Laser applications of Photonic Crystals

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Overview

Topics:

- State of the Art & Motivations
- PCSELs: Photonic Crystals + Lasers
  - Design
  - Inner Working
- High Brightness & Applications
- High Functionality & Applications
- Mass Production & Reliability
- New Trends:
  - Short-Pulse Operation
  - Short-Wavelength Operation
  - AI-Controlled (Smart) PCSELs

A brief history:

1887 – **Lord Rayleigh**: early study of one-dimensional periodic structures (Bragg mirrors)
1987 – **Eli Yablonovitch & Sajeev John**: introduced the modern concept and coined “photonic crystals”
1999 – **S. Noda and collaborators**: first demonstration of photonic-crystal surface-emitting lasers (PCSELs)

Why new laser technology is needed

Applications

Smart mobility and smart manufacturing demand **compact**, **high-brightness** lasers

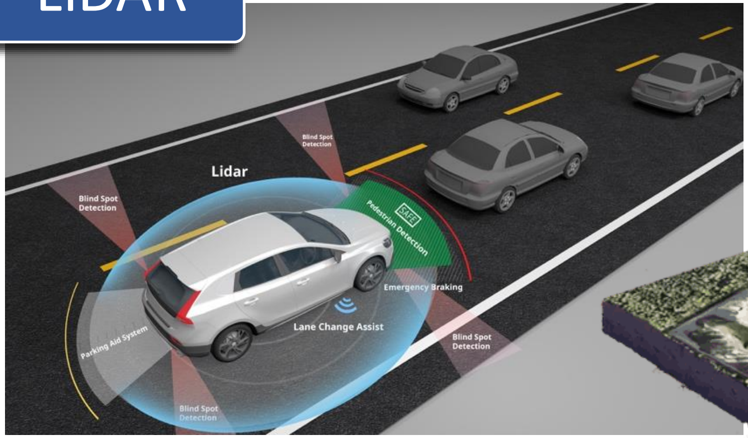
Existing solutions

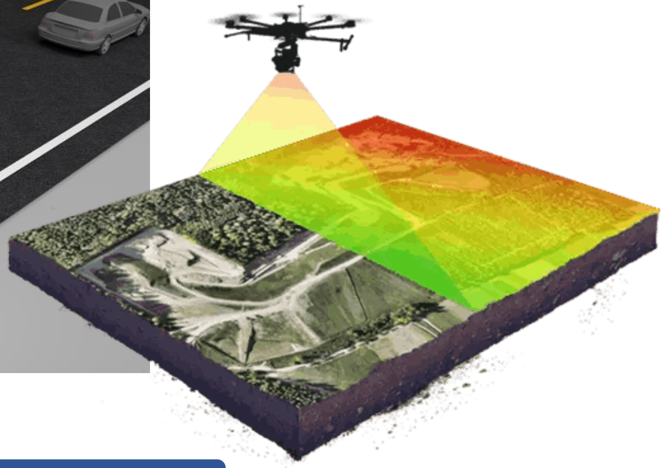
- **Semiconductor lasers**: efficient but low brightness and poor beam control
- **Gas/solid-state lasers**: bright but large and inefficient

We need a new type of laser that **combines the strengths** of both

PCSEL

LiDAR





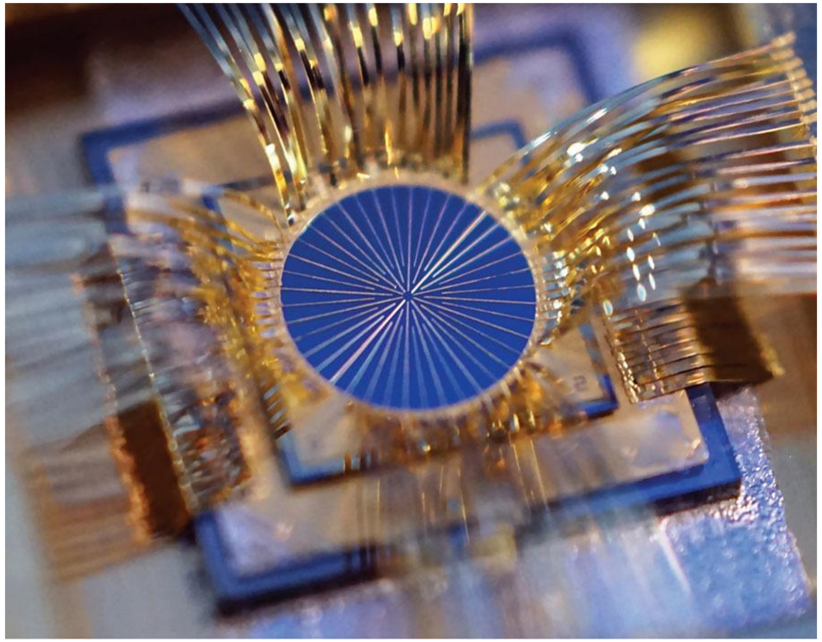
Laser Processing

What is a PCSEL?

PCSEL

Photonic-**C**rystal **S**urface-**E**mitting **L**aser

- Semiconductor laser with a **2D photonic-crystal layer**
- Uses **optical diffraction** to form a **large-area resonance**
- Emits a **narrow, coherent beam** directly from the surface
- **Compact**, **bright**, and **highly functional**



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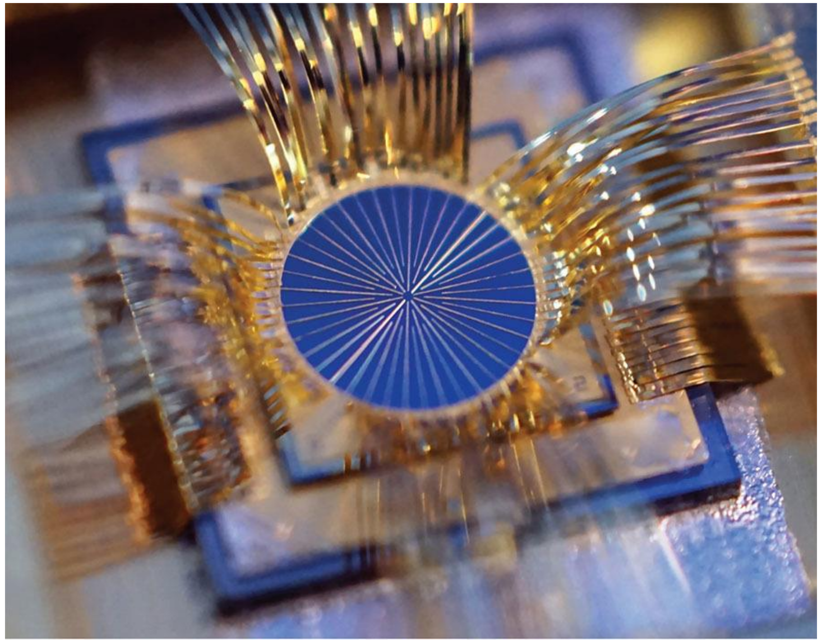
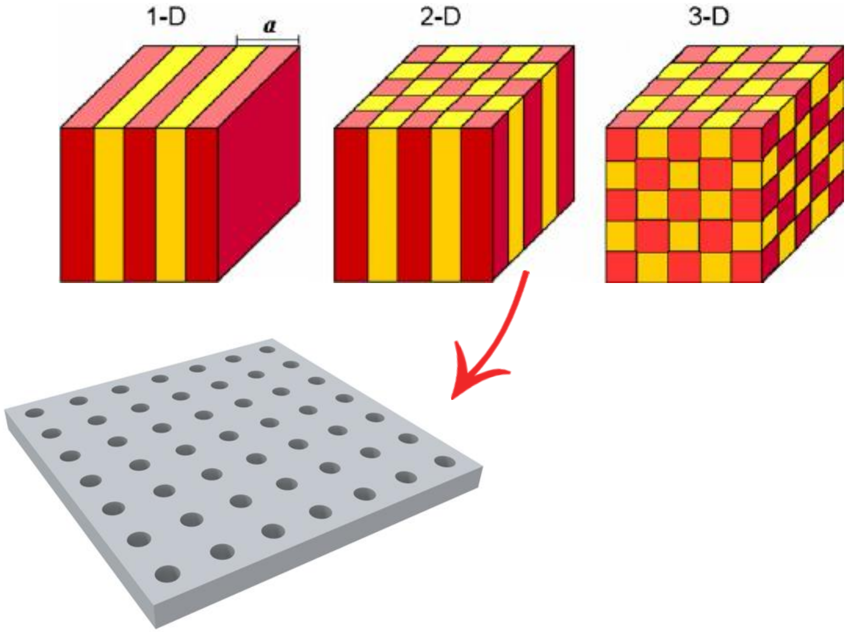


