Photonic crystals, PHYS-605

Ecole doctorale photonique

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Summer semester 2017

V Measurement techniques

Contents

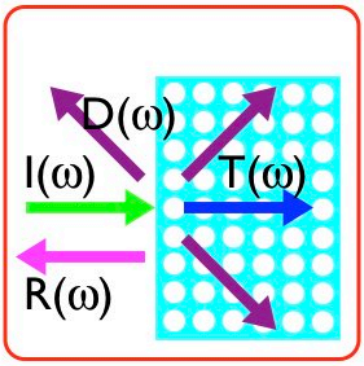
Goal

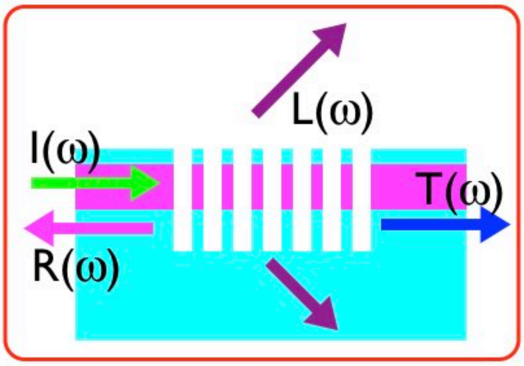
Once our photonic crystal structure has been (painfully) fabricated and characterised (SEM etc...)

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

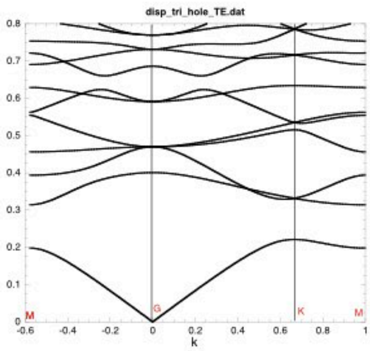
Which optical properties ?

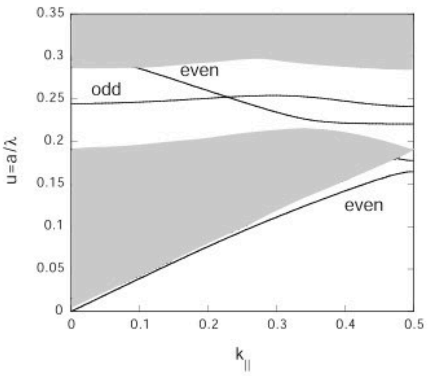
✳ Optical response
- Transmission, T
- Reflection, R
- Diffraction, D
- Absorption, A
- Losses, L=1-T-R-D-A





✳ Band structure
- Dispersion curve
- Group index

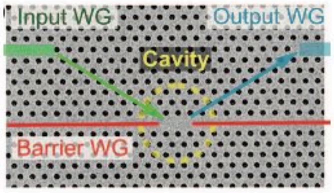


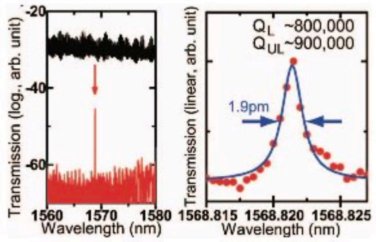


✳ Non-linear properties

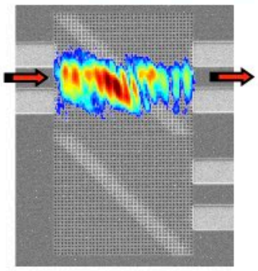
Which optical properties ?

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





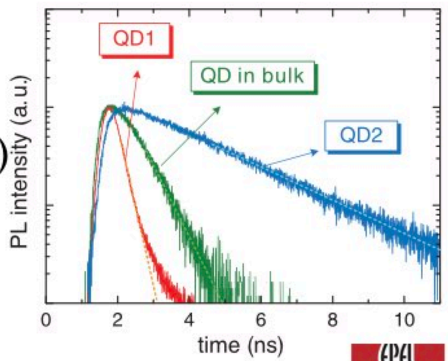
✳ Light propagation inside the photonic crystal



✳ Dynamic properties (time resolved)

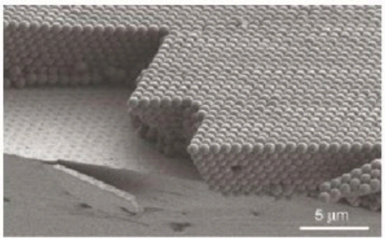
✳ Emission properties (spontaneous, amplified, laser)

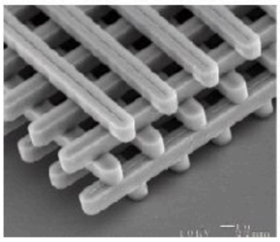
✳ Wavelength
- Visible / near infra-red
- Far infra-red
- Microwave



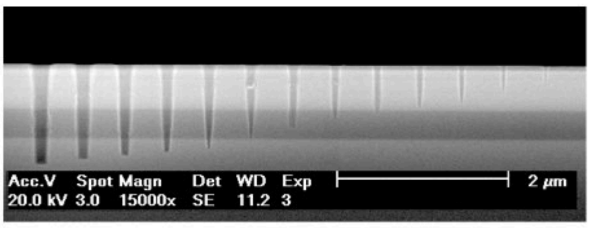
Which photonic crystal structure ?

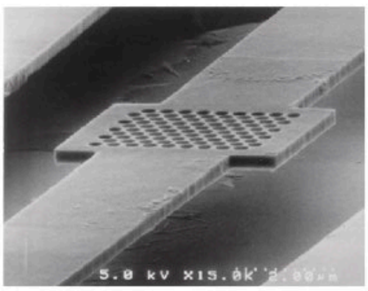
✳ 3D photonic crystal

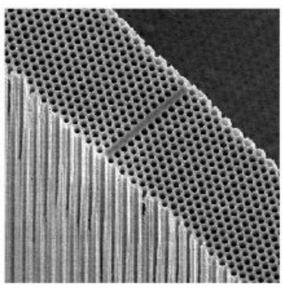




✳ 2D photonic crystal



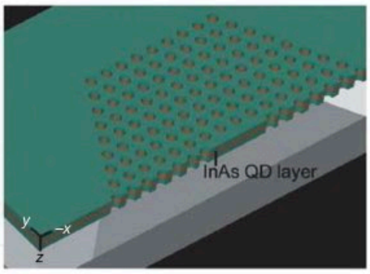


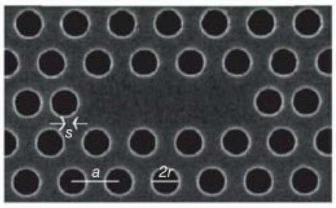


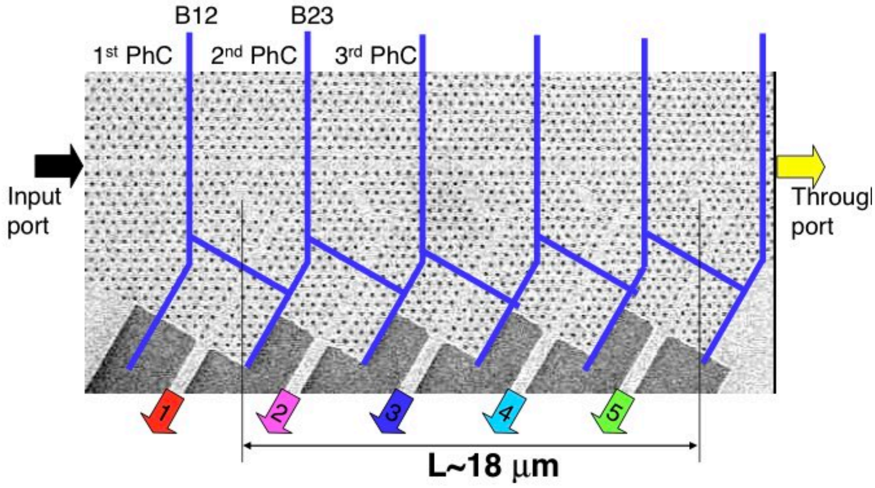
Which photonic crystal structure ?

✳ 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

$$r \rightarrow r' = r.s$$
$$\varepsilon(r) \rightarrow \varepsilon(r')$$
$$k \rightarrow k' = k/s$$
$$\omega \rightarrow \omega' = \omega/s$$
$$H(r) \rightarrow H(r')$$
$$E(r) \rightarrow E(r')$$

Reduced units

Energy : $u = \dfrac{a}{\lambda} = \dfrac{\omega a}{2\pi c}$

Wave vector : $\tilde{k} = \dfrac{ka}{2\pi}$

a : lattice parameter

Lithographic tuning

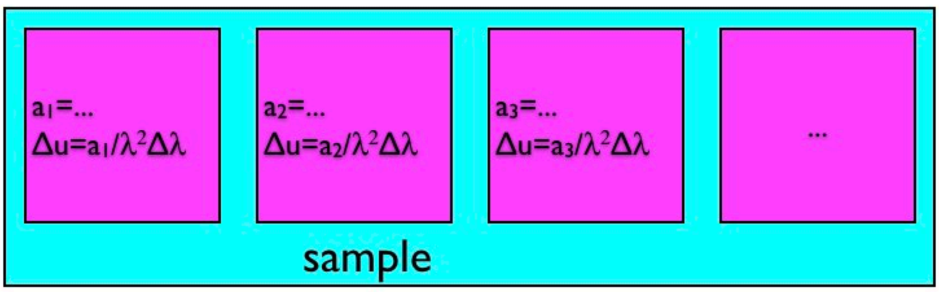
Wavelength, energy scan

Reduced energy : $u = \dfrac{a}{\lambda} = \dfrac{\omega a}{2\pi c}$

either scan u by changing the lattice constant. Often more convenient.

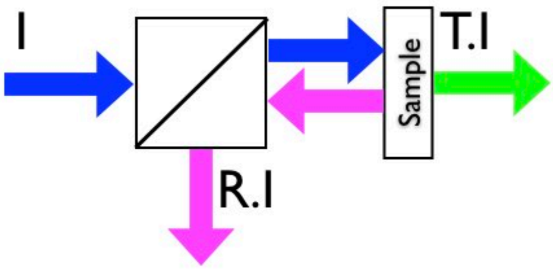
either scan u by changing the wavelength

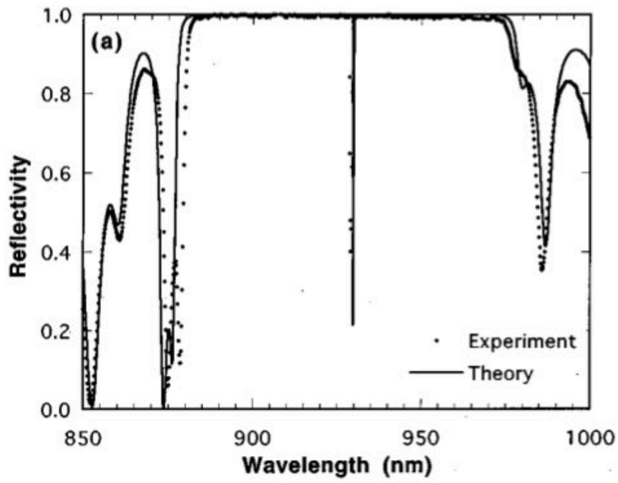
a : lattice parameter



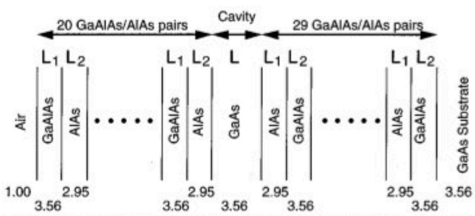
External source
Reflectivity & transmission measurements

Simple R&T measurements to probe the photonic bandgap





Similar to the measurement of a dielectric multi-layer sample



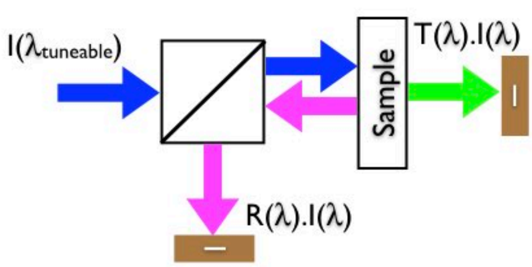
Planar GaAs/AlAs Fabry-Perot cavity

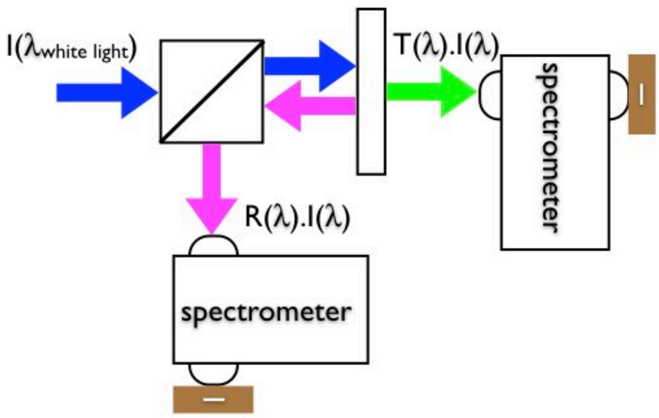
R.P. Stanley et al., Appl. Phys. Lett., 65, 1883, (1994)

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

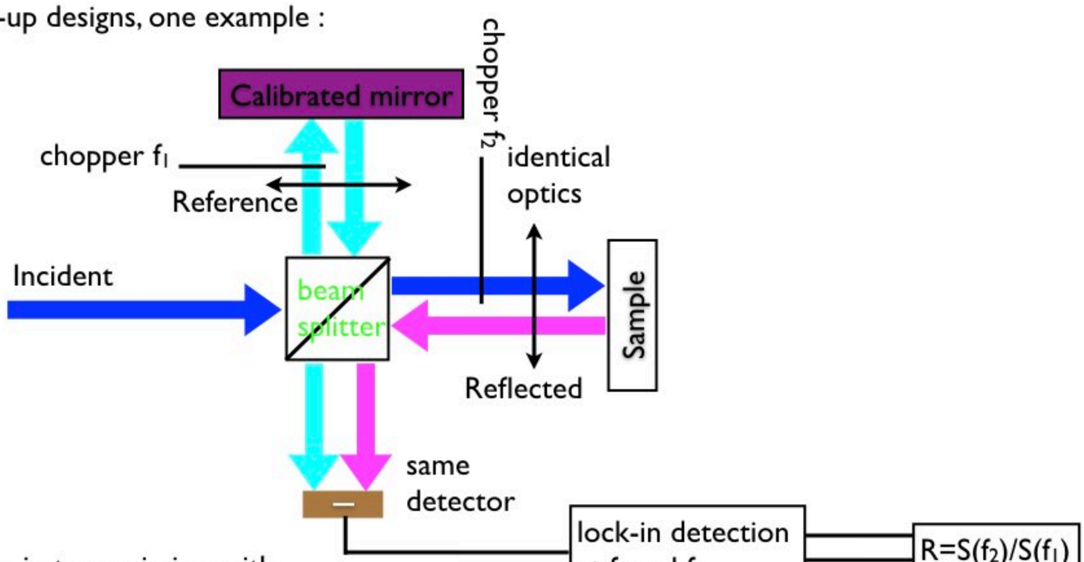




External source
Reflectivity & transmission measurements

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

Many set-up designs, one example :



Similar set-up in transmission with a Mach-Zehnders like geometry

External source
Reflectivity & transmission measurements

Quantitative measurement

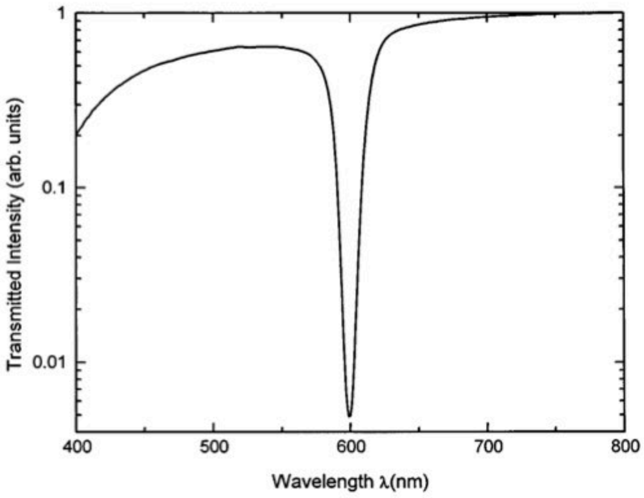
Note: it is not easy to measure directly reflectivity coefficients close to unity

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:

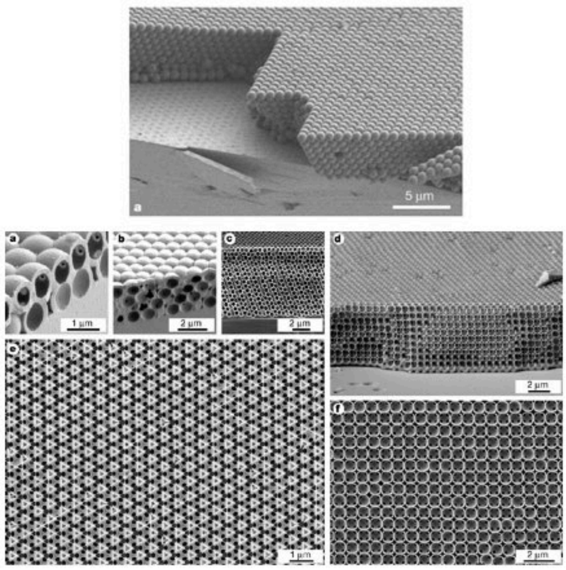
- T=0 does not prove R=1
- No angular investigation (full bandgap ?)
- Polarisation ?

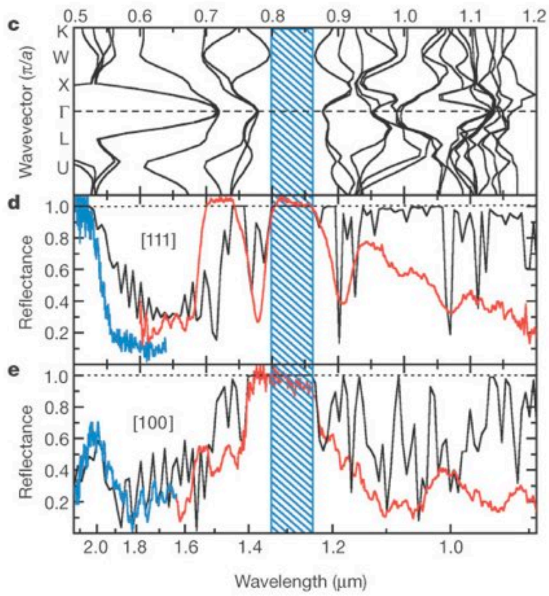
First measurements performed on opals of 0.11µm polystyrene microspheres

I. Inanç Tarhan et al., Opt. Lett., 20, 1571, (1995)

External source
Reflectivity & transmission measurements

Simple R&T measurements to probe the photonic bandgap



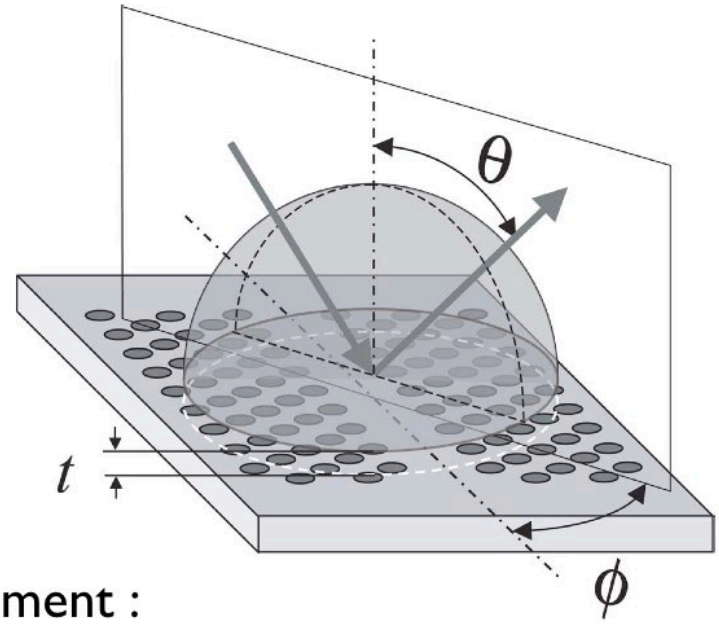


inverted opal

Y.A. Vlasov et al., Nature, 414, 289, (2001)

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

$$k_{//}^{ref} = k_{//}^{inc} + G = k_{//}^{inc} + \sum_i m_i G_i$$

G : vector of the reciprocal lattice

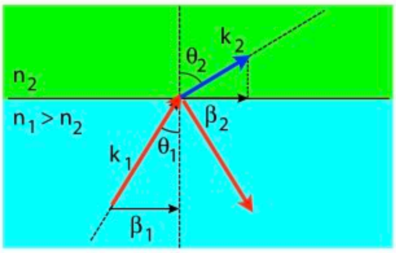
$m_i = 0$: specular reflection
$m_i \neq 0$: diffraction

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

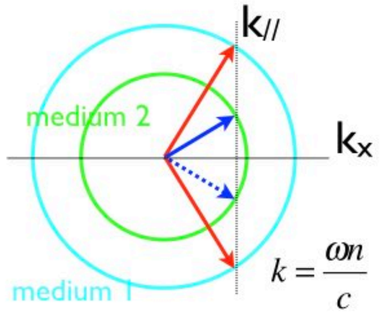
- Giving rise to a dip in the reflected intensity spectrum (Wood anomaly)
- Will provide information on the band structure k(ω)

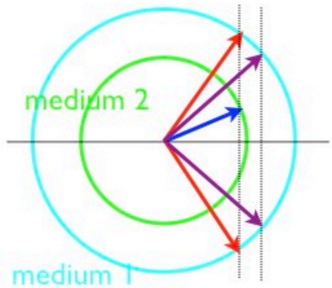
- Simple picture :



