Photonic crystals, PHYS-605

Ecole doctorale photonique

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V Measurement techniques

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   Novel materials (chalcogenide, diamond, GaN,...)
   Thermal photovoltaic
   Topological transitions
   ...
Goal

Once our photonic crystal structure has been (painfully) fabricated and characterised (SEM etc...)

How can we measure its optical properties, it was designed for ?

Which optical properties ?

- Optical response
  - Transmission, $T$
  - Reflection, $R$
  - Diffraction, $D$
  - Absorption, $A$
  - Losses, $L = 1 - T - R - D - A$

- Band structure
  - Dispersion curve
  - Group index

- Non-linear properties
Which optical properties?

- Localised state
  - Optical cavity
  - Resonance frequencies
  - Quality factor

- Light propagation inside the photonic crystal

- Dynamic properties (time resolved)
- Emission properties (spontaneous, amplified, laser)
- Wavelength
  - Visible / near infra-red
  - Far infra-red
  - Microwave

Which photonic crystal structure?

- 3D photonic crystal

- 2D photonic crystal
Which photonic crystal structure?

- **Material**
  - Dielectric / Semiconductor
  - Metal

- **Use**
  - Physics
  - Device

Techniques outline

Lithographic tuning

External light source
- Reflectivity
- End fire

Internal light source
- Internal light source
- Luminescence spectroscopy

Advanced techniques
- Local probe, SNOM
- Time resolved
- Fourier imaging
Lithographic tuning

Scaling laws

\[ r \rightarrow r' = rs \]
\[ \varepsilon(r) \rightarrow \varepsilon(r') \]
\[ k \rightarrow k' = k/s \]
\[ \omega \rightarrow \omega' = \omega/s \]
\[ H(r) \rightarrow H(r') \]
\[ E(r) \rightarrow E(r') \]

Reduced units

Energy:
\[ u = \frac{a}{\lambda} = \frac{\omega a}{2\pi c} \]

Wave vector:
\[ \mathbf{k} = \frac{ka}{2\pi} \]

\( a \) : lattice parameter

Lithographic tuning

Wavelength, energy scan

Reduced energy:
\[ u = \frac{a}{\lambda} = \frac{\omega a}{2\pi c} \]

\( a \) : lattice parameter

either scan \( u \) by changing the lattice constant. Often more convenient.
External source
Reflectivity & transmission measurements

Simple R&T measurements to probe the photonic bandgap

Similar to the measurement of a dielectric multi-layer sample

Planar GaAs/AlAs Fabry-Perot cavity

External source
Reflectivity & transmission measurements

Spectral resolution
In a linear regime, light source can be a wavelength tuneable source or a white light source and spectral resolution is performed afterwards
External source
Reflectivity & transmission measurements

Quantitative measurements require a good measurement of the reference (incoming intensity)

Many set-up designs, one example:

![Diagram of set-up](image)

Similar set-up in transmission with a Mach-Zehnder's like geometry

Quantitative measurement

Note: it is not easy to measure directly reflectivity coefficients close to unity

This would imply being able to discriminate between e.g. R=0.999 and R=0.997

It is much more convenient to use the mirror to build a high Q optical cavity and deduce R from Q
External source
Reflectivity & transmission measurements

Simple R&T measurements to probe the photonic bandgap

Note that:
- T=0 does not prove R=1
- No angular investigation (full bandgap ?)
- Polarisation ?

First measurements performed on opals of 0.11 μm polystyrene microspheres


External source
Reflectivity & transmission measurements

Simple R&T measurements to probe the photonic bandgap

inverted opal

External source
Angular reflectivity

Principle

Measurement:
- Intensity vs. angle(s) at constant wavelength
- Intensity vs. wavelength at constant angle(s)

Light is reflected according to the grating diffraction law

Conservation of the in-plane component of the wavevector

\[ k_{\parallel}^{\text{ref}} = k_{\parallel}^{\text{inc}} + G = k_{\parallel}^{\text{inc}} + \sum_i m_i G_i \]

\( G \) : vector of the reciprocal lattice

\( m_i = 0 \) : specular reflection
\( m_i \neq 0 \) : diffraction

As such, it will provide information on the reciprocal lattice but not the band structure (?)
• For some specific set of incident $k$ and wavelength, light can couple to a mode into the photonic crystal

• Giving rise to a dip in the reflected intensity spectrum (Wood anomaly)

• Will provide information on the band structure $k(\omega)$

• Simple picture:

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad \text{in-plane } k \text{ conservation}
\]

\[
k_0 n_1 \sin \theta_1 = k_0 n_2 \sin \theta_2 \quad \beta_1 = \beta_2
\]

• In the case of a bi-dimensional medium 2, the equi-frequency surface is reduced to a curve in the plane $k_x, k_y$, i.e. points in the $k_x, k_z$ plane
In real life experiment are not so straightforward to interpret due to the complex shape of the reflectivity spectrum

Macroporous silicon

For 3D structures, the measurement probes mainly the density of states and its associated singularities

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Measurement above the light line limit
Extension to larger $k$-values

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Measurement above the light line limit
Extension to larger k-values

$n_{\text{ZnSe}} = 2.4$

- Experiment is difficult
- Resolution is limited by the sphere astigmatism and field of view
- Analysis is delicate
- Experiment does not discriminate between true propagating slow modes and localised defect modes
External source
End-Fire

Principle

Light input or output:
- Optical fiber, single mode
- Free space

Light source:
- Tuneable source, laser
- Broadband source, white light, LED, super-luminescent LED, ...
External source
End-Fire

Principle

Light coupling in/out:
- Microscope objective, free space
- Tapered, microlensed fiber

Polarisation in/out:
- Polarisation maintaining fibers
- Polarisation control
- Polarisation analysis
- Polariser, $\lambda/2$ and $\lambda/4$ retarding plates
- Coiled fibers
- Often reduced to a TE/TM control / analysis

Newport App. Note 20
External source

End-Fire

Principle

Sample:
- Access waveguide
  - Deep / shallow etched ridge waveguide
- Taper access waveguide / PhC waveguide
- PhC device

External source

End-Fire

Principle

Sample:
- Access waveguide
  - Deep / shallow etched ridge waveguide
- Taper access waveguide / PhC waveguide
- PhC device
External source
End-Fire

Principle
Imaging set-up if working in free space can be convenient
- Si CCD
- IR Vidicon
- IR InGaAs CCD

Detector
- Si
- InGaAs
- + spectrometer

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End-Fire

Transmission spectrum, ideal case

InP-based W3: $W \approx 1 \mu m$

but more commonly:

due to internal reflections and cavity fringes

Examples, device characterisation


Measurement of R, T and propagation losses

Cut-back method

\[ \frac{S}{I} = Te^{-\alpha L} \]

\[ \text{Ln} \left( \frac{S}{I} \right) = \text{Ln}(T) - \alpha L \]

\[ \left( \frac{S}{I} \right)_{\text{dB}} = 10 \cdot \log_{10}(T) - \frac{\alpha}{\text{Ln}(10)} L \]

\[ A_{\text{dB/cm}} = 10 \cdot \frac{\alpha}{\text{Ln}(10)} = 4.34 \cdot \alpha_{\text{cm}^{-1}} \]

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Measurement of R, T and propagation losses

Cut-back method, examples


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End-Fire

Transmission spectrum, parasitic reflections

Due to internal reflections and cavity fringes:
- at the cleaved facets
- at the tapers
- inside the PhC structure
- ...

Undesirable for the device performance but let's make use of them for characterisation

Measurement of R, T and propagation losses

Hakki-Paoli method

Fabry-Perot cavity fringes equally spaced in energy

\[
T_{FP} = \frac{T^2 e^{-\alpha L}}{1 + R^2 e^{-2\alpha L} - 2 R e^{-\alpha L} \cos\left(\frac{4\pi n L}{\lambda}\right)}
\]

\[
T_{\min} = \frac{T^2 e^{-\alpha L}}{(1 + R e^{-\alpha L})^2}
\]

\[
T_{\max} = \frac{T^2 e^{-\alpha L}}{(1 - R e^{-\alpha L})^2}
\]

\[
u = \sqrt{\frac{T_{\min}}{T_{\max}}} = \sqrt{\frac{P_{\min}}{P_{\max}}}
\]

- \(u^2\) = inverse of the fringe contrast \(P_{\max}/P_{\min}\)
- does not require quantitative measurement

\[
f(u) = \ln\left(\frac{1 - u}{1 + u}\right) = \ln(R) - \alpha L
\]
Measurement of R, T and propagation losses

Example

![Image](image1.png)

InP

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Measurement of R, T and propagation losses

Hofstetter method

the Hofstetter method generalises the Hakki-Paoli method to the higher orders of the Fourier transform of the transmission spectrum

![Image](image2.png)

Amplitude decay of the harmonic n

\[ A_r = \text{attenuation after } n \text{ single passes} \]

\[ A_{r,n} = R^n e^{-n \alpha L} \]