Photonic Crystals

Periodic optic materials with refractive-index structures on the **wavelength scale** that can control and confine light propagation.
- Found in **devices** and **nature** (e.g. opals, butterfly wings)



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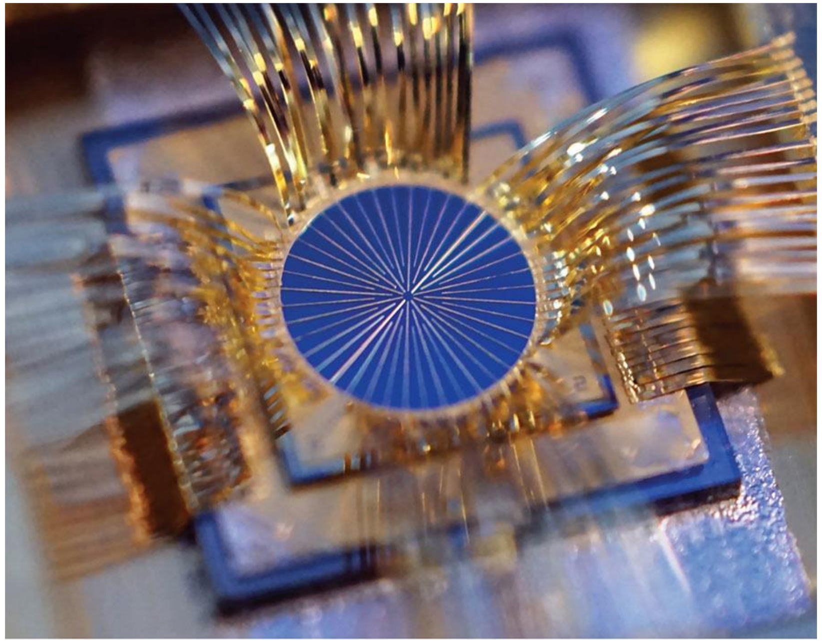
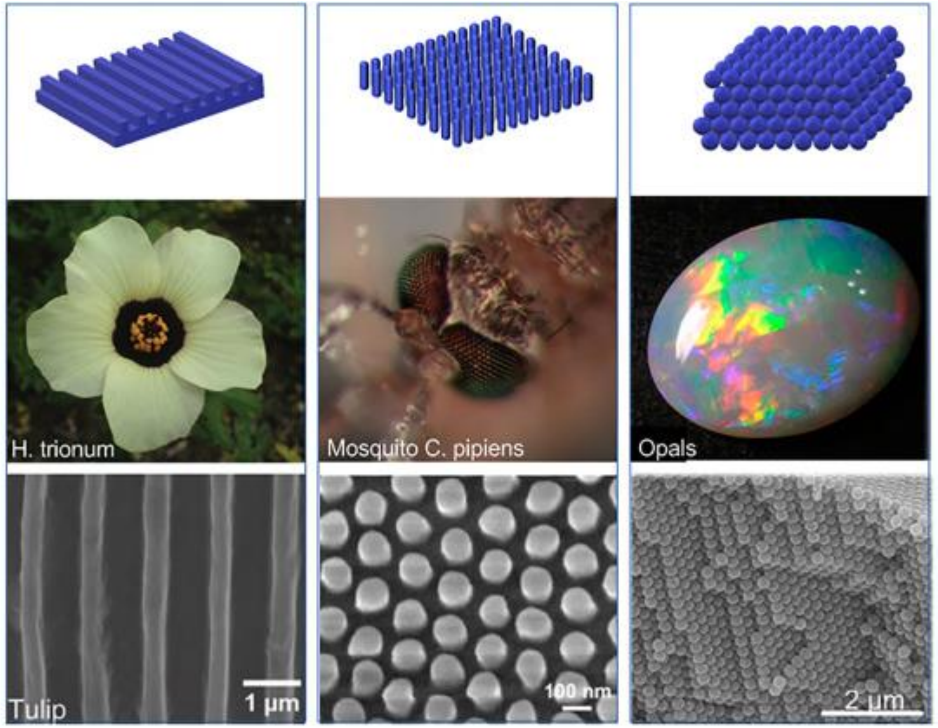


