Quality factor dependence on vertical slab structure in photonic crystal double heterostructure resonant cavities

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Outline

- Photonic crystal double heterostructure cavity and edge-emitting lasers
- Heat-sinking lower substrates for continuous-wave operation
- Novel cavity design for reduced out-of-plane radiation
- Comment on designs for electrically addressed photonic crystal lasers
Photonic crystal double heterostructure cavities

Photonic crystal double heterostructure resonant cavity

- $Q$ factor $\sim 10^5 - 10^6$
- Mode volume $\sim (\lambda/n)^3$

Song, et al. Nat. Mat. 4 207 (2005)

Good candidate for efficient, small-footprint on-chip optical source

Calculated using parallelized 3-D FDTD

$H_z(x,y,z=0)$

> 100 $\mu$W peak output power

Optically pumped photonic crystal lasers

- photonic crystal lattice
- defect waveguide
- thin suspended membrane 250nm

Pulsed optical pump allows sufficient carrier excitation with reduced heating.

material damage from high power optical pump

optical pump beam

CW pumped membrane
**Heat-sinking lower substrates**

Dielectric substrate acts as a heat sink allowing room temperature CW laser operation.

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>SiO$_2$</th>
<th>Sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity:</td>
<td>2.5x10^-5</td>
<td>0.015</td>
<td>0.5 (W/cm – K)</td>
</tr>
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Edge-emitting substrate bonded CW laser
Dependence of $Q$ factor on substrate index

![Graph showing the dependence of $Q$ factor on substrate index. The $y$-axis represents the quality factor with a scale ranging from $10^2$ to $10^7$, and the $x$-axis represents the substrate refractive index ranging from 1.0 to 2.0. The graph exhibits a decreasing trend as the substrate refractive index increases.]

- Substrate
- Patterned semiconductor slab
- Heterostructure cavity
Dependence of $Q$ factor on substrate index

\[
\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_{\text{WG}}} + \frac{1}{Q_{\text{PC}}} + \frac{1}{Q_{\text{air}}} + \frac{1}{Q_{\text{substrate}}}
\]
Strategy for reducing out-of-plane radiation

Type A cavity

Type B cavity

- $a/2$ lattice shift leads to $\pi$ phase shift between the two sides of the cavity

- out of phase components interfere destructively along the waveguide axis

Dependence of $Q$ factor on substrate index

Total $Q$ limited by waveguide $Q$ for substrate index $< 1.5$

Total $Q$ limited by substrate $Q$ for substrate index $> 1.5$
Dependence of $Q$ factor on substrate index

Type A cavity

Type B cavity

Laser threshold
• Electrical addressing scheme is necessary if PC lasers are to be a useful device for integrated photonics

Toward electrically pumped PC lasers

- Electrical addressing scheme is necessary if PC lasers are to be a useful device for integrated photonics
- Recent design proposals employ a semiconductor based p-i-n diode vertical slab geometry
- Small index contrast (3.4 – 3.2 for InP and GaAs alloys)

Can the Type B heterostructure geometry mitigate the out-of-plane radiation?


Toward electrically pumped PC lasers

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**Electrical Injection Scheme Using Edge-emitting Heterostructure Cavity**

- p-doped top cladding $n = 3.2$
- n-doped substrate $n = 3.2$
- active region (e.g. quantum wells) $n=3.4$
- electrical contact (metal)
Dependence of $Q$ factor on vertical slab structure

- Top cladding layer to preserve vertical symmetry (5x improvement in $Q$)
- Deeply etched photonic crystal hole patterns (10x improvement in $Q$)
Dependence of $Q$ factor on vertical slab structure

$Q > 1000$ for $n < 2.2$

- still unable to maintain a high $Q$ factor for a substrate refractive index of 3.2
- alternative substrates such as GaN and SiC may be used in initial demonstrations

![Diagram of a vertical slab structure with labeled layers and curves representing $Q$ factor vs. refractive index.]
Conclusion

- Photonic crystal heterostructure microcavities for edge-emitting lasers
  
- Type B cavity design with reduced out-of-plane radiation for CW laser operation
  
- Electrically addressed PC lasers with semiconductor diode based vertical slab structure

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Symmetric vertical cladding

In-plane $Q$ 10x larger for symmetric cladding

Out-of-plane $Q$ 2x larger for symmetric cladding
Intuitive picture of field dynamics in response to gain
Cavity design: reducing in-plane leakage

Perturbation breaks glide-plane symmetry and allows coupling between overlapping waveguide bands