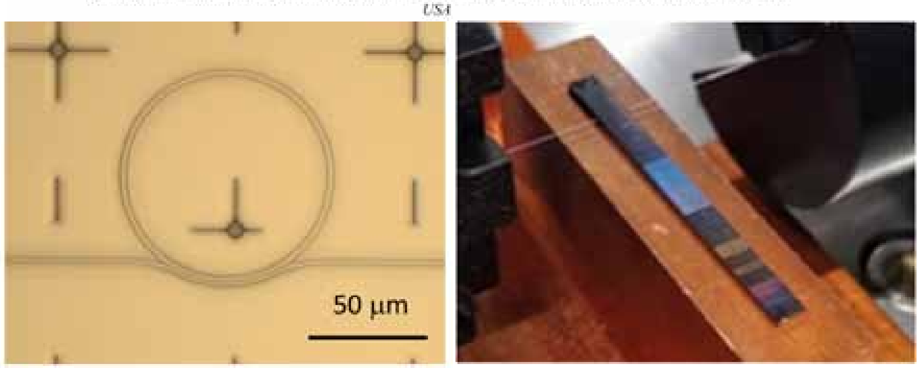
Featured in Physics

Ultrabright Entangled-Photon-Pair Generation from an AlGaAs-On-Insulator Microring Resonator

Trevor J. Steiner,[1] Joshua E. Castro,[2] Lin Chang,[2] Quynh Dang,[2] Weiqiang Xie,[2] Justin Norman,[2] John E. Bowers,[1,2] and Galan Moody[2,*]

[1] *Materials Department, University of California, Santa Barbara, California 93106, USA*

[2] *Electrical and Computer Engineering Department, University of California, Santa Barbara, California 93106, USA*



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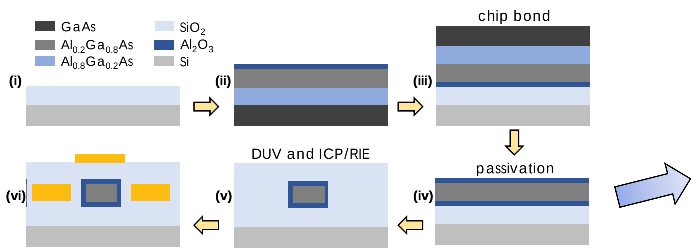
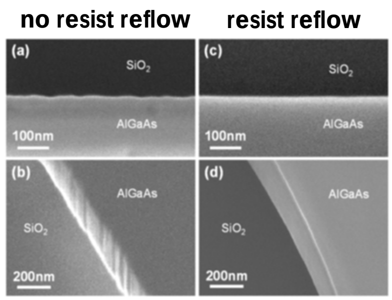
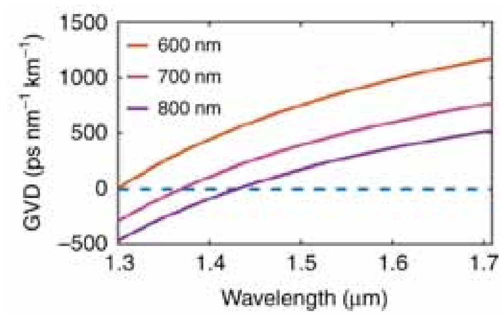
AlGaAs-on-Insulator Platform



- tight confinement
- 0.2 dB/cm loss





Xie, W. *et al. Opt. Express* 28, 32894 (2020)

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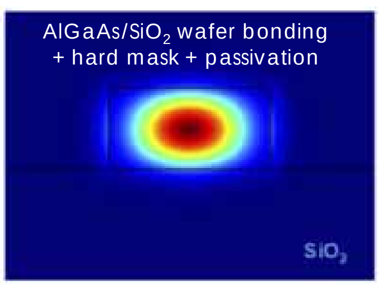
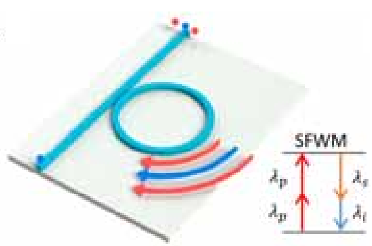
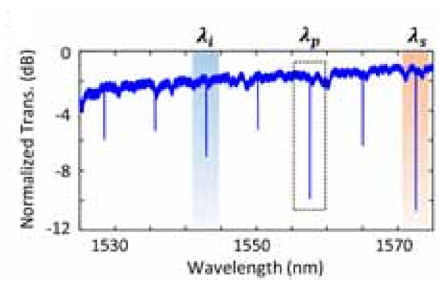
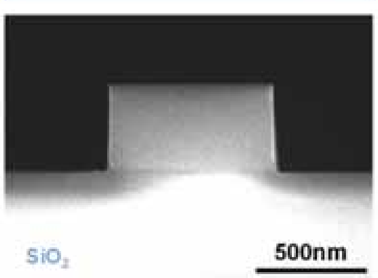
AlGaAsOI for Entangled-Pair Generation









$$|\Psi\rangle = \sum_{k=1}^{N} \alpha_k |k,k\rangle_{SI}$$

$$|k,k\rangle_{SI} = \int d\Omega\, \Phi(\Omega - k\Delta\omega)\, |\omega_p + \Omega, \omega_p - \Omega\rangle_{SI}$$