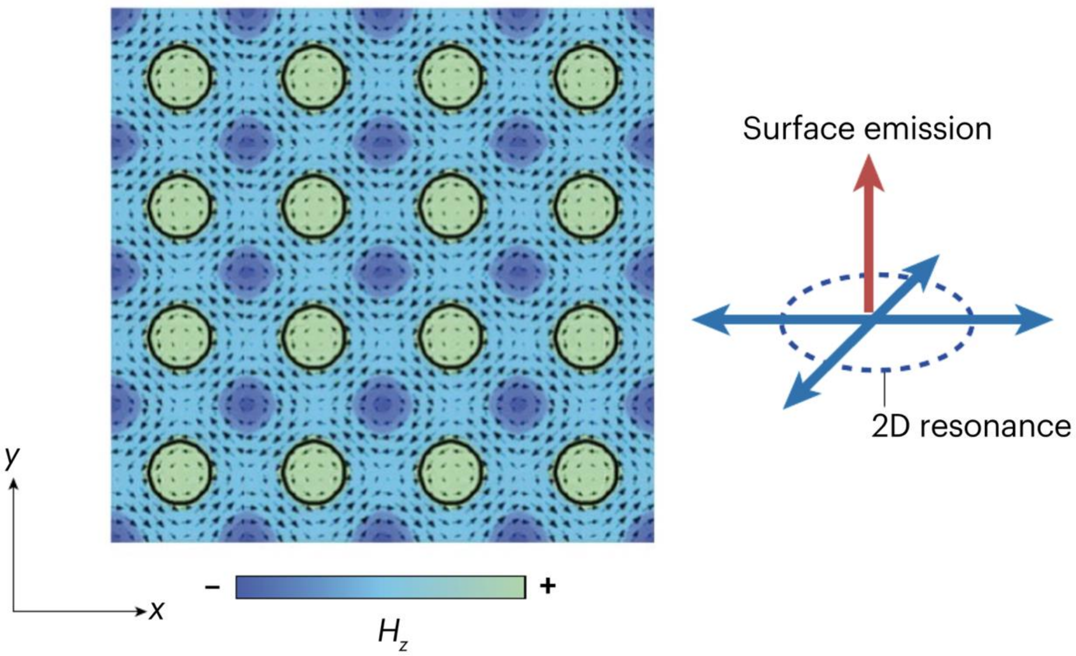
Photonic Crystals

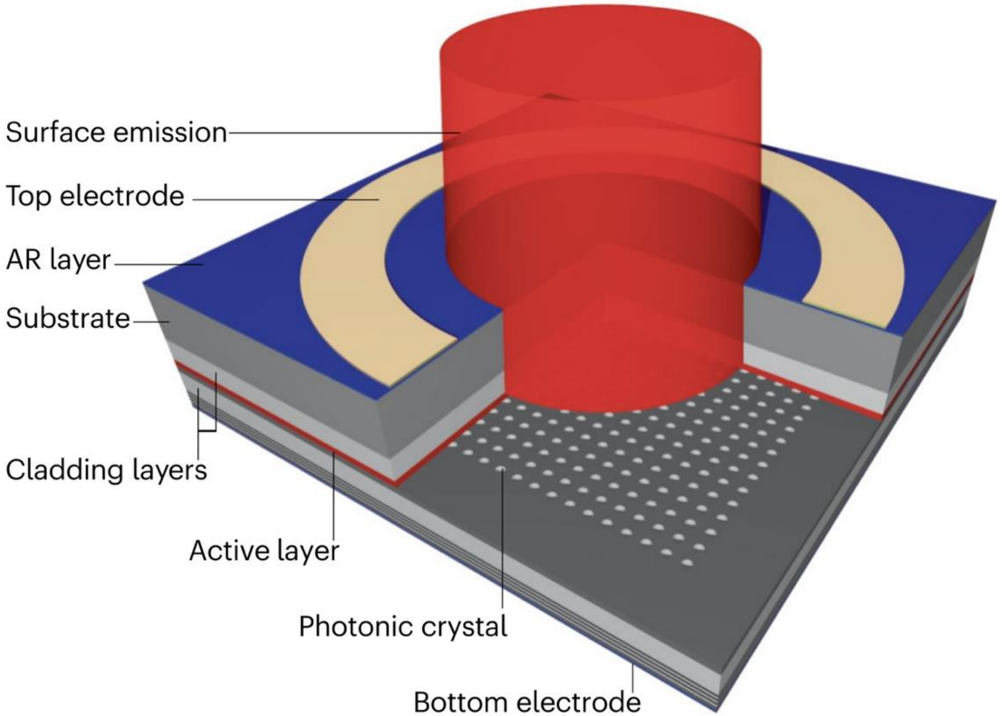


Structure of a PCSEL

Main components

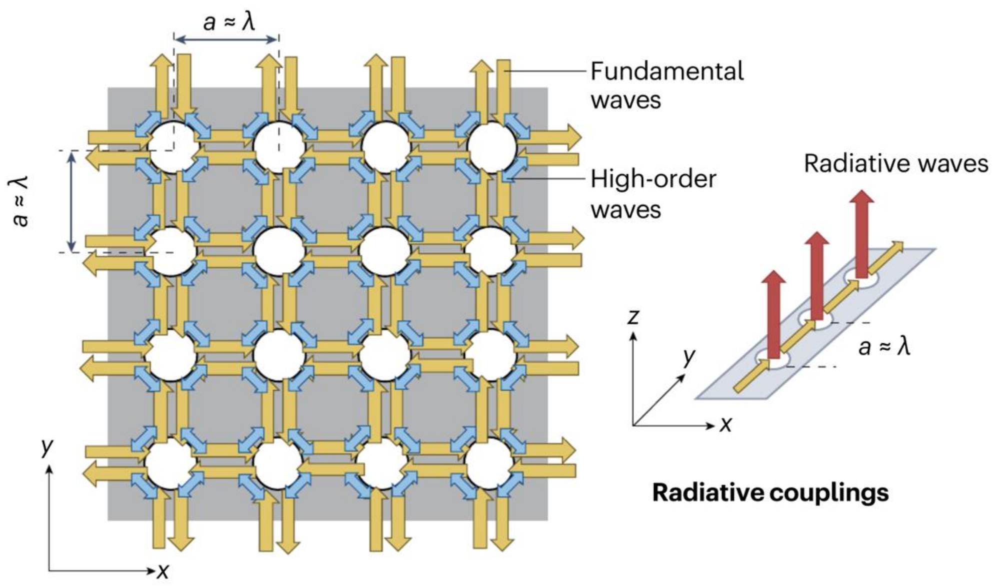
- **Photonic-crystal layer**: periodic refractive-index pattern
- **Active layer**: provides optical gain
- **Cladding and electrodes**: confine and inject current
- Surface emission via **2D standing-wave** resonance

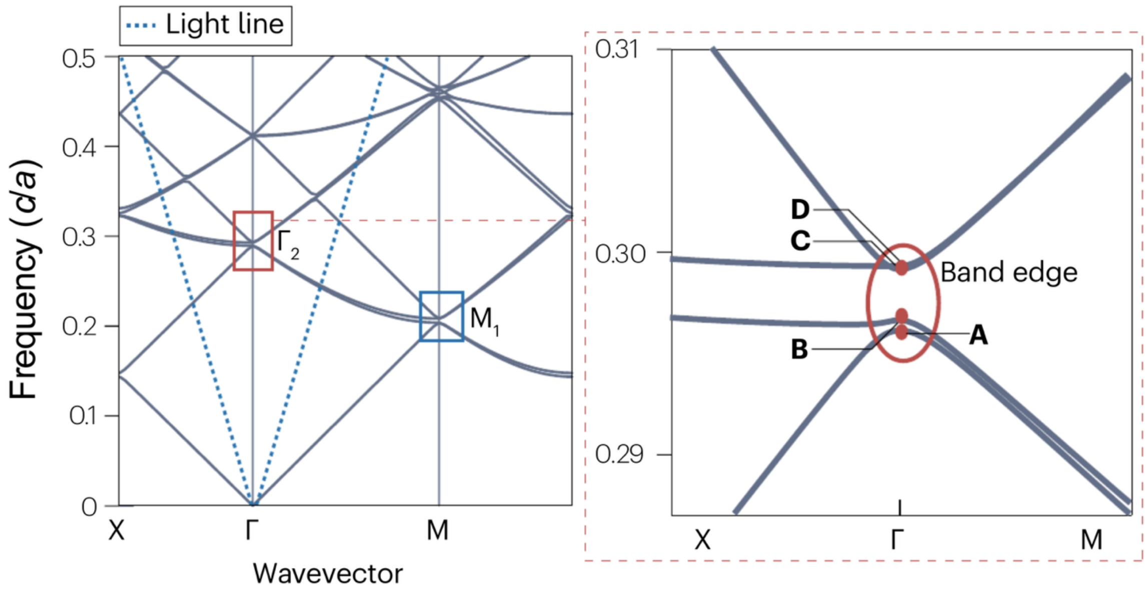




Lasing mechanism

- Current injection prompt **light generation** in active layer
- **Light confined** between claddings and **coupled into the photonic crystal**
- In-plane diffraction creates a **2D standing wave**
- The periodic pattern defines "**singularity points**" (Γ_2, M_1) where light effectively stops propagating and resonates strongly, giving rise to **coherent, narrow-beam emission**