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$ in-plane k conservation

$$k_0 n_1 \sin\theta_1 = k_0 n_2 \sin\theta_2 \qquad \beta_1 = \beta_2$$



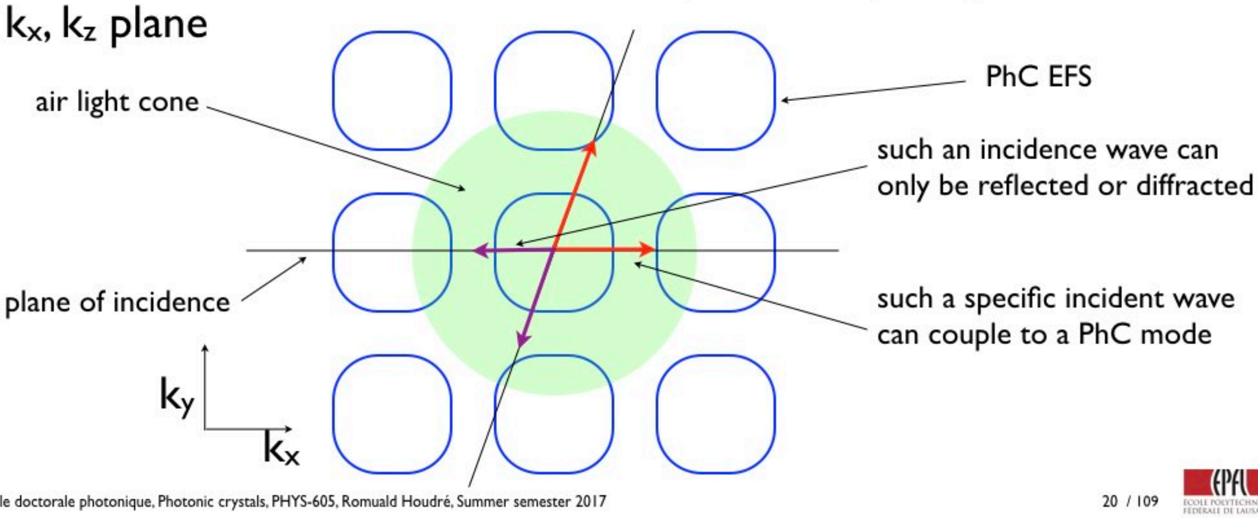


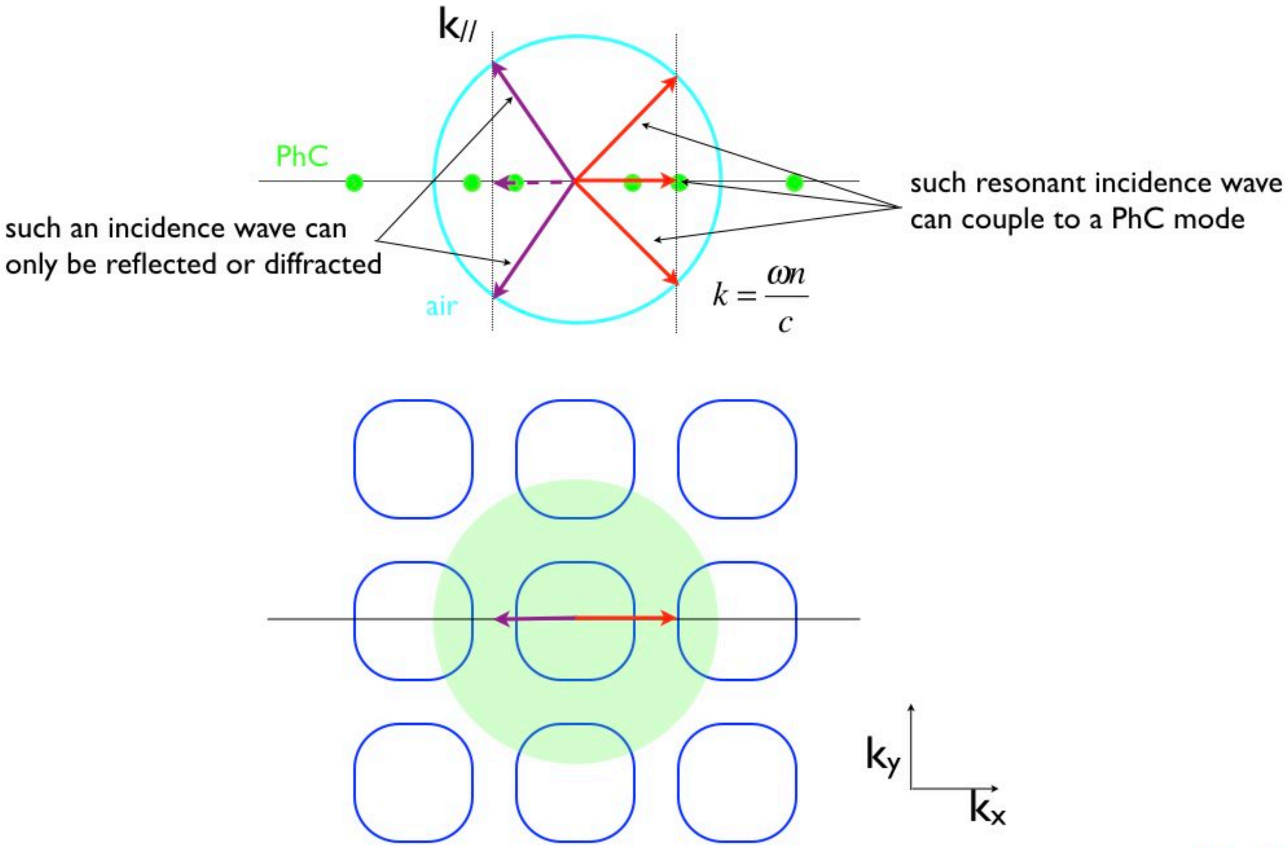
Total internal reflexion :

✳ $k<n_2\omega/c$: coupling 1 to 2 possible

✳ $k>n_2\omega/c$: coupling 1 to 2 impossible

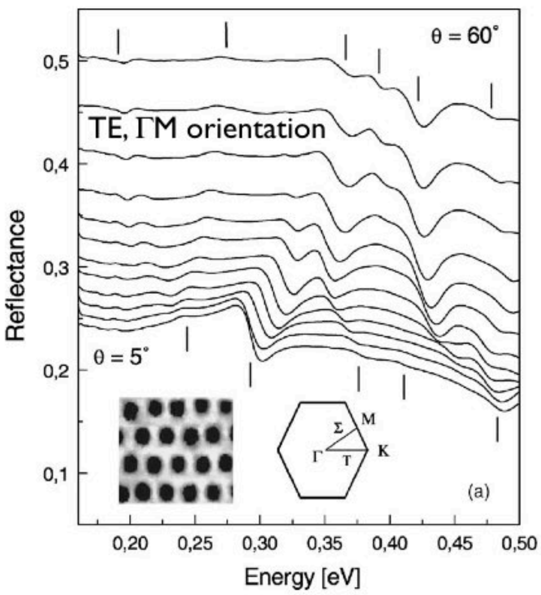
- In the case of a bi-dimensional medium 2, the equi-frequency surface is reduced to a curve in the plane k_x, k_y, *i.e.* points in the k_x, k_z plane

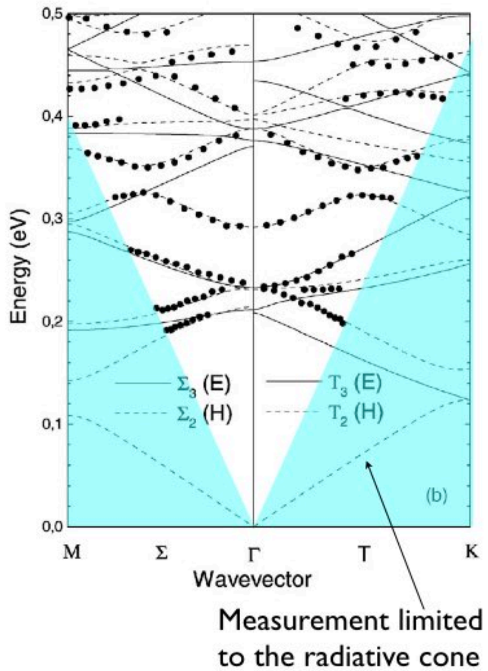




In real life experiment are not so straightforward to interpret due to the complex shape of the reflectivity spectrum

Macroporous silicon

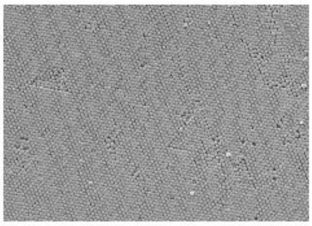


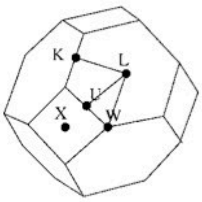


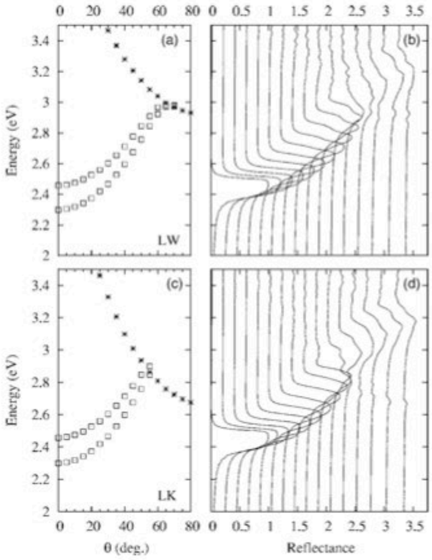
M. Galli et al., Phys. Rev. B, 65, 113111, (2002)

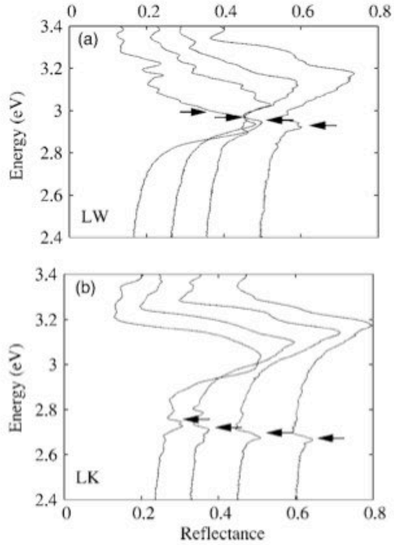
For 3D structures, the measurement probes mainly the density of states and its associated singularities

Artificial opals





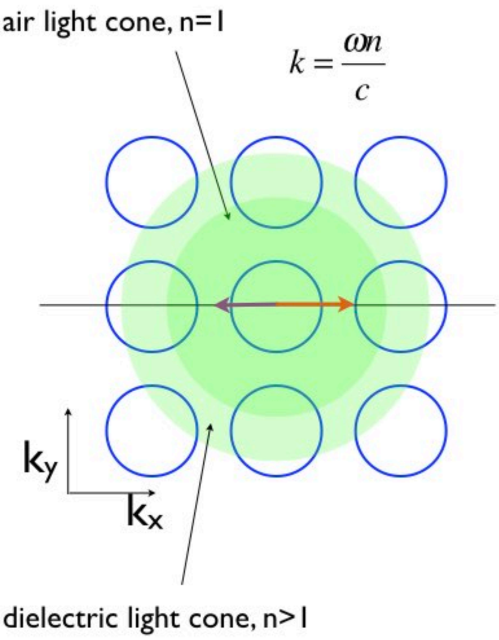


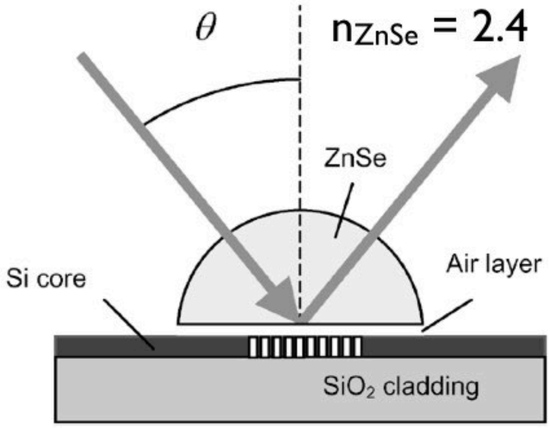


E. Pavarini. et al., Phys. Rev. B, 72, 045102, (2005)

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

$$k = \frac{\omega n}{c}$$





M. Galli et al., Phys. Rev. B, 70, 081307, (2004), M. Galli et al., Phys. Rev. B, 72, 125322, (2005)

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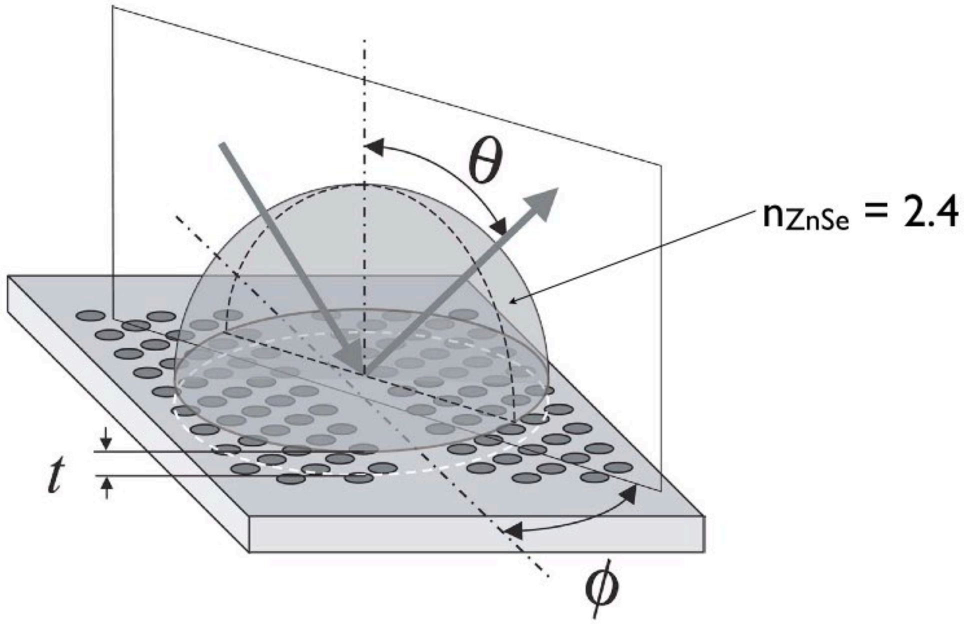

Measurement above the light line limit
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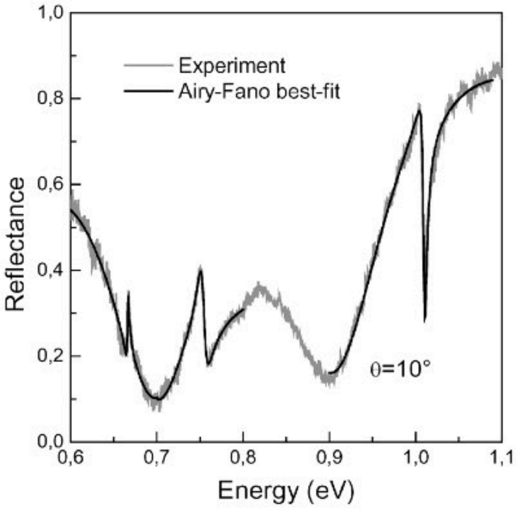
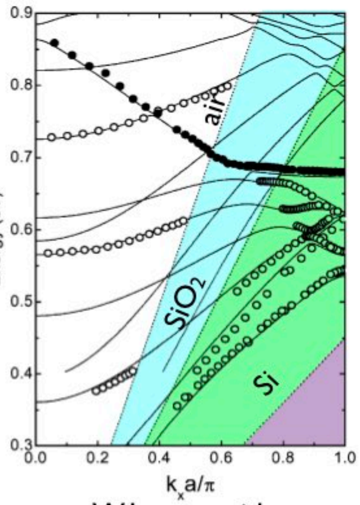
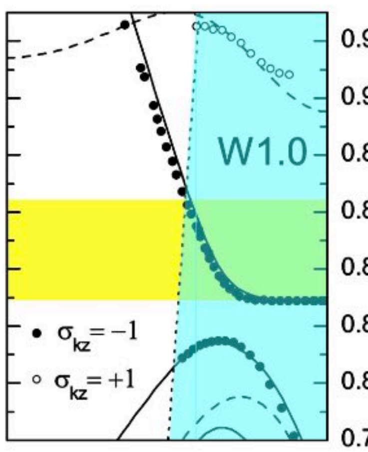




W1 waveguide

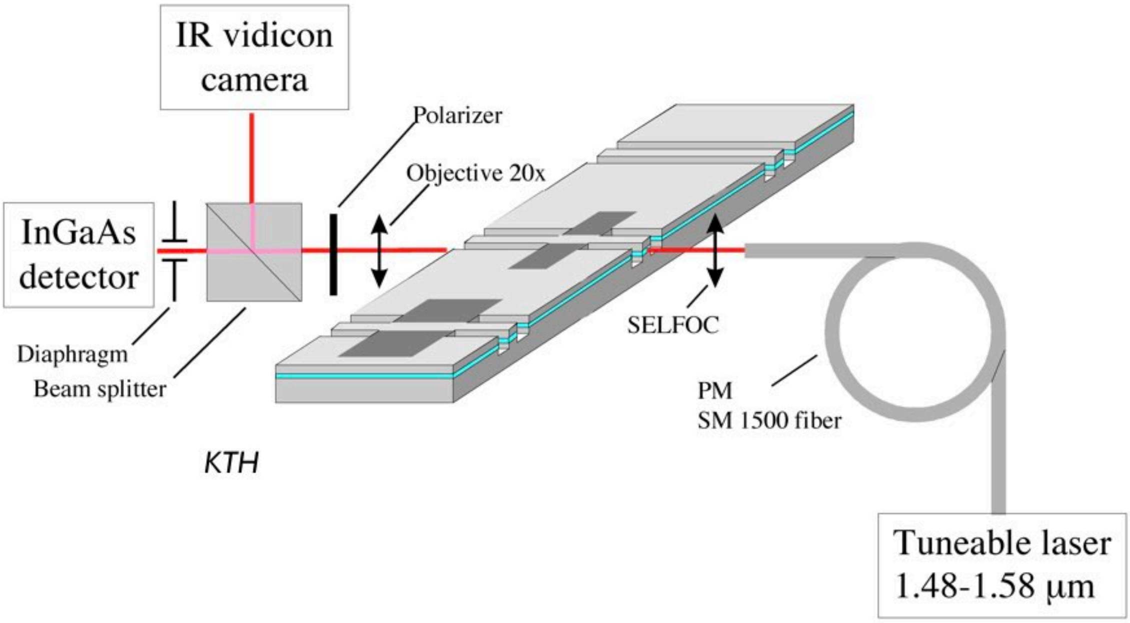


W1 waveguide

- 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

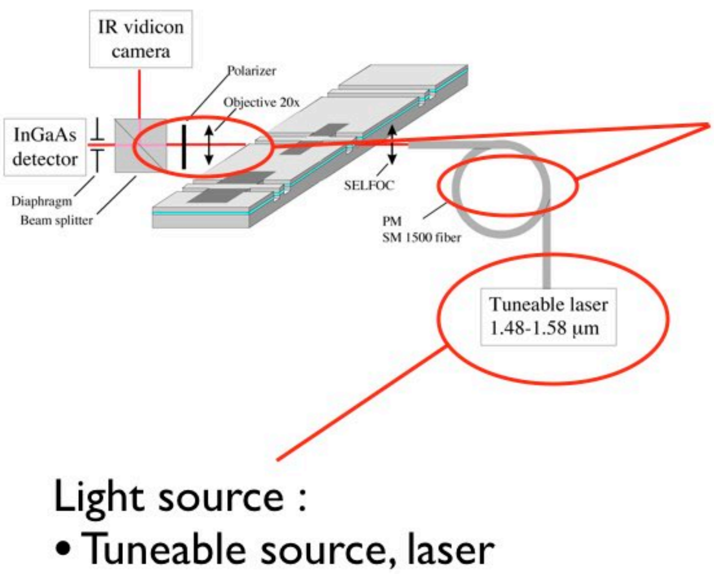
Principle



KTH

External source
End-Fire

Principle

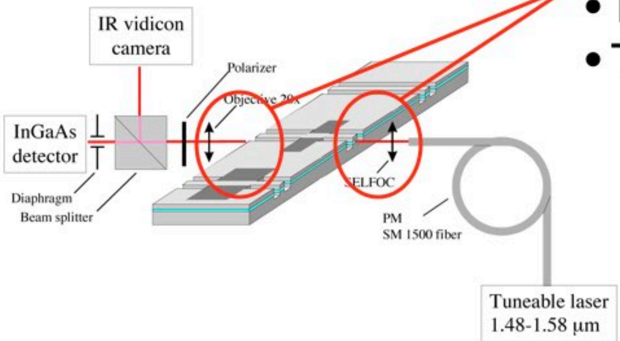


Light input or output :
- Optical fiber, single mode
- Free space

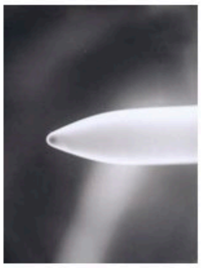
Light source :
- Tuneable source, laser
- Broadband source, white light, LED, super-luminescent LED, ...

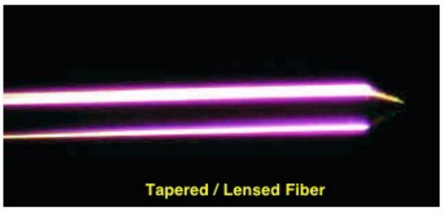
External source
End-Fire

Principle



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





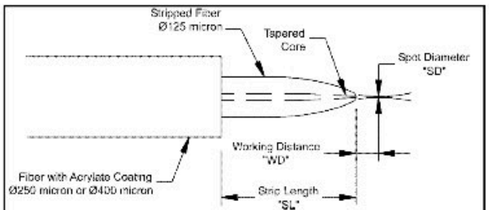


Figure 1: Laser Shaped Lensed Fiber (End Detail)

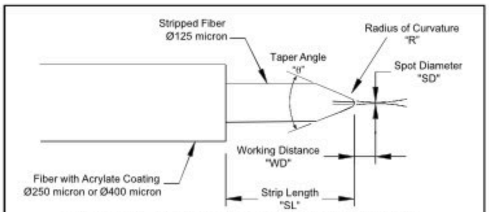
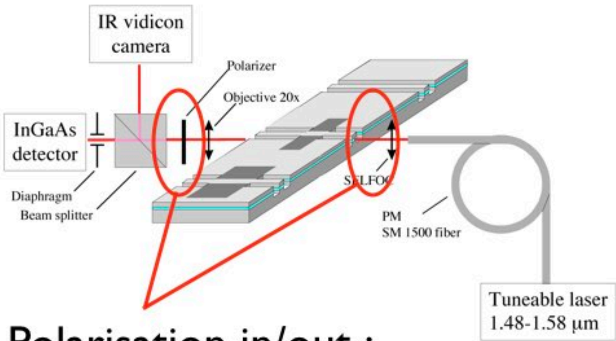


Figure 2: Polished Lensed Fiber (End Detail)

DTS0080 OZ Optics reserves the right to change any specifications without prior notice. 29-Nov-04

External source
End-Fire

Principle



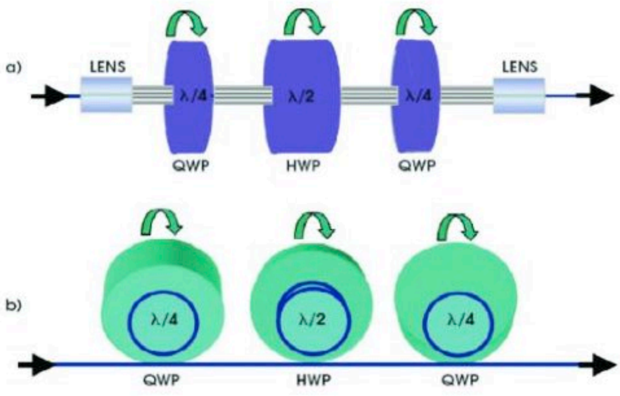


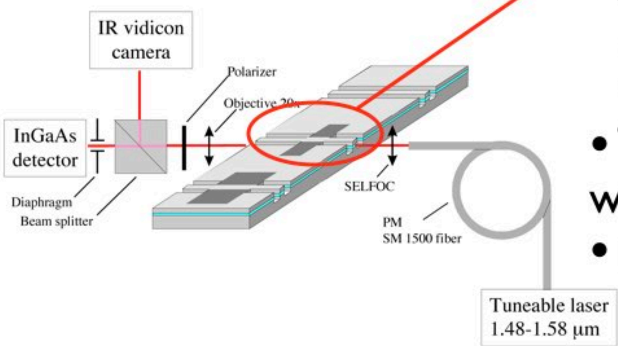
Figure 6. Polarization control using, a) multiple wave plates and, b) using multiple coiled fiber.

