Photonic Crystal Laser Monolithically Grown on Si Substrates for Si photonics

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CS International, Brussels, 17/04/2024

Outline

- Background
- Challenges
- Current works
- Conclusion
- Prospective

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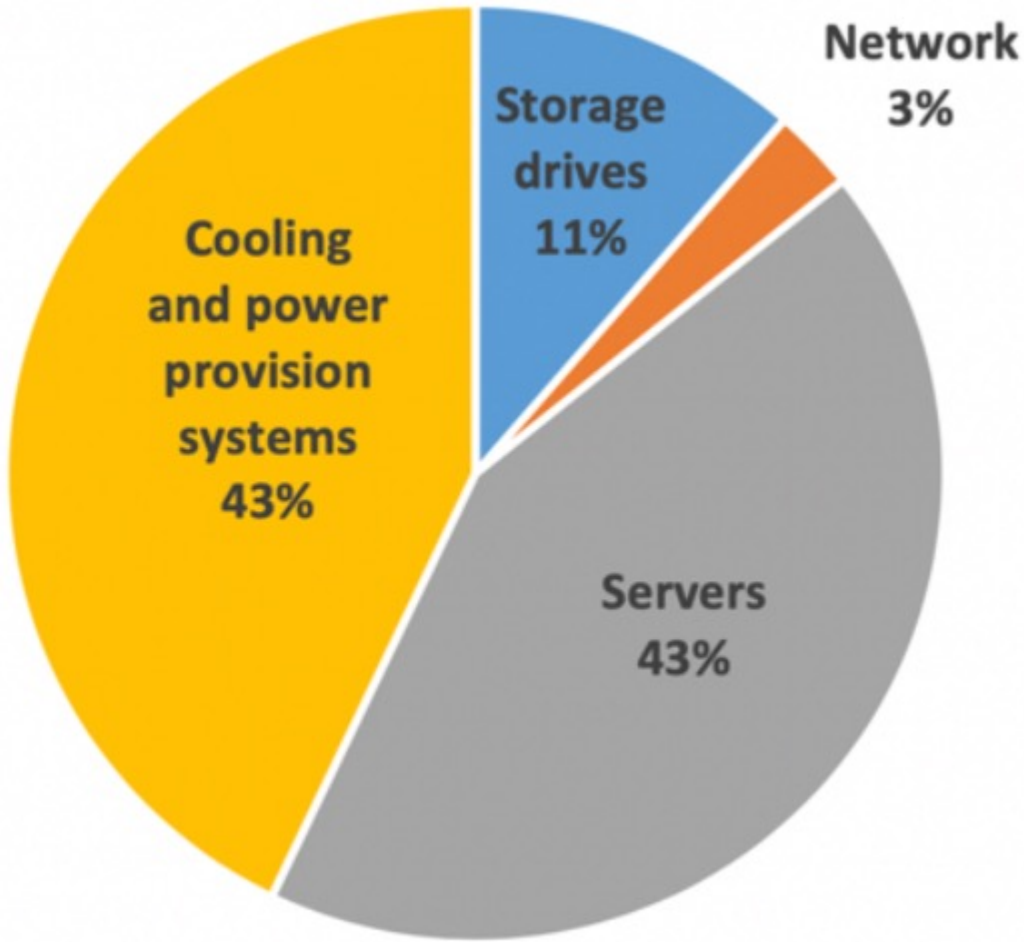

Figure 1. Fraction of U.S. data center electricity use in 2014, by end use. Source: Shehabi 2016.

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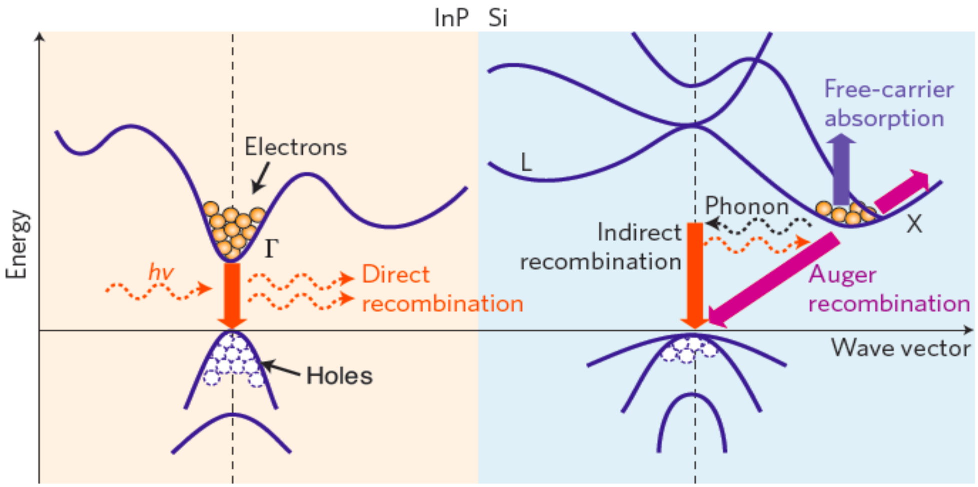
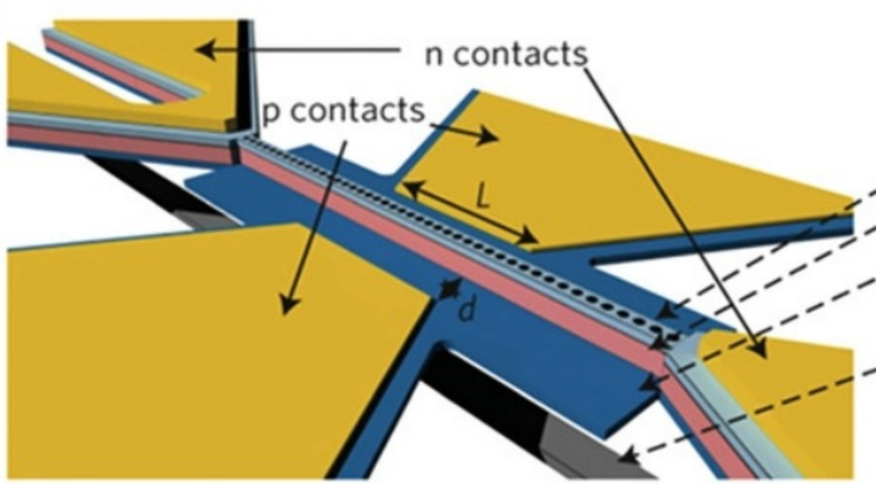
- **Si ph**
- **Si ph**

Source: Yole

Why Laser on Si

- III-V laser on Si is ideal solution, due to the low efficiency of group-IV laser
- Direct epitaxial growth III-V has been working on for 30 years, and there were III-V QW lasers on Ge and Si with high threshold current density and short lifetime.
- Monolithic growth of III-V QWs on silicon was studied at 30 years ago.
- The main problems for III-V/Si: Antiphase domains and Threading dislocations.
- Bonding?

