Nanomaterials and their Optical Applications

Winter Semester 2013
Lecture 08

December 17th 2013, No lecture
First Lecture in 2014: 7th of January
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<td>Egor Khaidarov</td>
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<td>Siyuan Wang</td>
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<td>Morozov Sergii</td>
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<td>Svetlana Shestaeva</td>
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<td>Kai Wang</td>
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You will be noted on the following criteria

• Quality of the slides: clear and comprehensive, references included
• Timing: no more than 15 minutes and not less either
• Oral expression: fluent
• Scientific content
• Answer to questions: precise and short
Materials for what?

The speed of photonics
The size of electronics

High transparency of dielectrics like optical fibre
Data transport over long distances
Very high data rate

Nanoscale data storage
Limited speed due to interconnect
Delay times

Lasing media for compact solid-state lasers

1. Edge emitting (also called in plane laser)

Material for laser diodes

Japan (Shuji Nakamura) developed the
The 1st green, blue, violet & white LEDs with GaN semiconductors (epitaxial MOCVD on a sapphire substrate -1993)
The 1st blue-light semiconductor laser (1995)

- Environmentally friendly compared to Arsenic
- High melting point
- Bandgap → blue or UV light Photon Emission
1. Edge emitting (also called in plane laser)

   Issues for blue diodes

   - Standard techniques (Czochralski, Bridgeman, Float Zone) used to make single crystal wafers (GaAs & Si) don't work for GaN.
   - GaN has a high melting temperature and a very high decomposition pressure.
   - The nitrogen evaporates out of the crystal as it grows and the GaN atoms won’t bond.
   - To keep the nitrogen in, need very high pressures (more than 1000 MPa), which are difficult to achieve in a commercial process.
1. Edge emitting (also called in plane laser)

Issues for blue diodes

The Problem

GaN grown on sapphire which has 15% smaller lattice constant. Leads to high defect density. Cracking of layers when structures are cooled down after growth due to high difference in thermal expansions of the two materials. GaN is ideal choice for substrate but this is still in research.

The Solution

- Akasaki proposed solution: developing AlN buffer layers
- Nakamura proposed solution: growth of GaAlN buffer layers
2. Surface emitting laser (SEL) : vertical laser output

**Vertical Cavity SEL**

*Easy to integrate to fibers*

*Heating effects in the multiple layer structure*

**Vertical External CSEL**
3. Quantum cascade laser

- Electrons from the conduction band only: unipolar
- Intraband transitions only
- Normal laser: 1 electron produces 1 photon
- QC laser: 1 electron produces 25 to 75 photons
- 4 to 24 microns wavelength, more than 1W
- Chemical sensing of toxic gas or pollutants
Quantum well absorption between two subband

Intersubband absorption in a multiquantum well designed for triply resonant non-linear susceptibility

**Key words**

- **Unipolar semiconductor laser**: relies only on one type of carrier
- **Superlattices**
- **Space charged effects**: excess electric charge is treated as a continuum of charge distributed over a region of space
- **Schawlow–Townes Linewidth**: the fundamental (quantum) limit for the linewidth of a laser ([Phys. Rev. 112 (6), 1940 (1958)])
Outline: Photonic crystals

1. Photonic crystals vs electronic crystal
2. 1D, 2D, 3D photonic crystals
3. Features of photonic crystal
4. Fabrication methods
5. Applications

Why dielectric photonics?

The speed of photonics
The size of electronics

High transparency of dielectrics like optical fibre
Data transport over long distances
Very high data rate

Nanoscale data storage
Limited speed due to interconnect
Delay times

Controlling the properties of materials

Mechanical properties: metallurgy, ceramics, plastics

Electrical properties: transistor revolution in electronics

Optical properties: optical fibers for telecom:

High speed, larger amount of info, less energy losses

What sort of material can afford us a complete control over light propagation?

A photonic crystal is a periodic arrangement of a dielectric material that exhibits strong interaction with light

http://www.physics.utoronto.ca/~john/

Analogy between electronics & optics

- The crystal is a **periodic potential** to an electron propagating through it
- The crystal **composition** and its **geometry** determines conduction properties
- Explained by quantum theory: electrons are **waves** that propagates through the periodic potential without scattering (except defects)
- **Bandgap**: the lattice can also prohibit the propagation of certain waves
Analogy between electronics & optics

Electronic...   photonic ...   crystal

- e⁻ free in the lattice
- Coulomb forces -> nuclei

Semiconductor crystal = periodic arrangement of atoms

- Periodic potential -> periodic dielectric function or index of refraction
- Required: sufficient different refractive index and low absorption of the material
- Consequences: light can be reflected and refracted
- Solution: Photonic crystal = low loss periodic dielectric medium

- Atoms -> media with a differing dielectric constant

Half-wavelength period

Periodic variation of the dielectric constant with dielectric spheres

0.5 nm

200 nm
Analogy in nature

each spine acting as a photonic crystal which only reflects light of a specified wavelength

Simultaneously in 1987...