Newport App. Note 20

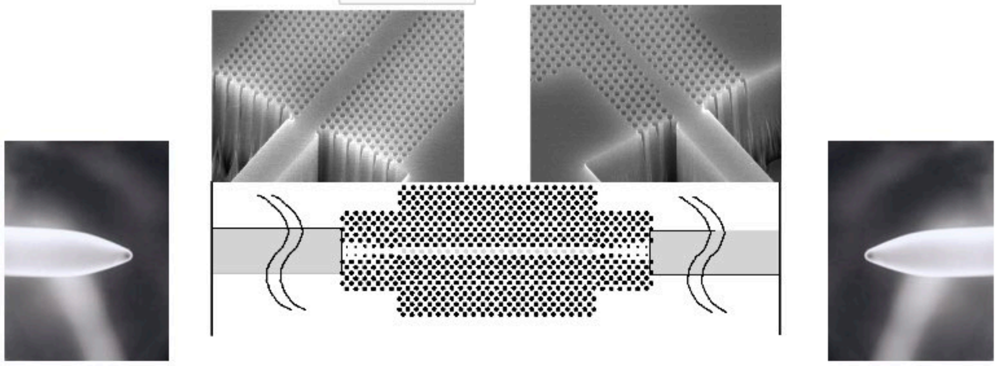
Polarisation in/out :
- Polarisation maintaining fibers
- Polarisation control
- Polarisation analysis
- Polariser, $\lambda/2$ and $\lambda/4$ retarding plates
- Coiled fibers
- Often reduced to a TE/TM control / analysis

External source
End-Fire

Principle

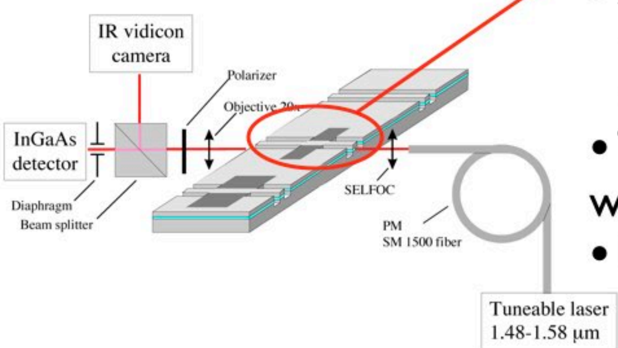


Sample :
- Access waveguide
  - Deep / shallow etched ridge waveguide
- Taper access waveguide / PhC waveguide
- PhC device



External source
End-Fire

Principle



Sample :
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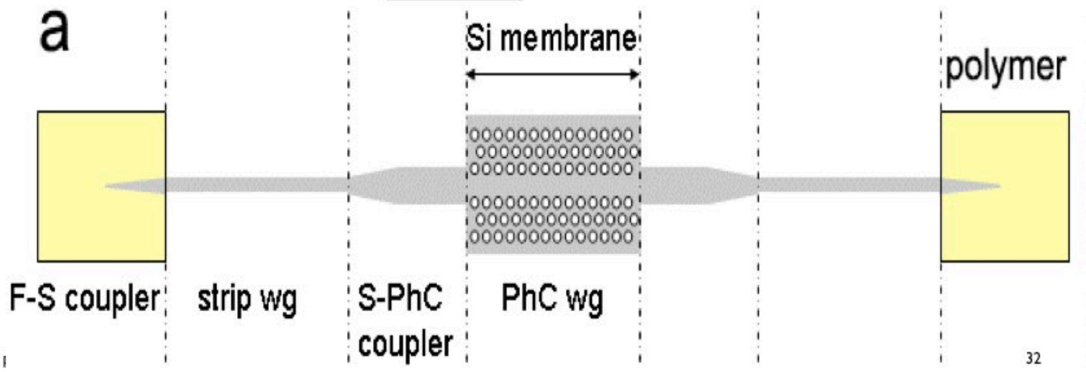
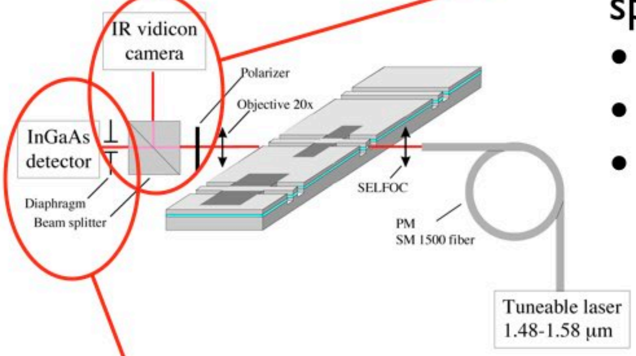


External source
End-Fire

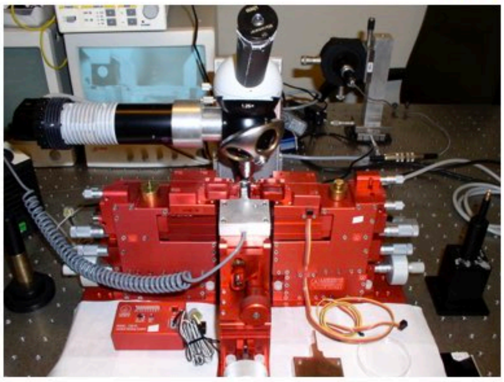
Principle

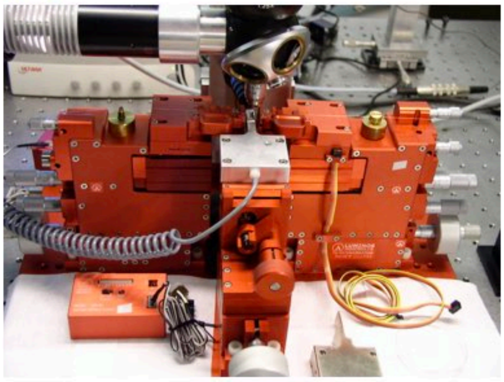


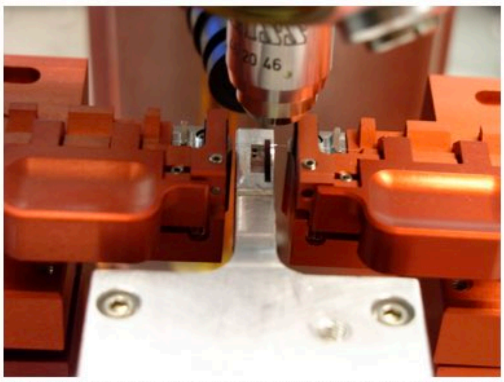
Imaging set-up if working in free space can be convenient
- Si CCD
- IR Vidicon
- IR InGaAs CCD

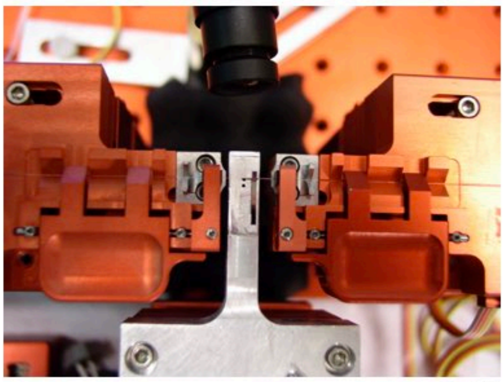
Detector
- Si
- InGaAs
- + spectrometer

External source
End-Fire



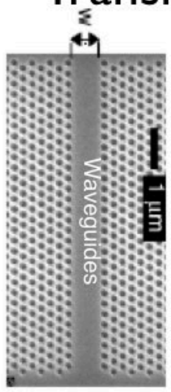


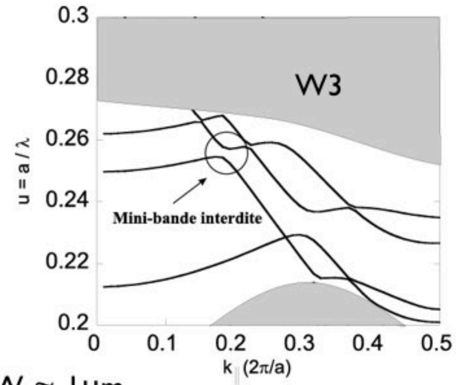


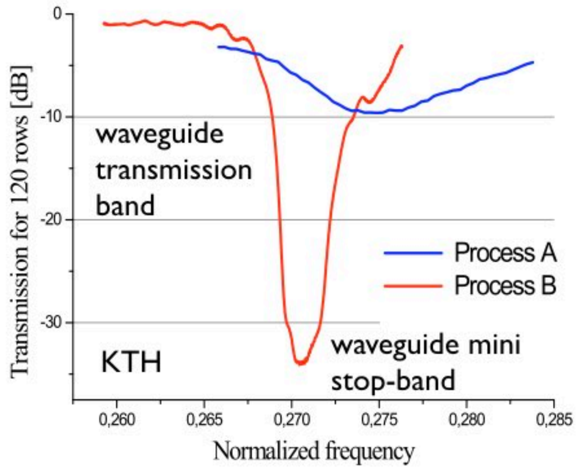


End-Fire

Transmission spectrum, ideal case

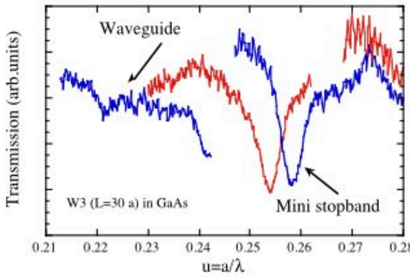




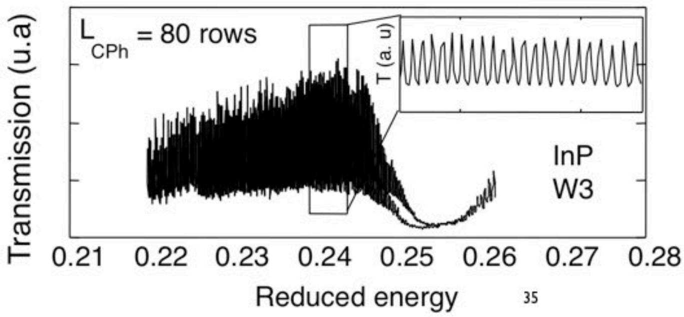


InP-based W3: W ≈ 1µm

but more commonly :

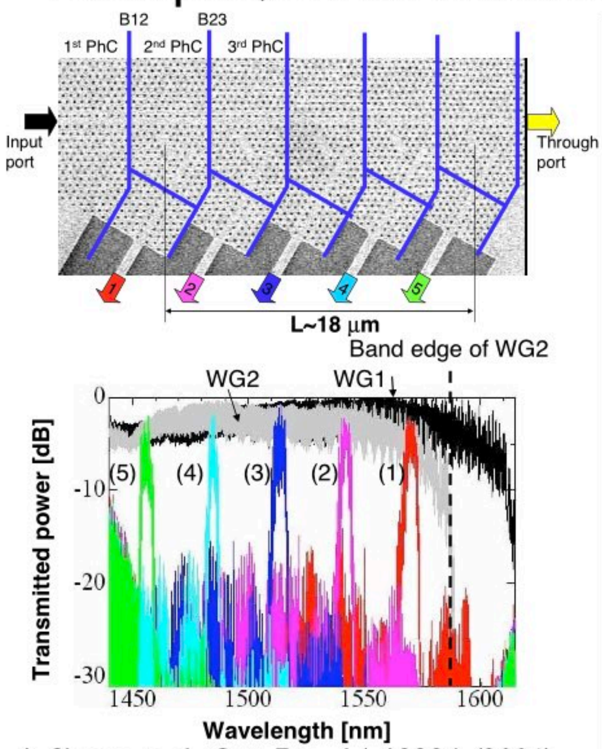


due to internal reflections and cavity fringes

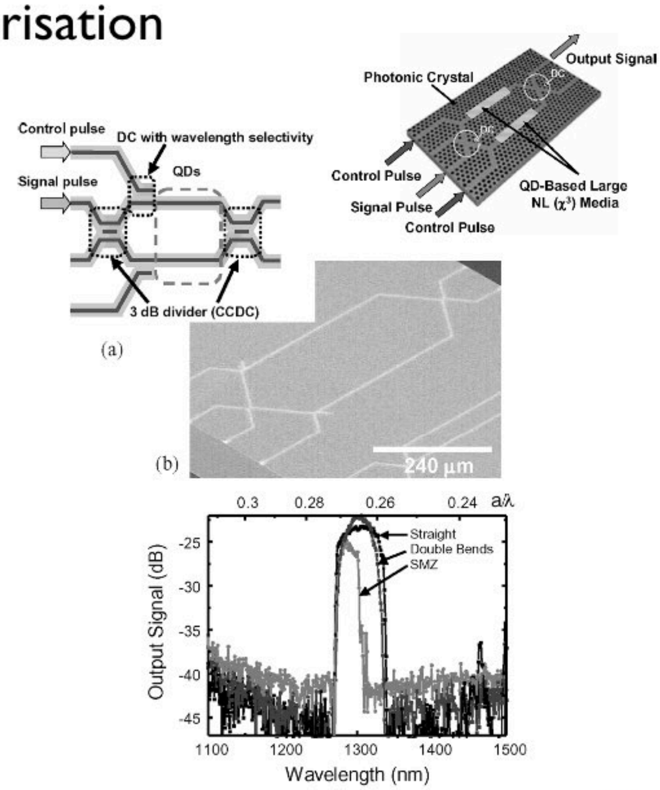


End-Fire

Examples, device characterisation



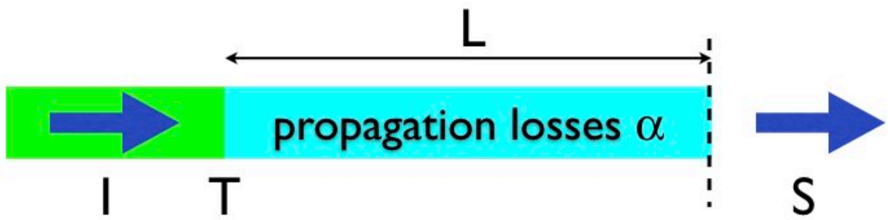
A. Shinya et al., Opt. Exp., 14, 12394, (2006)

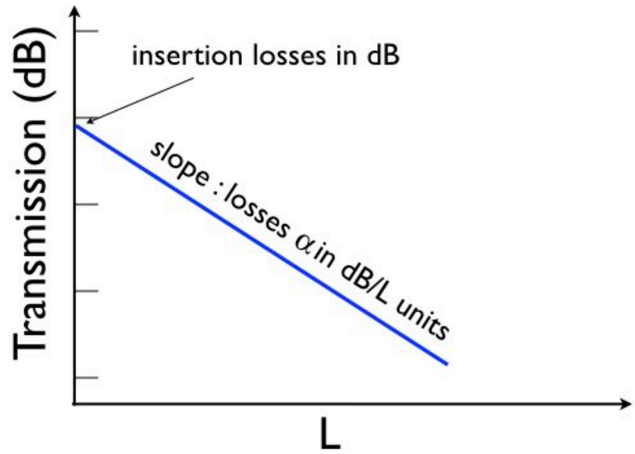


Y. Sugimoto et al., J. Sel. Area. Comm., 23, 1308, (2005)

Measurement of R,T and propagation losses

Cut-back method





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

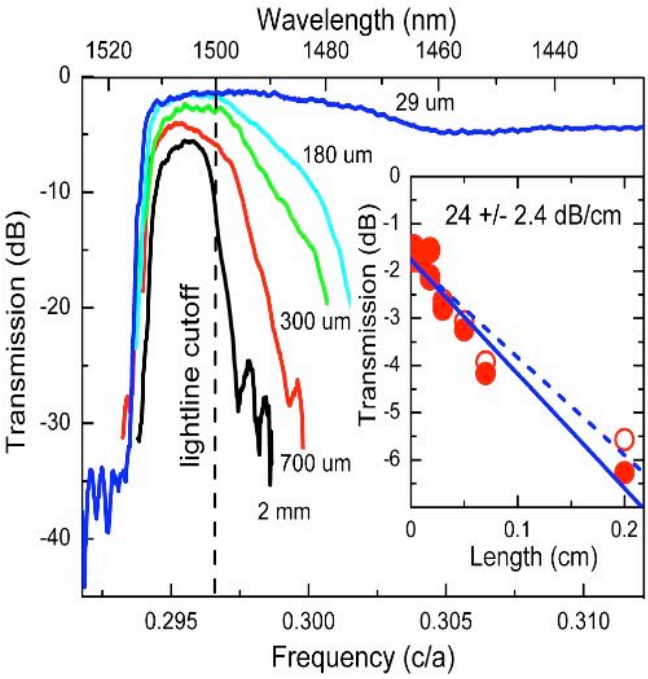
$$Ln\left(\frac{S}{I}\right) = Ln(T) - \alpha L$$

$$\left(\frac{S}{I}\right)_{dB} = 10.\log_{10}(T) - \frac{\alpha}{Ln(10)}L$$

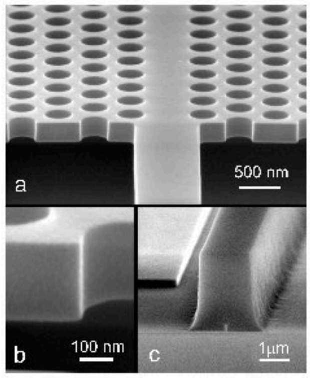
$$A_{dB/cm} = 10\frac{\alpha_{cm^{-1}}}{Ln(10)} = 4.34\,\alpha_{cm^{-1}}$$

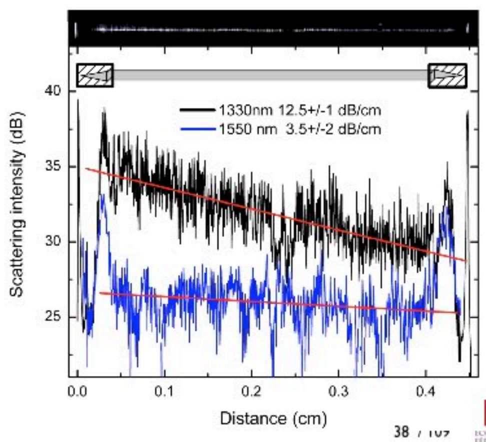
Measurement of R,T and propagation losses

Cut-back method, examples



SOI

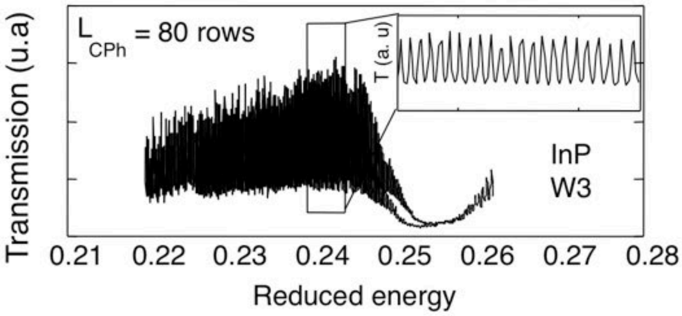




S. J. McNab et al., Opt. Exp., 11, 2927, (2003)

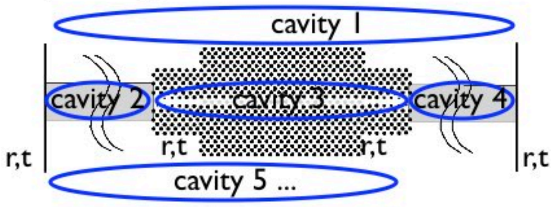
End-Fire

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

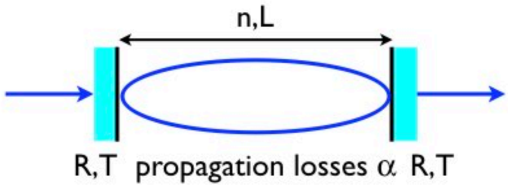
$$T_{FP} = \frac{T^2 e^{-\alpha L}}{1 + R^2 e^{-2\alpha L} - 2\mathrm{R}e^{-\alpha L}\cos(\frac{4\pi n L}{\lambda})}$$

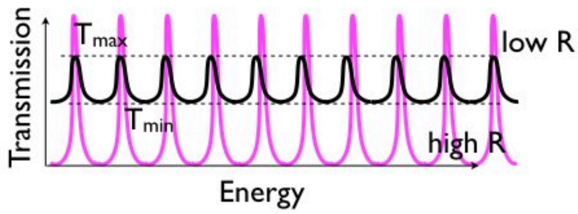
$$T_{\min} = \frac{T^2 e^{-\alpha L}}{\left(1 + \mathrm{R}e^{-\alpha L}\right)^2} \qquad T_{\max} = \frac{T^2 e^{-\alpha L}}{\left(1 - \mathrm{R}e^{-\alpha L}\right)^2}$$

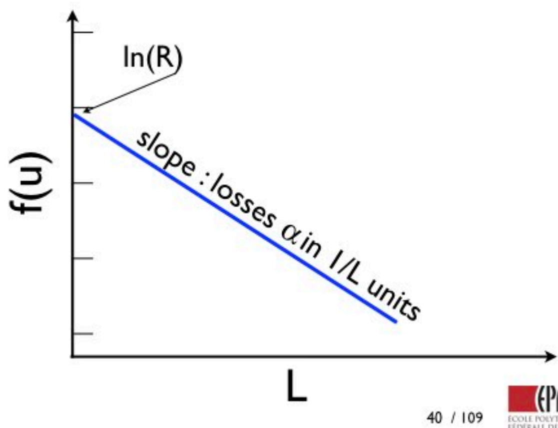
$$u = \sqrt{\frac{T_{\min}}{T_{\max}}} = \sqrt{\frac{P_{\min}}{P_{\max}}}$$

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

$$f(u) = \ln\left(\frac{1-u}{1+u}\right) = \ln(R) - \alpha L$$

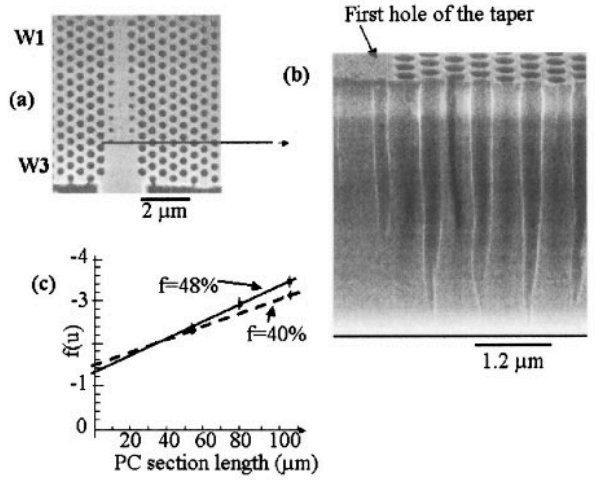






Measurement of R,T and propagation losses

Example



InP

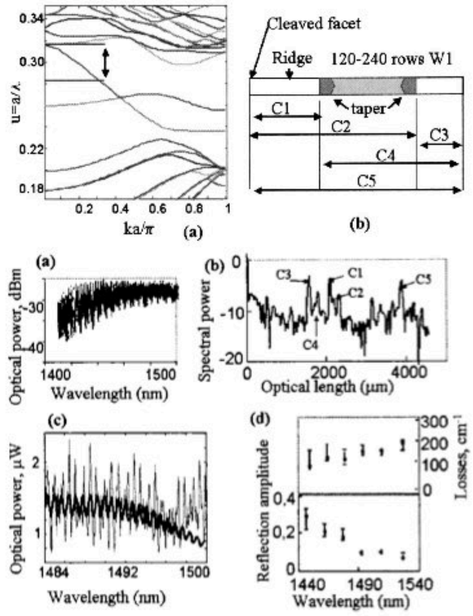


FIG. 3. 120 rows long $W1$–PCW with taper access: (a) transmitted power spectrum, (b) spectral power on the 1484–1500 nm window, (c) unfiltered (thin line) and filtered (bold line) transmitted power with a filter suited to $C1$ cavity, and (d) taper reflection and propagation losses as a function of wavelength.