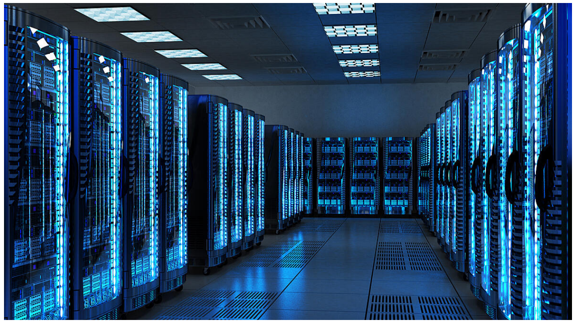




Nat. Photonics, 4, 511, 2010
Nat. Photonics, *11*, 297, 2017

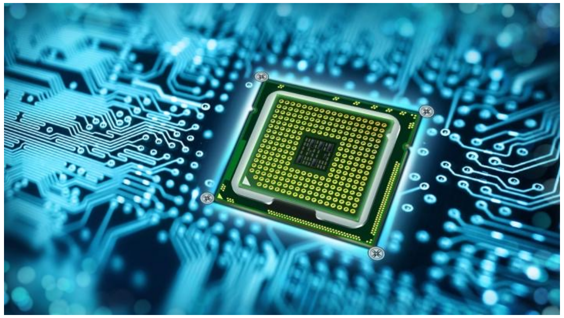
Long haul communication – optical fibre

Well-established



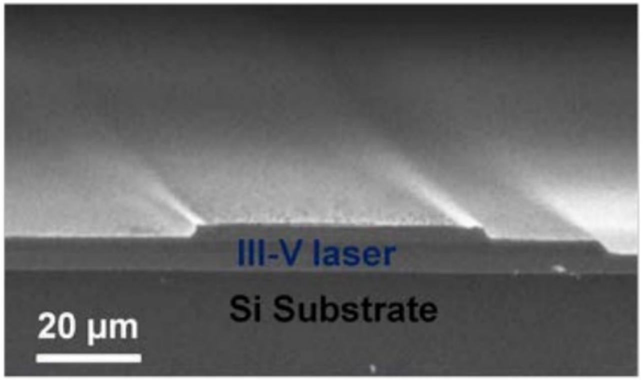
Data Centre – Optical Transceiver

On-going

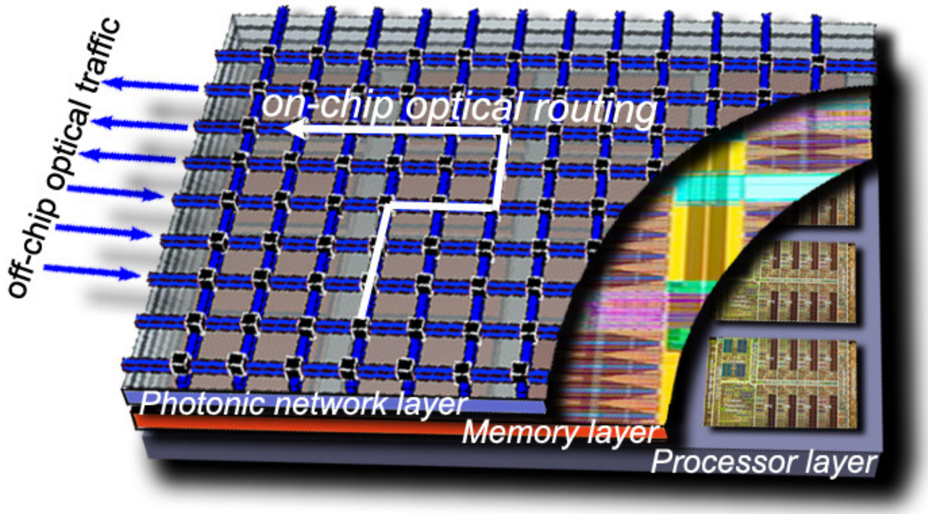


Microprocessor: inter-chip optical connection

?

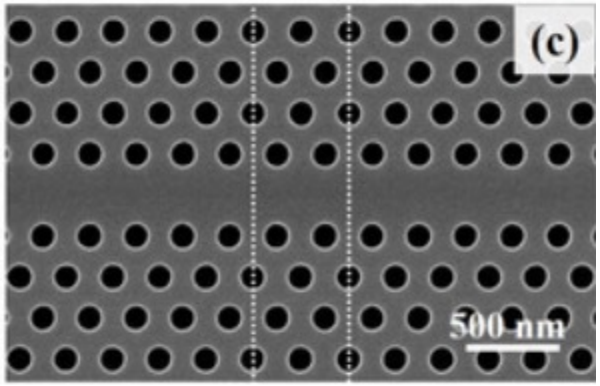


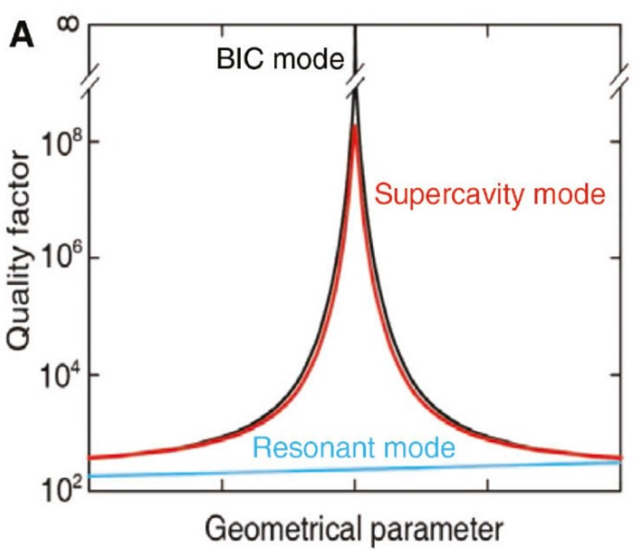
Ridge-waveguide laser
- on-chip/off-chip light source



