Advanced techniques
Local probes, SNOM

Principle
Probe the near field electromagnetic field with a local probe
Advanced techniques
Local probes, SNOM

Principle
Different configurations

Illumination

Collection

a) fiber tip sample
detector

b) Evanescent (TIR)

c) Apertureless

d) 

Advanced techniques
Local probes, SNOM

Principle

Tricks are in:
• Tip position control, as in STM, AFM
• Tip fabrication
Advanced techniques
Local probes, SNOM

Principle
Tricks are in:

• Tip position control, as in STM, AFM
• Tip fabrication

Examples, bends


with increasing shear force feedback (increasing tip distance)
Examples, cavities


Nice images, but difficult to be quantitative
SNOM

Examples, opals

Light of adjustable wavelengths
Near-field probe with 100nm aperture
constant gap ~10 nm

200nm thick
3D photonic crystal (opal)

Photodiode

vs. tip separation

vs. light wavelength

SNOM

Examples, 2D macroporous PhC

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

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)

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

Advanced techniques
Heterodyne SNOM

Amplitude

Phase

Length, μm

scan area of 35X35μm²

Courtesy I. Märki, Uni Neuchâtel
Once \textit{amplitude} is known, Fourier transform gives information on the Bloch wave

- Dispersion curves

Advanced techniques
Time resolved SNOM

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

Principle

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

optics $k//$ conservation
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

How?

with "well-known" and "old-fashioned" classical optics
Real space imaging of Bloch Waves propagating in PhCs

InP = 1.48 m

λ = 1.48 μm

36 μm

3 μm
Imaging of the scattered light
Propagation losses and defect characterization

\[ \lambda = 1.485 \mu m \]
\[ \lambda = 1.495 \mu m \]

Propagation losses

\[ u = 0.261 \]
\[ u = 0.253 \]
Fourier space imaging of Bloch wave emission diagram

InP 3μm

λ = 1.48 mm
Equi-Frequency surfaces mapping in PhCs

Real space

![Real space plots for different wavelengths](image)

\( \lambda = 1.48 \text{ \(\mu\)m} \)
\( \lambda = 1.51 \text{ \(\mu\)m} \)
\( \lambda = 1.55 \text{ \(\mu\)m} \)
\( \lambda = 1.63 \text{ \(\mu\)m} \)

Fourier space

![Fourier space plots for different wavelengths](image)
Dispersion curves

Reduced frequency $u = \frac{a}{\lambda}$

Wave vector $k \left( \frac{2\pi}{a} \right)$

TM

TE

Objective light line

coming soon
Intuitive image what is going on or avoiding some misinterpretations

Why do we observe emission in a direction determined by the in-plane wave vector conservation rule?

Ideal guided mode

\[ e^{ikr} \]

\[ \Delta \varphi = kr \]

No time averaged structures, just a permanent phase relation due to wave propagation
Intuitive image what is going on or avoiding some misinterpretations

Random defects scattering

No structures in k-space

Each defect has a different emission pattern in intensity and phase

No constructive interferences between scatterers, scattered emission loses phase information
Intuitive image what is going on or avoiding some misinterpretations

Identical defects scattering

\[ \Delta \varphi = kr \]

Structures in k-space at \( k = k_\parallel \)

Constructive interferences between scatterers
Intuitive image what is going on or avoiding some misinterpretations

Periodic identical defects scattering (a grating)

\[ \Delta \varphi = kr + 2m\pi \]

Constructive interferences between scatterers and possibly other diffraction orders

\[ \Delta \varphi = kd \]

Structures in k-space at \( k = Gk_{//} + mG \)
Intuitive image what is going on or avoiding some misinterpretations

- 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 defect W3 PhC waveguide

Real space

Fourier space

InP

$X$ $Y$

1.5$\mu$m

1.1$\mu$m

Real space images and Fourier space plots showing the imaging of defect W3 PhC waveguide. The InP layer is highlighted, and the X and Y axes are marked. The scale bars indicate the measured distances of 1.5$\mu$m and 1.1$\mu$m. The Fourier space plots display the u=0.266 defect. These images illustrate the spatial and spectral analysis of the waveguide's defect structure.
Experimental dispersion curves of a W3 PhC waveguide

Inside the mini-stopband

Above the mini-stopband
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](image1)

![Numerical 2D-FFT](image2)
Comparison SNOM high NA imaging

Near-field

Far-field

1550 nm
Real image

1524 nm
Simulation

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

TM polarized light

\[ T=35\% \]
\[ R=3\% \]

TE polarized light

\[ R=25\% \]
\[ T=0.2\% \]
In-situ characterization of a polarization splitter

TE polarized light

InP

18μm
Fourier space imaging with filtering in real space

TE polarized light

18 µm
Fourier space imaging with filtering in real space

TE polarized light

18μm
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

Stitching errors

SOI

240μm

Reduced energy $u = a/\lambda$

Wave vector

Light line

Objective line

SC 0.2236

I (W)

10^{-6}

10^{-7}

$\lambda$ (μm)

1520 1560 1600 1640
2 Make use of finite size effects
Dispersion curves and super-resolution: Size effect

Fourier space

Intensity (norm.)

k (2\pi/a)

I (arb. units)
Dispersion curves and super-resolution: Size effect

![Graph showing dispersion curves and super-resolution](image)

- Reduced frequency $u = \lambda / a$.
- Objective light line.
- Dispersion curves for TM and TE modes.
- Light lines for different wavelengths:
  - $\lambda = 1.550\,\mu m$
  - $\lambda = 1.630\,\mu m$
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

$18 \mu m$
3 Fold back the band structure into the light cone with an extra periodicity just a small amount to enable measurement
Imaging of Coupled Cavities based Waveguides

SEM

Optical microscope

5.76 μm

5.76 μm

581 μm

5.76 μm
Imaging of Coupled Cavities based Waveguides

SEM
Optical microscope

5.76\mu m

Objective light line

\( k_y (2\pi/a) \)

\( k_x (2\pi/a) \)

\( k (2\pi/a) \)

\( u = a/\lambda \)

\( G_{sc} \)

Imaging of Coupled Cavities based Waveguides
Imaging of slow light propagating below the light cone

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

Imaging of slow light propagating below the light cone

Imaging of slow light propagating below the light cone

Imaging of slow light propagating below the light cone

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