- Bi-photon frequency comb of time-energy entangled-photon pairs
- May be broadband, but made of narrow discrete frequency modes

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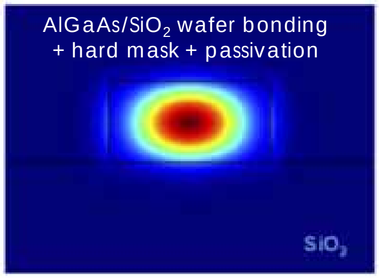
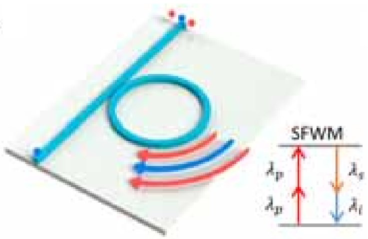
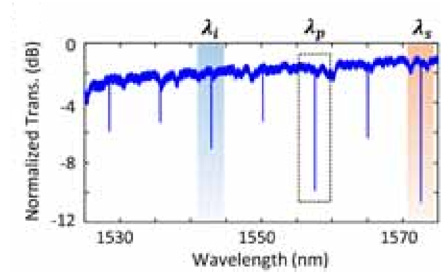
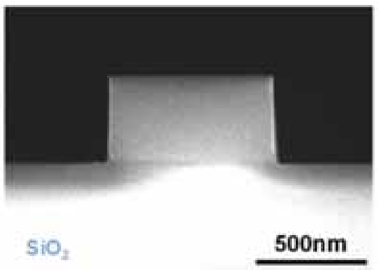
AlGaAsOI for Entangled-Pair Generation









Entangled Pair Generation Rate $\propto \gamma^2 Q^3 R^{-2}$

nonlinearity/ confinement

low loss

maintain high Q @ small R

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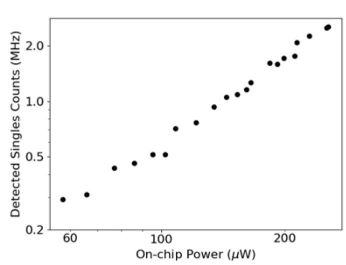
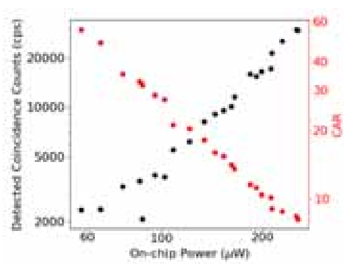
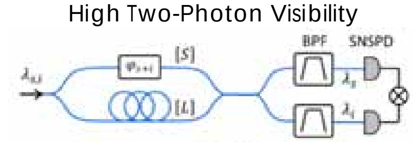
AlGaAsOI for Entangled-Pair Generation