Nat. Photonics 10, 307, 2016

Laser with microcavity - Photonic crystal laser





Advantages:

- Small footprint – high integration density
- Low operating power – good for low energy cost
- High Q-factor – single-mode lasing and narrow linewidth
- Can integrate with other optoelectronic devices with photonic crystal cavity

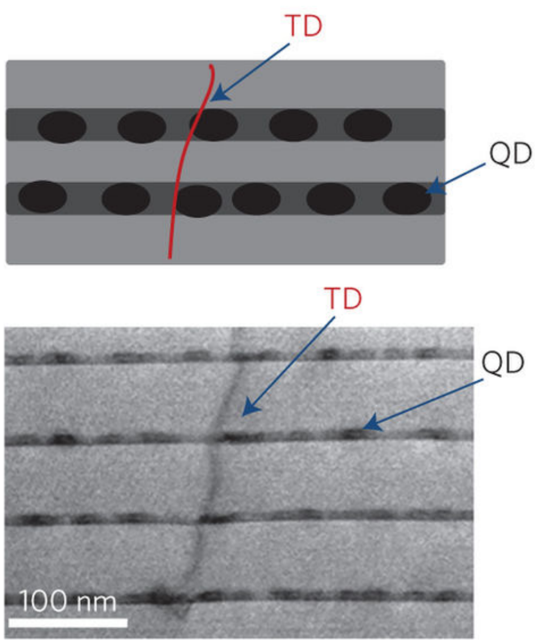
Challenges:

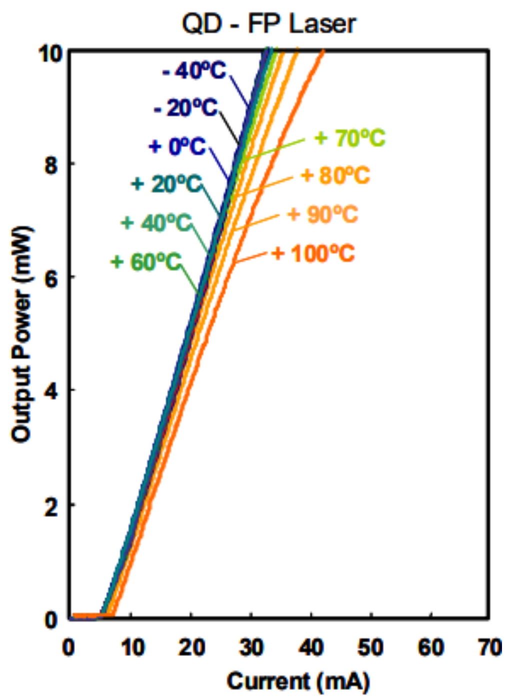
- Nanofabrication – imperfection cause optical and electrical loss
- Coupling to waveguide

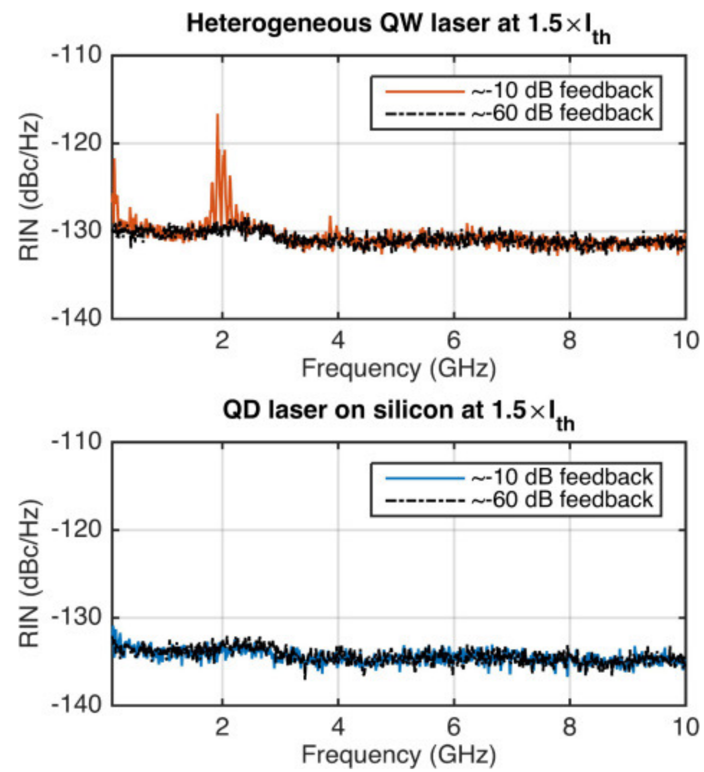
APL Photonics 5, 046106, 2020
Nanophotonics, 8(5): 725–745, 2019

Quantum dot laser

- Insensitive to crystal defects
- Nearly constant J_{th}, P_{out} and slope efficiency up to 100 ℃ [1]
- Feedback tolerance

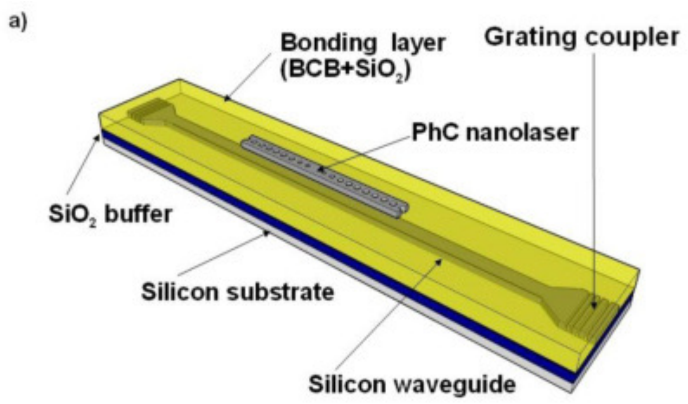




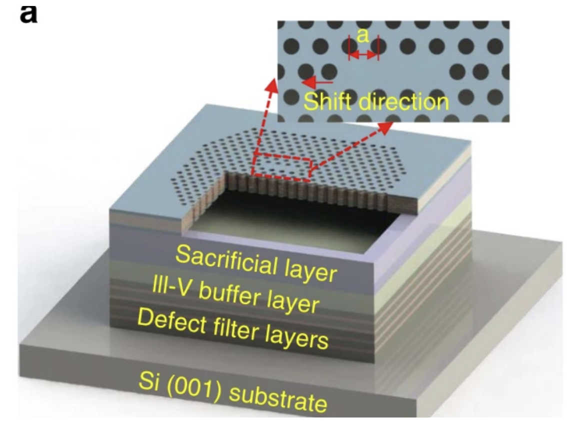


Nat. Photonics 10(5) 307, 2016QD
Laser Inc Whitepaper
Optics Express 25(9) 9535, 2017