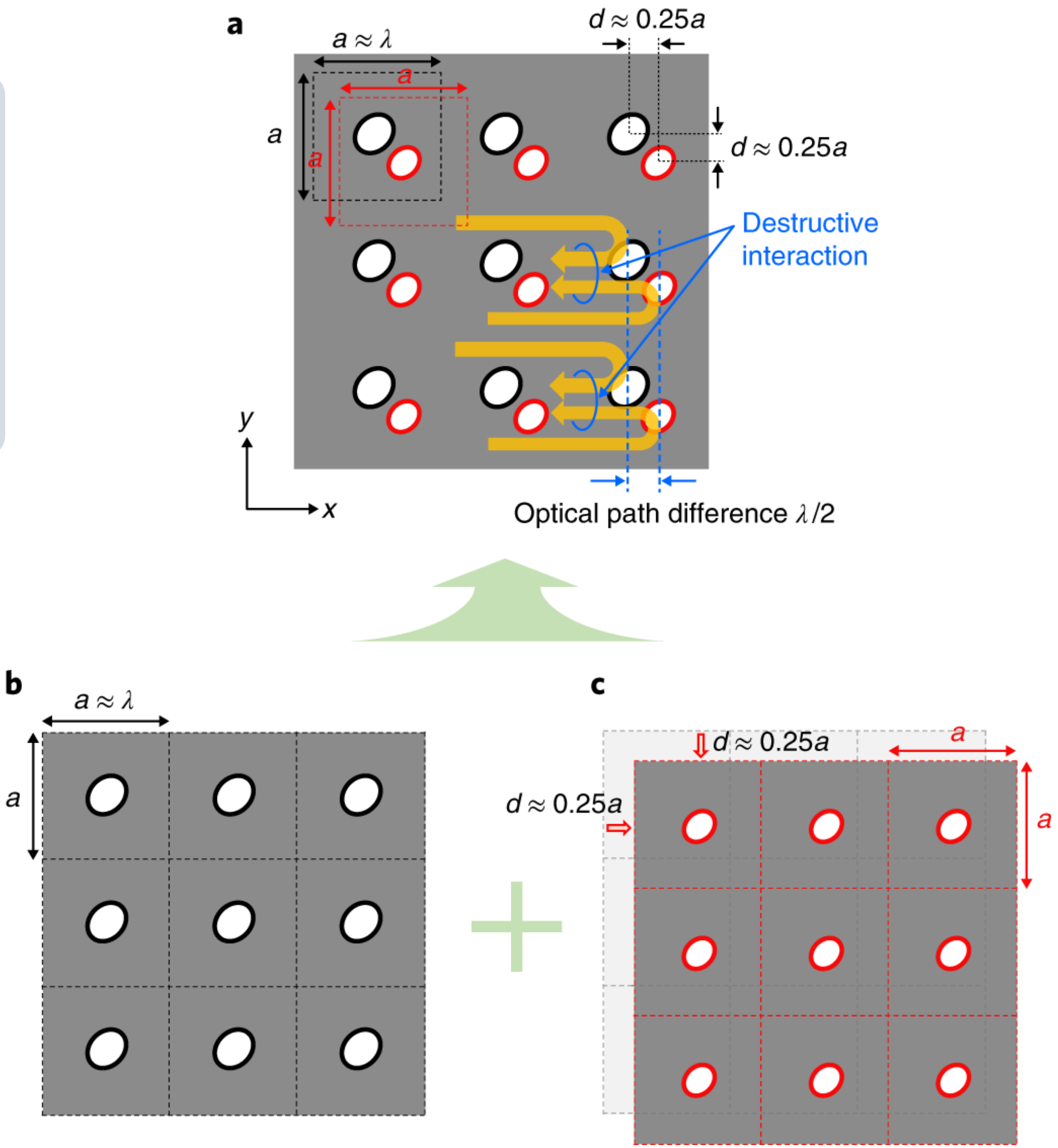


Different **modes of operation** can be achieved by using different lattice constant:

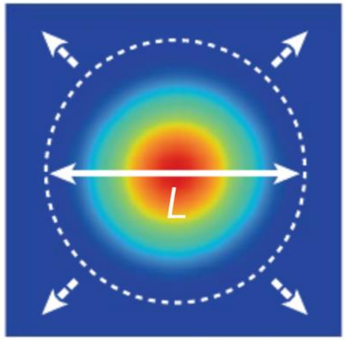
- $\Gamma_2 \rightarrow a = \lambda$
- $M_1 \rightarrow a = \frac{\lambda}{\sqrt{2}}$

Double-lattice design

- Two **overlapping lattices** offset by $\lambda / 4$
- Creates **destructive interference for higher-order modes**
- Enhances surface emission of the **fundamental mode**
- Enables **high-brightness** operation under both **pulsed** and **continuous-wave (CW)** conditions

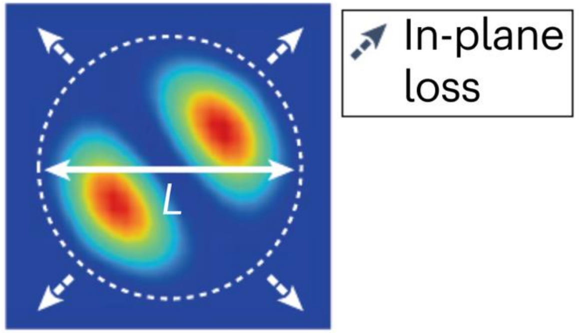


Fundamental mode



$k \approx \pi/L$

Higher-order mode (first order)



$k \approx 2\pi/L$

Achieving high brightness

Double-lattice design

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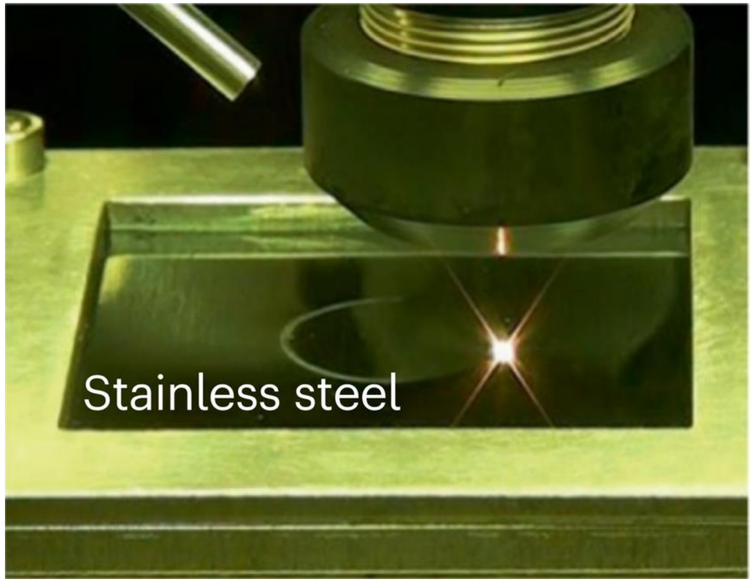