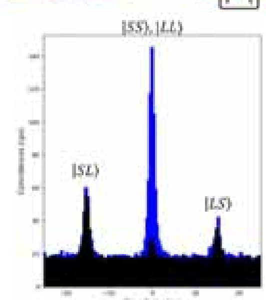
High Raw Photon Pair Flux



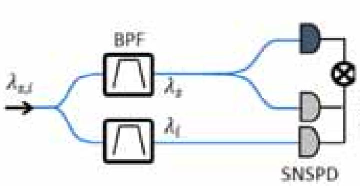


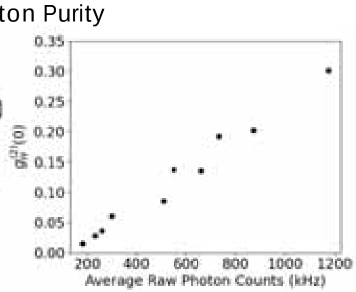
High Two-Photon Visibility

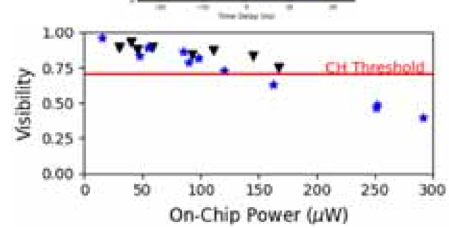




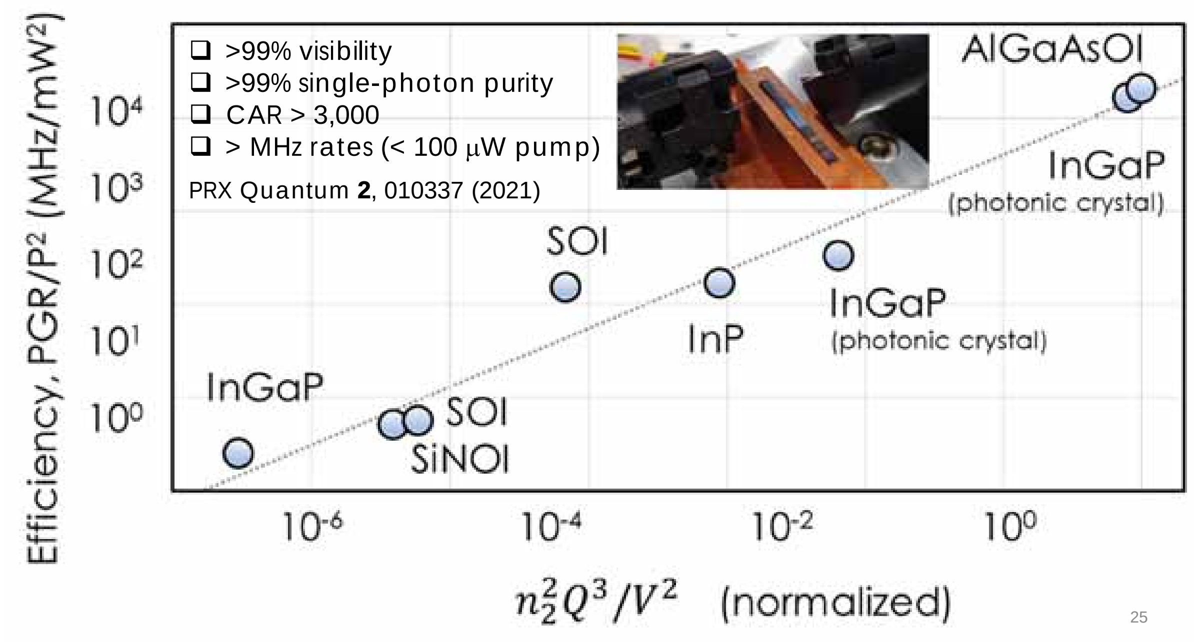
High Single Photon Purity



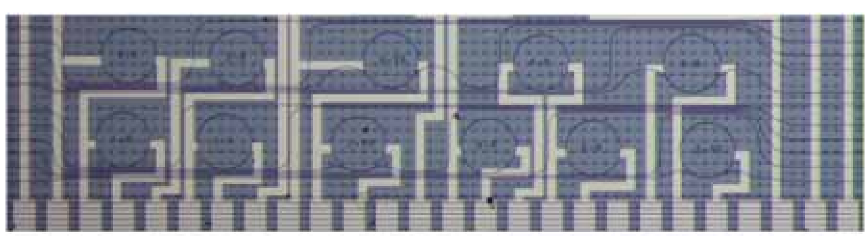


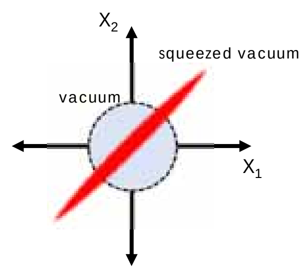


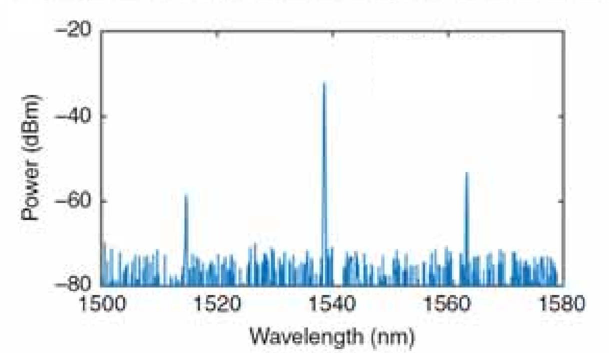
Ultra-Efficient Entangled-Photon Pair Generation

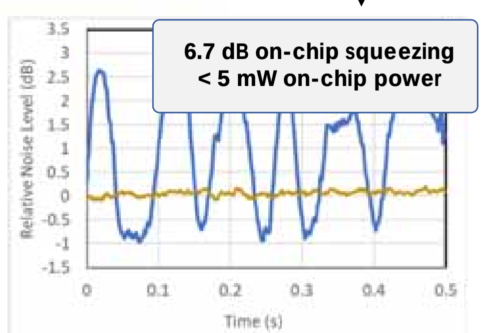


CV Sources: Squeezed Light Generation



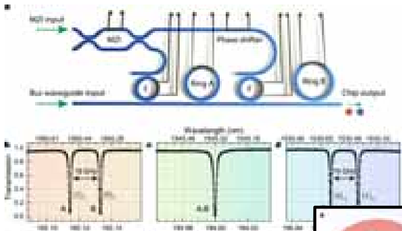




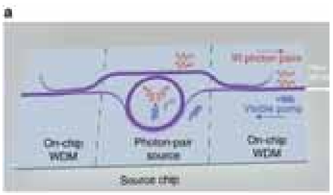


Progress on Other Material Platforms

Frequency-Bin Entanglement



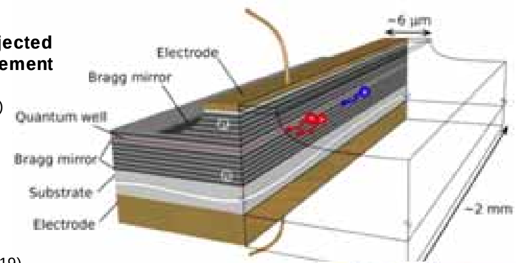
Silicon nitride: Clementi *et al.*, Nat. Commun. **14**, 176 (2023)