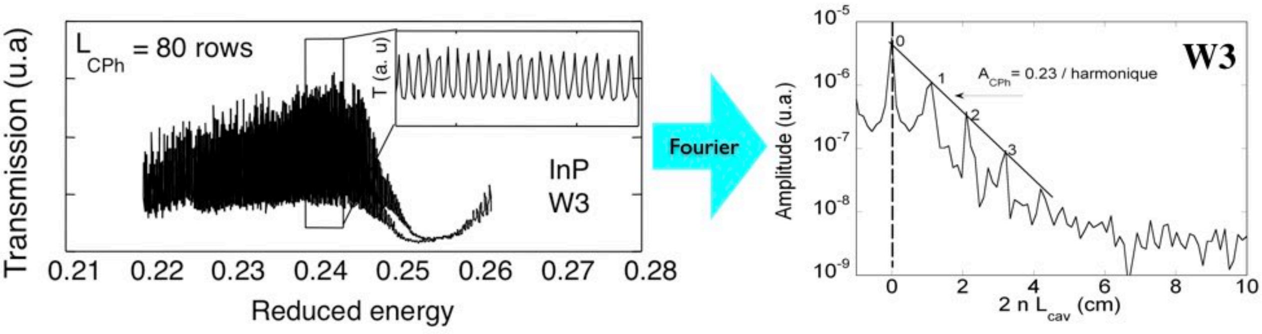
The method has also been used in the case of several coupled cavities with Fourier filtering
Exact theoretical proof of validity is missing

A. Talneau et al., Appl. Phys. Lett., 82, 2577, (2003)

Measurement of R,T and propagation losses

Hofstetter method

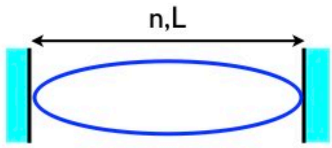
the Hofstetter method generalises the Hakki-Paoli method to the higher orders of the Fourier transform of the transmission spectrum



Amplitude decay of the harmonic n

A_r = attenuation after n single passes

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

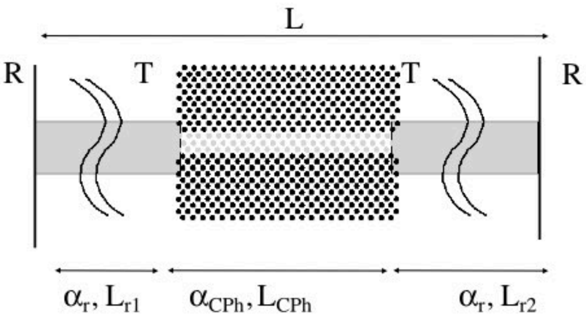


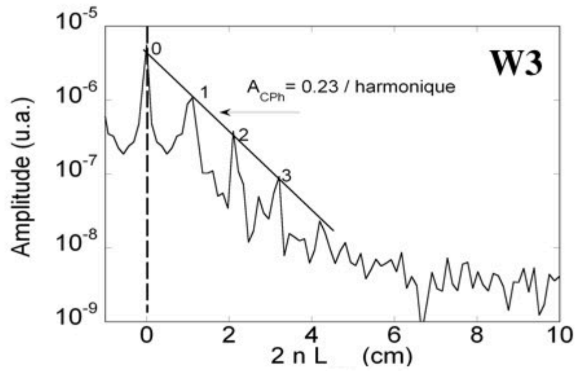
R,T propagation losses α R,T

D. Hofstteter et al., Opt. Lett., 22, 1381, (1997) and IEEE J. Quant. Elect., 34, 1914, (1998)

Measurement of R,T and propagation losses

Hofstetter method

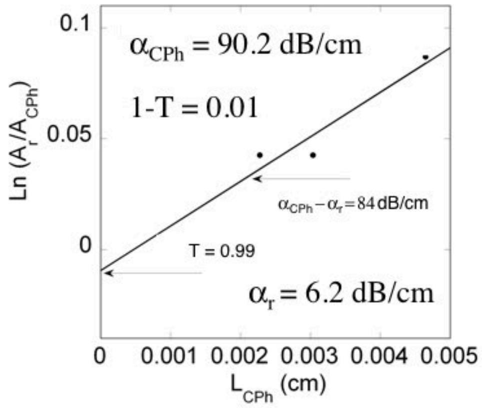




$$A = R.T^2 e^{-\alpha_{CPh} L_{CPh}} e^{-\alpha_R (L_{r1} + L_{r2})}$$

after division by a reference waveguide

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

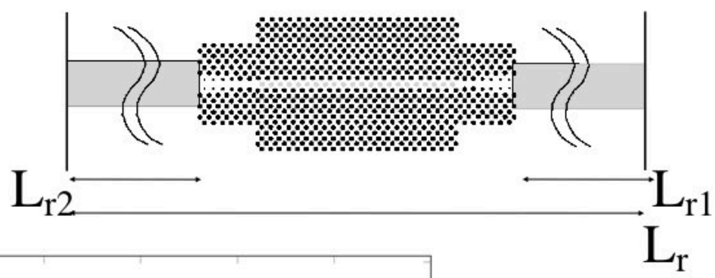


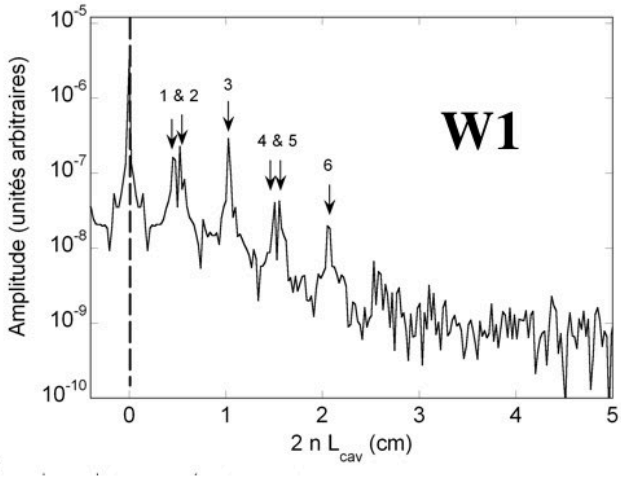
D. Hofstteter et al., Opt. Lett., 22, 1381, (1997) and IEEE J. Quant. Elect., 34, 1914, (1998)

Measurement of R,T and propagation losses

Hofstetter method

Internal reflections lead to multiple cavities

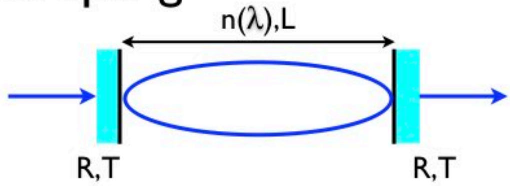




- harmonics 1 and 4 : L_{r1}
- harmonics 2 and 5 : L_{r2}
- harmonics 3 and 6 : L_r

Dispersion curve

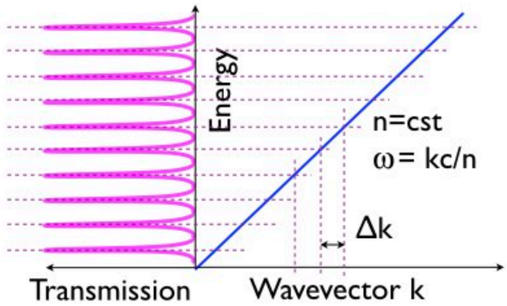
Fabry-Perot fringes and k-space sampling

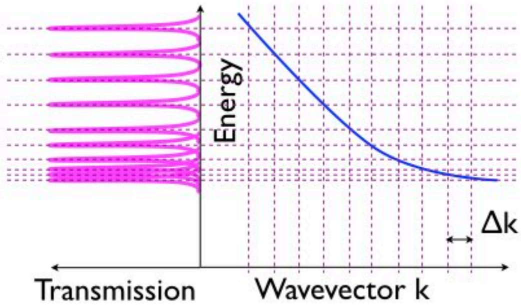


Fabry-Perot fringes equally spaced in energy ?

$$T_{FP} = \frac{T^2}{1 + R^2 - 2R\cos(\frac{4\pi n L}{\lambda})} \qquad T_{FP} = \frac{T^2}{1 + R^2 - 2R\cos(2kL)}$$

resonances equally spaced in k Δk = π/L

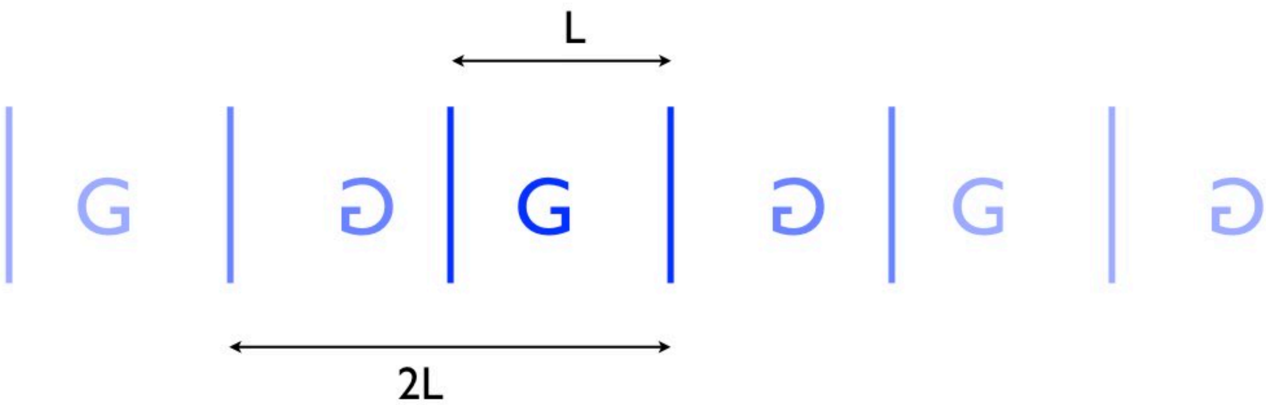




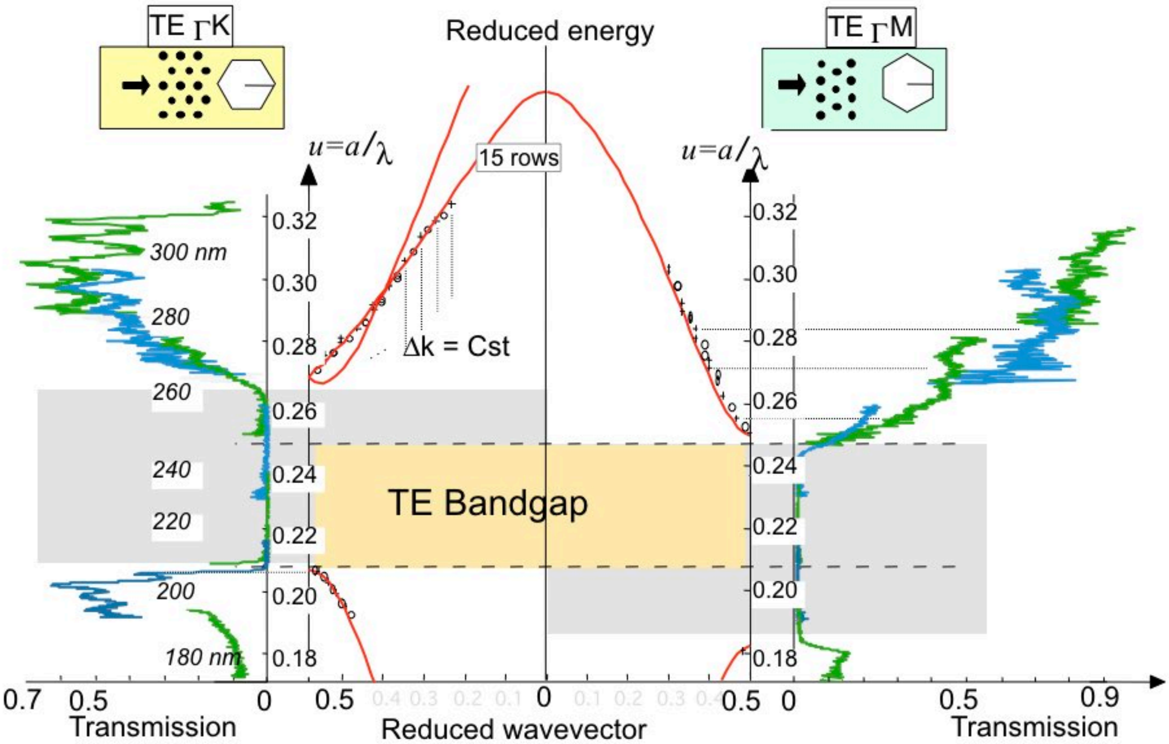
Note: sampling in Δk, exact k values are more difficult to determine

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 2π/2L=π/L periodicity in k-space



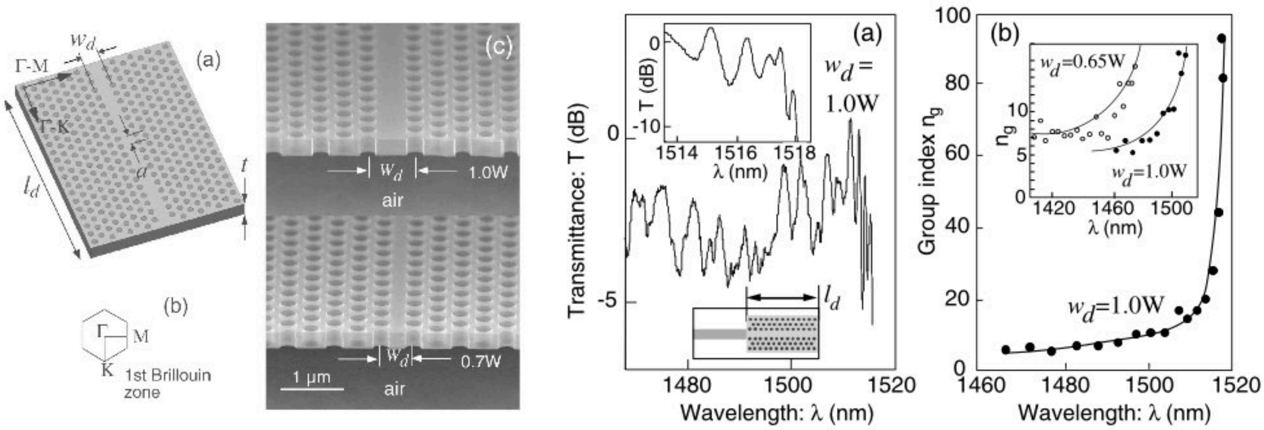
Dispersion curve measurement



GaAs, internal light source

D. Labilloy et al., Phys. Rev. B, 59, 1649, (1999)

Dispersion curve measurement



Si membrane

M. Notomi et al., Phys. Rev. Lett., 87, 253902, (2001)

Dispersion curve measurement

Mach-Zehnder interferometer

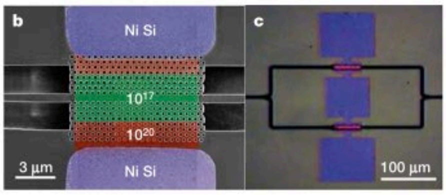


Figure 3 | Active electrically tunable MZI with lateral electrical contacts to photonic crystal waveguides. **a,** Time averaged magnetic field energy

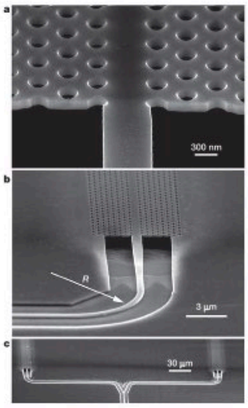
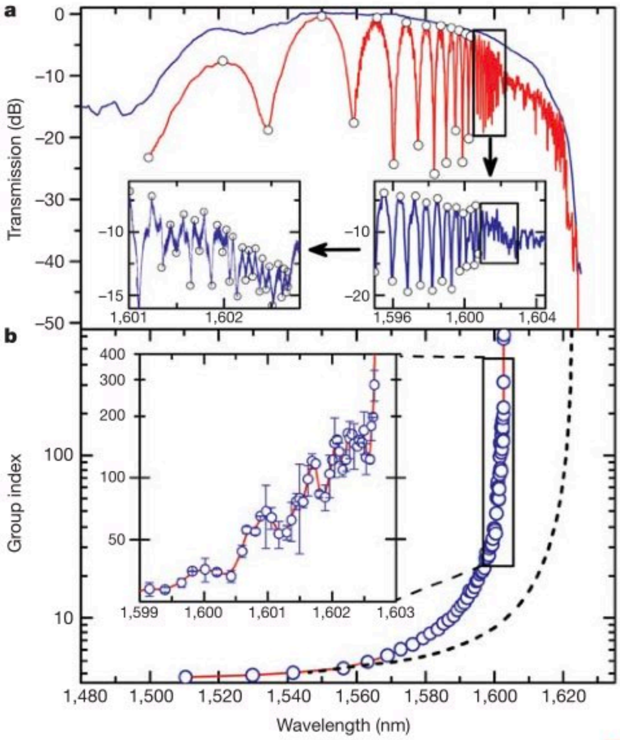


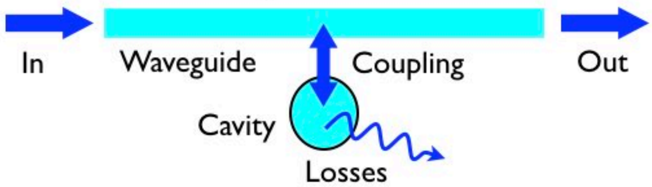
Figure 1 | SEM images of a passive unbalanced Mach–Zehnder interferometer using photonic crystal waveguides. **a,** Input section of the



Y. Vlasov et al., Nature, 438, 65, (2005)

Optical cavities, high quality factor

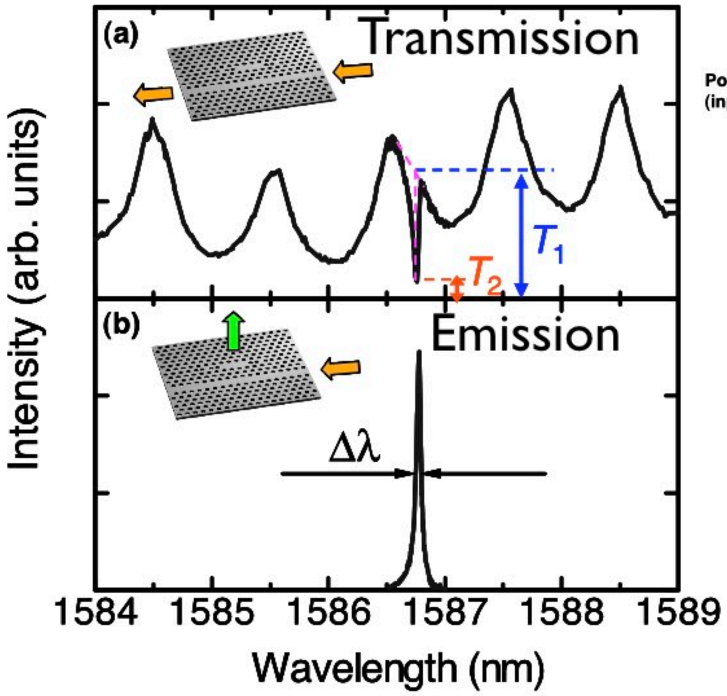
Measurement of the cavity requires coupling to a probe which affect the Q

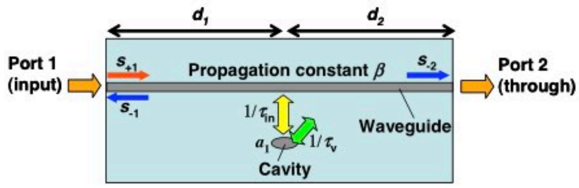


- Intrinsic Q = Q_{int}, unloaded cavity, coupling only to free space radiation and material losses, defects
- Coupling Q = Q_{probe}, additional losses due to the measurement
- Measured Q = Q_{meas}, loaded cavity

$$\frac{1}{Q_{meas}} = \frac{1}{Q_{int}} + \frac{1}{Q_{probe}}$$

Optical cavities, high quality factor



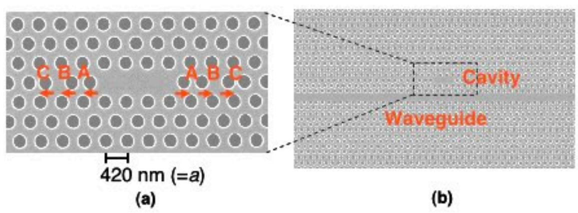


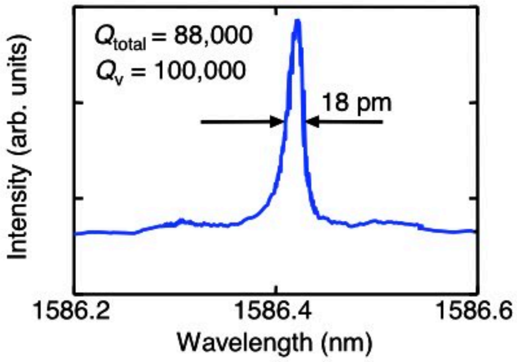
$$T = \frac{T_2}{T_1}$$

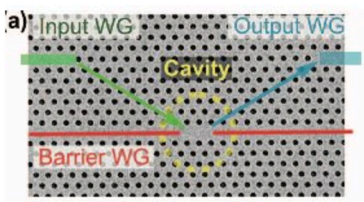
$$Q_{int} = \frac{Q_{meas}}{\sqrt{T}}$$

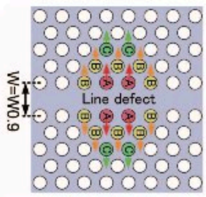
Y. Akahane et al., Opt. Exp., 13, 1202, (2005)

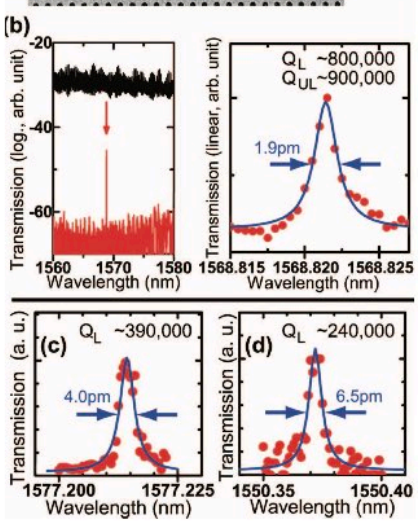
Optical cavities, high quality factor









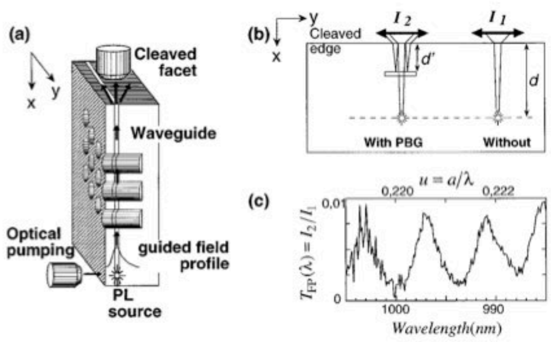


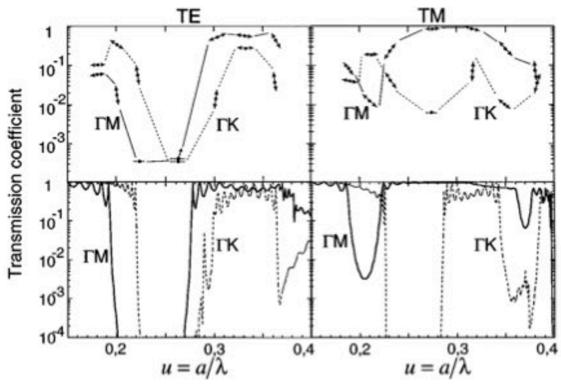
Y. Akahane et al., Opt. Exp., 13, 1202, (2005) E. Kuramochi et al., Appl. Phys. Lett., 88, 041112, (2006)

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





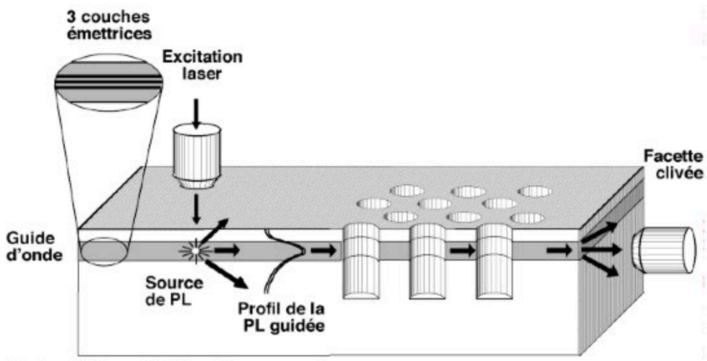
D. Labilloy et al., Phys. Rev. Lett., 79, 4147, (1997)

Historically, among the first actually quantitative transmission measurements on 2D PhC

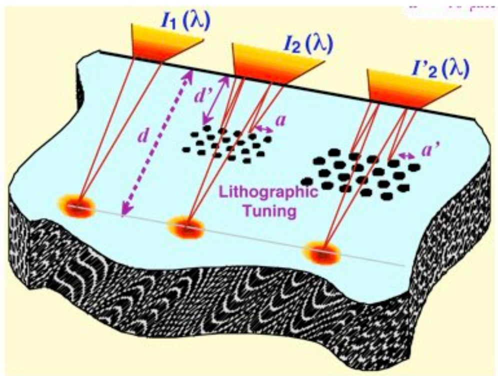
ILS

Principle: Insert light emitters inside the planar waveguide

- Quantum wells
- "bad" quantum dots (large emission band)



D. Labilloy PhD dissertation



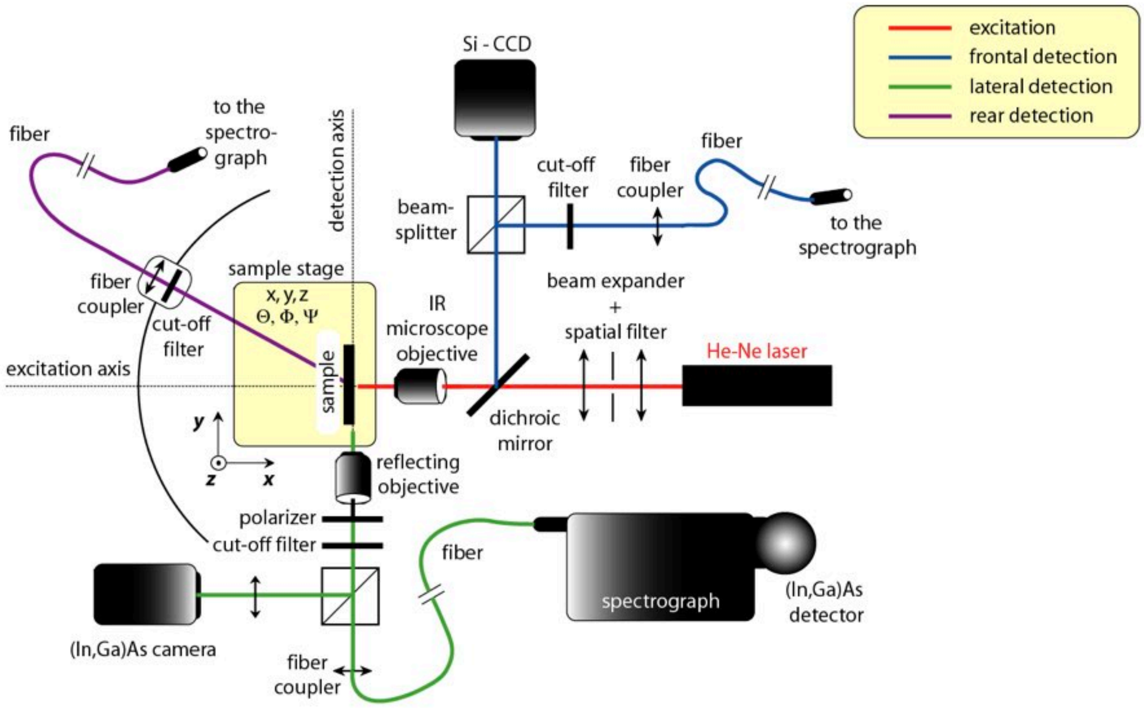
$$T_a(\lambda) = \frac{I_2(\lambda)}{I_1(\lambda)} \rightarrow T(u = \frac{a}{\lambda})$$

