Photonic Crystals

Introduction
Definition

Photonic crystals are new, artificially created materials, in which refractive index is periodically modulated in a scale compared to the wavelength of operation.

Photonic crystals (PhC) classification

Refractive index can be modulated in 1, 2 and 3 dimensions:

- 1D PhC – multilayer filter
- 2D PhC – Photonic Crystal Fiber (PCF) or planar PhC waveguide
- 3D PhC – ultimate photonic crystal
Photonic crystals history

Periodic media with optical bandgap:
“optical isolator”
Research statistics

Number of scientific papers according to SCI database

- **Photonic Crystal**
- **Integrated Optics**
Integrated Acousto-optic spectrum analyser: LiNbO₃
Add-drop multiplexers - comparison
Historical introduction

Influence of periodic structures on electromagnetic radiation was first proposed by William Lawrence Bragg in 1912.

Normal Plane
NaCl Crystal

Diffraction Calculation

William Lawrence Bragg
1890 - 1971, Nobel Prize in Physics 1915
A regular array of atoms diffracts X-rays when the Bragg condition is met. For incident X-rays of a given wavelength different planes reflect at different Bragg angles.

\[ 2d \sin \theta = n \lambda, \quad n = 1, 2, 3, \ldots \]

Bragg grating works like a reflector if \( \theta = 90^\circ \)
Bragg reflections

Bragg Scattering for Xrays. Each set of planes acts like a mirror in a small range of angles which do not overlap.
Bragg scattering for a photonic crystal

Each set of planes acts like a mirror in a large range of angles which overlap completely. Under these circumstances no radiation can penetrate into the material which is a photonic insulator. For a limit range of frequencies (the band gap) radiation is rejected whatever the incident angle.
Technologies for fabrication of Photonic Crystals

• Multi-step micro-structuring
• multi-stage lithography
• two photon absorption
The first approach – drilling (Yablonovitch)

‘Yablonovite’: a slab of material is covered by a mask consisting of a triangular array of holes. Each hole is drilled through three times, at an angle 35.26° away from normal, and spread out 120° on the azimuth. The resulting criss-cross of holes below the surface of the slab produces a fully three-dimensionally periodic fcc structure.
The very first approach (opal)

Opal comprises sub micron sized silica spheres arranged in a face centred cubic close packed structure. In this electron micrograph the individual spheres are clearly visible under a layer of surface clutter.
Nature’s approach – micro-structuring
The wing of a butterfly consists of a series of scales each a fraction of a millimetre long. In this photograph of an Adonis Blue (Lysandra Bellargus) the small scales are visible as striations of the blue section of the wing. The black spots are caused by the occasional missing scale.
Nature’s approach – micro-structuring

An electron micrograph of a broken scale taken from the butterfly Mitoura Grynea revealing a periodic array of holes responsible for the colour. The bar in the bottom left is one micron long.

*From Helen Ghiradella’s paper on ‘light and color on the wing: structural colors in butterflies and moths’*
Multi-stage lithography
Inexpensive technologies for large scale fabrication

- Self-organising materials
- Holographic lithography
Colloidal crystals

• Colloid scientists have perfected methods for making spherical microparticles of uniform size from polystyrene and silica.
• If left to settle under gravity from a liquid suspension, such microspheres will accumulate layer by layer in close-packed, orderly arrays called colloidal crystals.
• There is no need for any direct manipulation at all: the crystals simply self-assemble spontaneously.
Photonic crystals at Faculty of Microsystem Electronics and Photonics, WUT

SEM photograph of self-organized silica balls
Holographic interferometry

PATTERN GENERATION: Holographic lithography is the alternative method to electron-beam lithography as far as fabricating nano-sized features of relatively large area in photoresist although its usefulness is limited to some selected structures. **IBE** (Ion Beam Etching) is a chosen method of further pattern etching.