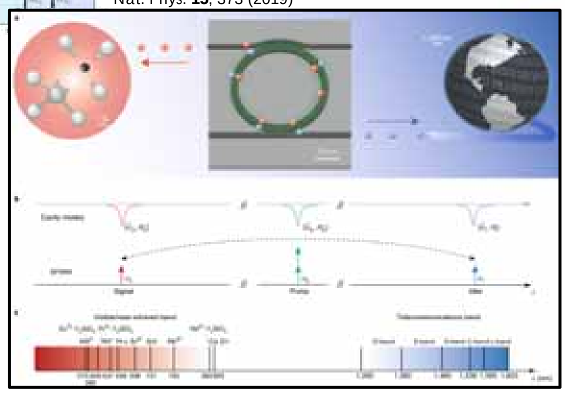
Aluminum Nitride: Guo *et al* LSA **6**, e16249 (2017)

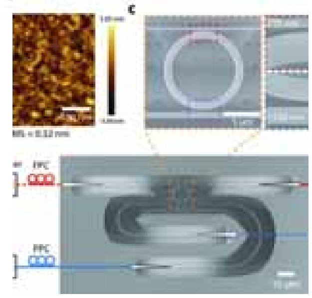
Electrically Injected Polarization Entanglement

AlGaAs: Boitier *et al.* PRL **112**, 183901 (2014)



SiNOI: Lu *et al.* Nat. Phys. **15**, 373 (2019)





InGaP: Zhao and Fang Optica **9**, 258 (2022)

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Status of Nonlinear Quantum Light Generation (2022)

Material	Q	On-Chip Efficiency	Brightness (pairs s^{-1} GHz^{-1}) @ 100 µW	Detected Singles (cps)	Detected CCs (cps)	Visibility (PGR)	Purity (PGR)	CAR (PGR)	On-Chip Squeezing	Squeezing Pump Power
SOI	~10^5	0.149 GHz/mW²	1.49 x 10^6	0.3 x 10^6	5 x 10^3	98.9% (1 MHz)	99.5% (1 MHz)	532 (1 MHz)	0.2 dB (microring)	3 mW
Si_3N_4	2 x 10^6	0.004 GHz/mW²	4.3 x 10^6	0.1 x 10^6	1.8 x 10^4	90% (1 MHz)	NA	~10 (1 MHz)	8 dB (molecule)	70 mW
$LiNbO_3$	-	0.778 GHz/mW (with 17 nm BW filters)	30 x 10^3	NA	NA	98.8% (380 kHz)	NA	~30 x 10^3 (1 MHz)	6.3 (PPLN WG)	304 mW
$LiNbO_3$	10^5	5.13 GHz/mW	8 x 10^5	NA	35	96.5%	99.1%	50 (50 MHz)	NA	NA
GaAs/ AlGaAs	1.2 x 10^6	20 GHz/mW²	1.3 x 10^9	5 x 10^6	30 x 10^3	97.1% (1 MHz)	99.6% (1 MHz)	~3 x 10^3 (1 MHz)	6.7 dB (microring)	5 mW
InGaP	1.75 x 10^5	27.5 GHz/mW	2.5 x 10^9	NA	NA	NA	NA	400 (1 MHz)	NA	NA
InP	4 x 10^4	0.145 GHz/mW²	1.45 x 10^6	NA	112	78.4% (1 MHz)	NA	277 (1 MHz)	NA	NA
AlN	1.1 x 10^5	0.006 GHz/mW	0.53 x 10^6	NA	80	NA	91.2% (1 MHz)	NA	NA	NA
GeSbS	1 x 10^6	0.07 GHz/mW²	4.3 x 10^6	0.8 x 10^6				2 (70 MHz)	NA	NA