And make use of lithographic tuning

D. Labilloy et al., Phys. Rev. Lett., 79, 4147, (1997) R. Ferrini et al., J. Quantum Electron., 38, 786, (2002)

ILS

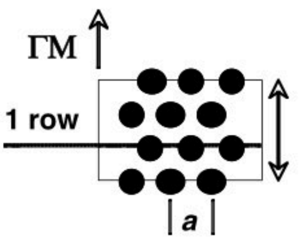
Experimental set-up



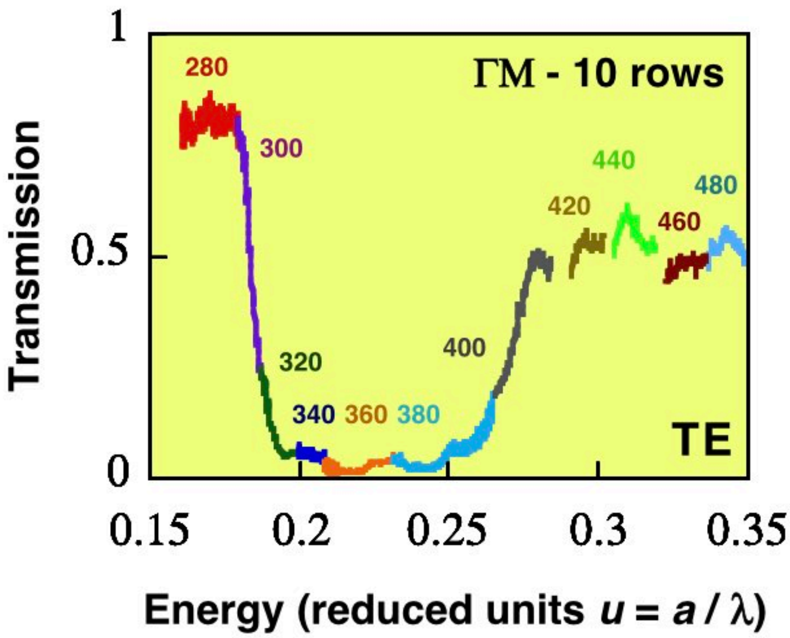
R. Ferrini et al., J. Quantum Electron., 38, 786 (2002)

Transmission spectrum

Examples



TE polarization



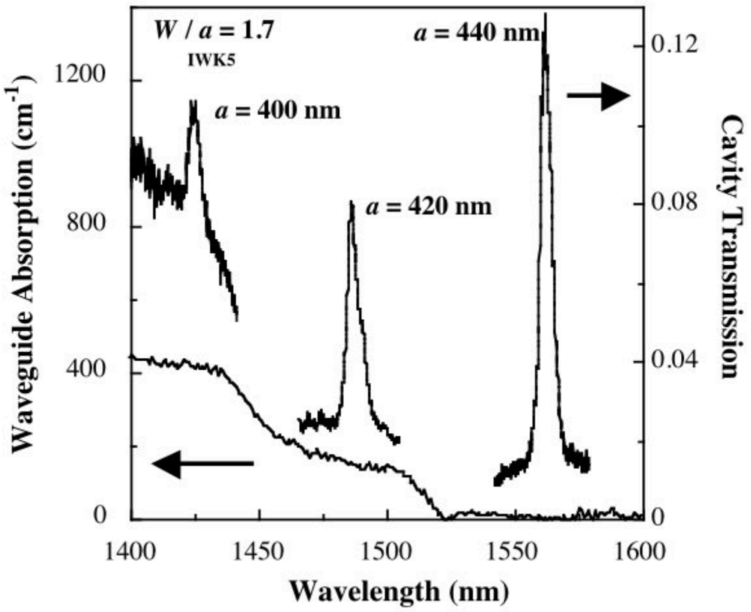
InP/(Ga,In)(As,P) QW

λ=1.55μm f=30%

R. Ferrini et al., J. Quantum Electron., 38, 786 (2002)

Limitation

QW or QD absorption in the waveguide

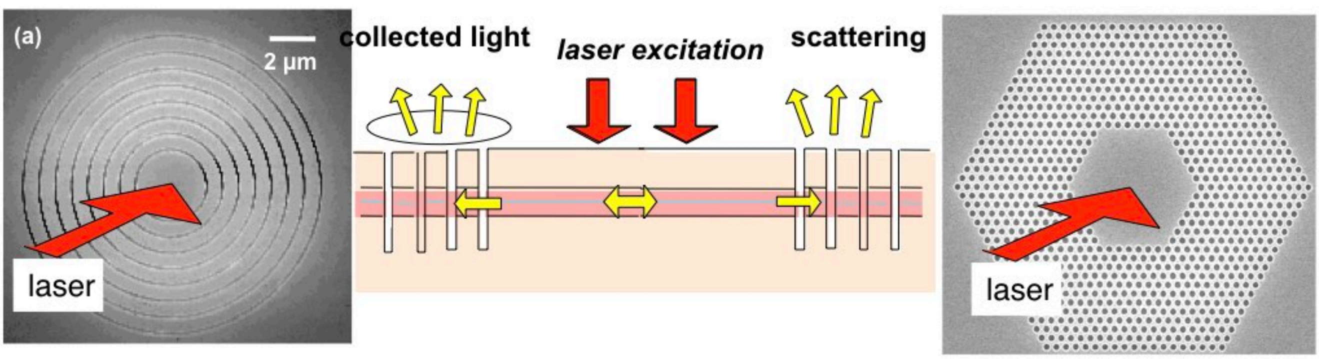


Photoluminescence

Light source inside the PhC structure

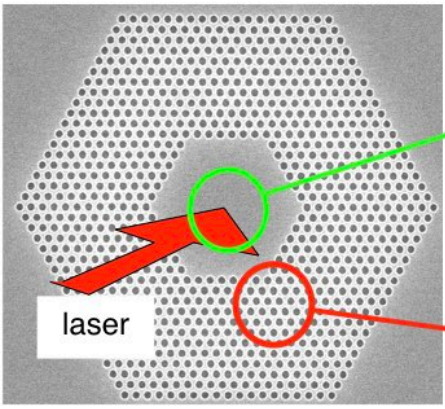
- PhC defect
  - Point defect, optical cavity

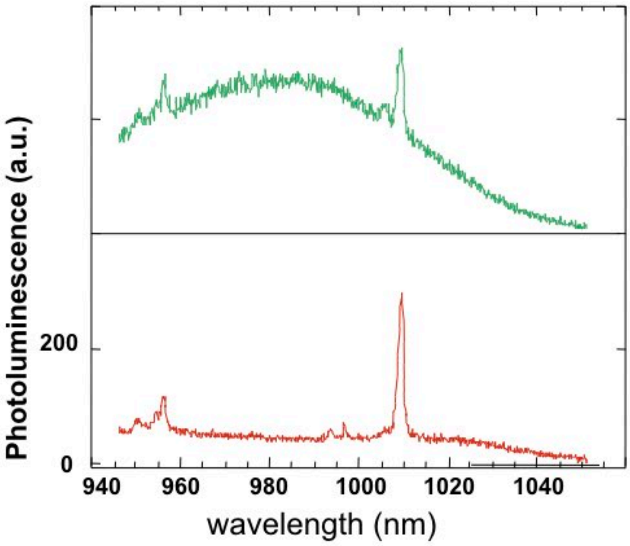
Front photoluminescence emission



Photoluminescence

Mode spectroscopy



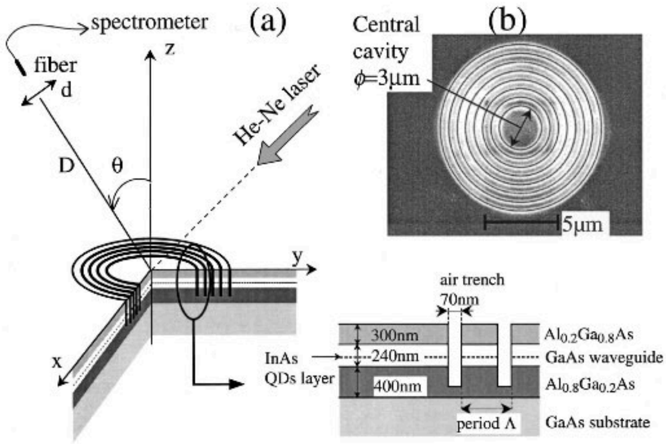


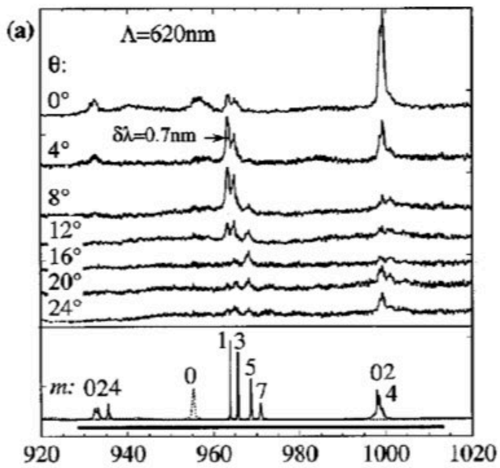
C.J.M. Smith et al., JOSA B, 17, 2043, (2000)

Photoluminescence

Mode spectroscopy

Coupled with angular resolution



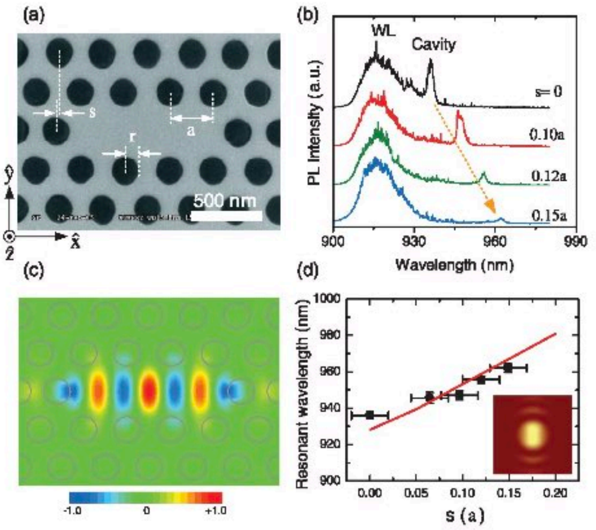


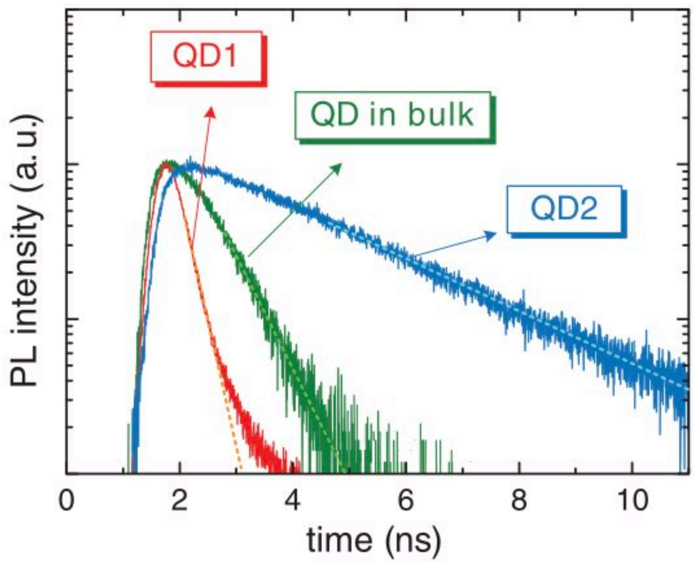
D. Ochoa et al., Phys. Rev. B, 61, 4806, (2000)

Photoluminescence

Time resolved

Life time modification, Purcell effect, emission enhancement and inhibition





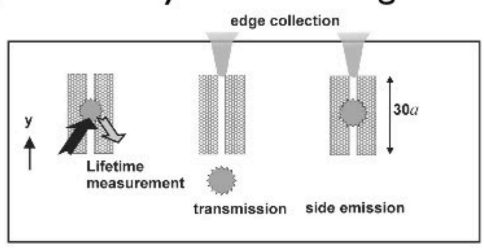
Wen-Hao Chang et al., Phys. Rev. Lett. 96, 117401, (2006)

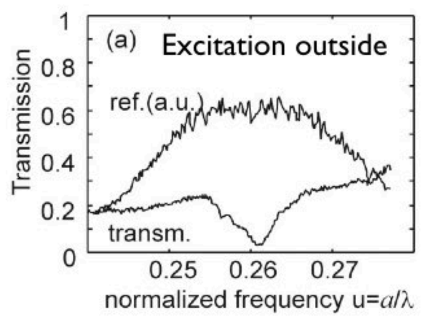
Photoluminescence

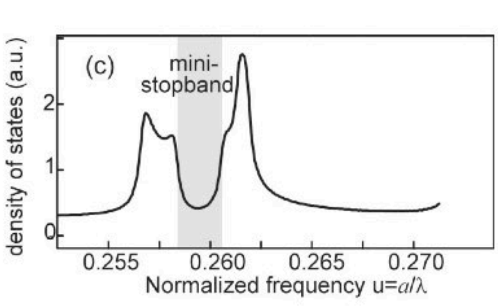
Light source inside the PhC structure

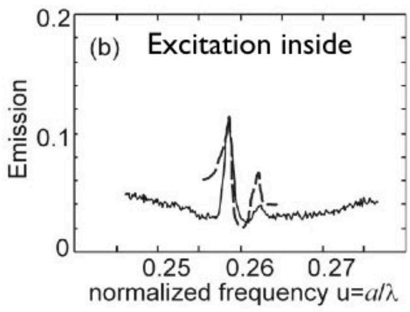
- PhC defect
  - Line defect, waveguide

Probing the density of states singularities









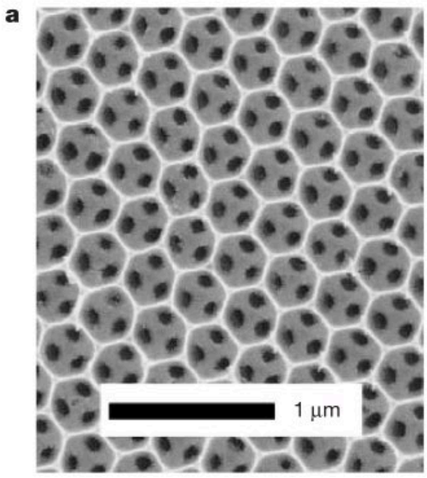
E.Viasnoff-Schwoob et al., Phys. Rev. Lett., 95, 183901, (2005)

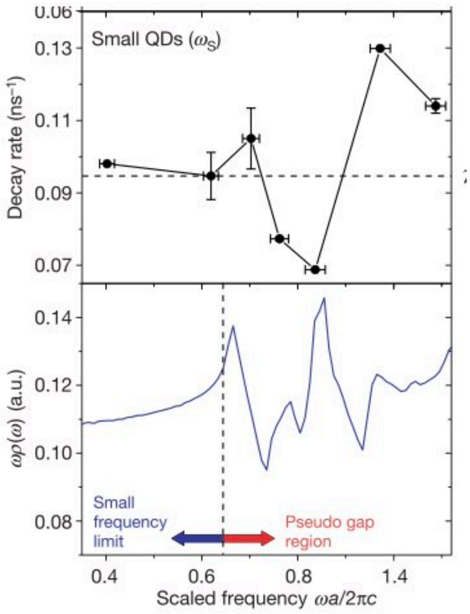
Photoluminescence

Light source inside the PhC structure

- Bulk 3D PhC

Probing the local density of states singularities, lifetime modification





CdSe nanocrystals in inverted opals

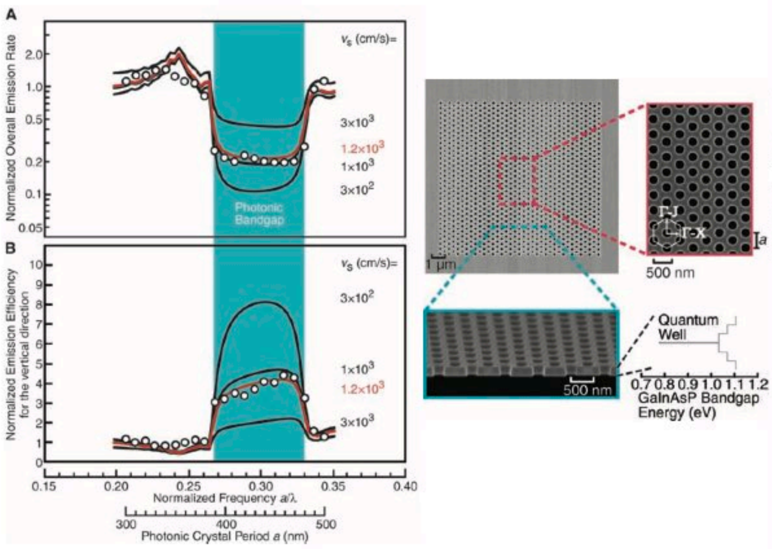
P. Lodahl et al., Nature, 430, 654, (2004)

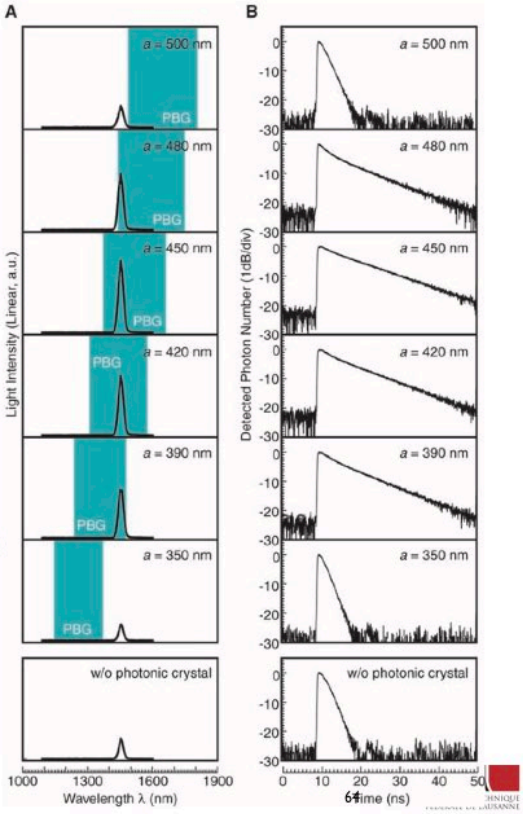
Photoluminescence

Light source inside the PhC structure

- Bulk 2D PhC

Probing the local density of states singularities, lifetime modification



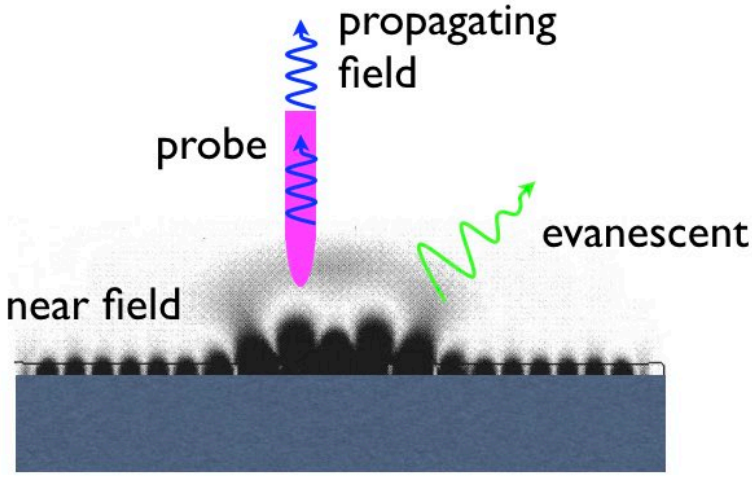


M. Fujita et al., Science, 308, 1296, (2005)

Advanced techniques
Local probes, SNOM

Principle

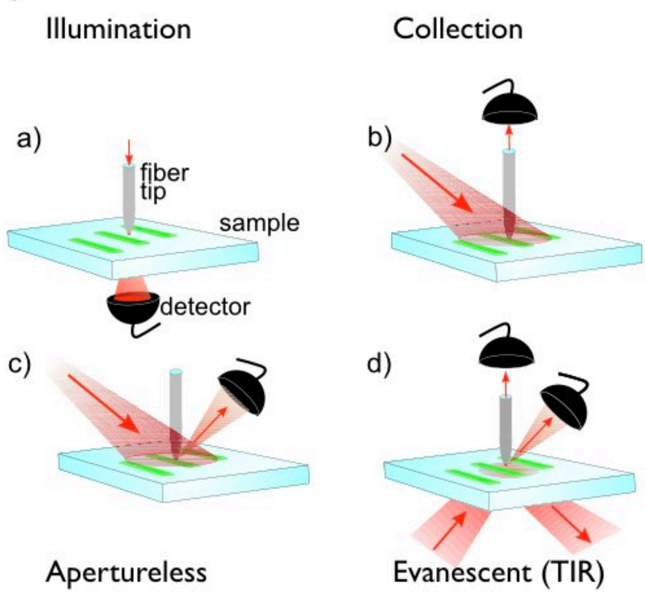
Probe the near field electromagnetic field with a local probe



Advanced techniques
Local probes, SNOM

Principle

Different configurations



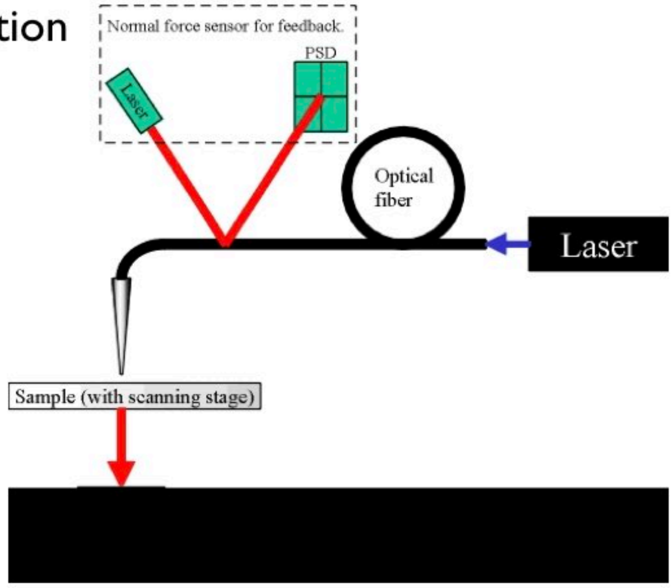
V. Sandogdhar et al.,"Photonic crystals ..." Wiley-VCH Berlin ,15, (2003)

Advanced techniques
Local probes, SNOM

Principle

Tricks are in :

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

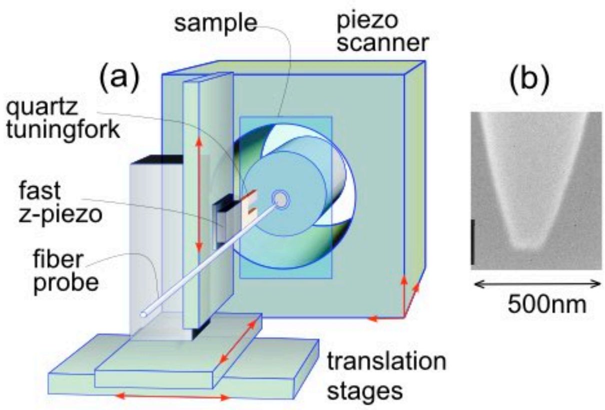


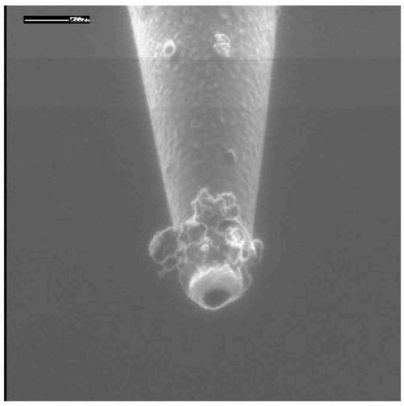
Advanced techniques
Local probes, SNOM

Principle

Tricks are in :