Integration strategy



Heterogeneous Integration



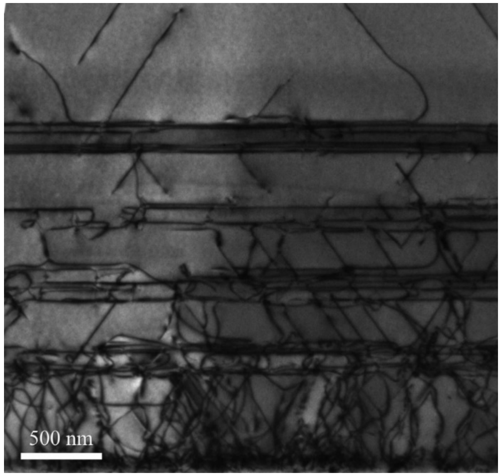
Monolithic integration

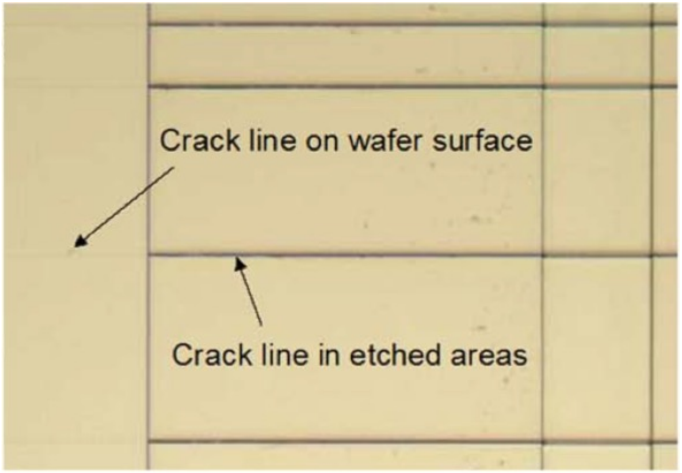
	Heterogeneous Integration	Monolithic integration
Advantages	Coupling to waveguide	Whole-wafer manufacturing
	Device performance	Integration with OEIC
Disadvantages	High cost and low yield	Difficult for waveguide coupling
		Material property degraded

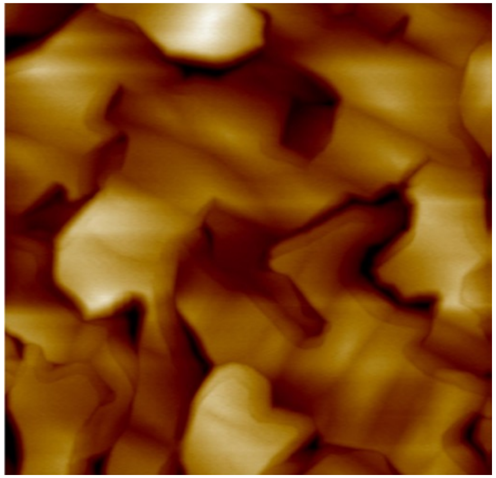
Optics Express 19(10), 9221, 2011
Nat. Communication 11, 1, 2020

Monolithic integration – challenges and solutions

- High density threading dislocations – defect filter layers
- Thermal cracks – reduce epitaxial layer thickness
- Anti-phase boundaries (APB) – offcut substrate or Si atomic step control