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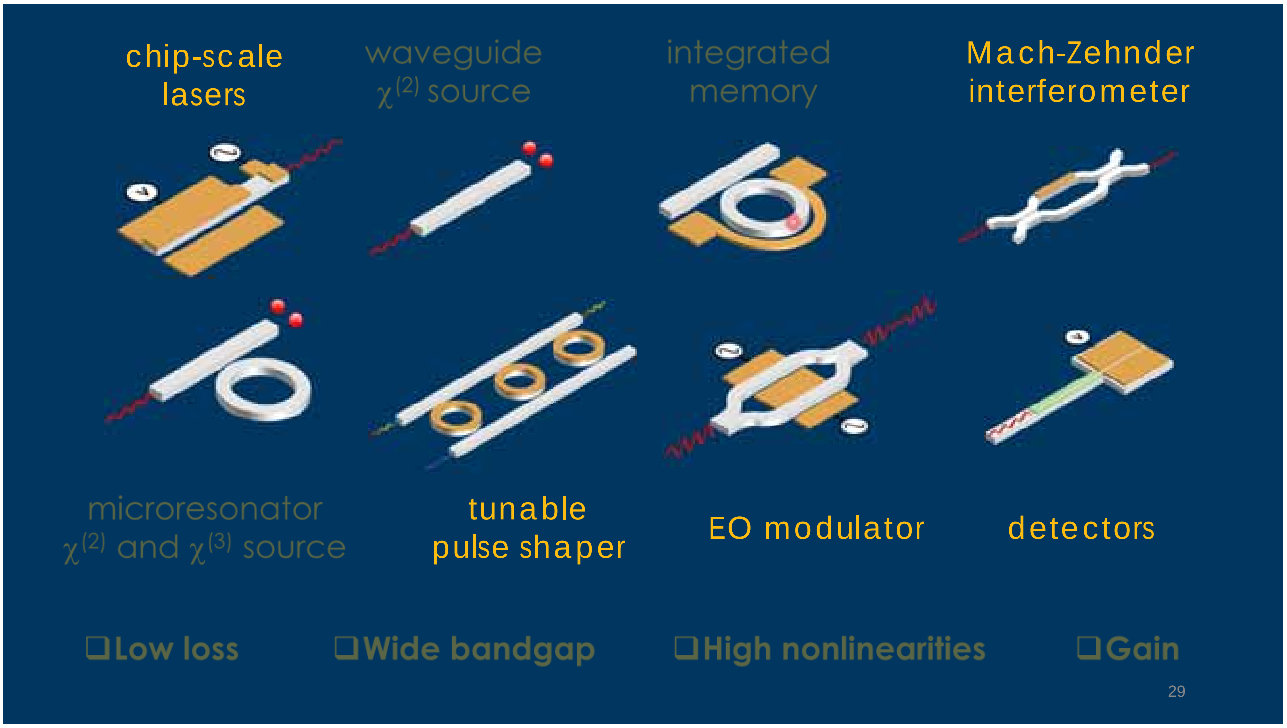
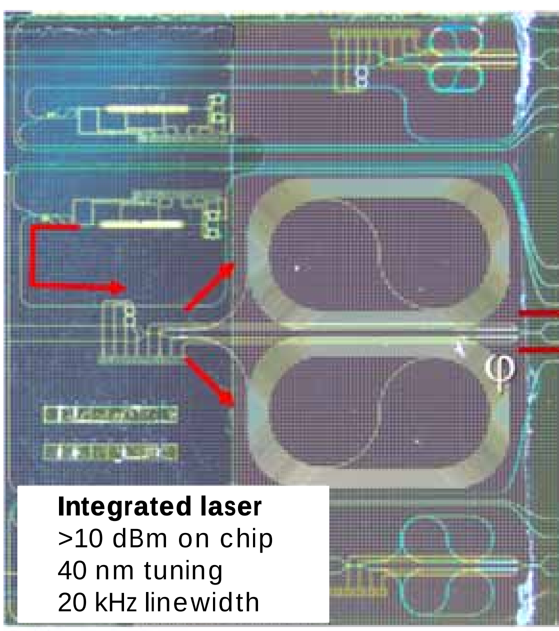
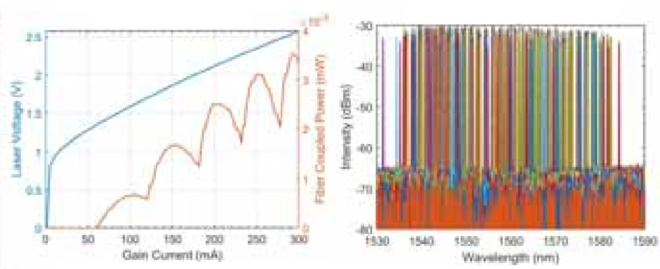


Towards Heterogeneous and Hybrid Laser Integration





- ❑ Tunable Bell-state generation from spiral SOI sources heterogeneously integrated with InP lasers
- ❑ Heterogeneous or hybrid laser integration possible, 10 dBm (or more with integrated amplifier). 1550 nm or 775 nm lasing.

Laser development: Bowers group Nexus Photonics

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Expanding the III-V Quantum Photonics Toolbox

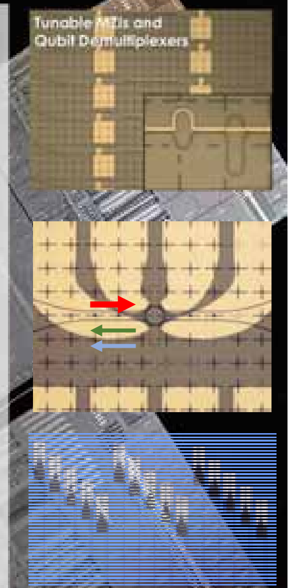
AlGaAsOI Component Library:

- ❑ Tunable MZIs for programmable circuits
- ❑ Qubit demultiplexers
- ❑ Optimized tunable rings for maximal entangled pair rates
- ❑ Waveguide crossers

Castro *et al.*, APL Photonics 7, 096103 (2022)

- ❑ Low-jitter, low-dark-count, high-efficiency SNSPDs
- ❑ Waveguide-integrated SNSPDs

Nature Photonics 14, 250 (2020)
APL 115, 081105 (2019)
APL 111, 141101 (2017)



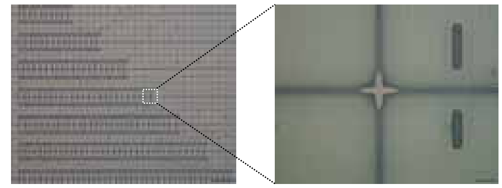


TABLE I. Table comparing the AlGaAsOI platform with SOI and Si_3N_4 designed for integrated quantum photonics.