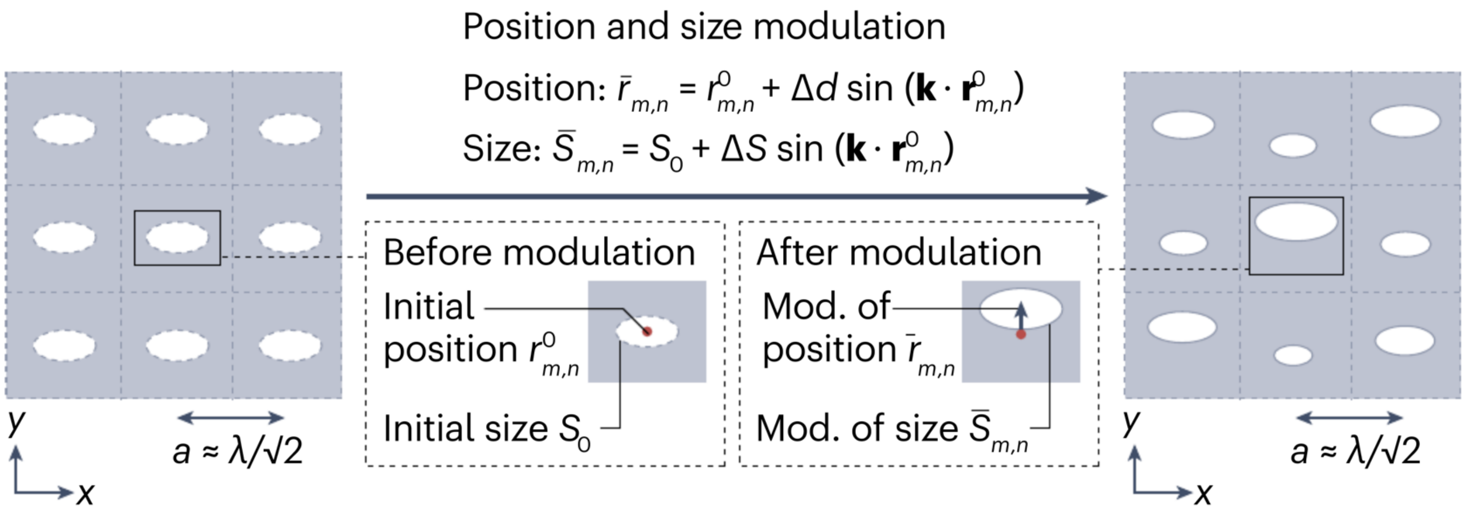
Applications of high-brightness PCSELs

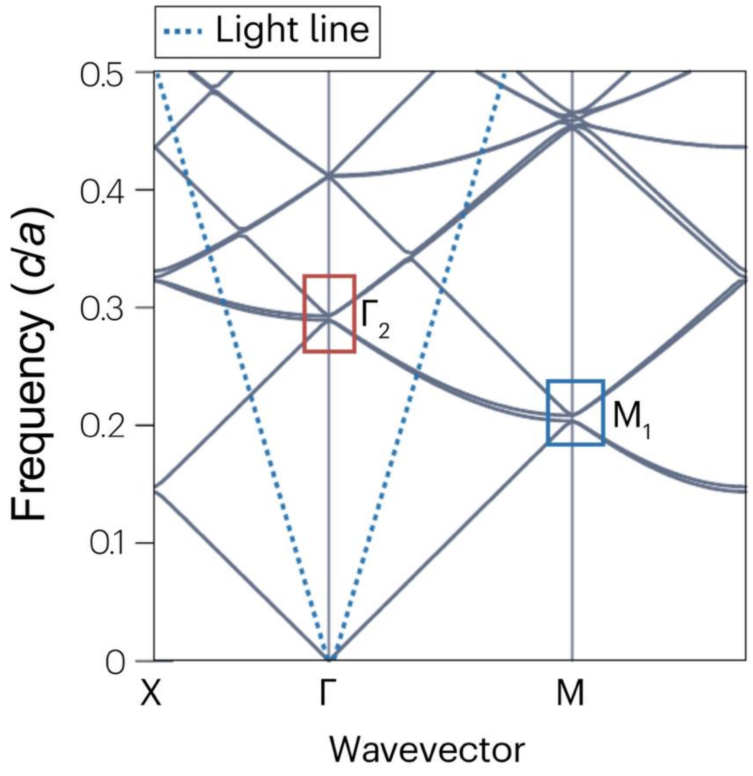
- **LiDAR**: **compact**, **lens-free systems** for robotics and vehicles
- **Laser processing**: cutting & colour marking of metals
- Compact, efficient, and highly directional beams
- $\mathbf{1\ GW\ cm^{-2}\ sr^{-1}}$ brightness allows industrial-grade performance

Beam control through photonic-crystal modulation

High-functionality PCSELs

- Varying **air-hole size or position** allows control of emitted laser beam
- Enables beam emission in **any direction or pattern**
- **No** moving **mirrors or external optics**
- Basis for on-chip 2D beam scanning and **pattern projection**





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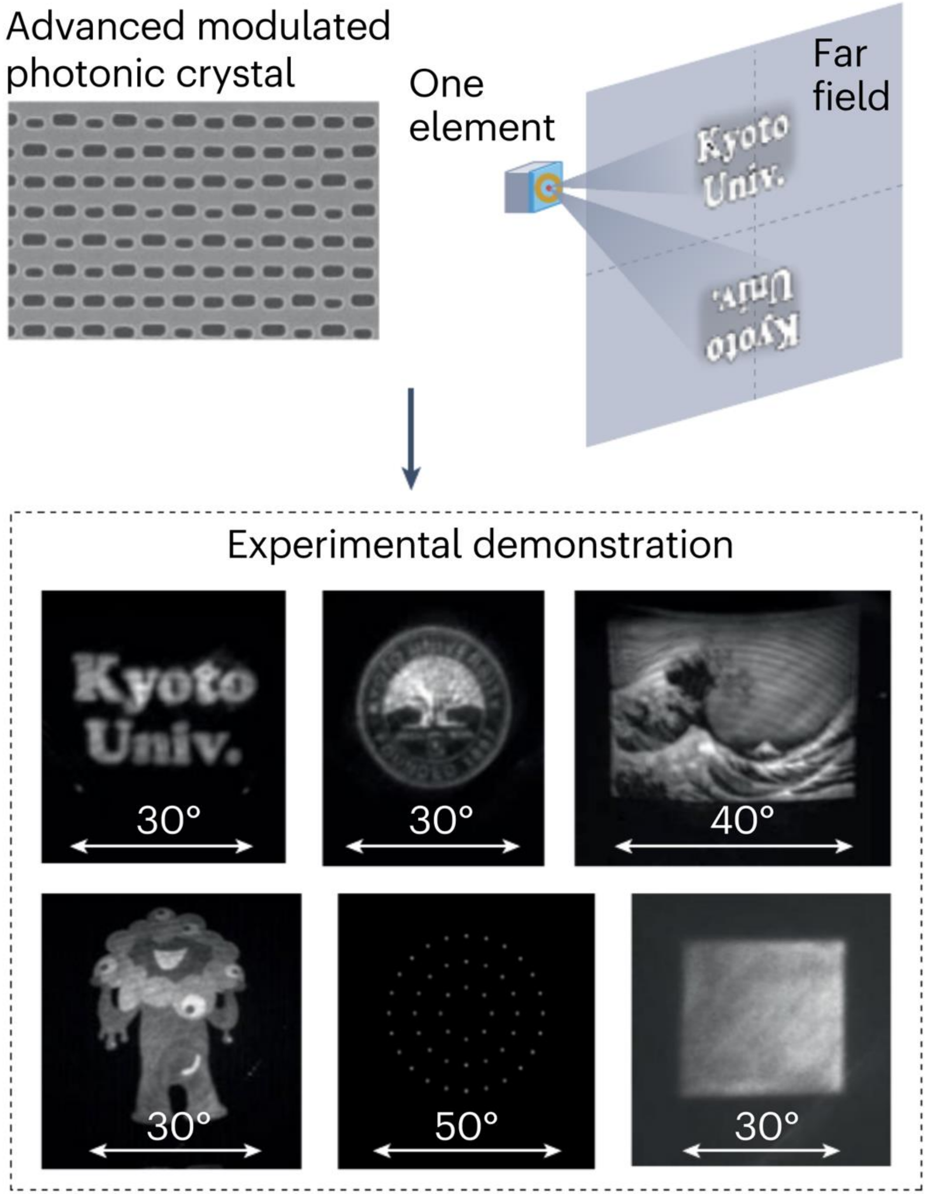
Demonstrations

- 2D PCSEL arrays allow fast electronic beam scanning
- Dual modulation allows emission of **complex patterns**
- Examples: "**The Great Wave**", **Osaka Expo mascot**
- Integrated PCSEL-LiDAR combining flash & scanning modes



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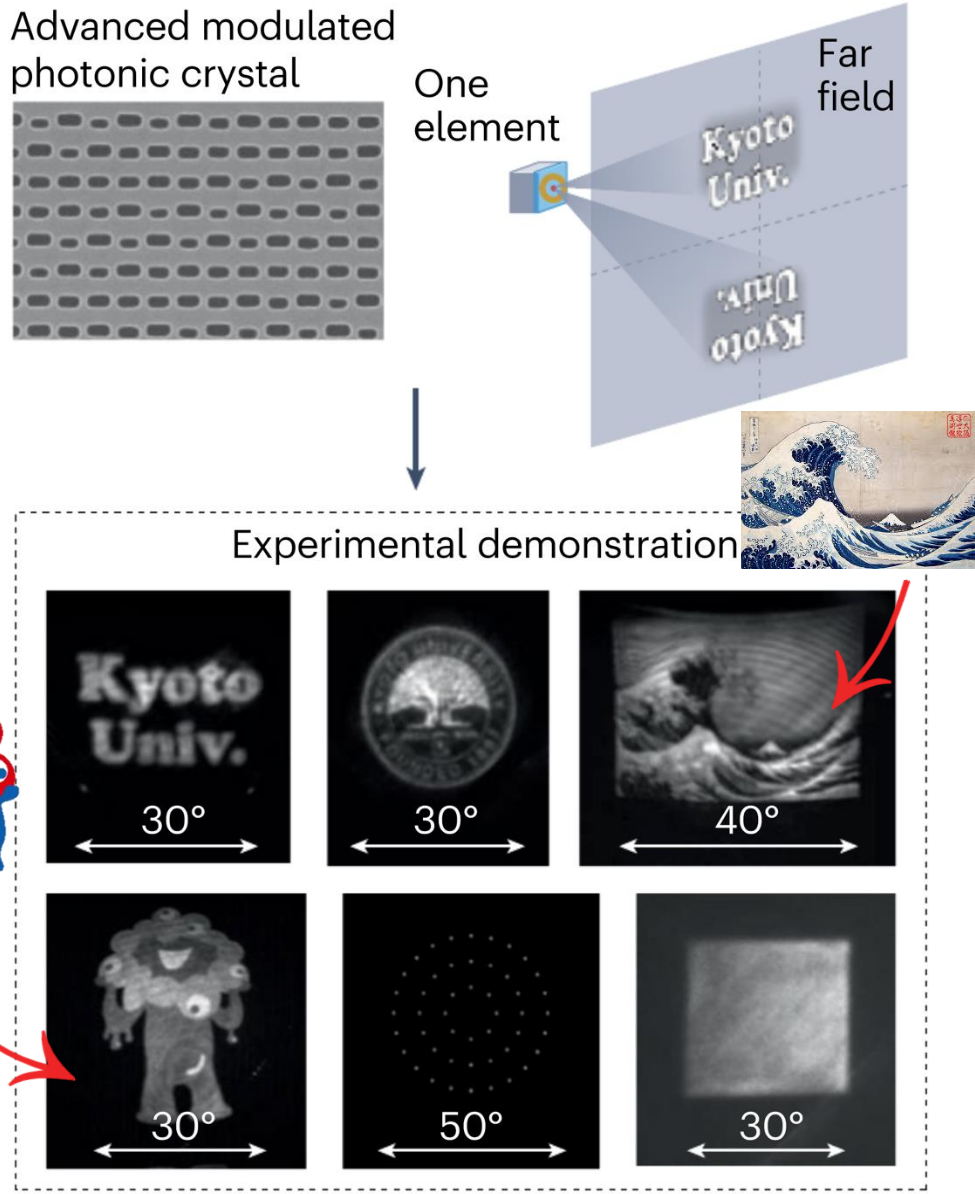