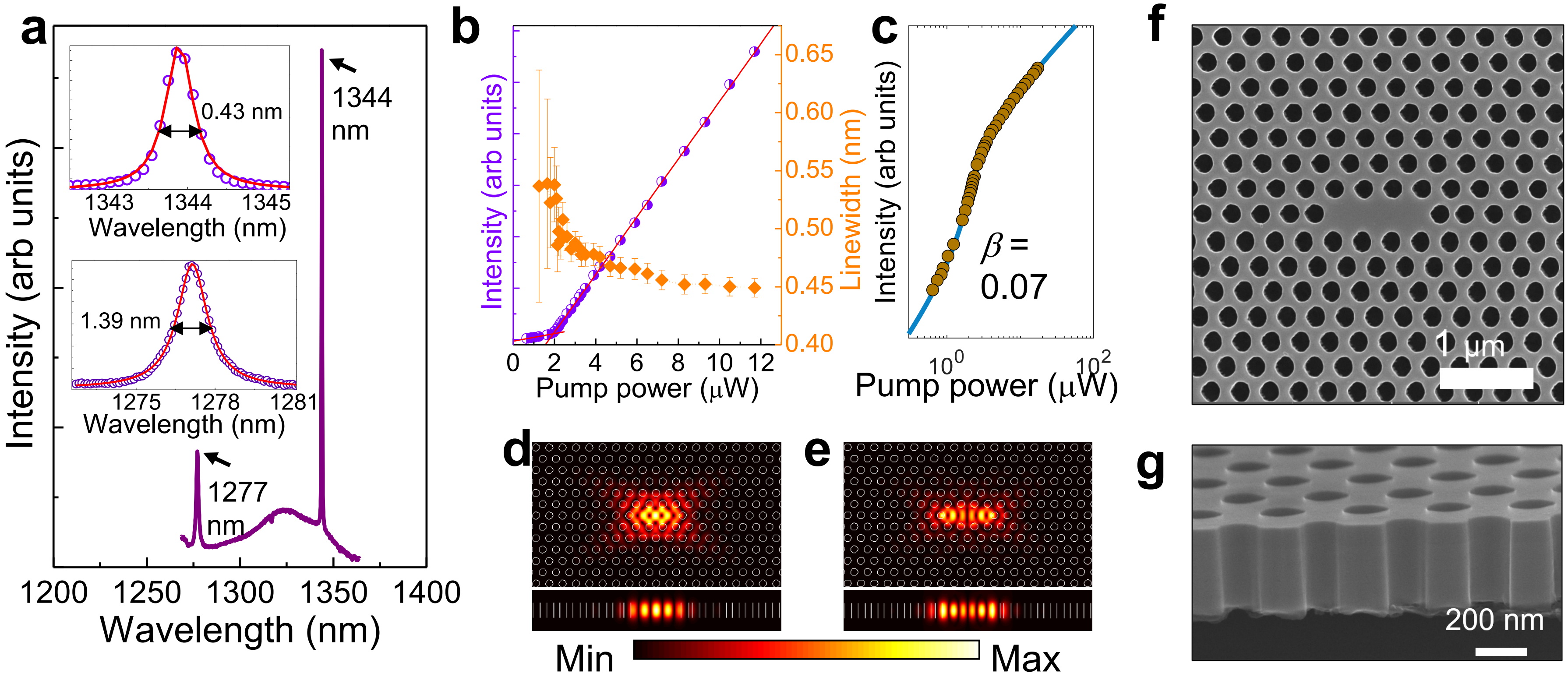






Semiconductor Science and Technology, 33(12) 123002, 2018

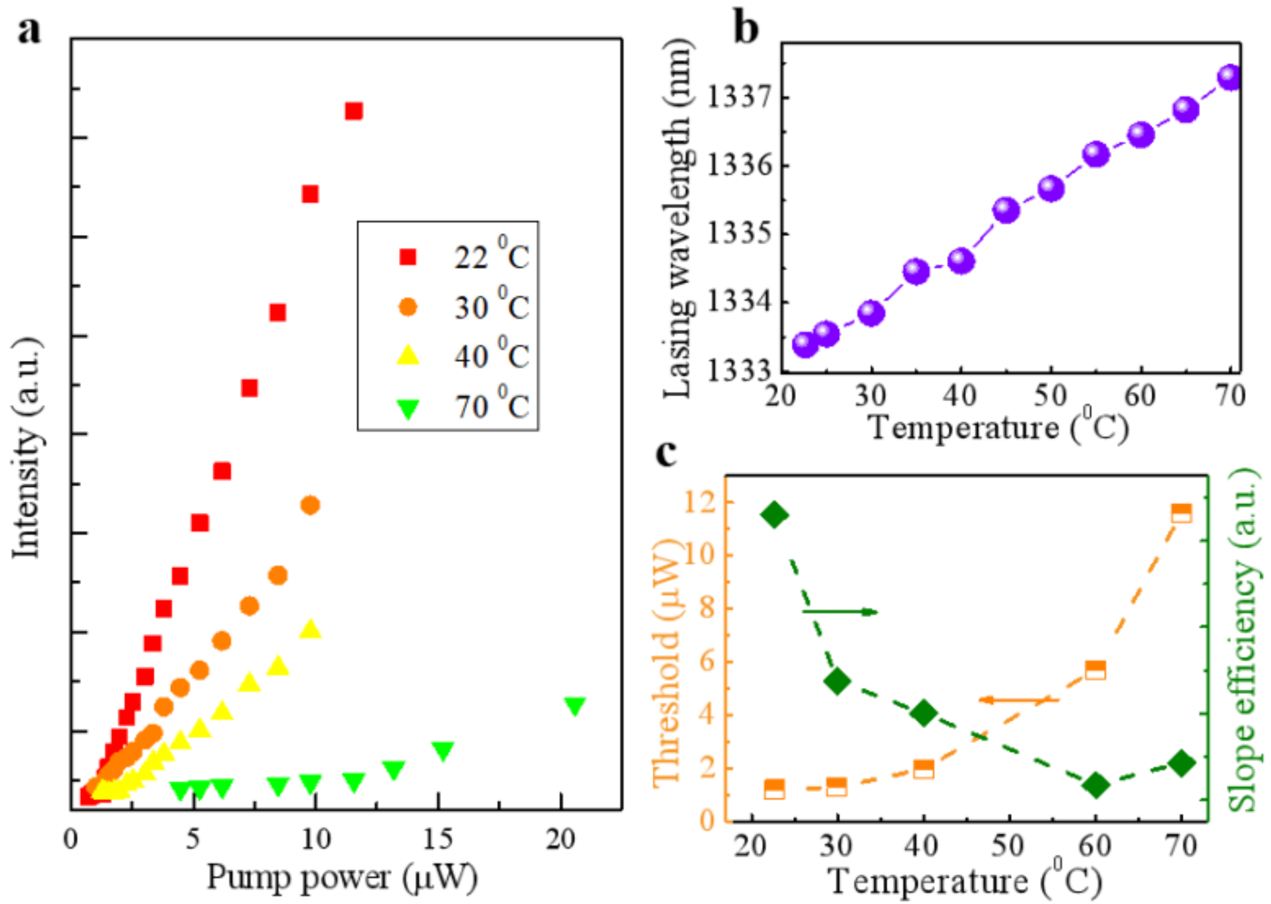
2D photonic crystal lasers grown on Silicon



- World-first 1.3 μm QD PhC laser grown on Si platform.
- Single-mode operation with high-temperature performance
- Ultra-low threshold with few μW