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



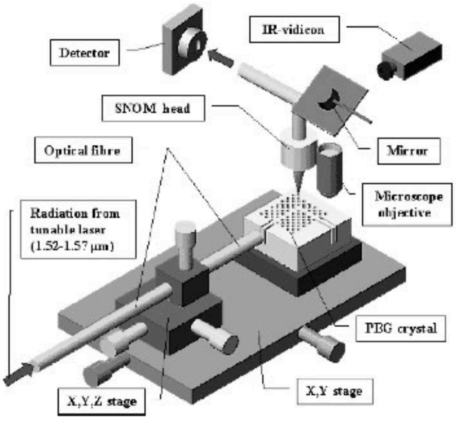


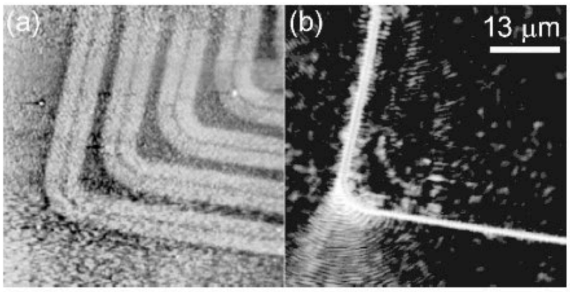
Metallized tapered fibre tip. SEM, H. Gersen

V. Sandogdhar et al.,"Photonic crystals ..." Wiley-VCH Berlin ,15, (2003)

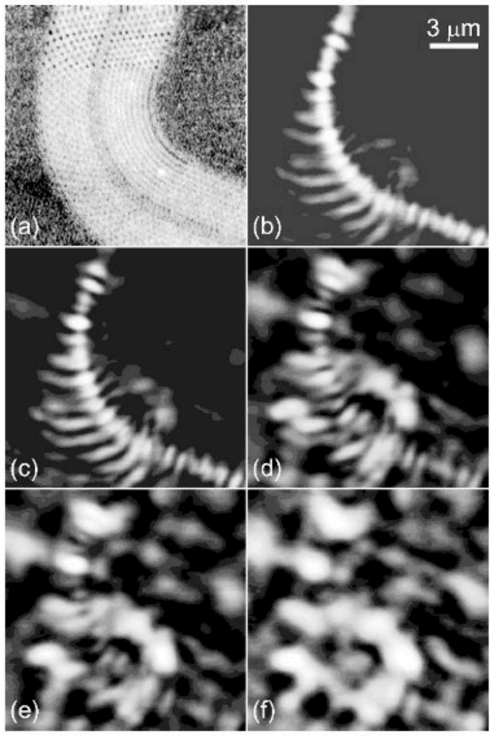
SNOM

Examples, bends





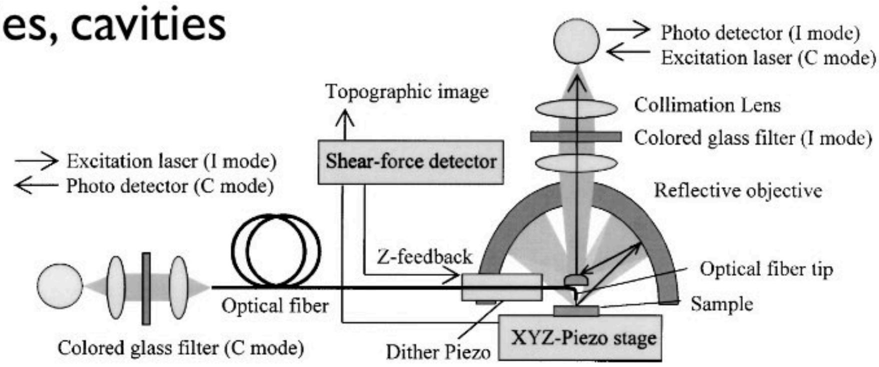
S.I. Bozhevolnyi et al., Phys. Rev. B, 66, 235204, (2002)

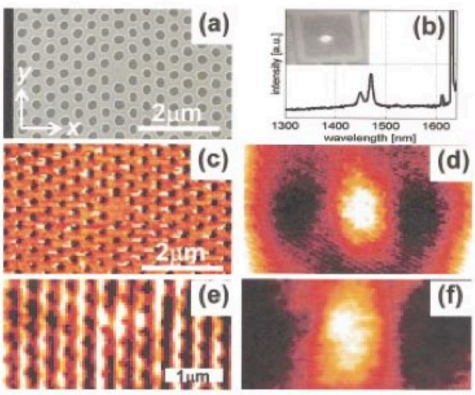


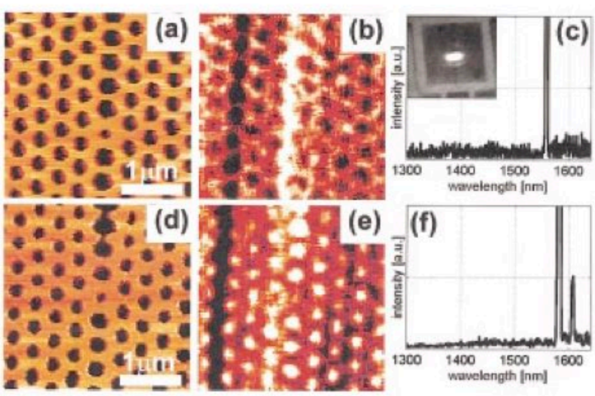
with increasing shear force feedback (increasing tip distance)

SNOM

Examples, cavities





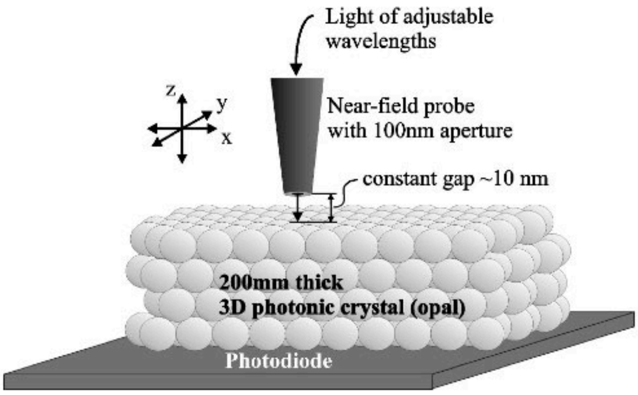


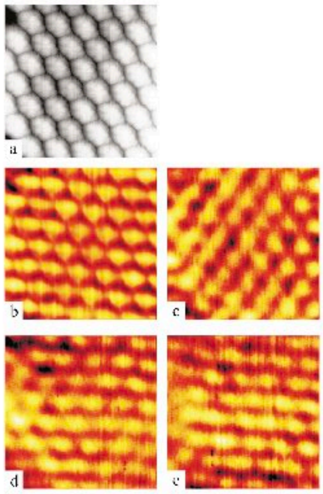
K. Okamoto et al., Appl. Phys. Lett., 82, 1676, (2003)

Nice images, but difficult to be quantitative

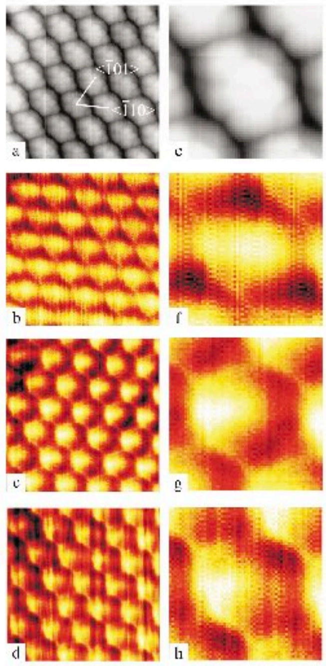
SNOM

Examples, opals





vs. tip separation

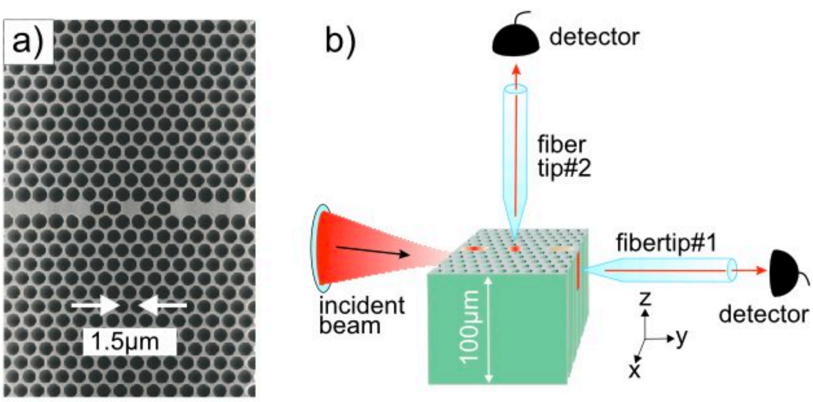


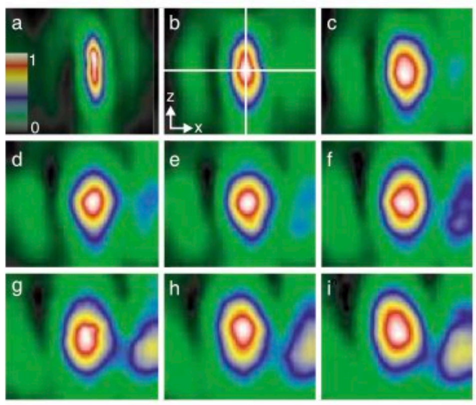
vs. light wavelength

E. Flück et al., Phys. Rev. E, 68, 015601R, (2003)

SNOM

Examples, 2D macroporous PhC



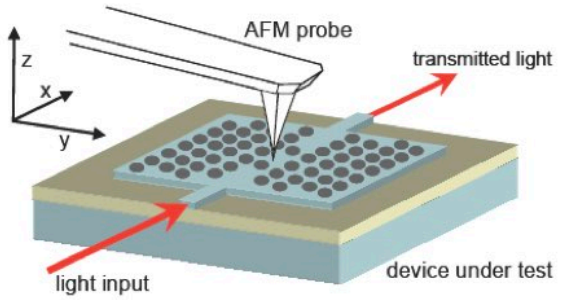


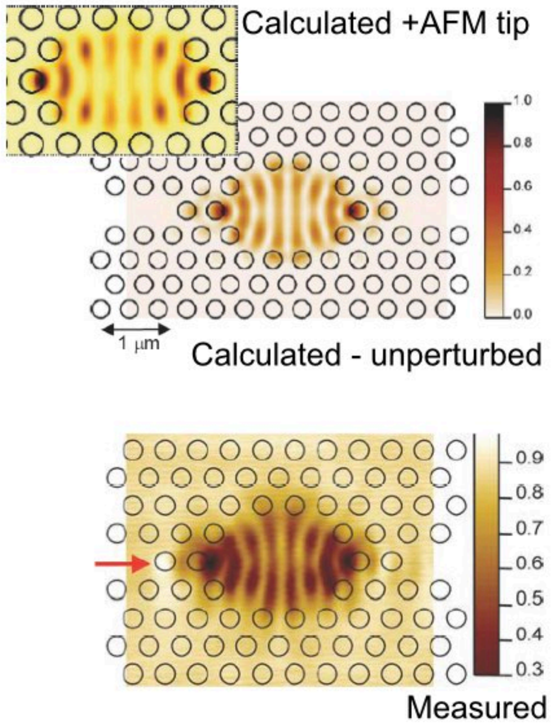
vs. tip 1 distance

V. Sandogdhar et al., Phys. Rev. Lett., 92, 113903, (2004)

T-SNOM

Mode field pattern mapping or modification with AFM tip





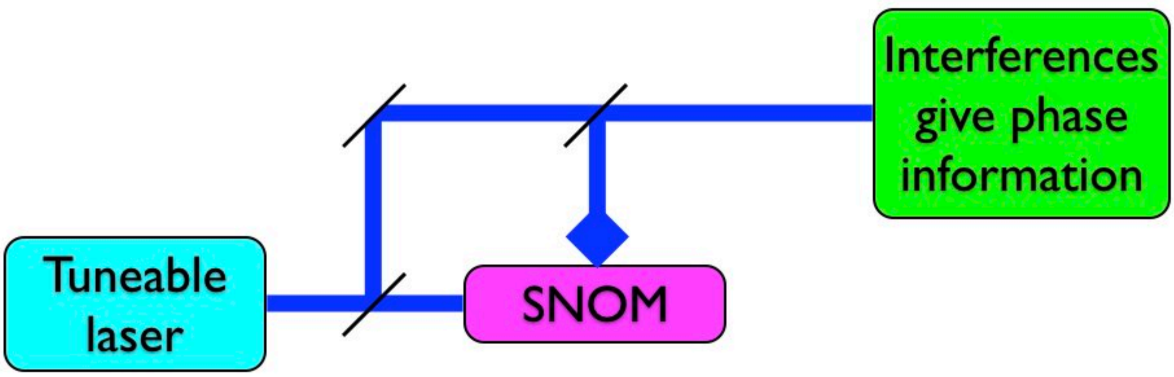
- scanning tip smaller, lower perturbation
- for small high Q cavities
- tip – change in Q factor or resonance wavelength

R. De Ridder, Twente, ECIO 2007 and Opt. Exp., 14, 8745 (2006)

Advanced techniques "Heterodyne" SNOM

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

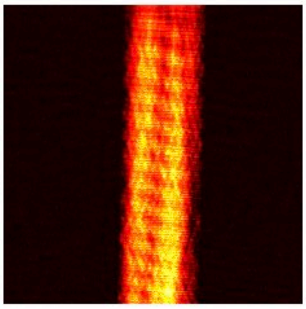
Insert the SNOM set-up in an interferometer (e.g. Mach-Zender)



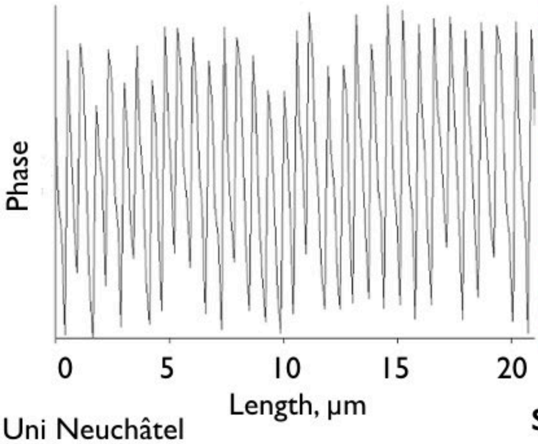
Note : amplitude information is necessary e.g. for numerical Fourier transform

Advanced techniques
Heterodyne SNOM

Amplitude



Phase



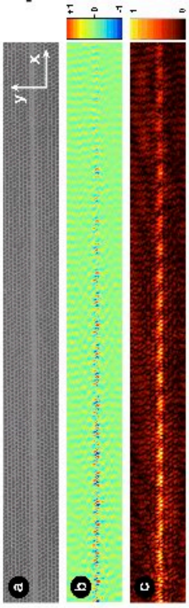
scan area of 35X35µm^2

Courtesy I. Märki, Uni Neuchâtel

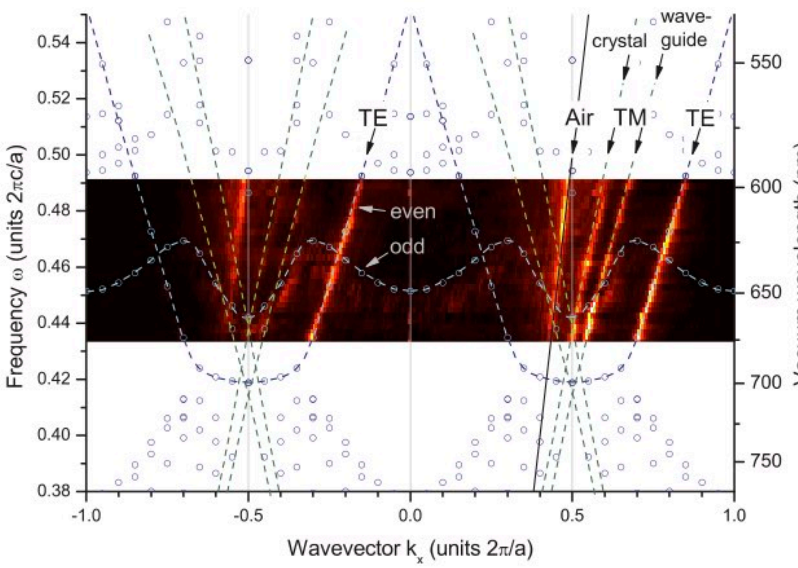
Heterodyne SNOM

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

- Dispersion curves



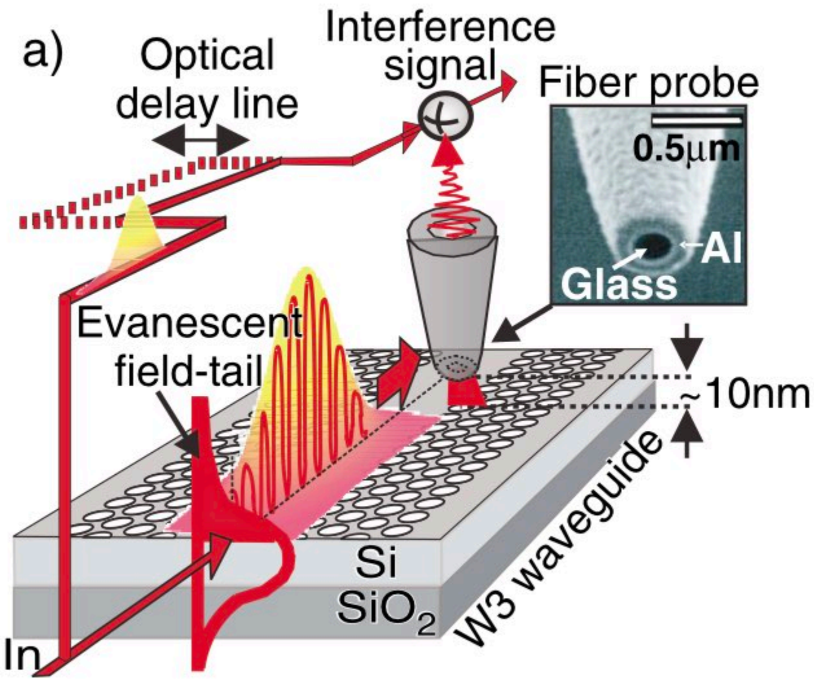
A.cos(ø) |A|

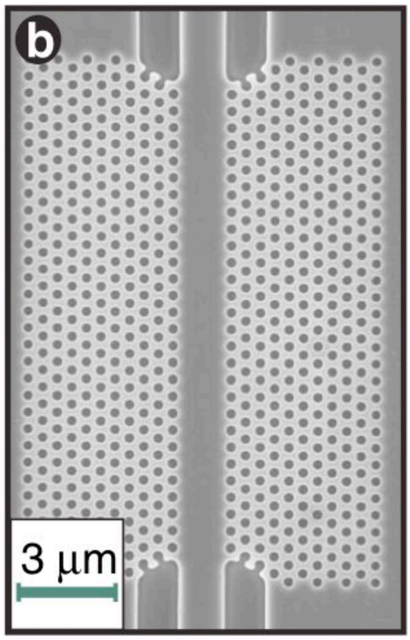


Fourier transform

R.J.P. Engelen et al., Opt. Exp., 13, 4457, (2005)

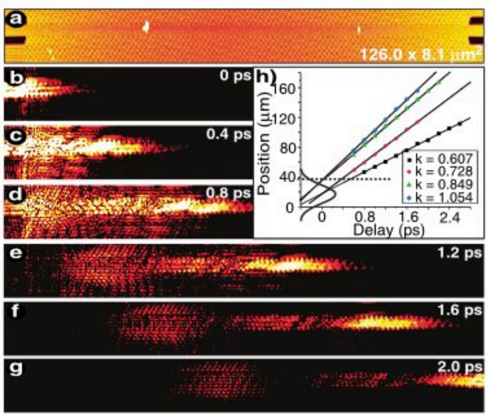
Advanced techniques
Time resolved SNOM

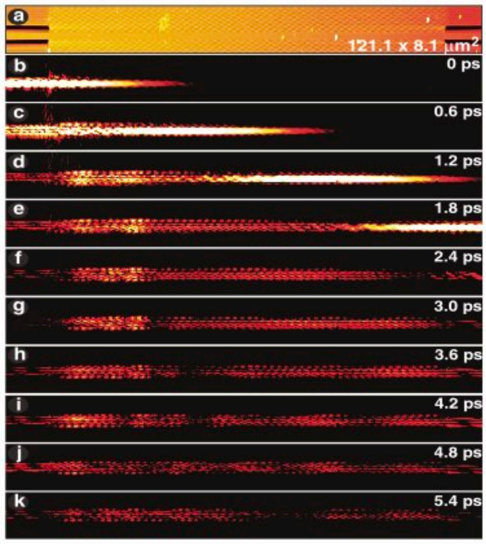


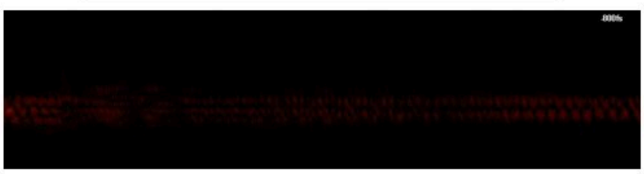


H. Gersen et al., Phys. Rev. Lett., 94, 073903, (2005)

Advanced techniques
Time resolved SNOM



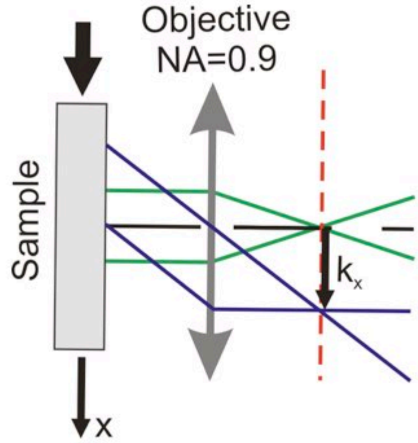




H. Gersen et al., Phys. Rev. Lett., 94, 073903, (2005)

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

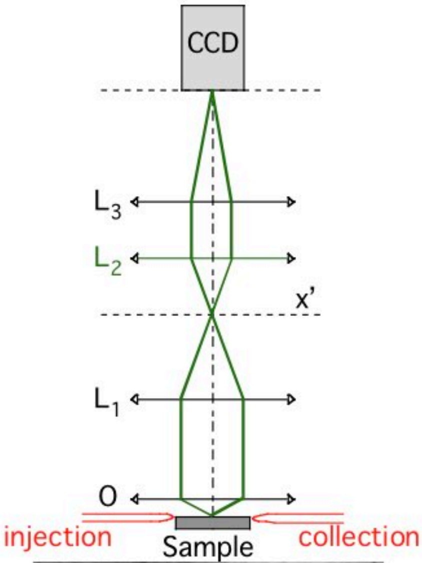
Principle

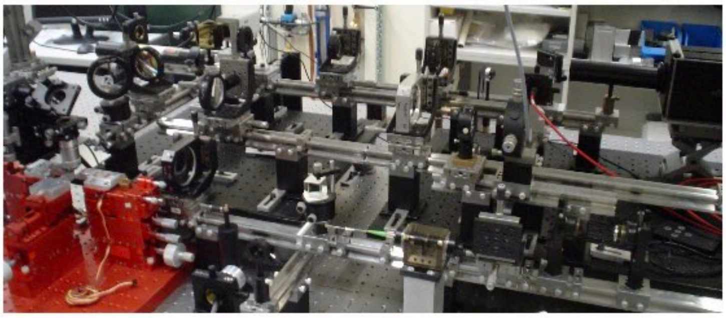
Make use of the light scattered off the propagation axis or plane

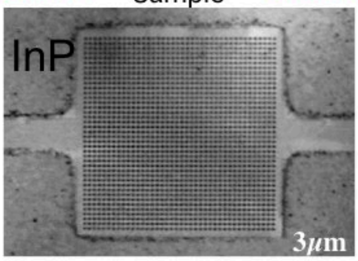
---

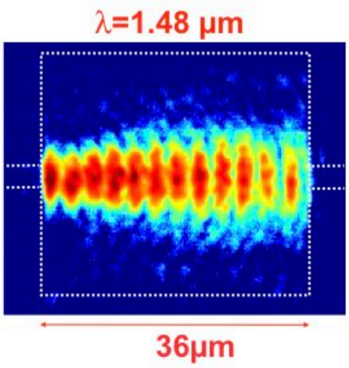
- ✳ intrinsically (above the light line)
- ✳ via imperfections / defects (below the light line)
- ✳ additional probe structures