**MATERIAL:** Alloys of III–Nitrides (*GaN*, *InN* and *AlN*) are ones of the most promising materials in modern photonics. They all have direct energy bandgap, which causes the high efficiency of photon’s emission, and absorption. In case of gallium nitride there is a possibility of forming solid solutions with *InN* and *AlN*, which allow tailoring of optical and electrical properties.
Holographic exposure

Grating period depends on exposure angle $\alpha$ and $\lambda$ - the wavelength of the laser source:

$$\Lambda = \frac{\lambda}{2 \sin \alpha}$$

<table>
<thead>
<tr>
<th>Exposure angle $\alpha$ [degrees]</th>
<th>Period $\Lambda$ [nm]</th>
<th>Stripe width [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.69</td>
<td>6000</td>
<td>3000</td>
</tr>
<tr>
<td>3.2</td>
<td>3170</td>
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<td>6.45</td>
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<td>790</td>
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<td>10.5</td>
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<td>485</td>
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<tr>
<td>15</td>
<td>685</td>
<td>342</td>
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<tr>
<td>20.4</td>
<td>509</td>
<td>255</td>
</tr>
</tbody>
</table>
The 1st step
– fabrication of a 1D grating

GRATING COUPLER OBTAINED WITH HOLOGRAPHIC EXPOSURE SETUP

Very useful method of producing corrugations in a photoresist film is exposing it with two interfering laser beams. It’s also known as holographic method of fabricating diffraction gratings. The photoresist patterns are made by exposing the resist, deposited on suitable substrate, to the holographic fringe pattern and immersing it in developer.
2nd step – fabrication of the photonic crystal

TWO-STEP HOLOGRAPHIC EXPOSURE: in first step of that process one diffraction grating is produced in photoresist by exposing it with two interfering laser beams. Exposure angle $\alpha$ is shown in below and grating period depends on that parameter. After that sample was rotated through an angle $\Theta$ (inclination angle).
Photonic crystals applications areas

- optics,
- optoelectronics,
- μ-wave technologies,
- quantum engineering,
- bio-photonics,
- acoustics,
- and many others.
2D photonic crystals
Photonic crystals - defects

Periodically structured materials

can collect energy inside microresonators

or guide it in waveguides
Defects – Electron beam deposition

Precursors: organometallic compound hydrocarbon
Pattern generation

Own result
Pattern generation

Own result
Modelling methods

• Frequency domain methods

Plane wave method
(bang gap)

• Time domain method

Finite Difference Time Domain
(band gap, defects, finite structure, transmission and reflection coefficient)
Maxwell equations

\[ \nabla \cdot D(r,t) = \rho \quad \nabla \times E(r,t) = -\frac{\partial B(r,t)}{\partial t} \]

\[ \nabla \cdot B(r,t) = 0 \quad \nabla \times H(r,t) = J(r,t) + \frac{\partial D(r,t)}{\partial t} \]

- Source free space \( \rho = J = 0 \)
- Lossless medium: \( \varepsilon(r) \) is real in our interested region
- \( \varepsilon(r) \) linear and time invariant \( \varepsilon(r, \omega) = \varepsilon(r) \)
- \( \mu(r) = 1 \)
Eigenvalue problem

\[ \nabla \times \frac{1}{\varepsilon(r)} \nabla \times \vec{H}(r) = \frac{\omega^2}{c^2} \vec{H}(r) \]

Hermitian operator

\[ H_1(r) \quad \text{dla} \quad \omega_1 \quad \quad H_2(r) \quad \omega_2 \]

\[ (H_1, H_2) = 0 \]

Eigenvalue

\[ \omega^2 \]

Real

Positive value
Various photonic crystal structures of different dimensions and corresponding Brillouin zones.
Square lattice of columns

Columns n=3.6
Backgrounds n=1

1 Brillouin zone
Square lattice of holes

Holes n=1
Background n=3.6

I Brillouin zone
Triangular lattice

Columns $n=3.6$
Backgrounds $n=1$

I Brillouin zone
Photonic crystals slab

SC (Semiconductor Clad)
Dry Etching
High Aspect-Ratio
Clad
AB (Air Bridge)
Selective Wet Etching
OC (Oxide Clad)
Selective Oxidization

Photonic crystals – examples of application

• light sources including nanolasers,
• waveguide components for a next era functional circuits by photons,
• passive components and fibers
Fabrication technologies for photonic crystals

- semiconductor process techniques,
- nano-manipulation techniques,
- self-organization techniques,
- holographic techniques,