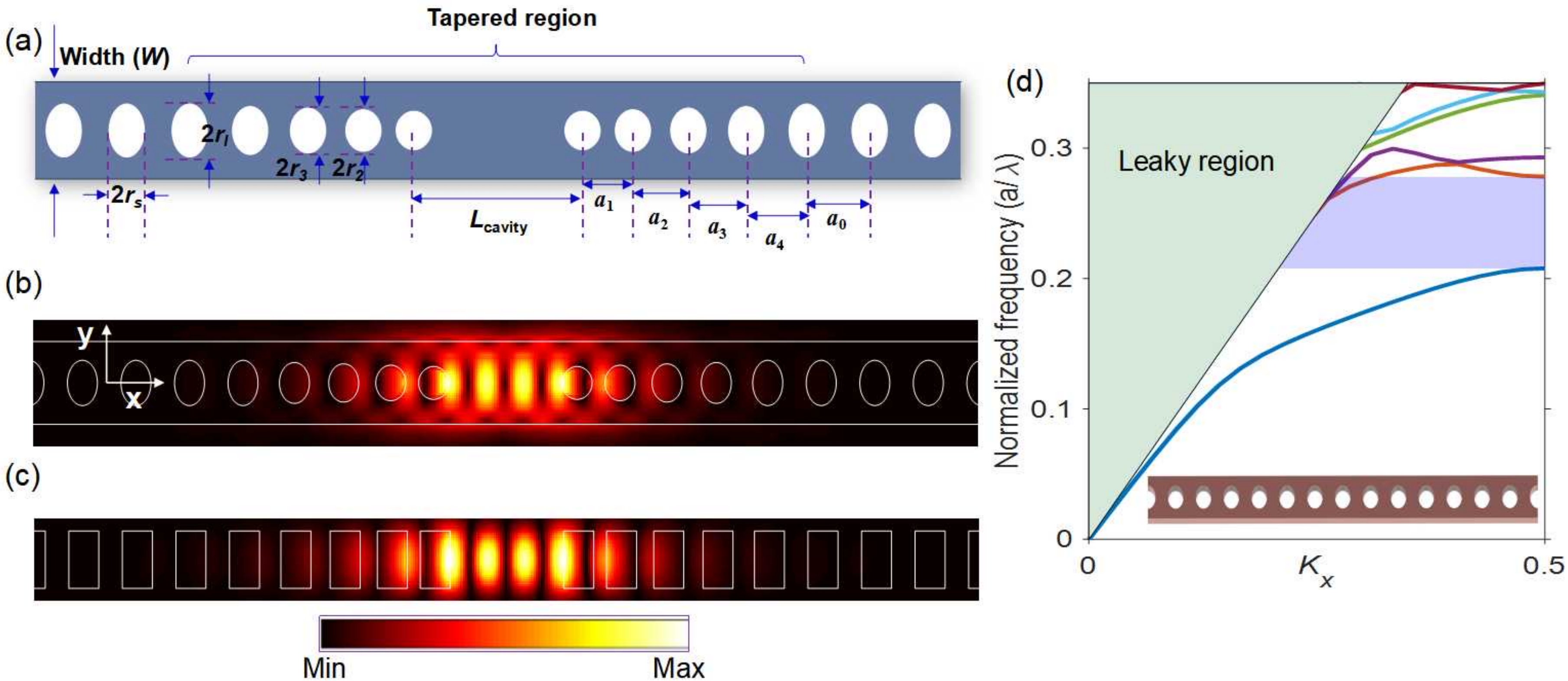
Nat. Communication 11, 1, 2020

Temperature dependence measurements



- Measured from 22 to 70 ℃
- Slightly red shift observed with temperature increasing
- High temperature performance need to be improved

1D Nanobeam laser on Si

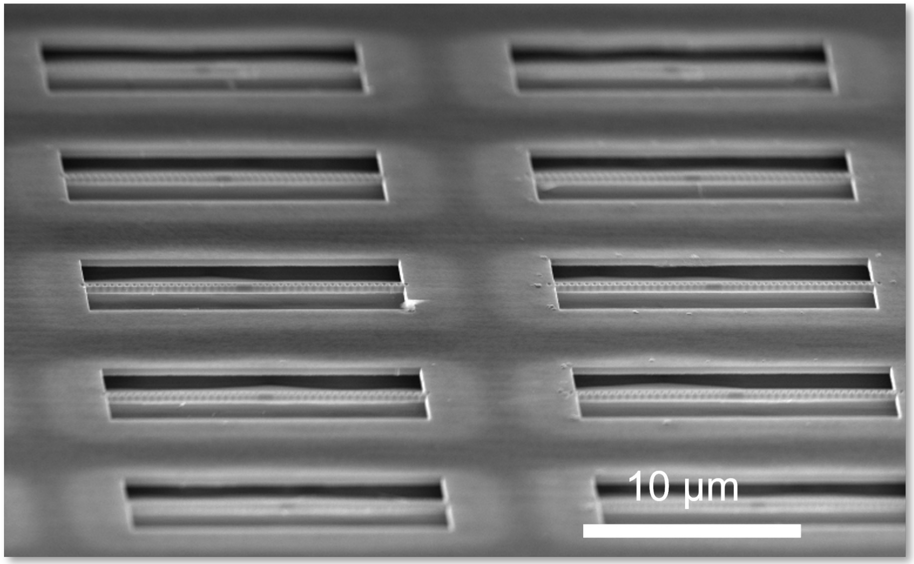


- Using 3D-FDTD simulation by Lumerical
- The structural parameters are W = 524 nm, a_0 = 340 nm, r_s/a_0 = 0.27, r_l/r_s = 1.5
- $L_{cavity} = 2.64 \times a_0$, $a_4 = a_0 \times 0.96$, $a_i = a_{i+1} \times 0.96$, $r_{i+1}/a_0 = r_i/a_0 + 0.025$ (i = 1 - 3), r_l/r_s = 1.5 and a thickness of ~ 362 nm.

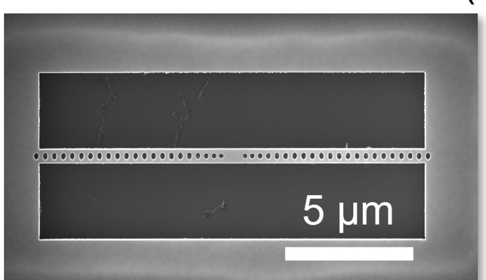
IEEE JSTQE, 28, 1501906, 2021

Device Fabrication

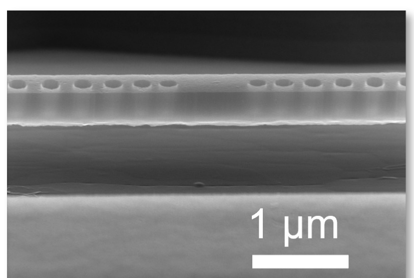
(a)



(b)



(c)



Hard mask: 120 nm SiO_2 (PECVD)

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PC pattern: E-beam lithography