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Measurement of R, T and propagation losses

Hofstetter method

\[ A = RT^2 e^{-\alpha_{\text{CPh}} L_{\text{CPh}}} e^{-\alpha_R (L_{r1} + L_{r2})} \]

after division by a reference waveguide

\[ \ln(A_r/A_{\text{CPh}}) = - \ln T^2 + (\alpha_{\text{CPh}} - \alpha_r) L_{\text{CPh}} \]


Internal reflections lead to multiple cavities

- harmonics 1 and 4 : \( L_{r1} \)
- harmonics 2 and 5 : \( L_{r2} \)
- harmonics 3 and 6 : \( L_T \)
Dispersion curve

Fabry-Perot fringes and k-space sampling

Fabry-Perot fringes equally spaced in energy?

\[ T_{FP} = \frac{T^2}{1 + R^2 - 2R \cos\left(\frac{4\pi nL}{\lambda}\right)} \quad \text{or} \quad T_{FP} = \frac{T^2}{1 + R^2 - 2R \cos(2kL)} \]

resonances equally spaced in k \( \Delta k = \frac{\pi}{L} \)

Note: sampling in \( \Delta k \), exact k values are more difficult to determine

Sampling

A simple way to see that, consists in unfolding the images from both mirrors. This leads to a periodic structure with period 2L and a \( 2\pi/2L = \pi/L \) periodicity in k-space
Dispersion curve measurement

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Dispersion curve measurement

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Dispersion curve measurement

Mach-Zehnder interferometer

![Diagram of Mach-Zehnder interferometer](image)

**Figure 3**: Active electrically tunable MZI with lateral electrical contacts to photonic crystal waveguides. a. Time averaged magnetic field energy

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Optical cavities, high quality factor

Measurement of the cavity requires coupling to a probe which affect the Q

- Intrinsic $Q = Q_{\text{int}}$, unloaded cavity, coupling only to free space radiation and material losses, defects
- Coupling $Q = Q_{\text{probe}}$, additional losses due to the measurement
- Measured $Q = Q_{\text{meas}}$, loaded cavity

\[
\frac{1}{Q_{\text{meas}}} = \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{probe}}}
\]
Optical cavities, high quality factor

\[
T = \frac{T_2}{T_1}
\]

\[
Q_{\text{int}} = \frac{Q_{\text{meas}}}{\sqrt{T}}
\]

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Internal source

ILS

Goal, a versatile technique that:
- does not require the full fabrication of device with access waveguides etc...
- allows the light source to be injected where needed
- allows quantitative measurements

ILS

Principle: Insert light emitters inside the planar waveguide
- Quantum wells
- "bad" quantum dots (large emission band)

\[ T_a(\lambda) = \frac{I_2(\lambda)}{I_1(\lambda)} \Rightarrow T(u = \frac{a}{\lambda}) \]

And make use of lithographic tuning

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Experimental set-up

Transmission spectrum

Examples

\[ \text{Transmission} \]

\[ \begin{align*}
\Gamma M & : 10 \text{ rows} \\
\text{TE polarization} & \\
\text{InP/(Ga,In)(As,P) QW} & \\
\lambda & = 1.55 \mu m \ f = 30% \\
\end{align*} \]
Limitation

QW or QD absorption in the waveguide

![Graph showing absorption and transmission spectra.]

Photoluminescence

Light source inside the PhC structure

- PhC defect
  - Point defect, optical cavity

Front photoluminescence emission

![Diagram illustrating light collection and scattering.]
Photoluminescence

Mode spectroscopy

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Photoluminescence

Mode spectroscopy

Coupled with angular resolution

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Photoluminescence

Time resolved

Life time modification, Purcell effect, emission enhancement and inhibition

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Photoluminescence

Light source inside the PhC structure
- PhC defect
  - Line defect, waveguide

Probing the density of states singularities

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Photoluminescence

Light source inside the PhC structure
• Bulk 3D PhC

Probing the local density of states singularities, lifetime modification

CdSe nanocrystals in inverted opals

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- Photoluminescence

Light source inside the PhC structure
• Bulk 2D PhC

Probing the local density of states singularities, lifetime modification

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Advanced techniques
Local probes, SNOM

Principle
Probe the near field electromagnetic field with a local probe

![Diagram showing near field, evanescent, propagating field and probe]

Advanced techniques
Local probes, SNOM

Principle
Different configurations

Illumination

Collection

a) fiber tip sample
b) b)

c) detector
d) Evanescent (TIR)

