COUPLED-CAVITY STRUCTURES IN PHOTONIC CRYSTALS

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OUTLINE

- **Motivations**
- **Underlying Physics**
  - Investigation of coupled-cavity structures: FDTD, TMM, experiment, and tight-binding approximation
    - Localized cavity modes
    - Eigenmose splitting
    - Photonic molecules
  - Observation of a new type of waveguiding mechanism: Coupled-cavity waveguides (CCWs)
- **Possible Applications**
  - Waveguides, waveguide bends, splitters, switches
  - WDM: adding or dropping a selective wavelength or band
  - Strong enhancement of the spontaneous emission
  - Increasing efficiency of nonlinear processes
  - Dispersion compensators
- **Summary**
MOTIVATIONS

PHOTONIC INTEGRATED CIRCUIT

[from Krauss' paper]

TO CONSTRUCT ALL OPTICAL COMPONENTS ON A SINGLE CHIP
Observation of strongly localized cavity modes within the photonic band gap analogous to acceptor impurity state in semiconductors
EIGENMODE SPLITTING

\[ E_\omega (r) = A E_\Omega (r) + B E_\Omega (r - \Lambda) \]

Linear combination of the individual evanescent cavity modes

\[ \nabla \times [\nabla \times E_\omega (r)] = \left( \frac{\omega}{c} \right)^2 \varepsilon_0 (r) E_\omega (r) \]

\[ \omega_{1,2} = \Omega \sqrt{\frac{l \pm \beta}{l \pm \alpha}} \]

Formation of bonding and antibonding photonic modes

\[ E_{\omega_1} = \frac{E_\alpha (r) - E_\alpha (r - \Lambda)}{\sqrt{2}} \]

\[ E_{\omega_2} = \frac{E_\alpha (r) + E_\alpha (r - \Lambda)}{\sqrt{2}} \]
\[ E_{n_1} = \frac{E_n(r) - \sqrt{2}E_n(r-A) + E_n(r-2A)}{2} \]

\[ E_{n_2} = \frac{E_n(r) - E_n(r-2A)}{\sqrt{2}} \]

\[ E_{n_3} = \frac{E_n(r) + \sqrt{2}E_n(r-A) + E_n(r-2A)}{2} \]

PHOTONIC MOLECULES

Experiment FDTD

Transmission (dB)

Frequency \((\omega/\omega_0)\)

- Benzene-like molecule
Dispersion relation, group velocity, and photon lifetime depend only a single tight-binding parameter \( \kappa \) that can be directly determined from experiments.

\[
\nabla \times \left[ \nabla \times \mathbf{E}(\mathbf{r}) \right] = \left( \frac{\omega}{c} \right)^2 \varepsilon_0(\mathbf{r}) \mathbf{E}(\mathbf{r})
\]

\[
\mathbf{E}(\mathbf{r}) = E_0 \sum_n e^{-ink\Lambda} \mathbf{E}_\Omega(\mathbf{r} - n\Lambda)
\]

\[
\omega(k) = \Omega \left( 1 + \kappa \cos(k\Lambda) \right)
\]

\[
\nu_g(k) = \nabla_k \omega(k) = -\Omega\Lambda\kappa \sin(k\Lambda)
\]

\[
\tau_p(k) = L / \nu_g(k) - 2\pi L / c
\]

Formation of a cavity band (waveguiding band) due to interaction between the localized modes

Demonstration of a new type of waveguiding mechanism in photonic crystals.

Full transmission is measured throughout the CCW band

Very sharp band edges can be used for switching applications

\[
\frac{\omega(k)}{\Omega} = \Omega \left(1 + \kappa \cos(k\Lambda)\right)
\]

\[
v_g(k) = -\Omega \Lambda \kappa \sin(k\Lambda)
\]

\[
\tau_p(k) = \frac{L}{v_g(k)} - 2\pi L/c
\]

\[v_g \to 0 \quad \text{at the CCW band edges} \quad \tau_p \to \infty\]

BENDING OF EM WAVES ALONG ARBITRARY PATH

Problem of guiding light around very sharp corners in conventional waveguides

➢ Possibility of constructing lossless and reflectionless bends in optical circuits

The electromagnetic power in the input port splits equally into the two output ports throughout the waveguiding band.

COUPLED CAVITY SWITCHES

![Image of coupled cavity switches](image)

**Left Port**

Experiment

FDTD

Transmission (dB)

**Frequency \( (\omega/\omega_0) \)**

-60 -50 -40 -30 -20 -10 0

**Right Port**

Experiment

FDTD

Transmission (dB)

Frequency \( (\omega/\omega_0) \)

-60 -50 -40 -30 -20 -10 0
Single wavelength dropping

\[ \lambda_1, \lambda_2 \ldots \lambda_N \]

Band dropping

\[ \lambda_1, \lambda_2 \ldots \lambda_N \]

Bayindir and Ozbay, APL [submitted]
DROPPING OF A SELECTIVE FREQUENCY FROM PW

FDTD Simulation

Transmission (dB)

Frequency ($a/\lambda$)

Measurement

Transmission (dB)

Frequency ($a/\lambda$)

F_{k}
DROPPING OF A SELECTIVE FREQUENCY FROM CCW

FDTD Simulation

Transmission (dB)

Frequency (a/λ)

T1-2
T1-3
T1-4
T1-5

Dropping of a selective frequency from CW
BAND DROPPING FROM PW

FDTD Simulation

Transmission (dB)