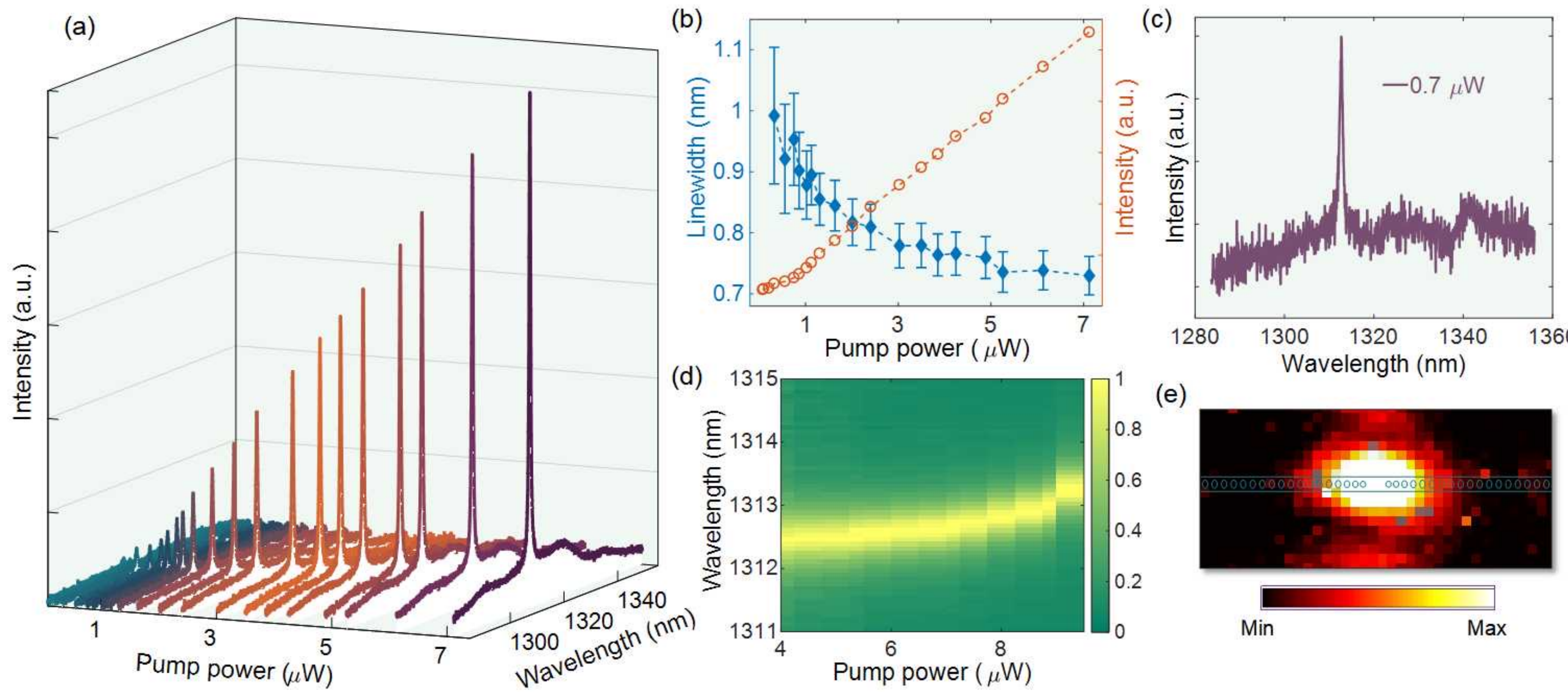
↓

Nanobeam structure: ICP-RIE

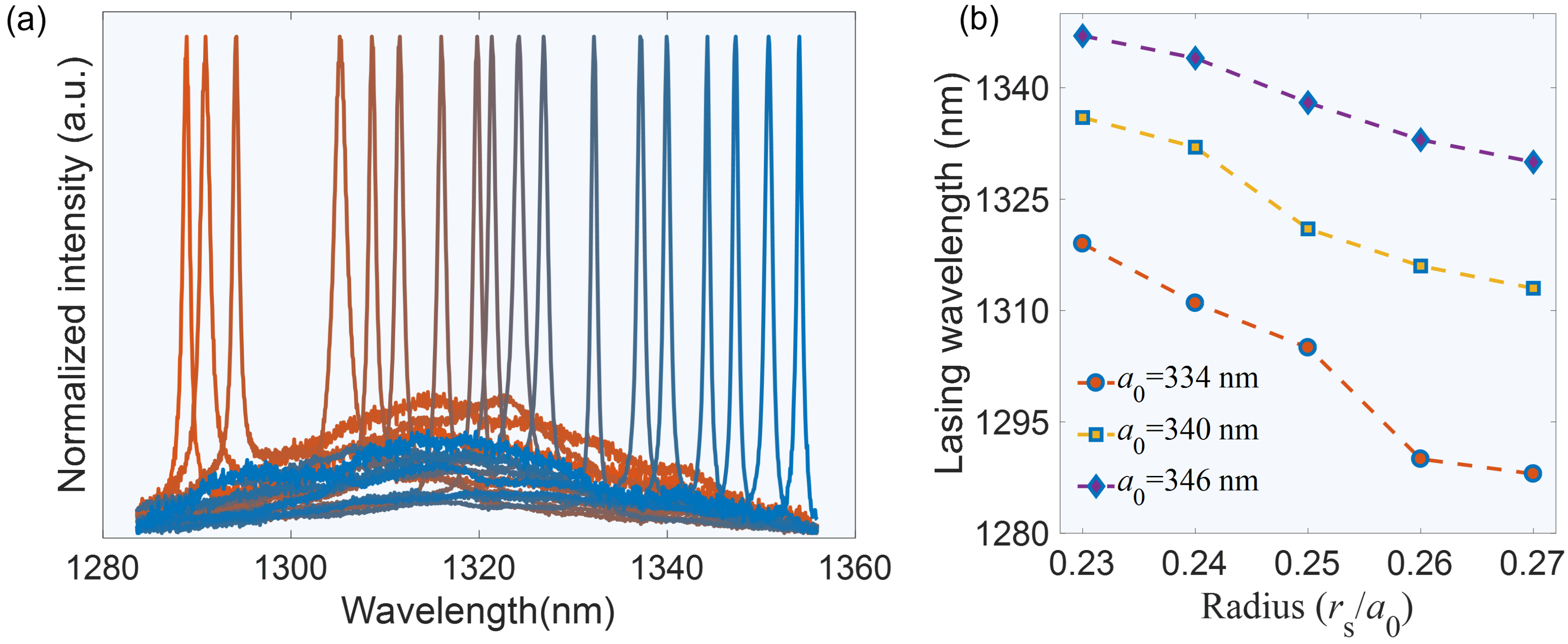
↓

SiO_2/Sacrificial layer etching: Wet-etching

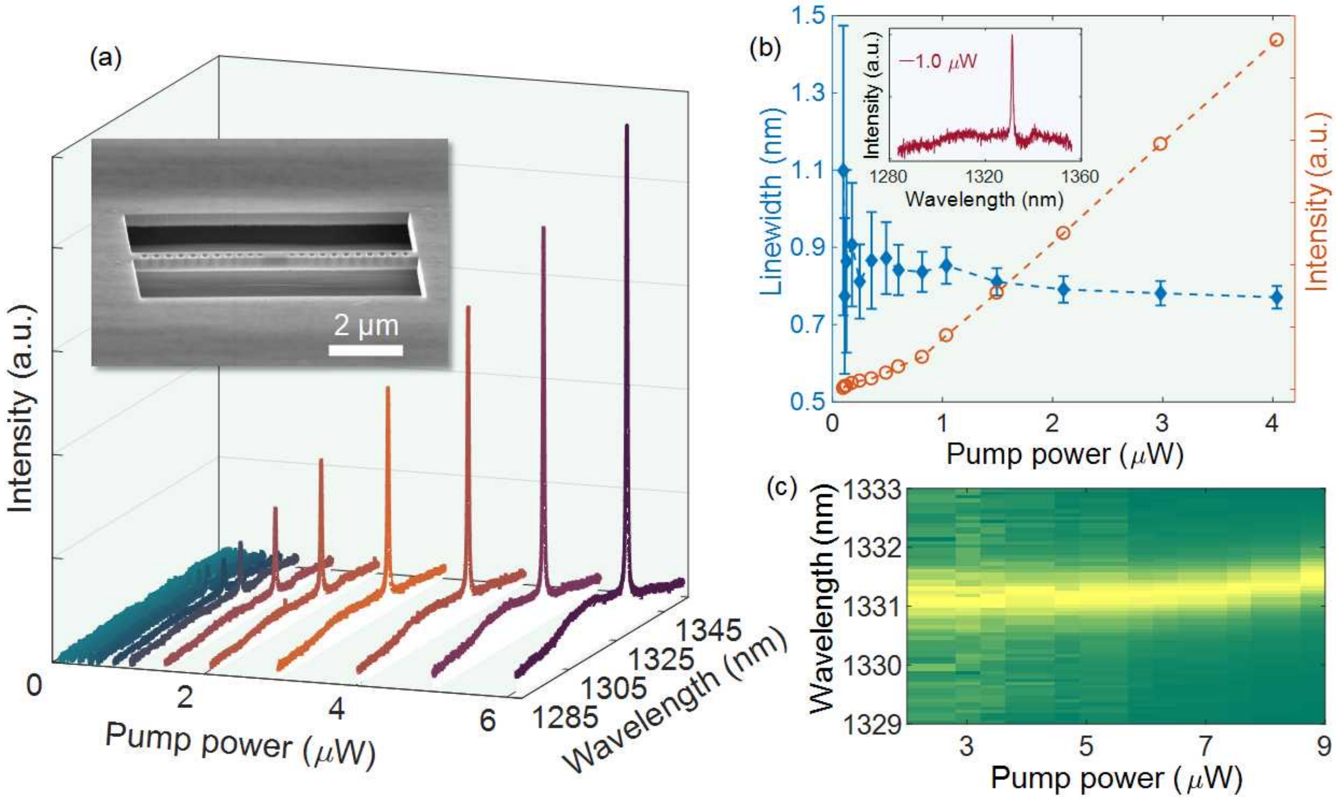
Device Measurements



- lasing peak (~ 1313 nm) is observed at room temperature under optically pumped
- Threshold ~ 0.8 μW
- Q-factor ~ 1500
- Red-shift with increasing pumping power



- ➢ Lasing wavelength variable from 1285 to 1355 nm
- ➢ Clear blueshift observed with increased radius

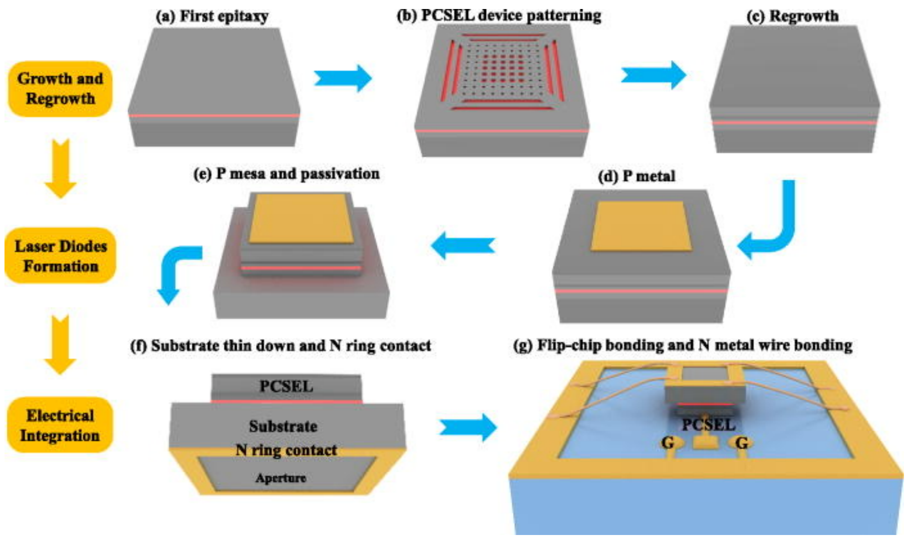


- A less air-hole nanobeam laser is developed with size of 8 × 0.53 × 0.36 μm³ (~ 25 $(\lambda n^{-1})^3$)
- Ultra-low threshold power of 0.9 μW obtained