E. Yablonovitch
“Inhibited spontaneous emission in solid state physics and electronics”
*Physical Review Letters*, vol. 58, pp. 2059, 1987

S. John
“Strong localization of photons in certain disordered dielectric superlattices”
*Physical Review Letters*, vol. 58, pp. 2486, 1987

Face-centered cubic lattice

Complete photonic band gap
First example: one dimensional photonic crystal

- If light is generated inside the Photonic Crystal: no propagation
- If light is sent through the crystal from outside: reflection

**Order of magnitude**
Telecom industry: 1.5 µm
Then 500 nm Photonic crystal size
First example: one dimensional photonic crystal

Bragg–Snell law

\[ m\lambda = 2(n_l d_l + n_h d_h) \]

where \( m \) is the diffraction order, \( n_l \) and \( n_h \) are the refractive indices of the low- and high-refractive-index materials, the respective thicknesses.

reflectivity \( R \) of the Bragg stack

\[ R = \left[ \frac{n_0 - n_s (n_l/n_h)^{2N}}{n_0 + n_s (n_l/n_h)^{2N}} \right]^2 \]

number of bilayers \((N)\)

the bandwidth of the photonic stop band

\[ \Delta\lambda_0 = \frac{4\lambda_0}{\pi} \arcsin \left( \frac{n_h - n_l}{n_h + n_l} \right) \]

increasing the refractive index contrast between the materials in the Bragg pairs increases both the reflectivity and the bandwidth, and increasing the thickness of the layers increases the diffraction wavelength.

First example: one dimensional photonic crystal

Field penetration into a Bragg mirror, calculated with the software RP Coating.

Reflectivity (black curve) and chromatic dispersion (blue curve) of the same mirror as above.
**Other dimensions**

*No complete* gap for 1D

Complete gap not only for 3D photonic crystal:
- non periodic material using Anderson localization
- Quasi-crystalline structures
No complete gap for 1D

Complete gap not only for 3D photonic crystal:

- non periodic material using Anderson localization
- Quasi-crystalline structures

1D: Bragg Reflector       2D: Si pillar crystal       3D: colloidal crystal
Dimensionality effects

Real space

3D

2D

1D

Reciprocal space

http://luxrerum.icmm.csic.es/?q=node/research/pcintro
Dimensionality effects

- Glass or polysterene spheres
- Complete bandgap
- Not dependent on the direction of $k$
- DOS = 0 in the bandgap
- Sometimes called OPAL structure
- Inverse OPAL structure: void surrounded by higher refractive index material

Fig.1: Opal structure
Inverse Opal Structure

http://hera.physik.uni-konstanz.de/research/photonic/main.htm
Dimensionality effects

- Stack of cylinders
- Photonic crystal fiber
Theoretical modeling of Photonic crystals

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<th>Photons</th>
<th>Electrons</th>
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<td>$\lambda = \frac{h}{p} = \frac{c}{v}$</td>
<td>$\lambda = \frac{h}{p} = \frac{\hbar}{m v}$</td>
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**Hermitian operator**

\[
\left\{ \nabla \times \frac{1}{\varepsilon(r)} \nabla \times \right\} B(r) = \left( \frac{\omega}{c} \right)^2 B(r)
\]

**Eigenvalue (Wave) Equation**

\[
\hat{H}\psi(r) = \frac{\hbar^2}{2m} (\nabla \cdot \nabla + V(r))\psi(r) = E\psi
\]

**Free-Space Propagation**

- Plane wave:
  - Plane wave: $\Psi = c(e^{i\mathbf{k} \cdot \mathbf{r} - i\omega t} + e^{-i\mathbf{k} \cdot \mathbf{r} + i\omega t})$
  - $\mathbf{k} = \text{wavevector, a real quantity}$

- No analytical solution because no separation is possible as $V$ for electrons
- Thus: mostly numerical solutions
Theoretical modeling of Photonic crystals

No analytical solutions of the master equation

\[
\left\{ \nabla \times \frac{1}{\varepsilon(r)} \nabla \times \right\} B(r) = \left( \frac{\omega}{c} \right)^2 B(r)
\]

- In the absence of external currents and sources
- The region of all allowed wavevectors: Brillouin zone
- The collection of all solutions: the band structure

Theoretical modeling of Photonic crystals

No analytical solutions of the master equation

\[ \nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times \right) B(r) = \left( \frac{\omega}{c} \right)^2 B(r) \]

Frequency domain techniques:

- to solve the master equation and find eigenvalue
- It provides the allowed states and their energies thus the band structure
- **Plane wave expansion** method and the **transfer matrix** method

Time domain techniques:

- Calculation of the temporal evolution of the input electromagnetic field propagating through the crystal
- It needs a Fourier transformation to obtain the band structure
- Widely used method: Finite-difference time domain (FDTD)
Features of Photonic crystals

1. Presence of bandgaps

Bandgaps or pseudo-gaps (stop-gaps)

Suitable for:
- High quality narrow band filters, tunable by changing the lattice constant
- Chemical sensing using the change in the effective periodicity

2. Local Field Enhancement

The electric field distribution of the modes associated with the upper or lower band is higher or lower depending on the material
3. Anomalous group velocity dispersion