	AlGaAsOI (this work)	SOI	Si_3N_4
Inverse Taper Coupling Loss	2.9 dB	< 3 dB[35]	2 – 3 dB[60]
Waveguide Crossing Loss	0.23 dB	0.2 dB[45]	0.3 dB[46]
MZI Extinction Ratio	> 30 dB	> 30 dB[61]	> 40 dB[62]
MZI Bandwidth (> 10 dB ER)	200 nm Cross 90 nm Through	> 40 nm[57]	180 nm[62]
MZI Heater Efficiency	20 mW/π (10.2 nm FSR)	12 mW/π[56] (5.8 nm FSR)	200 mW/π[55] (NA)

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Outline

- ❑ Introduction
- ❑ Nonlinear Quantum Photonics
- ❑ AlGaAsOI
- ❑ **Applications:**
  - ❑ **Path Encoding**
  - ❑ **Multi-photon Cluster State Generation**
  - ❑ **Frequency Bin Quantum Information Processing**

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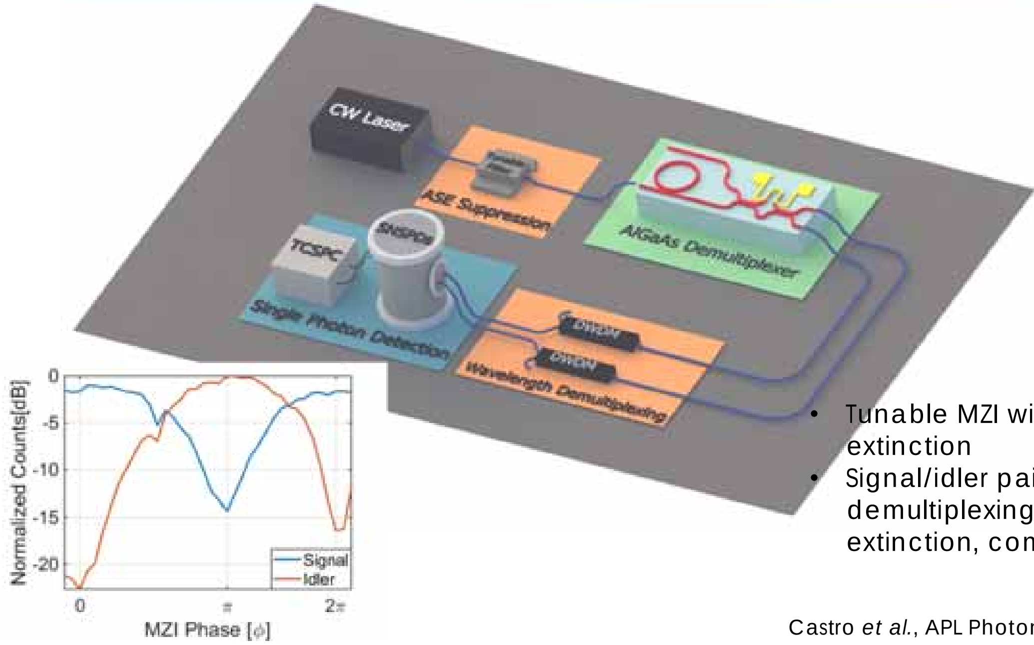
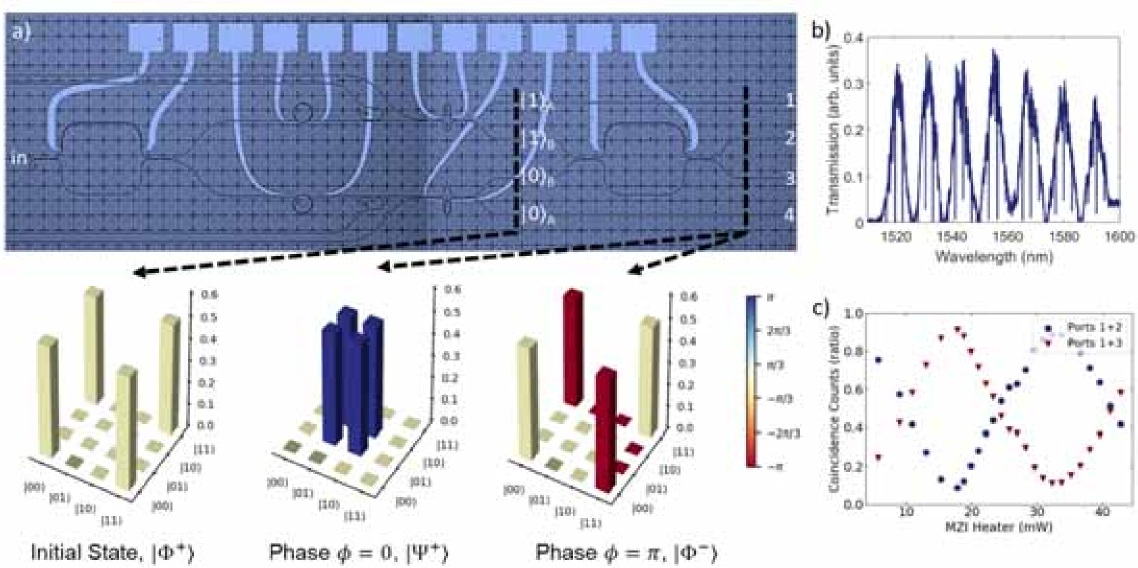
Path Encoded Qubits



