1. Photonic crystal “band-edge” lasers

Photonic Crystal Band-Edge Lasers

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Mar 21, 2018

Photonic Crystal Band-Edge Resonant Modes

\[
\beta = \frac{\partial \omega}{\partial n} \quad \text{around “band-edge”, } V_g \sim 0
\]

i.e. high-Q resonant waves

Science 319, 445 (2008); Optics Express 16, 6033 (2008)
2. Photonic crystal “defect” lasers

- **D1 and larger cavities**
  - Membrane vs. Substrate
  - Ultra-high Q cavities
  - Ultra-small cavities
  - Others

**D1 Photonic Crystal Defect Lasers**

- First demonstration of the photonic crystal defect lasers
- InGaAsP Suspended membrane structure
- 2-D photonic crystals support in-plane confinement, while suspended membrane gives the vertical confinement
- Nano-fabrication technology improved a lot since 1999


**D1 Photonic Crystal Defect Lasers**

- Gain peak of MQWs is around 1550 nm communication wavelength
- Lasing wavelength is 1504 nm
- External threshold power is about 6.75 mW under optical pumping conditions (10ns pulse, 4% duty cycle) at 143K

**D₃ Suspended Membrane Photonic Crystal Defect Lasers**

- How to characterize and verify the operated lasing modes in the photonic crystal lasers?
- Fine-tuning of lattice constant of photonic crystal D₃ defect lasers
- The lattice constant varied from 490 nm to 550 nm with a 2 nm tuning step


**The lasing wavelengths collected from the photonic crystal cavities with varied lattice constants**

**The lasing wavelength is linear dependent with the lattice constant (a)**

**The results indicate that the same cavity operated mode in those D₃ cavities**

**The normalized frequency (a/λ) of this mode is 0.337**


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**Photonic Crystal Defect Lasers on a Substrate**

- Membrane vs. Substrate

(a) Suspended membrane structure of photonic crystal lasers

(b) Semiconductor substrate structure of photonic crystal lasers

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2. Photonic crystal “defect” lasers

- Membrane vs. Substrate
Suspended Membrane and Sapphire-Bonded Structure

- Air-dielectric-air structure has better confinement for the localized fields
- The structure only lase under pulsed conditions
- Air-dielectric-sapphire structure has less confinement for the localized fields
- This structure can lase under continuous wave (CW) conditions

Thermal conductivity
Air: $2.5 \times 10^{-5}$ W/cm·K and Sapphire: $5 \times 10^{-1}$ W/cm·K

Big Issues ..

1. High Q value
2. Small mode volume
3. Electrically injection

Quality Factor (Q) of Sapphire-Bonded Photonic Crystal Cavity

- Ultra-high Q cavities

2. Photonic crystal “defect” lasers
The lasing mode profiles from finite-difference time-domain (FDTD) simulation

The E-field amplitude of y-dipole mode

The defect mode has a large overlap with the gain region due to the antinode at the center of the defect.

The Ey-field profile obtained from FDTD simulation for the L3 cavities

The 2-D Fourier transform spectra of the calculated mode profiles

The leaky region surrounded by the light cone (white-circle) in k-space

The fabricated photonic crystal waveguide - cavity coupled structure

The measured spectra from the modified L3 cavities with varied air hole shifts

The highest Q is obtained from the cavity with 0.15a lattice shift

Photonic Crystal Heterostructure Cavity

- Waveguide type cavity
- Q > 600,000


Photonic Crystal W3 Heterostructure Cavity

Band diagram of W3 membrane waveguide

Q spectrum of W3 heterostructure cavity from 3-D FDTD

\[ \Delta a = +2.5\% \]

Quality Factor (Q)

Normalized Frequency

In-Plane Propagation Constant (x \( \pi / a \))

Photonic Crystal Heterostructure Laser

- Waveguide type cavity
- Q > 600,000

W3

a=430 nm

a=430 nm

a=441 nm

Photonic Crystal Heterostructure Cavity

Calculated Quality Factor

Output Intensity (a.u.)

Output Power (a.u.)

Incident Pump Power (mW)
Photonic Crystal Nanobeam Cavity

- Single-line type cavity
- Q > 1,000,000

Photonic Crystal Nanobeam Laser

Ultra-small Mode Volume Photonic Crystal Laser
**Why Ultrasmall Cavity??**

- Cavity quantum electrodynamics (QED):

  ![Image of without Cavity and with Cavity](image)

- Purcell factor:
  
  \[ F_p = \frac{3}{4\pi^2} \left( \frac{\lambda}{n} \right)^2 \left( \frac{Q}{V_m} \right) \]

  (E.M. Purcell, *Phys. Rev.* 69, 681 (1946))

  Spontaneous emission rate enhancement factor

**Why Ultrasmall Cavity??**

- Spontaneous emission coupling factor \( \beta \):

  Efficiency of coupling emitter into a single resonant mode, and \( \beta = 1 \) for “threshold-less” laser.

\[
\beta = \frac{F_p}{F_p + \gamma} \leq 1
\]

**Zero-Cell Photonic Crystal Defect Cavity**

-- from “Zero”...

from \( L_3 \) cavity .......  from \( D_0 \) cavity .......

**Ultrasmall Mode Volume**

*Photonic Crystal Laser*

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Ultrasmall Mode Volume Photonic Crystal Laser

Photonic Crystal Point-Shift Cavity


Optics Express 15, 7506 (2007)
3. Electrically-Pumped Photonic Crystal Lasers

- Vertical current injection structure
- In-plane current injection structure
Lasing wavelength ~ 1520 nm
The threshold current ~ 250 μA
The spontaneous emission coupling factor $\beta \approx 0.25$.

The electrical resistance $\approx 2000 \, \Omega$.
Electrically-Pumped Photonic Crystal Laser (II)

Directly Modulated PhC Nanolaser

Electrically-Pumped Photonic Crystal Laser (III)

Directly Modulated PhC Nanolaser