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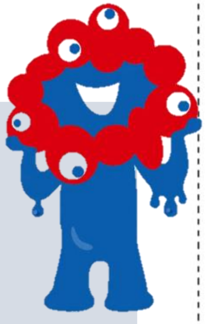

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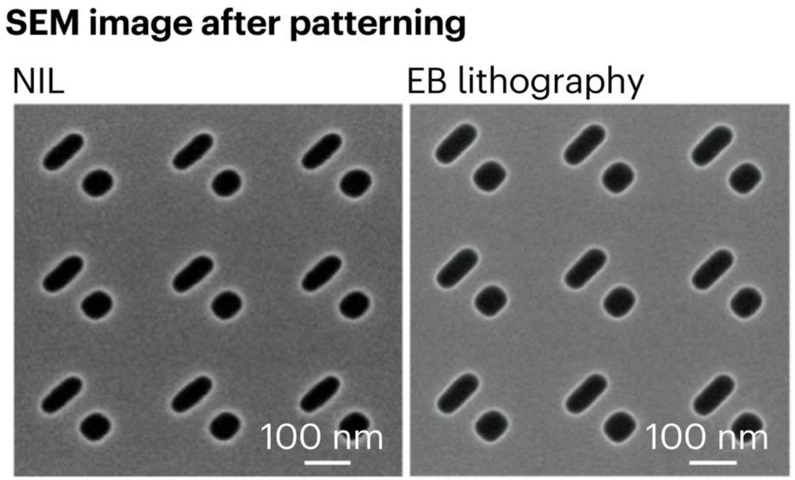
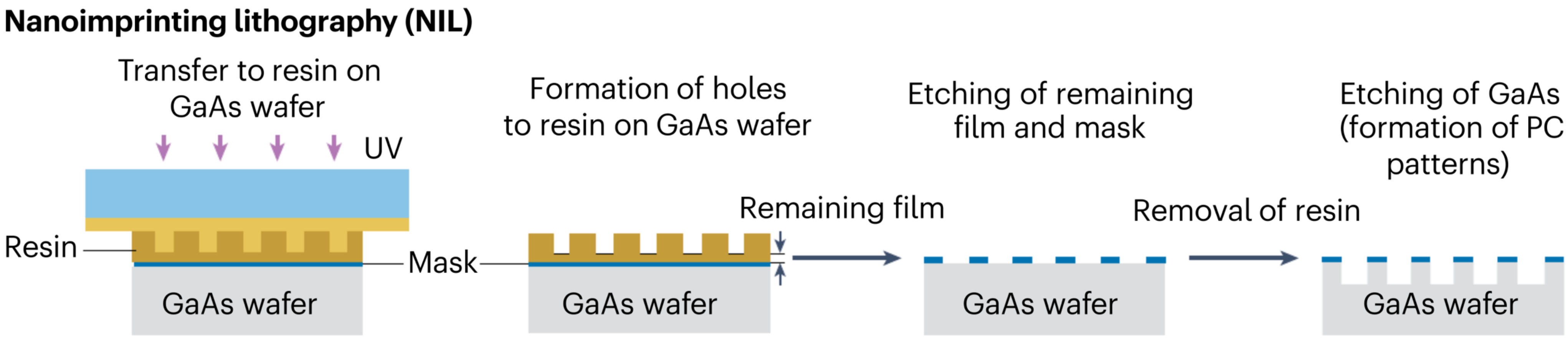
Mass production and reliability

Nanoimprinting lithography (NIL)

- **Fast, low-cost** replication of photonic-crystal patterns
- **Comparable performance** to electron-beam lithography
- 12-month reliability at **125 °C and 300 temperature cycles**
- PCSELs proven suitable for **large-scale production**





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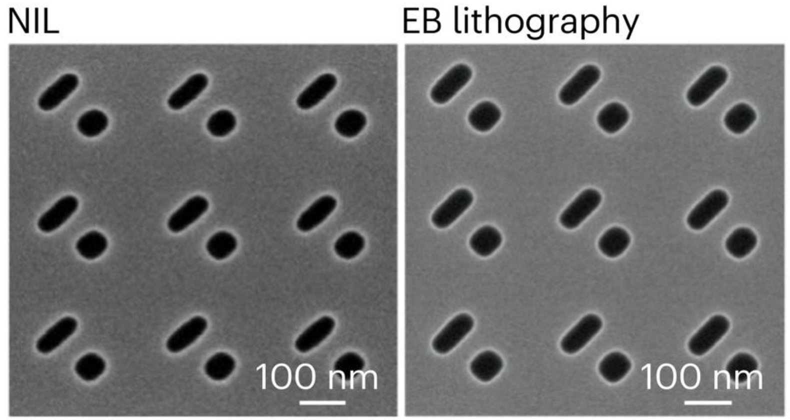
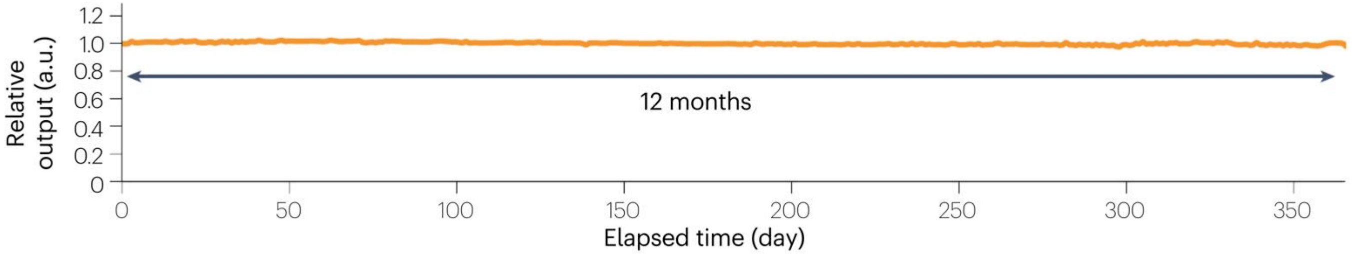
SEM image after patterning