Real space imaging of Bloch Waves propagating in PhCs

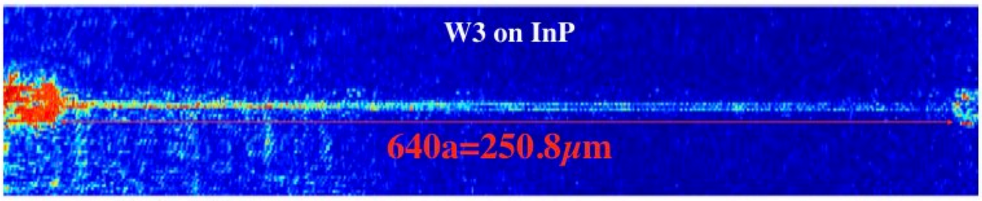


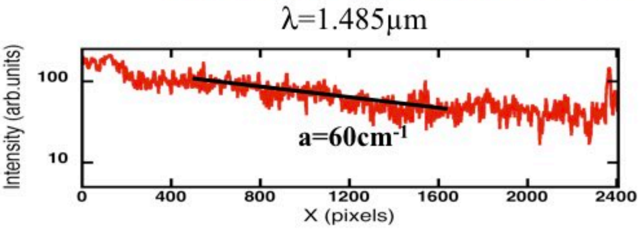


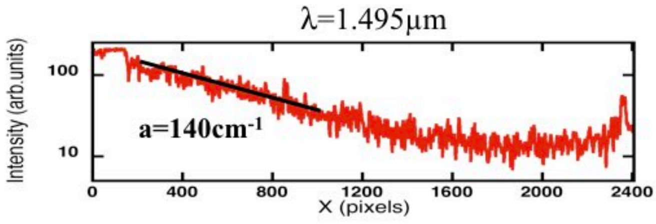




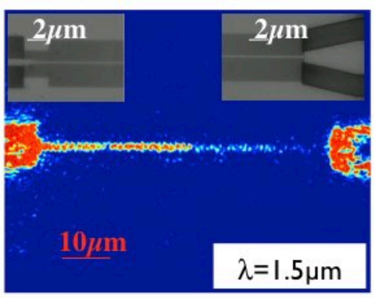
Imaging of the scattered light Propagation losses and defect characterization

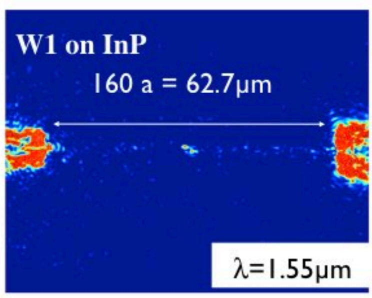






Propagation losses



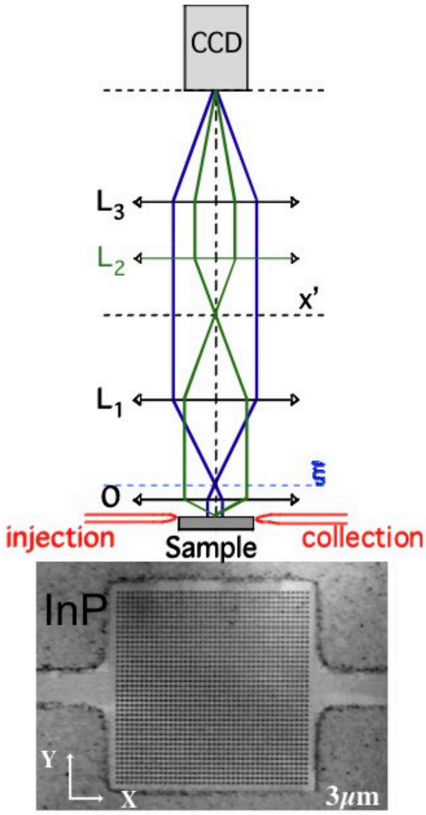


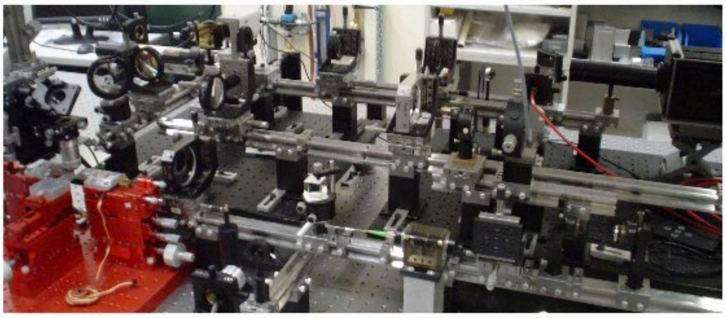
Defect

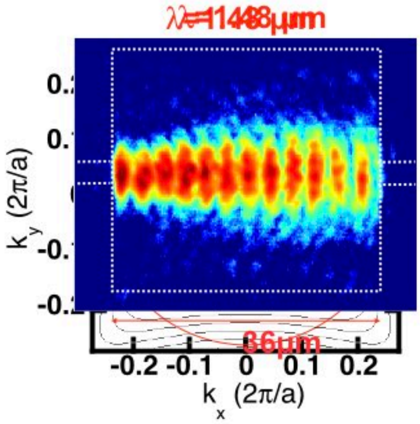
u = 0.261

u = 0.253

Fourier space imaging of Bloch wave emission diagram

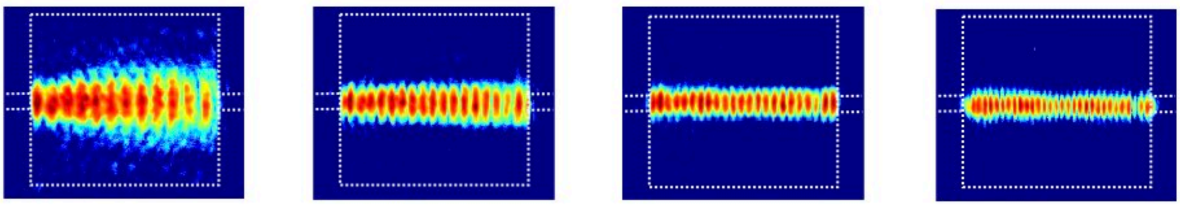






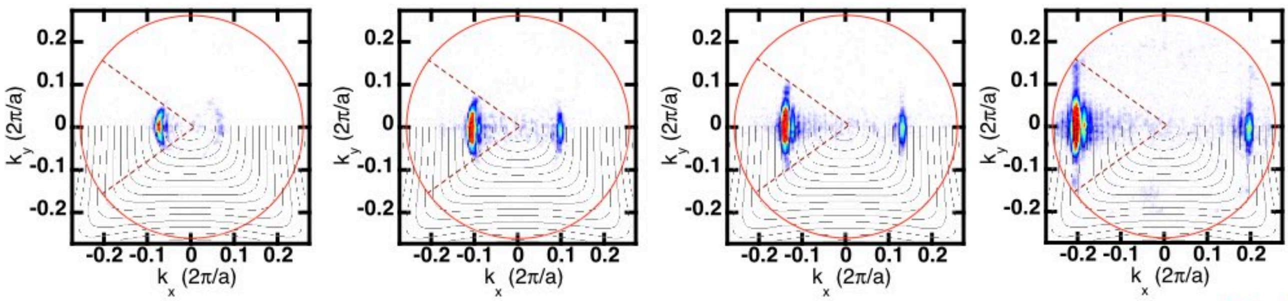
Equi-Frequency surfaces mapping in PhCs

Real space

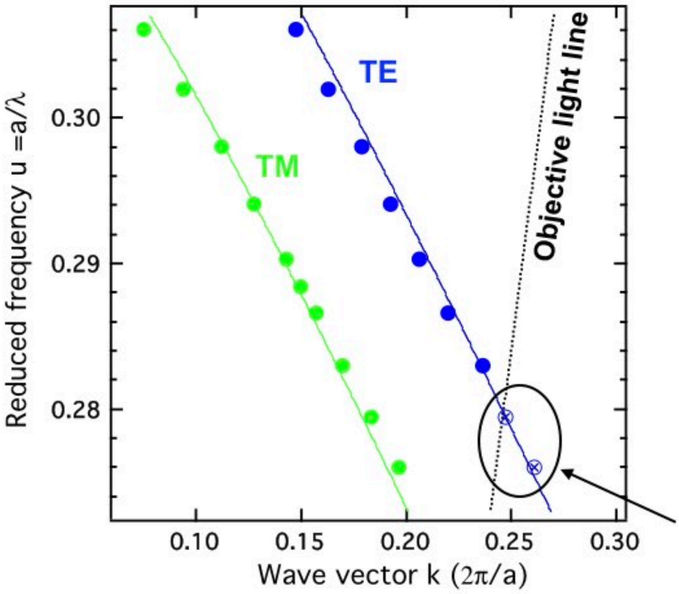


λ =1.48 μm λ =1.51 μm λ =1.55 μm λ =1.63 μm

Fourier space

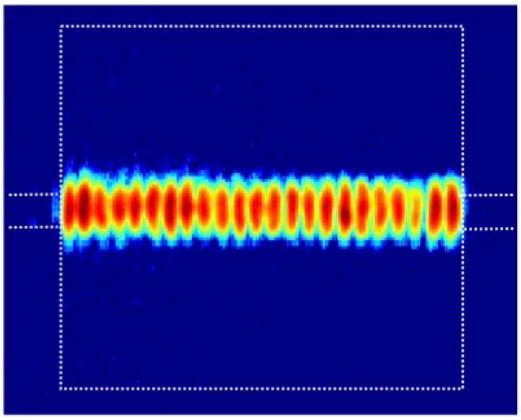


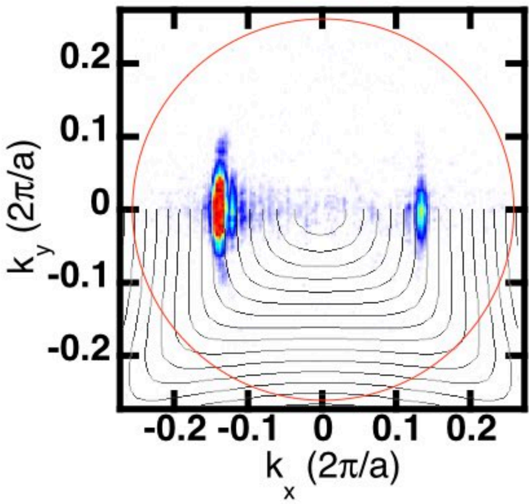
Dispersion curves



coming
soon

Misinterpretation

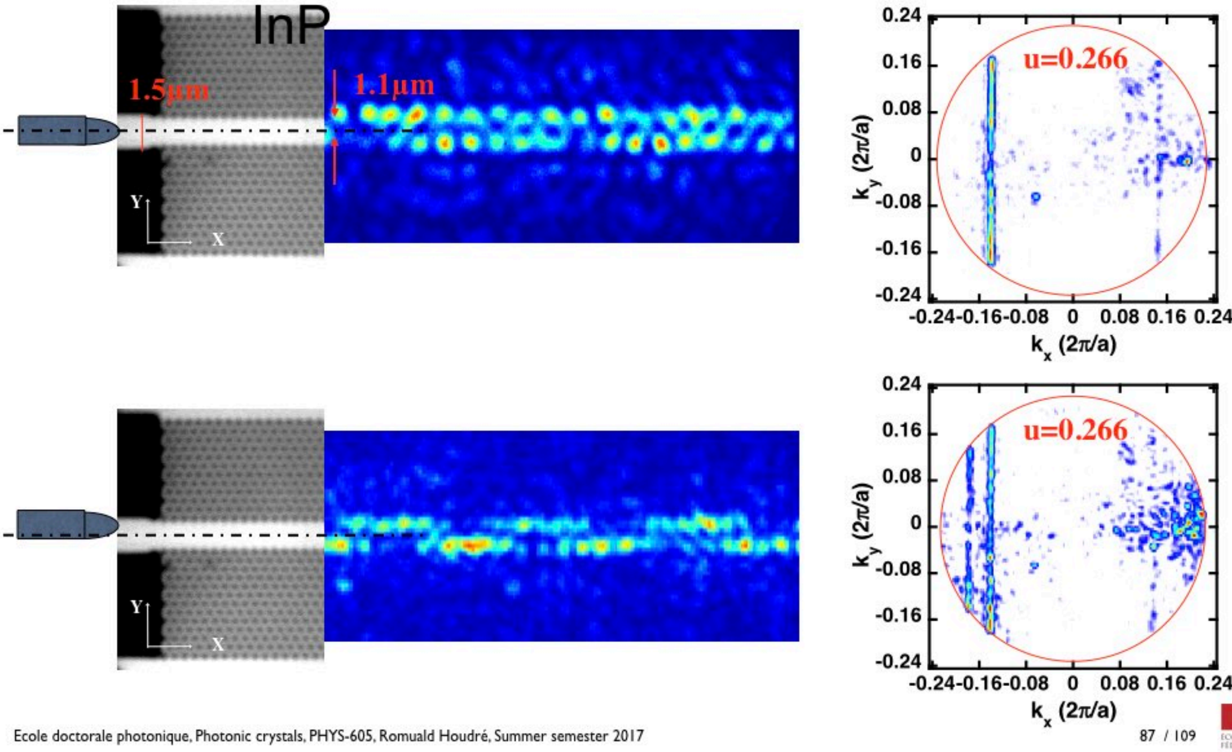




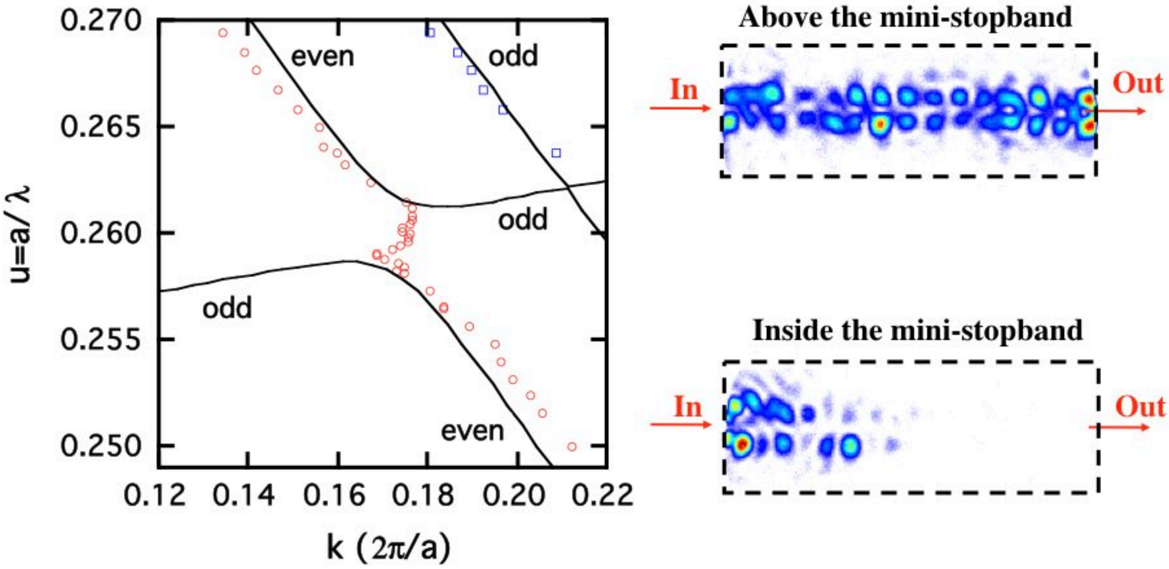
- The fringes are *not* an image of the Bloch mode.
- They originate from the interference between the forward and backward propagating mode, which are different modes at +k+mG and -k+mG

Imaging of W3 PhC waveguide

Real space | Fourier space

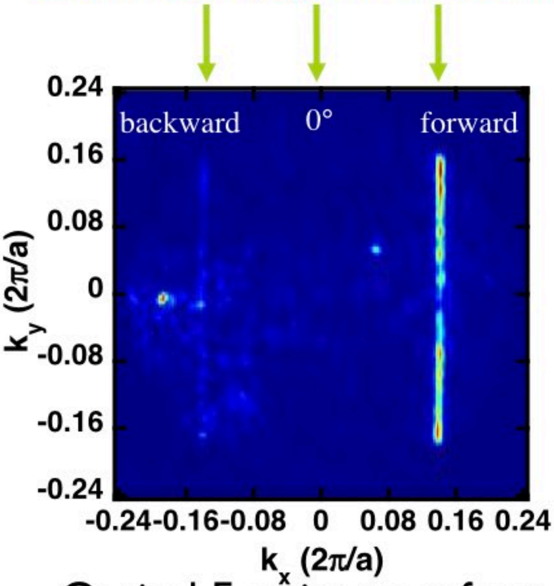


Experimental dispersion curves of a W3 PhC waveguide

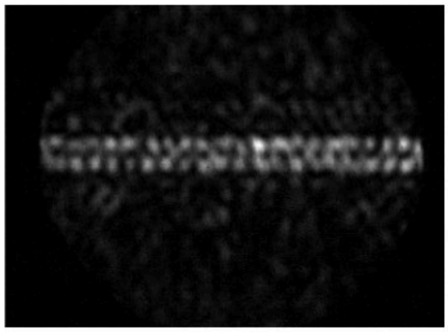


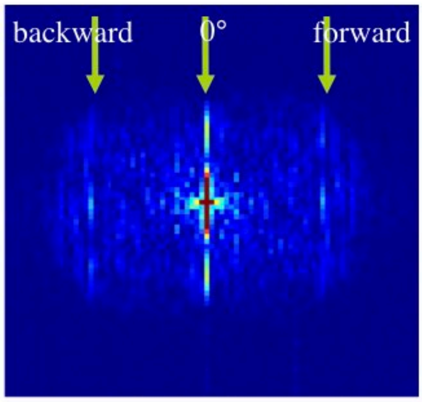
Optical and numerical FFT

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.



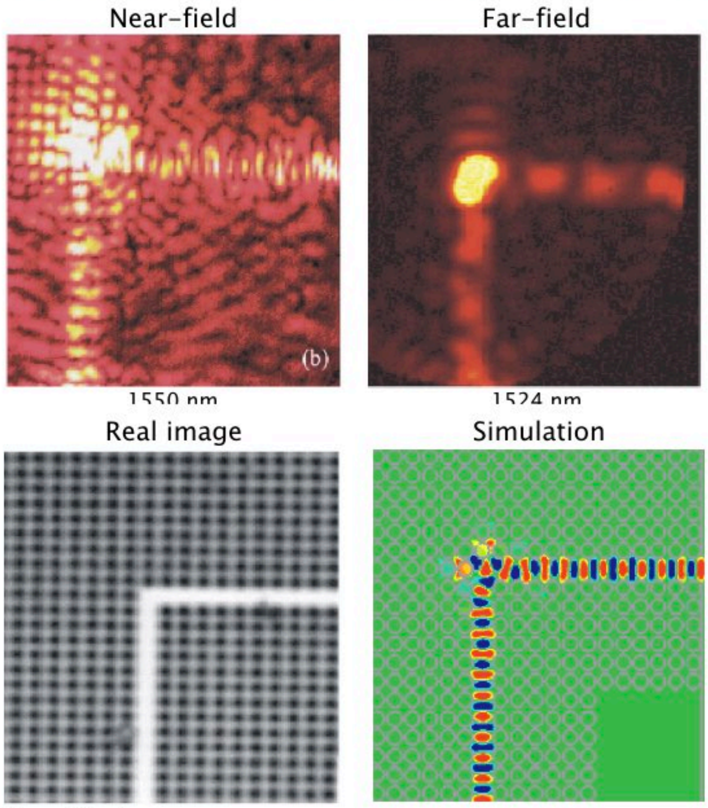
Optical Fourier transform





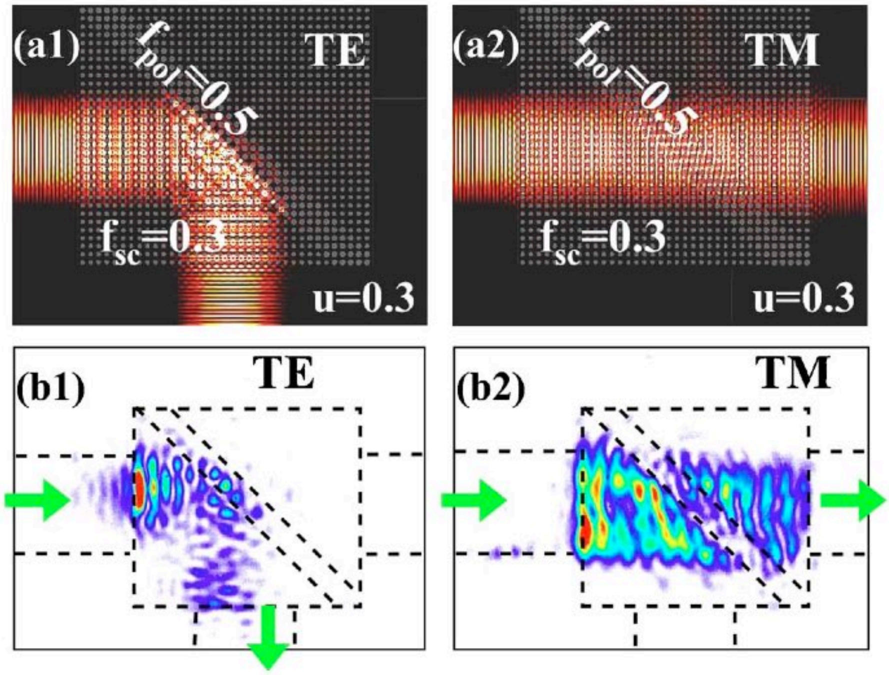
Numerical 2D-FFT

Comparison SNOM high NA imaging



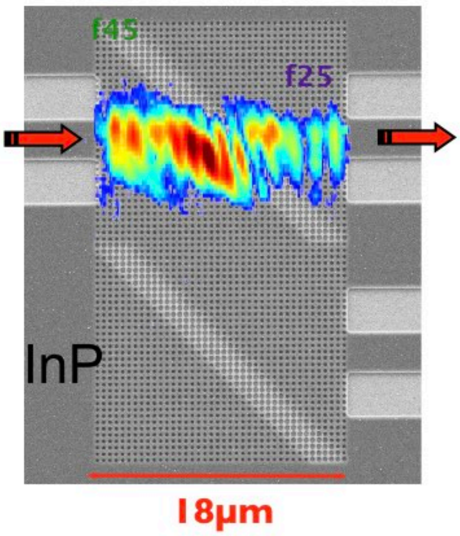
Courtesy I. Märki, Uni Neuchâtel

In-situ characterization of a polarization splitter

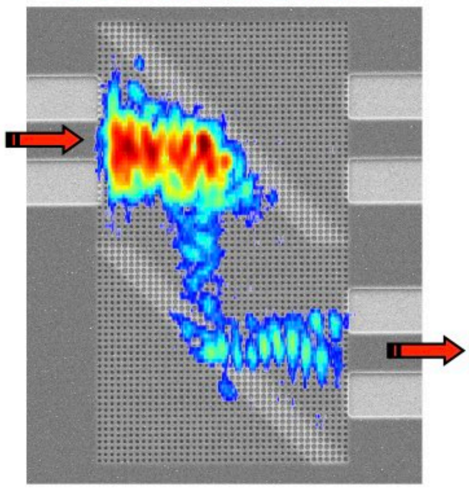


In-situ characterization of a polarization splitter

TM polarized light



TE polarized light



T=35%

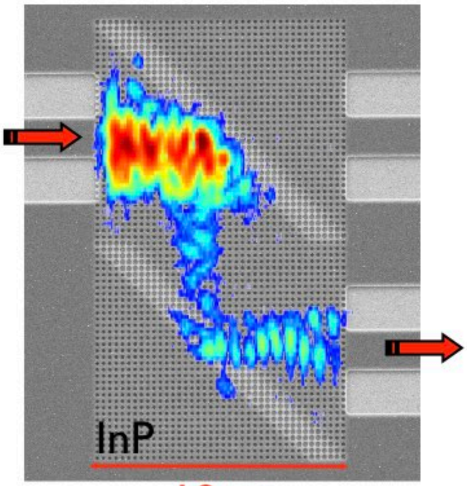
R=3%

R=25%

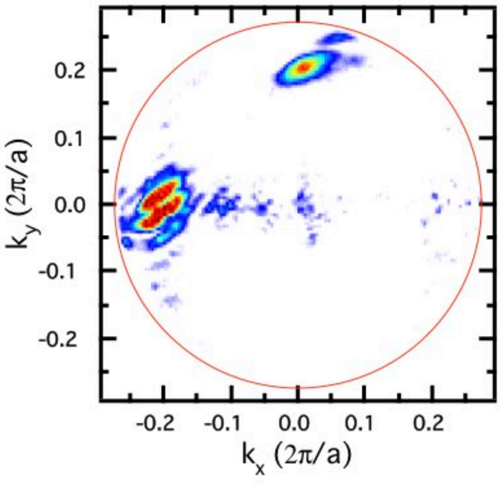
T=0.2%

In-situ characterization of a polarization splitter

TE polarized light

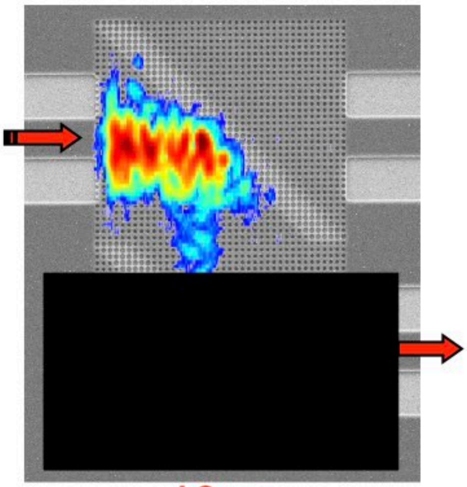


18μm

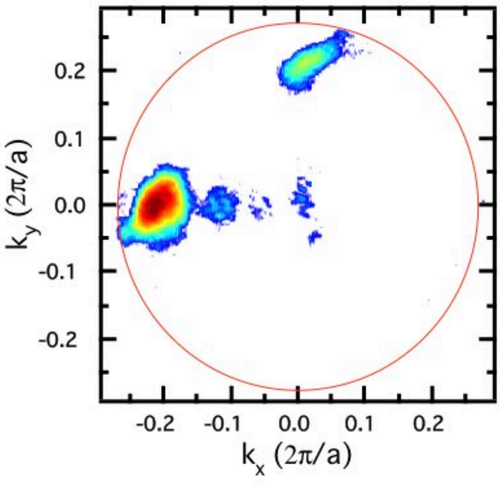


Fourier space imaging with filtering in real space

TE polarized light

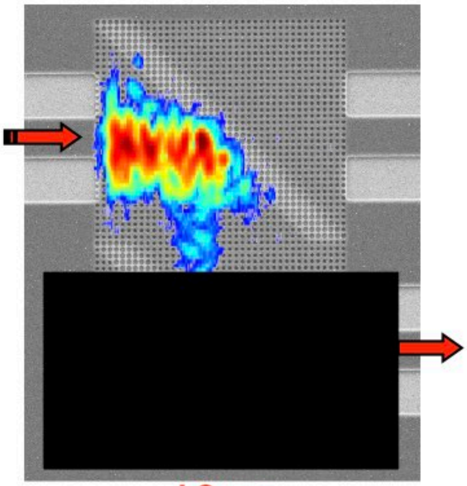


18μm

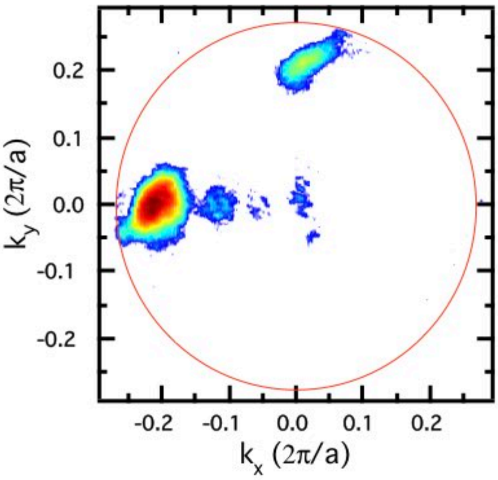


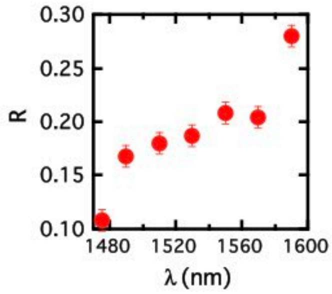
Fourier space imaging with filtering in real space