Frequency ($a/\lambda$)
BAND DROPPING FROM CCW

FDTD Simulation
COUPLED WAVEGUIDES: DIRECTIONAL COUPLERS

Bayindir and Ozbay, Optics Express [in preparation]
DIRECTIONAL COUPLERS: COUPLED-CAVITY WAVEGUIDES

FDTD Simulation

Measurement

Transmission (dB)
Frequency \((a/\lambda)\)

TIGHT-BINDING MODEL: INTERACTING CHAINS

\(t_2 \ll t_1\)
APPLICATIONS

INCREASING EFFICIENCY OF NONLINEAR PROCESSES

\[ \eta \propto \frac{1}{\nu_g} \quad \nu_g \to 0 \quad \text{Large gain} \]

DISPERSION COMPENSATORS

\[ D = -\frac{2\pi c}{\lambda^2} \frac{d^2 k}{d\omega^2} \]
QUASIPERIODIC [ PENROSE ] PHOTONIC CRYSTALS

Transmission (dB)

Defect Band

Frequency (GHz)

Measurement
Calculation

k\lambda/\pi

Frequency (GHz)
\[ z_i \rightarrow z_i r e^{i\varphi} \]

\( r \): randomness parameter

\( \varphi \): random variable between \([0, \pi]\)
3D LAYER-BY-LAYER PHOTONIC CRYSTALS

Symmetry: Face centered tetragonal (fct)
Material: Alumina of refractive index $\varepsilon = 3.1$

at microwave frequencies
Dimensions: $0.32 \text{ cm} \times 0.32 \text{ cm} \times 15.25 \text{ cm}$
Three-dimensional stop band: from $10.6 \text{ GHz}$ to $12.8 \text{ GHz}$

All phenomenon were observed in 3D layer-by-layer or woodpile structures

Coupled-Cavities in 1D Structures

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>d [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si$_3$N$_4$</td>
<td>2.10</td>
<td>70</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>1.47</td>
<td>97</td>
</tr>
</tbody>
</table>

Experimental results agree well with TMM and TB predictions for the three coupled-cavities.


<table>
<thead>
<tr>
<th>Mode</th>
<th>Measurement [THz]</th>
<th>TMM [THz]</th>
<th>TB [THz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>490.08</td>
<td>491.30</td>
<td>489.85</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>516.53</td>
<td>516.80</td>
<td>516.83</td>
</tr>
<tr>
<td>$\Gamma_3$</td>
<td>543.65</td>
<td>542.81</td>
<td>544.10</td>
</tr>
</tbody>
</table>

![Diagram of coupled cavities]
Efficiency of the second harmonic generation process can be increased as a result of large optical field amplitude and low group velocity at the waveguiding band edges.

Nearly full transmission was measured throughout the CMC band.

The transfer matrix method results agree well with the experimental observations.

The position and bandwidth of waveguiding band can be adjusted by changing the thicknesses of the layers and the distance between the cavity layers.

Heavy photon
The photoluminescence spectrum was strongly modified in the presence of Fabry-Perot microcavity.

A strong spontaneous emission was achieved for a wide range of wavelengths.

The spontaneous emission was significantly enhanced at the coupled-cavity band edges.
HIGHLY CONFINED WAVEGUIDES

Full confinement of electromagnetic waves in 3D layer-by-layer photonic crystals

Noda et al., APL 75, 3739 1999;
Bayindir et al., PRB 63, 081107(R) (2001)
**EXPERIMENTAL SETUP**

Symmetry: Face centered tetragonal (fct)
Material: Alumina of refractive index 
\[ \varepsilon = 3.1 \text{ at microwave frequencies} \]
Dimensions: 0.32 cm × 0.32 cm × 15.25 cm
Photonic band gap: 10.6 GHz -12.8 GHz
Nearly full transmission was achieved for certain frequencies.
The full transmission within the waveguiding band was a proof of how well the wave was confined and guided without losses.
The full transmission through a 90° bent was achieved for certain frequencies throughout the waveguiding band.

Comparison with simulation [Noda’s Group, APL (1999)]:

The bending band covers 68% of the stop band which is very close to the simulation results value of 67%.
The electromagnetic power in the input port splits into the two output ports throughout the guiding band.
The coupling between these localized cavity modes allows propagation of photons by hopping through the vacancy of the missing rod.

Each vacancy just below the removed rod behaves as a boxlike cavity.
\[ \omega(k) = \Omega \left( 1 + \kappa \cos(k\Lambda) \right) \]

\[ \tau_p(k) = \frac{L}{v_g(k)} + 2\pi L/c \]

Experimental results were in good agreement with the tight-binding approximation predictions.
WDM APPLICATIONS: DROPPING A SELECTIVE WAVELENGTH

Electromagnetic wave with a specific frequency can be dropped from the guided mode inside the waveguide.

Tunability can be achieved by changing properties of the cavity.

Bayindir and Ozbay [in preparation]

- Electromagnetic wave with a specific frequency can be dropped from the guided mode inside the waveguide.
- Tunability can be achieved by changing properties of the cavity.
Highly confined waveguides, waveguide bends, power splitter, add-drop filters, switches can be used in future ultrasmall optoelectronic integrated circuits.
SUMMARY

- Various applications of 1D, 2D, and 3D coupled-cavity structures were demonstrated.
- The tight-binding approximation was successfully applied to the photonic structures.
- The finite-difference-time-domain (FDTD) and the transfer matrix method (TMM) results agree well with our measurements.

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MORE INFORMATION

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