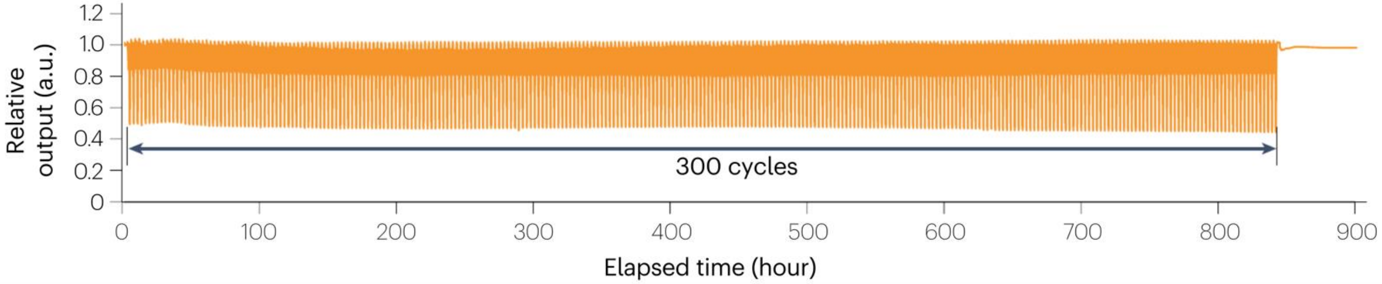
High-temperature test (compliant with AEC-Q102)



Test conditions

Surrounding temperature: +125 ºC
(Package temperature: +139 ºC)
Input current: 10 A, 100 ns, 10 kHz

Temperature cycle test (compliant with IEC 60068-2-14)



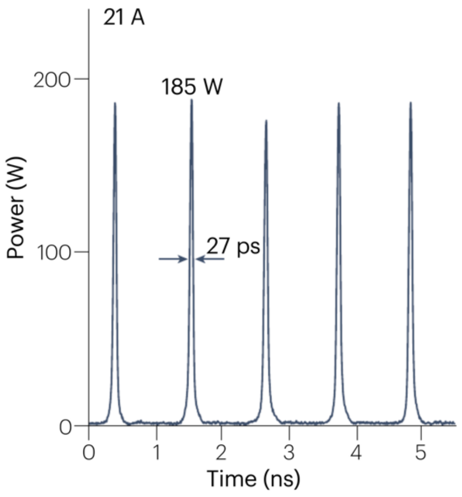
Test conditions

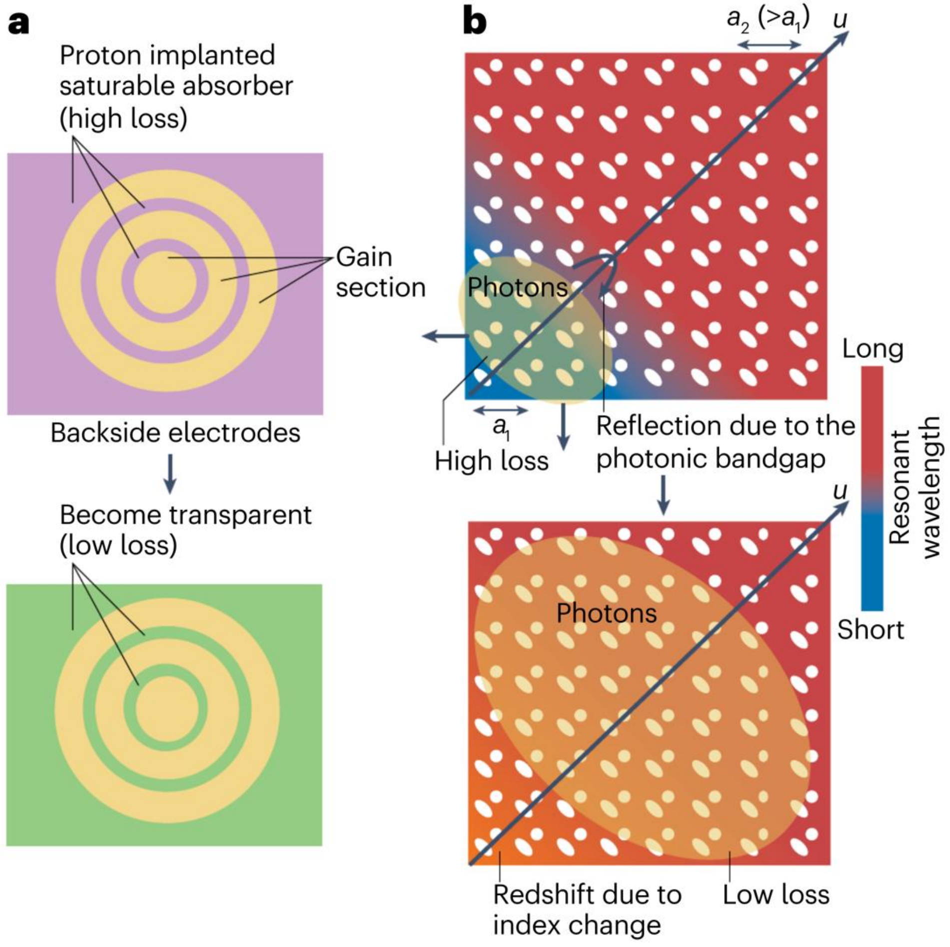
Surrounding temperature: −40 ºC ↔ +125 ºC
×300 cycles
Input current: 10 A, 100 ns, 1 kHz

Short-pulse operation

High-peak-power PCSELs

- **Q-switching**: **saturable absorber** turns high loss into gain burst
- **Self-evolving photonic crystal**: dynamic lattice change reduces losses during lasing
- Combined designs: $< \mathbf{30\ ps}$ pulses, $> \mathbf{200\ W}$ peak power
- **Applications**: non-thermal processing, long-range LiDAR, bioimaging