Apertureless

Advanced techniques
Local probes, SNOM

Principle
Tricks are in :
- Tip position control, as in STM, AFM
- Tip fabrication

Examples, bends

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Examples, cavities

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Nice images, but difficult to be quantitative
SNOM

Examples, opals

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SNOM

Examples, 2D macroporous PhC

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T-SNOM

Mode field pattern mapping or modification with AFM tip

- scanning tip smaller, lower perturbation
- for small high Q cavities
- tip – change in Q factor or resonance wavelength

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Advanced techniques
"Heterodyne" SNOM

Usual SNOM measures intensity, what about amplitude? (i.e. intensity and phase)

Insert the SNOM set-up in an interferometer (e.g. Mach-Zender)

Interferences give phase information

Tuneable laser

SNOM

Note: amplitude information is necessary e.g. for numerical Fourier transform
Heterodyne SNOM

Once *amplitude* is known, Fourier transform gives information on the Bloch wave

- Dispersion curves
Advanced techniques
Time resolved SNOM

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Advanced techniques
High Numerical Aperture Fourier Space Imaging of Planar Photonic Crystals

Principle

![Diagram showing principle of Fourier imaging with a sample and objective NA=0.9.]

Single point in the Fourier image (back focal plane) ↔ unique direction of emission ↔ unique in-plane wavevector

Fourier imaging

Principle

Make use of the light scattered off the propagation axis or plane

- intrinsically (above the light line)
- via imperfections / defects (below the light line)
- additional probe structures
Real space imaging of Bloch Waves propagating in PhCs

Imaging of the scattered light
Propagation losses and defect characterization

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Fourier space imaging of Bloch wave emission diagram

Equi-Frequency surfaces mapping in PhCs

Real space

$\lambda = 1.48 \mu m$  $\lambda = 1.51 \mu m$  $\lambda = 1.55 \mu m$  $\lambda = 1.63 \mu m$

Fourier space
Dispersion curves

![Graph showing dispersion curves with TE and TM modes]

Coming soon

Misinterpretation

![Image showing misinterpretation with fringes]

- The fringes are not an image of the Bloch mode.
- They originate from the interference between the forward and backward propagating mode, which are different modes at $+k+mG$ and $-k+mG$
Imaging of W3 PhC waveguide

Real space

InP

1.5μm

1.1μm

Fourier space

k_x (2π/λ)

k_y (2π/λ)

u=0.266

Experimental dispersion curves of a W3 PhC waveguide
Optical and numerical FFT

Because the phase information is still present during the formation of the Fourier image, there is no DC component and forward and backward propagation can be distinguished.

Optical Fourier transform

Numerical 2D-FFT

Comparison SNOM high NA imaging

Near-field

Far-field

Real image

Simulation

Courtesy I. Märki, Uni Neuchâtel
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In-situ characterization of a polarization splitter

(a1) \( f_{\text{pol}} = 0.5 \), \( f_{\text{sc}} = 0.3 \), \( u = 0.3 \)

(a2) \( f_{\text{pol}} = 0.5 \), \( f_{\text{sc}} = 0.3 \), \( u = 0.3 \)

(b1) TE

(b2) TM

In-situ characterization of a polarization splitter

TM polarized light

TE polarized light

T=35%

R=3%

R=25%

T=0.2%
In-situ characterization of a polarization splitter

TE polarized light

Fourier space imaging with filtering in real space

TE polarized light
Fourier space imaging with filtering in real space

TE polarized light

but ...

Problem: most of the interesting structures work below the light line

How to go beyond the light cone limit or how to convert evanescent waves into propagating waves for imaging?
I Make use of fabrication imperfections

Imaging of Bloch wave propagating below the light cone

SC Self-collimation regime

B

Wave vector

Reduced energy $\varepsilon = a^2$

$\lambda \text{ (nm)}$

$\text{REF}$

$\text{SC}$
Make use of finite size effects

Dispersion curves and super-resolution:
Size effect

Fourier space
Dispersion curves and super-resolution: 
Size effect

Dispersion curves and super-resolution: 
Size effect and analytical prolongation

Effective NA = 2.5
Fourier space imaging with filtering in real space

Characterisation below the light cone

TE polarized light

3 Fold back the band structure into the light cone with an extra periodicity

just a small amount to enable measurement
Imaging of dispersion curve below the light cone

\[ G = \frac{2\pi}{\Lambda} \]

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Imaging of dispersion curve below the light cone

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Imaging of Coupled Cavities based Waveguides
Imaging of Coupled Cavities based Waveguides

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