TE polarized light



18µm





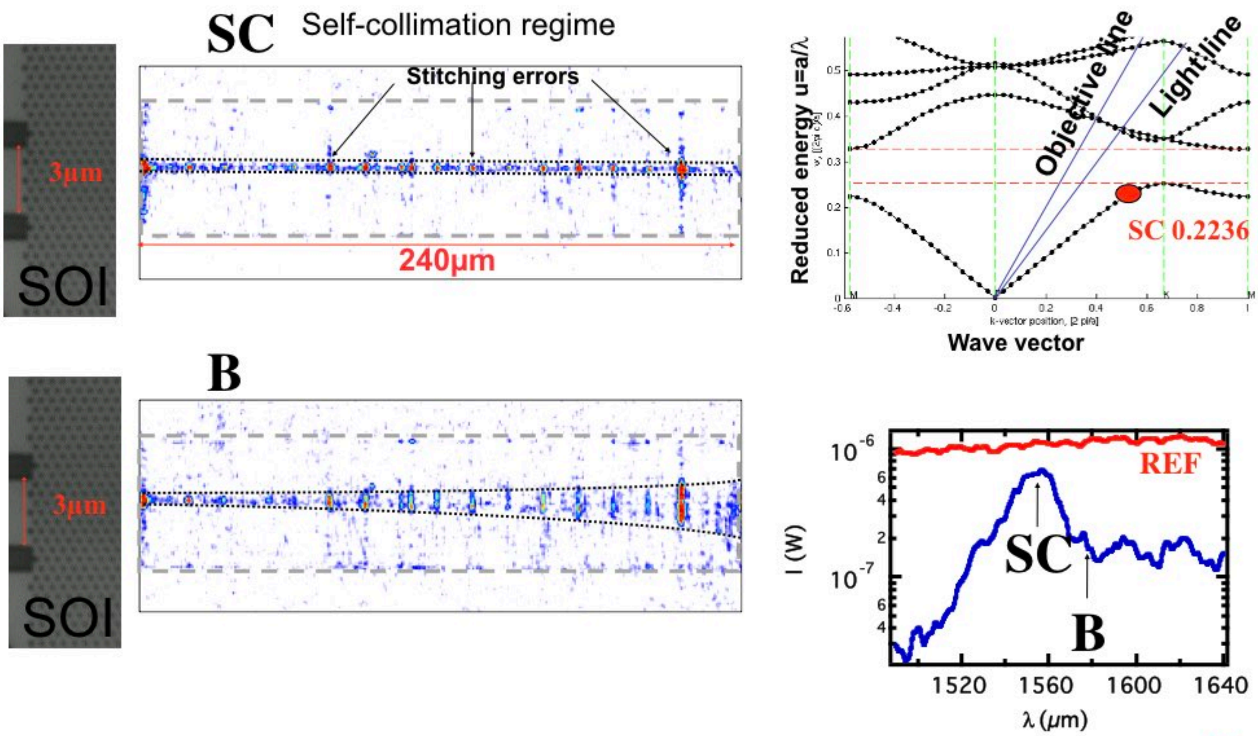
but ...

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 ?

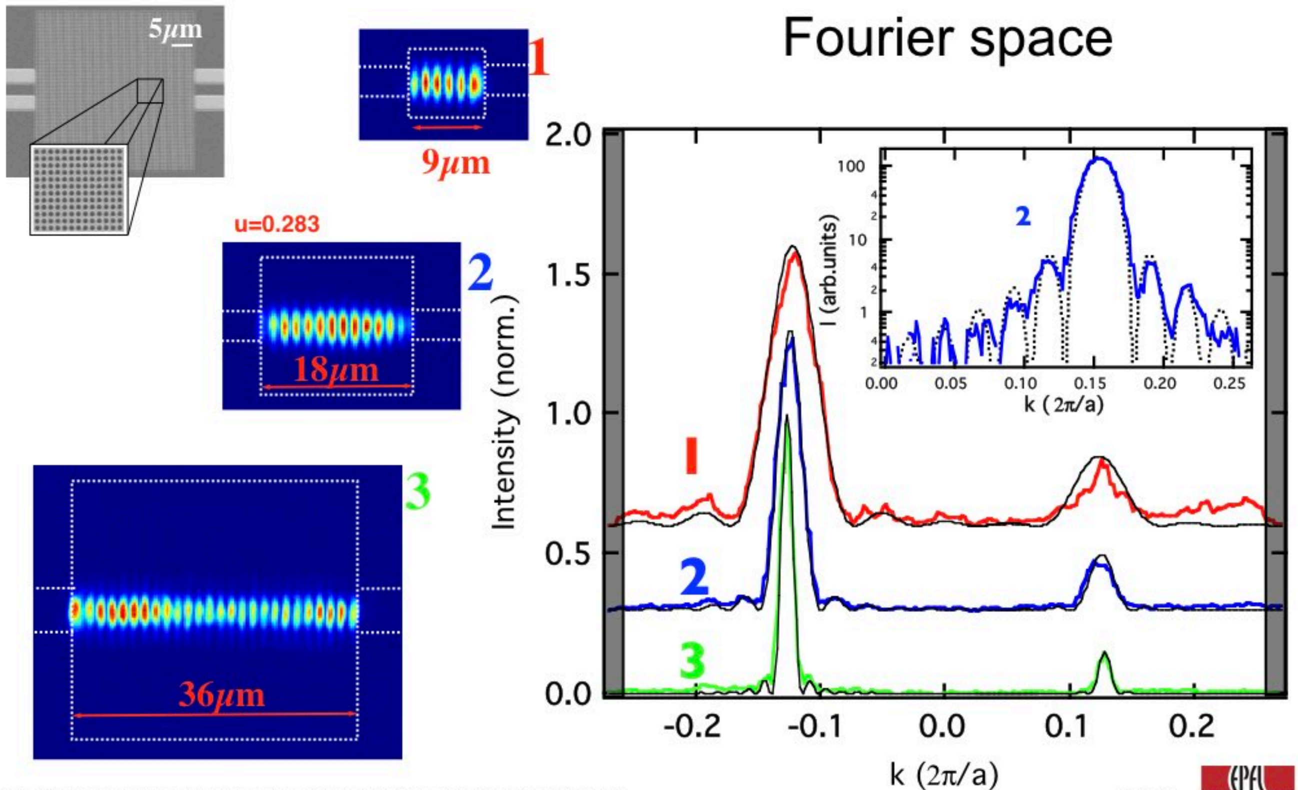
I Make use of fabrication imperfections

Imaging of Bloch wave propagating below the light cone

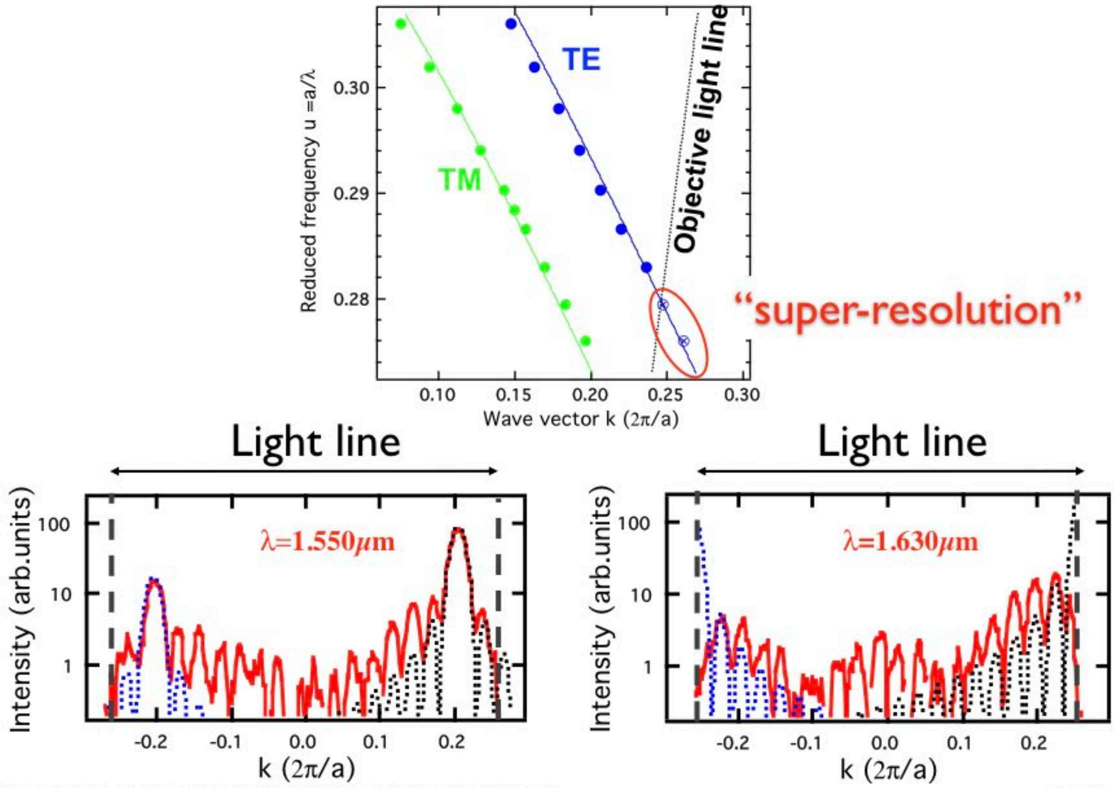


2 Make use of finite size effects

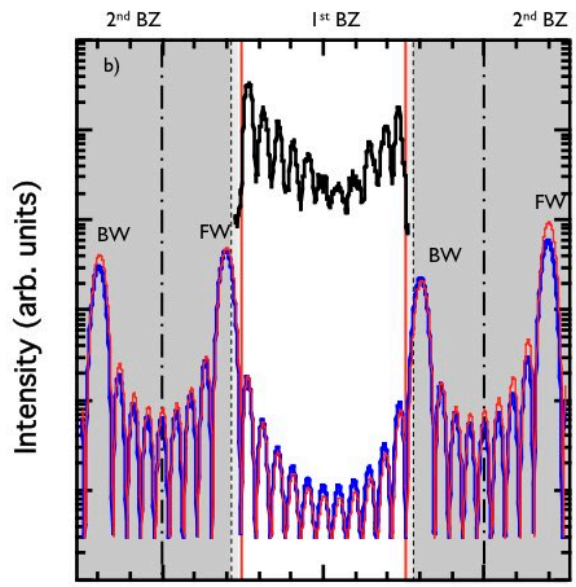
Dispersion curves and super-resolution: Size effect

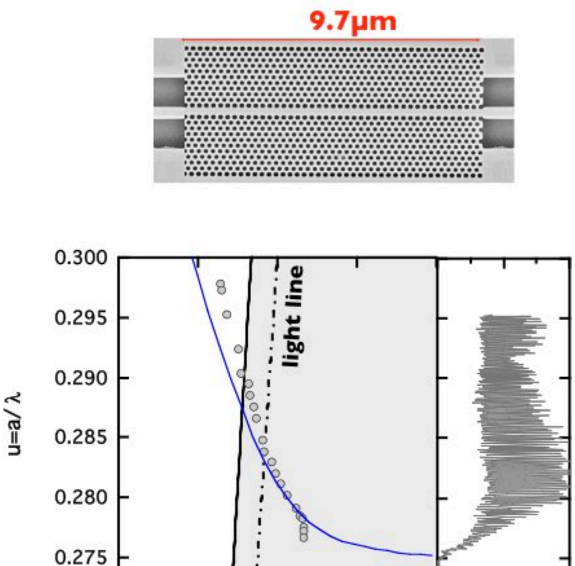


Dispersion curves and super-resolution: Size effect



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



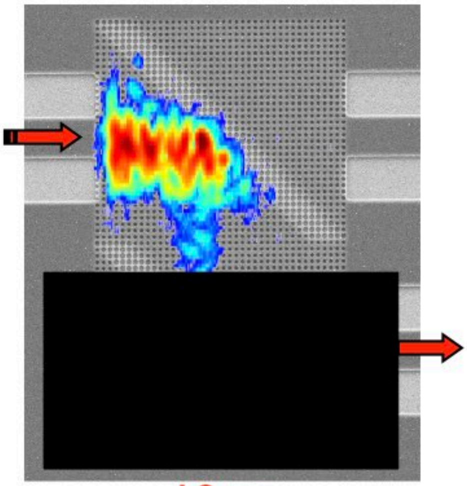


Effective NA = 2.5

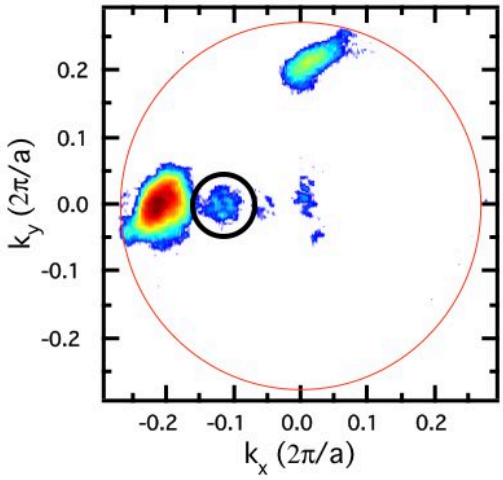
Fourier space imaging with filtering in real space

Characterisation below the light cone

TE polarized light



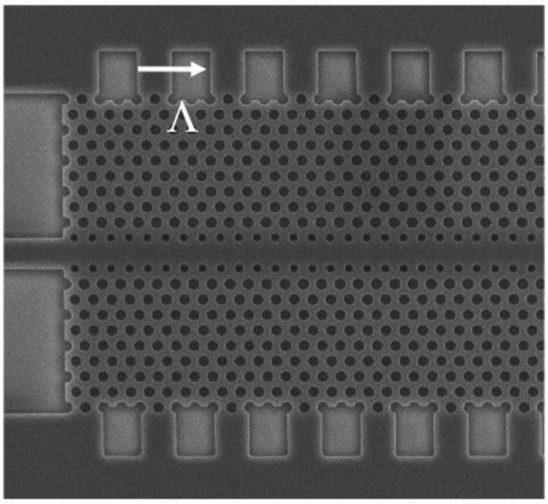
18µm



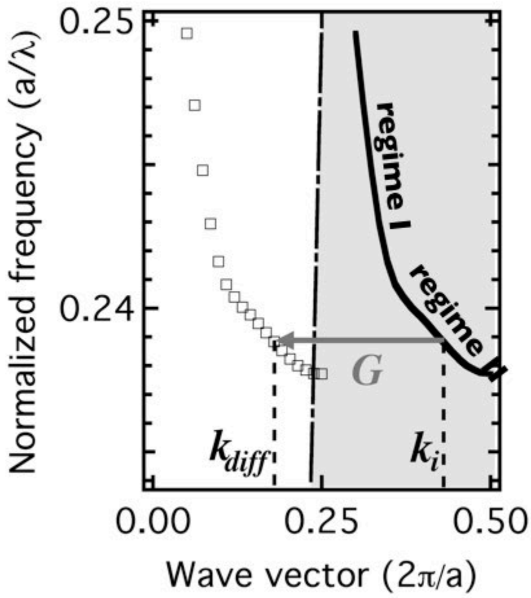
3 Fold back the band structure into the light cone with an extra periodicity

just a small amount to enable measurement

Imaging of dispersion curve below the light cone

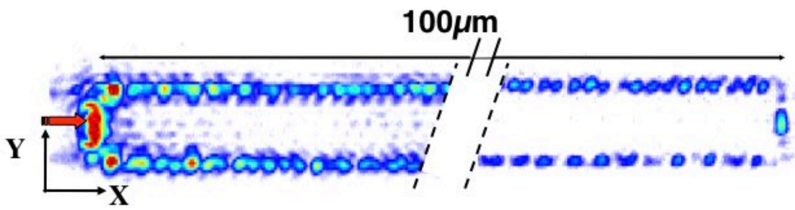


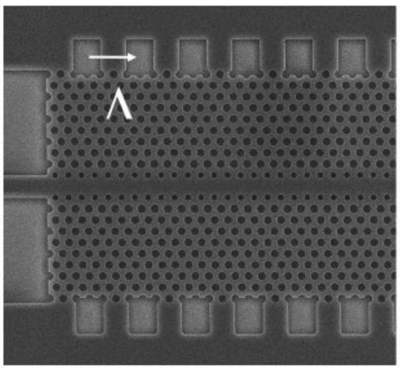
$$G = \frac{2\pi}{\Lambda}$$

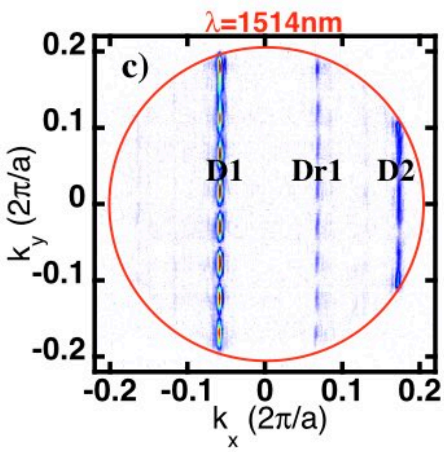


N. Le Thomas et al., Phys. Rev. B 76, 035103 (2007)

Imaging of dispersion curve below the light cone







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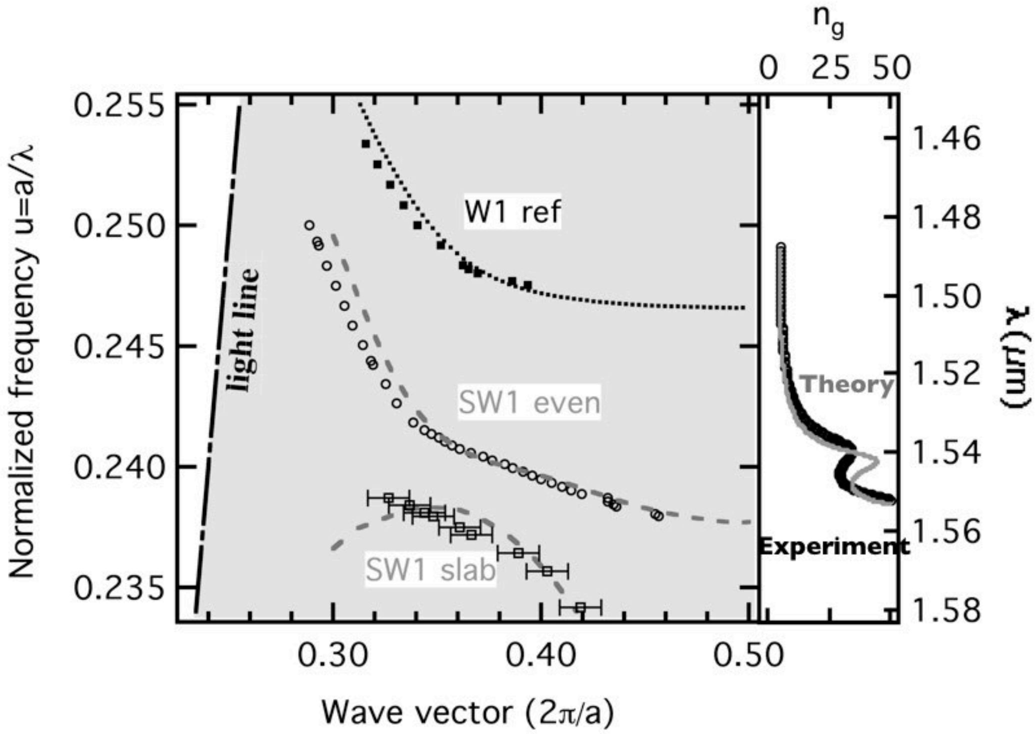
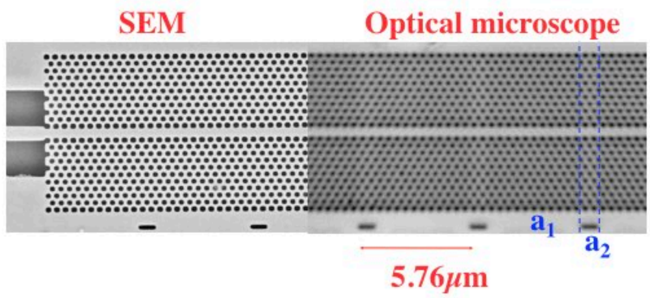
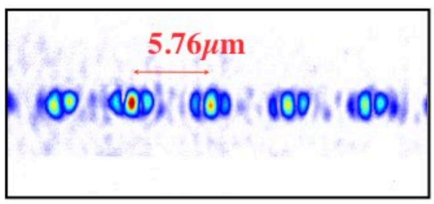
Imaging of dispersion curve below the light cone

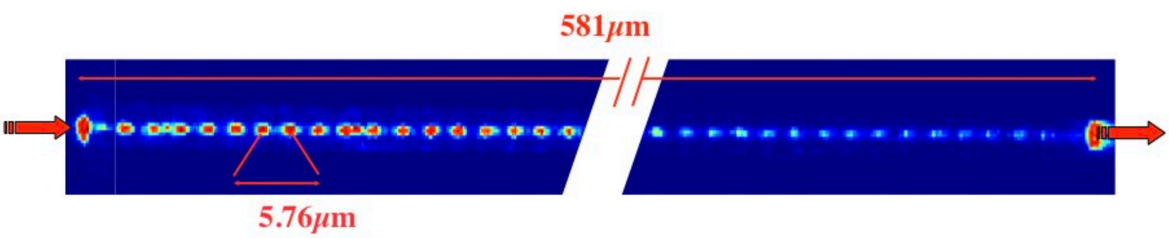


N. Le Thomas et al., Phys. Rev. B 76, 035103 (2007)

Imaging of Coupled Cavities based Waveguides







Imaging of Coupled Cavities based Waveguides