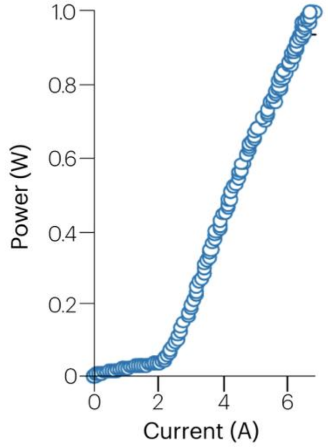


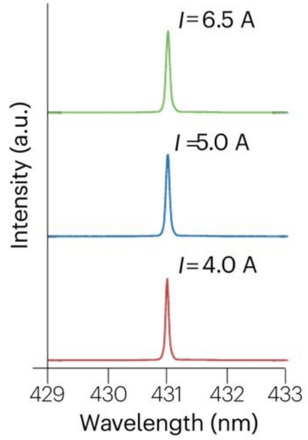


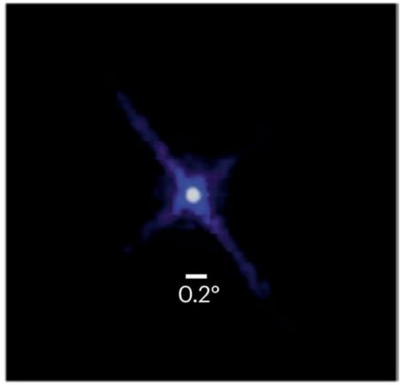
Blue GaN-based PCSELs

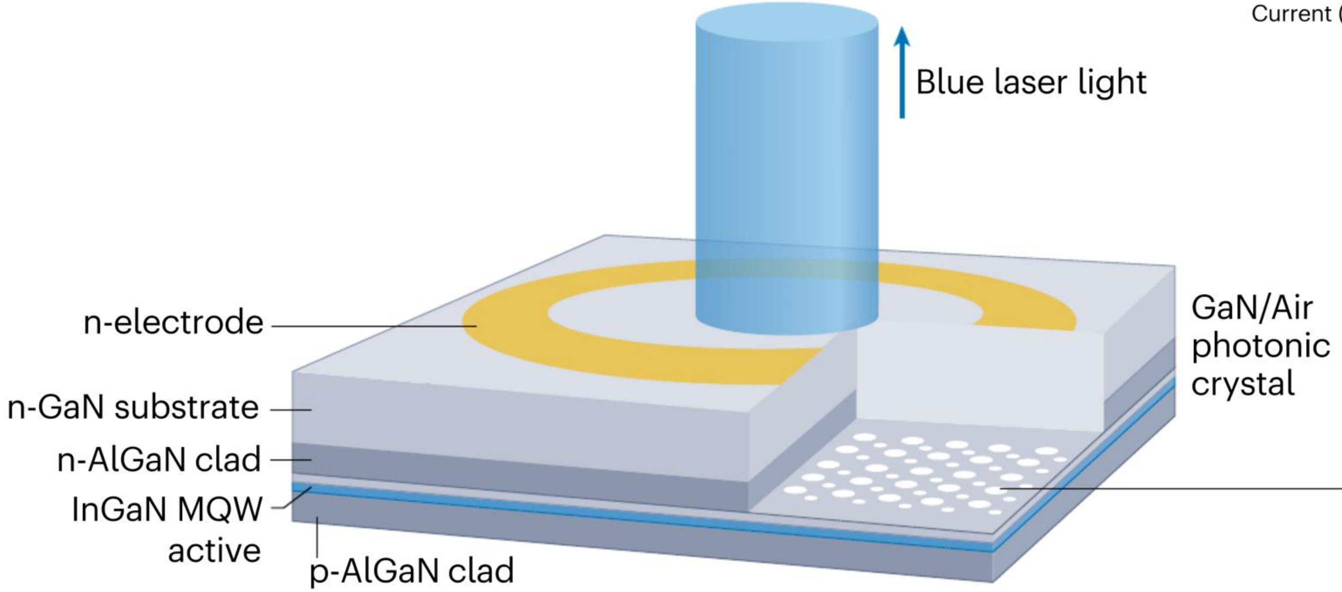
Short-wavelength PCSELs

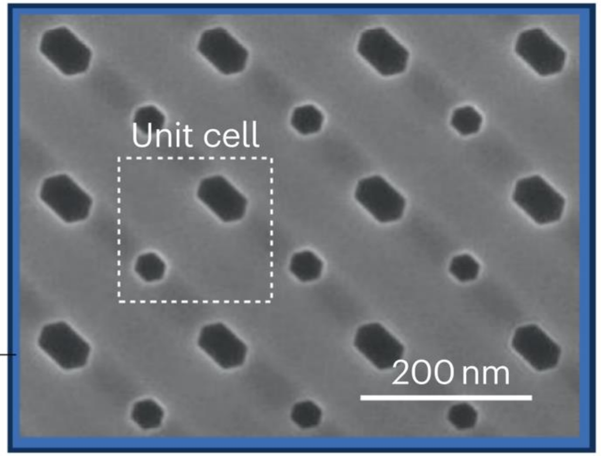
- Built on GaN **materials**, produce blue emission (~ 430 nm)
- Achieved **watt-class power**, $0.15°$ divergence
- **Works underwater** (low absorption in blue)
- Enables **underwater LiDAR**, Cu processing, laser displays







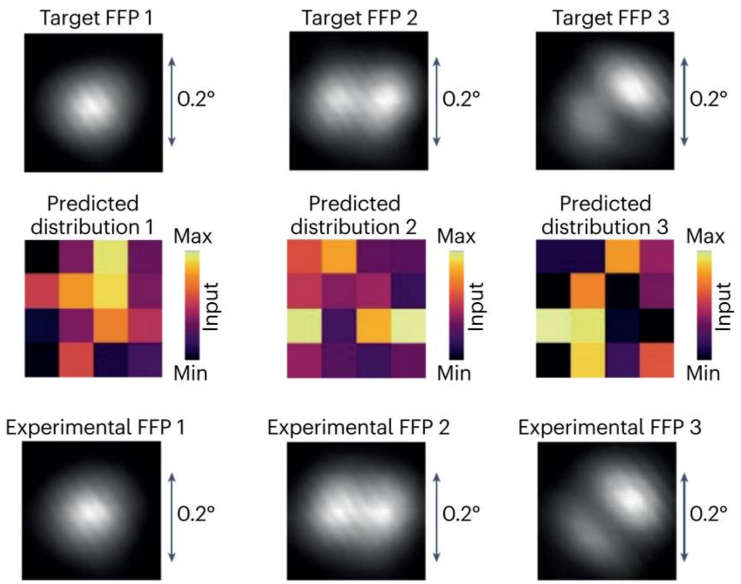


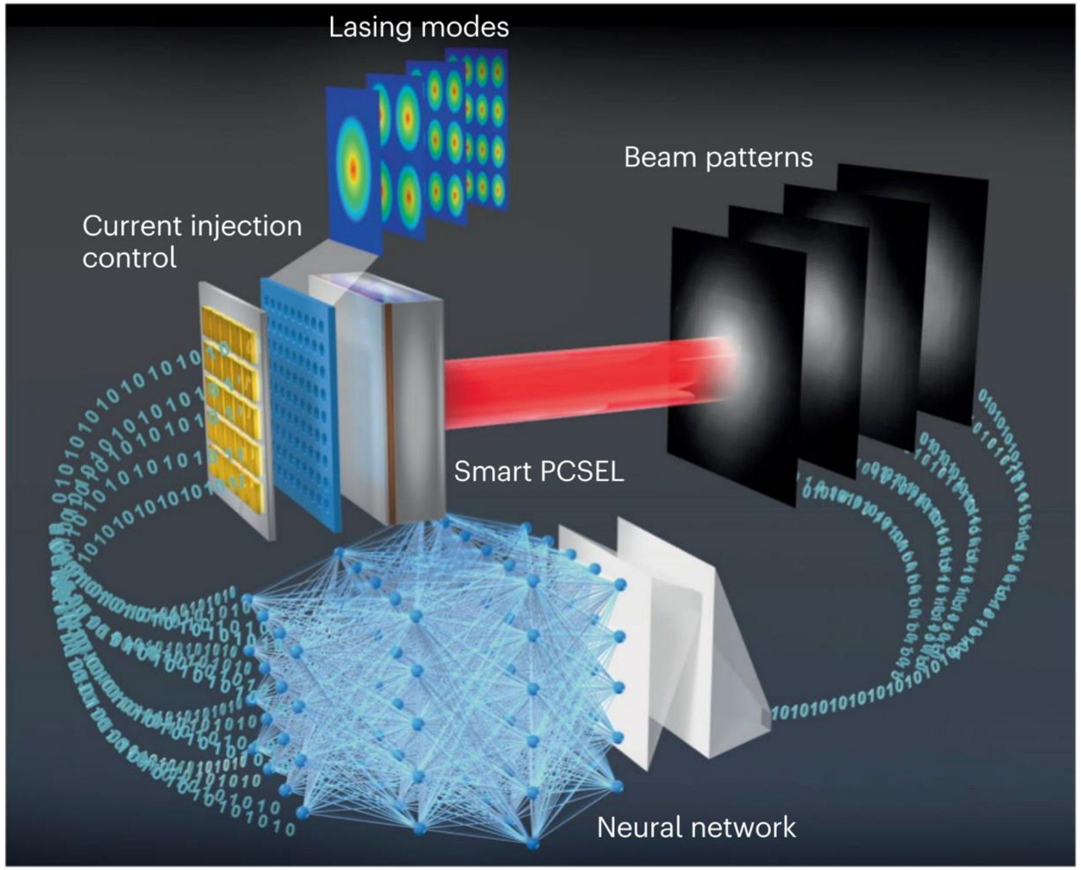


Smart PCSELs with AI control

Machine-learning-driven beam shaping

- **Multiple electrodes** modulate local current injection
- **Neural network** learns link between current map and beam pattern
- Enables **real-time generation** of target beams
- **95% resemblance** between predicted and experimental patterns





Conclusions

Key takeaways:

- PCSELs combine semiconductor **efficiency** with **high brightness**
- Enable **compact**, **lens-free**, **electronically steerable systems**
- Progress: **1 GW** $\mathbf{cm^{-2}\ sr^{-1}}$ brightness, **high functionality**, **ps pulses**, **blue** emission
- **Future**: kilowatt-class devices and quantum-optimised designs
- Applications from **industry** to **aerospace** and **fusion**

References:

- S. Noda et Al., "*Photonic-crystal surface-emitting lasers*", [Nat. Rev. Electr. Eng. 1, 802 (2024)]
- M. Imada et Al., "*Coherent two-dimensional lasing action in surface-emitting laser with triangular-lattice photonic crystal structure*", [Appl. Phys. Lett. 75, 316 (1999)]
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Thank you for your attention