- Tunable MZI with up to 40 dB extinction
- Signal/idler pair demultiplexing with high extinction, comparable to SOI

Castro *et al.*, APL Photonics **7**, 096103 (2022)

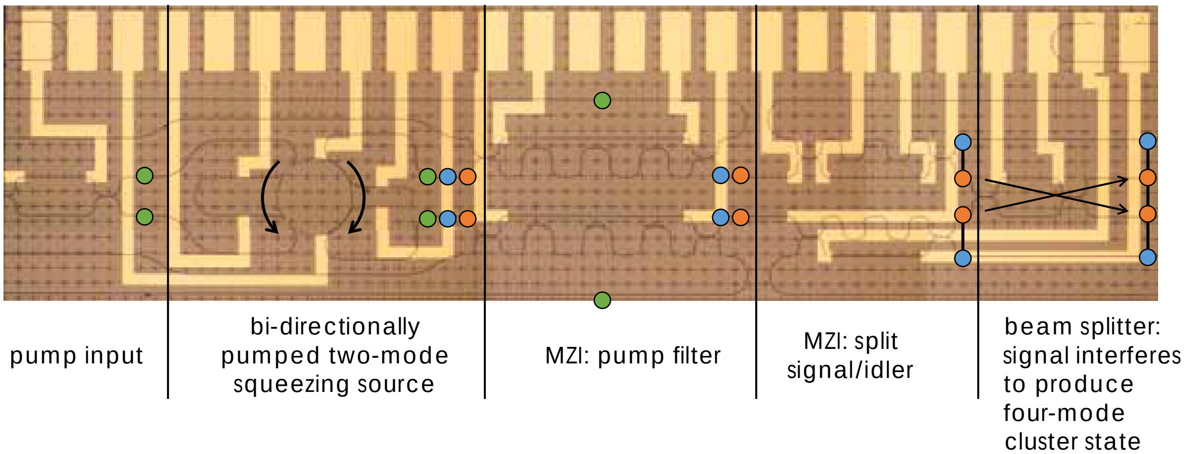
Tunable Two-Photon Entanglement



- ❑ 1 MHz detected rates with <100 μW on-chip power
- ❑ Indistinguishability > 90%
- ❑ Up to 100 mHz four-fold rates (5X > SOI)

Multi-Photon Cluster State Generation

expand entanglement to four photons across four spatial modes (waveguides) using squeezed light



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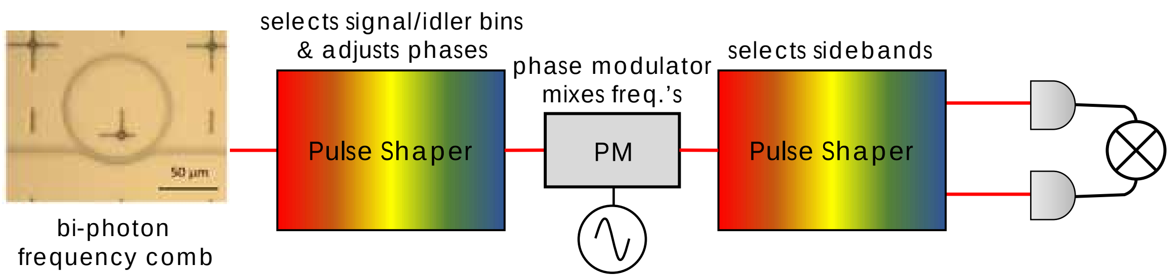
Frequency Bin Entanglement

Use a phase modulator to project a single frequency into multiple side bins



- ❑ Phase modulator acts as a frequency mixer, creating coherent superpositions of frequency bins and allowing for 2-photon interference measurements
- ❑ Analogous to
  - ❑ Wave plates and polarized for polarization-entangled photons
  - ❑ Path-imbalanced interferometers to mix time bins for time-bin entangled photons