**Group velocity**: the velocity with which the envelope of a weak narrow-band optical pulse propagates in a medium

**Group velocity dispersion**: the frequency dependence of the group velocity in a medium

Highly anisotropic and complicated band structure can strongly modify the group velocity

Value slower than the vacuum speed of light

\[ \nu_g = \left( \frac{\partial k}{\partial \omega} \right)^{-1} \]

Highly anisotropic and complicated band structure can strongly modify the group velocity

Value slower than the vacuum speed of light

\[ \text{GVD} = \frac{\partial}{\partial \omega} \frac{1}{\nu_g} = \frac{\partial}{\partial \omega} \left( \frac{\partial k}{\partial \omega} \right) = \frac{\partial^2 k}{\partial \omega^2} \]

How a pulse with polychromatic light will spread
3. Anomalous group velocity dispersion

**Superprism**

- Superdispersion
- ultra-refraction

2 orders of magnitude stronger than in conventional prism
4. Anomalous refractive index dispersion

Normal refractive index dispersion in non-absorbing region: decrease with increasing wavelength

Near optical absorption:
Anomalous dispersion

Useful for phase-matching that requires the same phase velocities for the fundamental and the harmonic wave
5. Effects of defects

To introduce a defect in order to trap or localize the light such as in waveguiding

Analogy with dopants in semiconductors

5.1 The waveguide: line defects

• Different from fibers: **total internal reflection**
• 98% of the light is present at the output, only 30% in a similar dielectric waveguides
• Only losses at the input facet
5.1 The waveguide: line defects
5.1 The waveguide: line defects

Zijlstra, van der Drift, De Dood, and Polman (DIMES, FOM)
Features of Photonic crystals

5. Effects of defects

5.2 The cavity: point defects

Changing the dielectric medium in some local region of the crystal:
1. Change $\varepsilon$ of a single dielectric atom
2. Change the size
3. Remove one dielectric atom

Why? To control spontaneous emission

How?
• Changing the coupling between the atom and the photon by changing the properties of defect states
• Control the rate of spontaneous emission by changing the densities of allowed states
5. Effects of defects

5.2 The cavity: point defects

Cavity optical response is defined with a Quality factor $Q = \frac{\omega}{\Delta\omega}$, where $\Delta\omega$ is the spectral width of the cavity mode

$Q \sim 10^4$

- $Q$ values is to use supermirrors with extremely low losses, suitable for ultra-high $Q$ factors of the order of $10^{11}$
- toroidal silica microcavities with dimensions of the order of 100 μm and $Q$ factors well above $10^8$
- whispering gallery resonator modes exhibiting $Q$ factors around $10^{10}$
### Optical microcavities

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<th>Fabry–Perot</th>
<th>Whispering gallery</th>
<th>Photonic crystal</th>
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<td>$Q/V = 10^2$</td>
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Highest $Q/V$: geometries useful for fundamental research on QED (Kimble, Caltech) but not practical for devices.


$Q/V$ in units $(\lambda/n)^3$
Methods of fabrication

- Self-assembly: vertical deposition methods
  - Two-photon lithography
  - E-beam lithography
  - Etching methods: dry or wet
  - Holographic methods
Photonic crystal fibers (PCF)

- Periodic modulation of the refractive index in its clad
- Made by melting and pulling a close stack of bare fibers

- Single mode guidance at all wavelengths
- Large bending does not affect the waveguiding
- Enhanced nonlinearity: broadband continuum generation
Slow light

300 million meters per second  \(\xrightarrow{17 \text{ m/s}}\)

- Slow light occurs when a propagating pulse is substantially slowed down by the interaction with the medium in which the propagation take place.
- When light is slowed down, it is forced to interact more strongly with the confining material.

Courtesy of the University of Sydney.
Responsive Photonic crystals

PC properties can be tuned by external stimuli

- color displays
- sensors
- inks and paints

Applications:
- security of banknotes

Parameters that can be tuned in a 3D responsive photonic crystal structure.

Thermoresponsive Photonic Crystals

*Figure 2.* Temperature dependence of the reflection spectrum of porous NIPAM gel built with a colloidal crystal template composed of 210 nm silica particles. \( R = \) reflectance. From Ref. [117].
Chemically Responsive Photonic Crystals

Figure 3. Reflection spectra and related photographs of periodically ordered interconnecting porous gels responding to sodium and potassium ions of different concentrations. From Ref. [112].

Electrically Responsive Photonic Crystals

Full-color tuning of an electric RPC in an electrochemical cell

Rewritable Photonic Paper

Writing on photonic paper can be simply realized by changing the lattice constant through solvent swelling.

Xia and Fudouzi have developed a photonic paper/ink system using a PDMS/PS colloidal crystal composite film as paper and organic solvents as ink.

Figure 25. Patterns printed on the photonic papers with firm and soft substrates using silicone fluid as ink. The photonic paper was assembled from 202 nm PS beads in a PDMS matrix. From Ref. [221].
Paper 8

Optional readings