- Linewidth of ~0.8 nm
- A slightly redshift observed with increasing pump power.

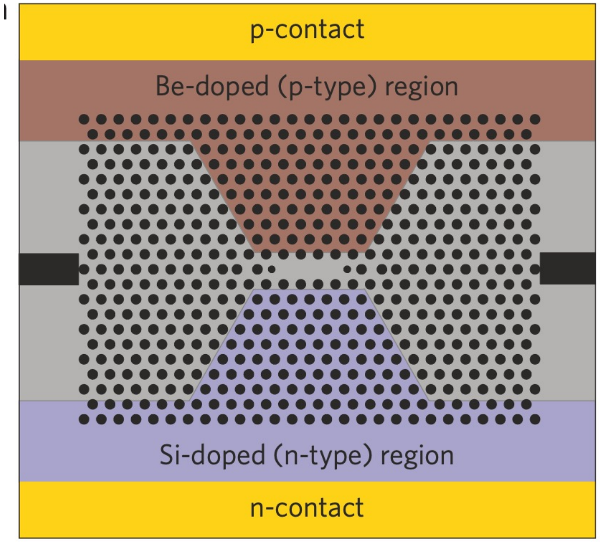
Conclusion

- 1D-photonic crystal laser is obtained with ultra-small footprint on on-axis Si (001) substrate.
- Ultra-low threshold under optically pumping (0.9 μW) with single mode operation.
- Demonstrated various wavelength in the nanobeam array – potential multi-channel application

Prospective – Electrically pumped operation



Contact layer done by regrowth



Ion-beam implantation

Appl. Phys. Lett. 123, 140501, 2023
Nature Photonics 5 297–300, 2011

Acknowledgement

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LTM LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE