Strategies for Reducing the Out-of-Plane Radiation in Photonic Crystal Double Heterostructure Resonant Cavities

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CLEO - CThCC6
Introduction to photonic crystal double heterostructures and numerical method

Out-of-plane radiation with the addition of dielectric lower substrates for CW room-temperature laser applications

Quality factor as a function of index of lower substrate

Poynting vector analysis to quantify directional power flow

Alternative geometries to reduce out-of-plane radiation
Finite Difference Time Domain Analysis of Photonic Crystal Double Heterostructures

**Structure parameters**
- lattice constant: \( a \)
- slab thickness: \( d = 0.6a \)
- hole radius: \( r = 0.3a \)
- white holes: \( a' = 1.05a \) (5% perturbation)
- index of refraction: \( n = 3.4 \)

20 uniform photonic crystal waveguide cladding periods on each side

**Numerical simulation**

Three-dimensional finite-difference time domain calculation

950 x 340 x 200 data points parallelized on ~ 100 processors

200K time steps obtained from ~ 20 hours of computation
Finite Difference Time Domain Analysis of Photonic Crystal Double Heterostructures

Our structure:
- \( r = 0.3a \)
- 2-D perturbation
- 5% perturbation

\[ Q \approx 10^6 \text{ experimentally demonstrated}^* \]

\[ Q = 1900 \]
\[ Q = 2200 \]
\[ Q = 140000 \]

Out-of-Plane Radiation in Photonic Crystal Double Heterostructure Membranes

$H_z(\beta_x, \beta_y)$: spatial Fourier transform of $H_z(x, y, z = 0)$

Cross section schematic of photonic crystal double heterostructure

Guided wavevector component (outside light cone)

Leaky wavevector component (inside light cone)

Light cone projection for suspended membrane $n_{\text{substrate}} = 1.0$
Out-of-Plane Radiation in Photonic Crystal Double Heterostructure Membranes on Dielectric Substrates

Cross section schematic of photonic crystal double heterostructure

More wavevectors become leaky as the light cone becomes larger due to the dielectric lower cladding

Leaky wavevector component (inside light cone)

Dielectric lower cladding (e.g. sapphire)

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity:</td>
<td>2.5x10^{-5}</td>
<td>0.5 (W/cm – K)</td>
</tr>
</tbody>
</table>

Sapphire substrate acts as a heat sink allowing room temperature CW laser operation
Reported Experimental Lasing Results

Goal: edge-emitting PCDH laser on a sapphire substrate to achieve high power room temperature CW lasing


Dependence of Photonic Crystal Double Heterostructure Quality Factor on Index of Lower Dielectric Cladding

Experimental evidence indicates that sapphire bonded photonic crystal lasers require $Q$ of around 1000 to reach CW threshold at room temperature.

It is desirable to achieve high unloaded $Q$, so that preferential output coupling may be achieved by loading the cavity with an output waveguide.
Parity of Electric Field as a Function of Number of Perturbed Holes Adjacent to Photonic Crystal Waveguide Core

2 perturbed holes next to the waveguide core

$E_y(x,y)$ at slab midplane

$E_y(x,y)$ is even about $x = 0$

3 perturbed holes next to the waveguide core

$E_y(x,y)$ is odd about $x = 0$

Can we use control of field parity along $x$ to reduce out-of-plane radiation?
Field Parity Approach for Reducing the Out-of-Plane Power Flow

Out-of-plane power flow is defined by the $z$-component of the Poynting vector which turns out always to be an even function

$$S_z = E_x H_y - E_y H_x$$
Time Averaged Poynting Vector to Estimate Directional Dependence of Power Leakage

High $Q$ cavities require fine temporal resolution in the time step to achieve accurate one period time average.

Surface and volume integrals in Poynting theorem match to within $<1\%$

\[ P_{ave} = \frac{1}{T} \int_0^T \left[ -\oint \vec{S} \cdot d\vec{A} \right] dt = \frac{1}{T} \int (\epsilon \vec{E} \cdot \vec{E} + \mu \vec{H} \cdot \vec{H}) dV \bigg|_{t=T} - \frac{1}{T} \int (\epsilon \vec{E} \cdot \vec{E} + \mu \vec{H} \cdot \vec{H}) dV \bigg|_{t=0} \]
Out-of-Plane Power Flow: z-Component of Poynting Vector for Air-clad Photonic Crystal Double Heterostructures

\[
S_z = E_x H_y - E_y H_x
\]

| air clad membrane          | \( E_x \cdot H_y \) | \( E_y \cdot H_x \) | \( |<E_x H_y>/ <E_y H_x>| \) |
|---------------------------|---------------------|---------------------|-----------------------------|
| 2 adjacent holes          | odd \cdot odd       | even \cdot even     | 1.4                         |
| 3 adjacent holes          | even \cdot even     | odd \cdot odd       | 0.6                         |

Odd field components carry about 50% more power out of plane than the even components

<table>
<thead>
<tr>
<th>air clad membrane</th>
<th>( P_\perp / P_\parallel )</th>
<th>( Q_\perp )</th>
<th>( Q_\parallel )</th>
<th>( Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 adjacent holes</td>
<td>2.85</td>
<td>191000</td>
<td>544000</td>
<td>141000</td>
</tr>
<tr>
<td>3 adjacent holes</td>
<td>2.13</td>
<td>204000</td>
<td>435000</td>
<td>139000</td>
</tr>
</tbody>
</table>

In both geometries, out-of-plane power flow is the dominant loss mechanism
Dependence of Photonic Crystal Double Heterostructure Quality Factor on Index of Lower Dielectric Cladding