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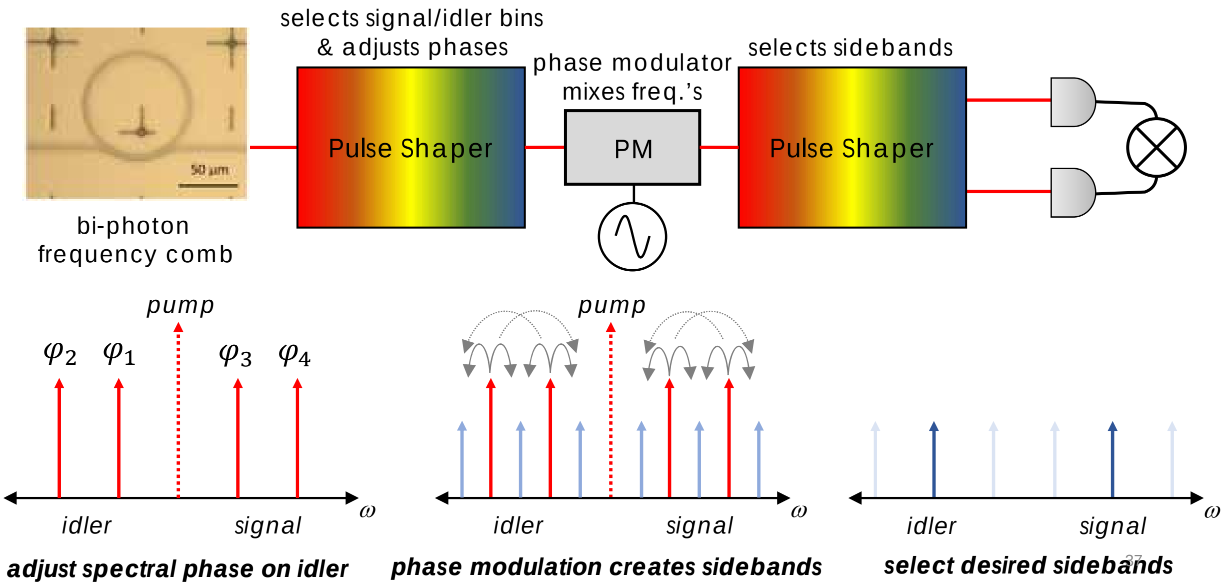
Frequency Bin Entanglement

Use a phase modulator to project a single frequency into multiple side bins



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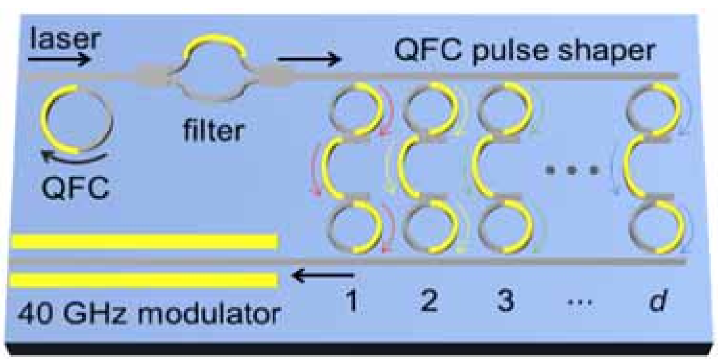
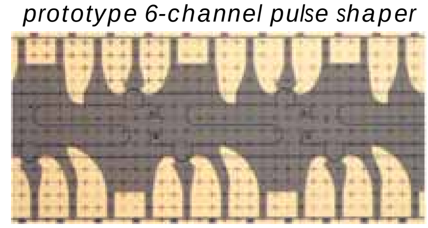
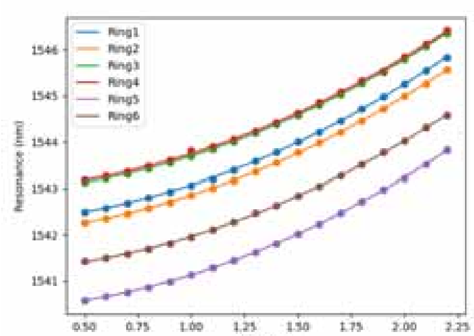
Frequency Bin Encoding



prototype 6-channel pulse shaper





- ❑ Should reduce loss of bulk component implementations (~15 dB/channel) to the few dB level
- ❑ Modulator simulations: 40 GHz bandwidth with VπL < 10 V cm (fab ongoing now)
- ❑ Applicable to quantum frequency encoding and entanglement characterization

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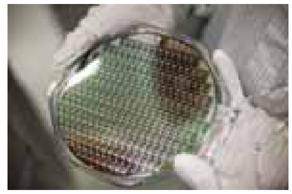
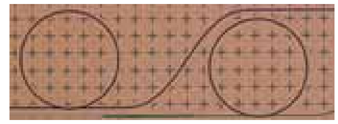
Quantum Photonics Goals for the Next 5 Years

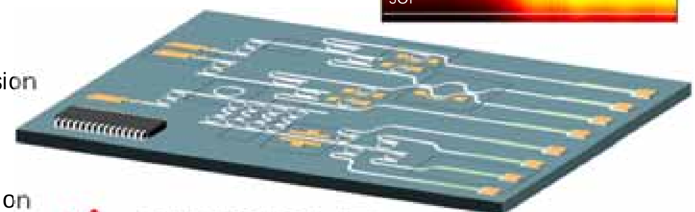
- **Heterogeneous PICs, wafer scale**
  - Nonlinear actives
  - SOI/SiNOI passives
- **Improving efficiency 1000X**
  - $\chi^{(2)}$ vs $\chi^{(3)}$
  - < 0.1 dB chip-to-fiber at scale
- **Systems-on-chip**
  - Lasers + sources
  - Lasers + sources + frequency conversion
  - Lasers + sources + microelectronics
- **Near-term applications**
  - Space-based Quantum Key Distribution
  - Quantum frequency conversion
  - Quantum-enhanced sensors
  - High-speed (GHz) programmable quantum photonic resource states

100-200 mm, foundry



AlGaAs-on-SOI (1550 nm)





Thank You!

not pictured: Lilli Thiel, Max Shen, Sammy Umezawa, Trung Kien Le, Daniella Polishchuk, Liao Duan, Yiming Pang, Audrey Pechilis

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