Dynamic Photonic Crystal Superlattices

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Outline

- Introduction/Motivation
- Structure & method of analysis
- 2D slab triangular lattice
  - Tunability with electo-optic materials
- New concept:
  - Superlattice photonic crystal
  - Refraction behavior
  - Switching effects
- Summary
- Acknowledgements
Introduction/Motivation

- Fabrication of 2D photonic crystals not as complicated as 3D
- Integration onto opto-electronic systems directly on common substrate
- Large refraction effects (superprism) for beam steering, signal processing, demultiplexing
- Investigate methods to electro-optically tune these effects
  - Infiltrate with electro-optical or nonlinear materials (eg. liquid crystal)
  - Tunable refraction
  - Switching
2D Slab configuration suspended air, thickness = 0.5\(a\)

3-D Finite difference time domain (FDTD) calculations with:
- one mirror boundary
- one perfectly matched layer (PML) boundary
- four periodic boundaries

Triangular lattice of holes

Fill holes with electro-optic materials
- Dynamic modification of band structure
Triangular Lattice

Holes filled with LC

- $1.5 \leq n \leq 2.1$
- Silicon slab, $n=3.46$
- Even mode

'Cones shaped' curve

Γ

$\omega_n=0.36$

$r=0.3a$

$n_{LC}=1.5$
Refraction in PCs

- Refraction angle determined by dispersion curve
- Conservation of tangential wave vector component, $k_{//}$, at the interface
- Final direction of travel is normal to the dispersion curve at intersection
- Tunability ~7° at 13° incidence
- Range of operating angles 0° to ~18°
- As $\Delta n$ is increased
  - Tip of cone is cut off by the light cone
  - Thus at small incident angles, modes are decaying

Incident vs Refraction Angle

$\Delta n =$

- 0.0
- 0.2
- 0.4
- 0.8
New Idea: Alternating Addressing Scheme

- Address alternating rows of holes individually instead of homogeneously
- Creates superlattice with new Brillouin Zone shape
- More control over structure
- Electrical or optical biasing

$\Delta n =$ difference between refractive indices of the holes

$V+$ $V+0$ $V+$

$V+0$ $V+0$
Photonic Crystal Superlattice

Need a larger unit cell with two atom basis

Consequent Brillouin zone

New labeling scheme for symmetry points

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Superlattice Effect on Band Structure

- ‘Artificial’ Superlattice ($\Delta n=0$ between rows) to test calculation
- Bands translated according to new BZ scheme
- Results valid $\rightarrow$ band gap same, shape of bands remain intact except for some translations introduced by the superlattice

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Superlattice Effect on Dispersion Diagram

- Additional periodicity changes shape of 1st Brillouin Zone
- No longer 6-fold symmetric
- When compared to homogeneous case, BZ appears ‘folded’ inward due to translation of bands
- Outcoupler/switch

Arrows indicate translations of curves

- $\omega_n = 0.34$

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>Regular lattice</td>
</tr>
<tr>
<td>Orange</td>
<td>Superlattice</td>
</tr>
<tr>
<td>Red</td>
<td>Cutoff circle</td>
</tr>
</tbody>
</table>
Band Shift with Change in $\Delta n$ for SL

Photonic Bands of 2D Slab SL-PC $\Delta n=0.1$

- $n_{LC}=1.5$ for one row
- $1.5 < n_{LC} < 2.1$ for second row
- Difference in $n$ between rows is $\Delta n$
- Bands shift to lower frequency with greater $\Delta n$.
- Separation between translated bands widen.

$\Delta n=0.6$

Photonic Bands of 2D Slab SL-PC $\Delta n=0.6$

- $\phi_n=0.3545$
Evolution of Dispersion Curves

As $\Delta n$ is increased, the separation between certain modes in the BZ widen.

- As $\Delta n$ is increased, the 3rd band intersects the isofrequency line.

- Mode disappears

- Gap widens

- Mode 1

- Mode 2

- 3rd band

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Refraction Angle (Mode 1)

- Large tunability at negative incident angles, >50° at -20° for \( \Delta n=0.5 \)

\( \Delta n=0.3 \)

Input vs. Refraction Angle (Mode 1)

Incident Angle (degrees)

Refraction Angle (degrees)

\( \Delta n=0.1 \)
\( \Delta n=0.2 \)
\( \Delta n=0.3 \)
\( \Delta n=0.4 \)
\( \Delta n=0.6 \)

>50°

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Refraction Angle (Mode 2)

- Decaying mode
- Propagating mode

\[ \Delta n = 0.3 \]

Input vs. Refraction Angle (Mode 2)

- Cutoff at light cone
- \( \Delta n = 0.2 \)
- \( \Delta n = 0.3 \)
- \( \Delta n = 0.4 \)
- \( \Delta n = 0.6 \)

- Tunability approaches 10°
- Limited range of angles due to light cone and BZ edge

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Switch is very sensitive to small changes in $\Delta n \sim 0.005$

- Behavior comes from 2nd band in the band diagram
- Arrows indicate movement of dispersion curve with increasing $\Delta n$. 

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Summary

- 2D slab LC infiltrated regular triangular lattice
  - Beam steering approx. 10° with ~15% change in $n$.
- New superlattice configuration proposed by additional index modulation
  - Creates new allowed modes and drastic changes in dispersion
- New functionality to control optical properties
  - Improved beam steering >50°
  - Directional dependent switching, outcoupling
- Further studies required
  - Optimization of hole size & slab thickness
  - Superprism effects
  - Integration of fast non-linear materials for optical signal processing
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