Adjacent to Waveguide Core

2 perturbed holes
3 perturbed holes

7.5% increase in $Q$ at $n = 1.2$

2 perturbed holes next to the waveguide core

3 perturbed holes next to the waveguide core
Introducing Asymmetry About $y = 0$

3 perturbed holes next to the waveguide core

Also known as Type-B in the photonic crystal waveguide literature
Lattice-Shifted Photonic Crystal Double Heterostructure

Photonic crystal waveguide dispersion diagram

Photonic crystal double heterostructure resonance spectrum

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

\( Q = 5750 \)

\( Q = 2010 \)

\( a' = 1.025a \) (2.5% perturbation)
### Directional Power Flow and Q Dependence for the Lattice-Shifted Photonic Crystal Double Heterostructure

<table>
<thead>
<tr>
<th></th>
<th>$P_\perp / P_\parallel$</th>
<th>$Q_\perp$</th>
<th>$Q_\parallel$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air clad membrane</td>
<td>0.21</td>
<td>32000</td>
<td>7000</td>
<td>5700</td>
</tr>
<tr>
<td>Sapphire lower substrate</td>
<td>0.48</td>
<td>15600</td>
<td>7600</td>
<td>5100</td>
</tr>
<tr>
<td>(n = 1.74)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**Diagram:**
- Lattice-shifted photonic crystal double heterostructure
- Graph showing $Q$ vs. index of lower cladding
Directional Power Flow and $Q$ Dependence for the 3 Geometries Discussed in this Presentation

<table>
<thead>
<tr>
<th>Unit</th>
<th>$P_\perp / P_\parallel$</th>
<th>$Q_\perp$</th>
<th>$Q_\parallel$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>air clad</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>membrane</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>139000</td>
</tr>
<tr>
<td>lattice shifted</td>
<td>0.21</td>
<td>32000</td>
<td>7000</td>
<td>5700</td>
</tr>
</tbody>
</table>

Dominant loss mechanism has switched to in-plane leakage in lattice-shifted geometry
Summary

Dielectric substrate for heat sinking to achieve room temperature CW laser operation in photonic crystal double heterostructure resonant cavities

Dependence of $Q$ on index of dielectric lower cladding

Field symmetry based on number of perturbed holes adjacent to waveguide core

Poynting vector calculation to quantify directional power flow

Lattice-shifted geometry to reduce out-of-plane power flow

Acknowledgements
Defense Advanced Research Projects Agency (DARPA)
National Science Foundation (NSF)
University of Southern California Center for High Performance Computing and Communications (USC HPCC)
Light cone projection for suspended membrane
$n_{\text{substrate}} = 1.0$
In CLEO Conference Submission

d1 = \frac{a'}{2} + a \\
d2 = a' + a

\text{Standard Geometry}

d1 = \frac{a'}{2} + \frac{(a'-a)}{2} + a \\
d2 = a' + a

d2 - d1 = \frac{a'}{2} \\
d2 - d1 = a/2
In CLEO Conference Submission

<table>
<thead>
<tr>
<th>2 perturbed holes</th>
<th>3 perturbed holes</th>
<th>lattice shifted</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q = 195,000 )</td>
<td>( Q = 93,020 )</td>
<td>( Q = 3,080 )</td>
</tr>
<tr>
<td>( P_{\perp} / P_{\parallel} = 4.56 )</td>
<td>( P_{\perp} / P_{\parallel} = 2.94 )</td>
<td>( P_{\perp} / P_{\parallel} = 0.185 )</td>
</tr>
<tr>
<td>( Q_{\perp} = 238,000 )</td>
<td>( Q_{\perp} = 125,000 )</td>
<td>( Q_{\perp} = 19,670 )</td>
</tr>
<tr>
<td>( Q_{\parallel} = 895,000 )</td>
<td>( Q_{\parallel} = 367,000 )</td>
<td>( Q_{\parallel} = 3,630 )</td>
</tr>
</tbody>
</table>

| Standard Geometry |
|-------------------|-------------------|----------------|
| 2 perturbed holes | 3 perturbed holes | 3 perturbed holes |
| \( Q = 141,000 \) | \( Q = 139,000 \) | \( Q = 5,750 \) |
| \( P_{\perp} / P_{\parallel} = 2.85 \) | \( P_{\perp} / P_{\parallel} = 2.13 \) | \( P_{\perp} / P_{\parallel} = 0.213 \) |
| \( Q_{\perp} = 191,000 \) | \( Q_{\perp} = 204,000 \) | \( Q_{\perp} = 32,700 \) |
| \( Q_{\parallel} = 544,000 \) | \( Q_{\parallel} = 435,000 \) | \( Q_{\parallel} = 6,970 \) |

\( Q_{\text{sapphire}} = 2855 \)  
\( Q_{\text{sapphire}} = 5100 \)
Photonic Crystal Double Heterostructure on a High Index Post

<table>
<thead>
<tr>
<th>Adjacent Holes</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 adjacent holes</td>
<td>330</td>
</tr>
<tr>
<td>3 adjacent holes</td>
<td>500</td>
</tr>
<tr>
<td>3 adjacent holes</td>
<td>460</td>
</tr>
<tr>
<td>4 adjacent holes</td>
<td>320</td>
</tr>
</tbody>
</table>
Dependence of $Q$ on Distance Between Perturbed Holes and PCWG Holes

![Graph showing the dependence of $Q$ on distance $\Delta$]

$Q$ vs. $\Delta$ (in units of $a$)

$\Delta = 0$

$\chi = 0$