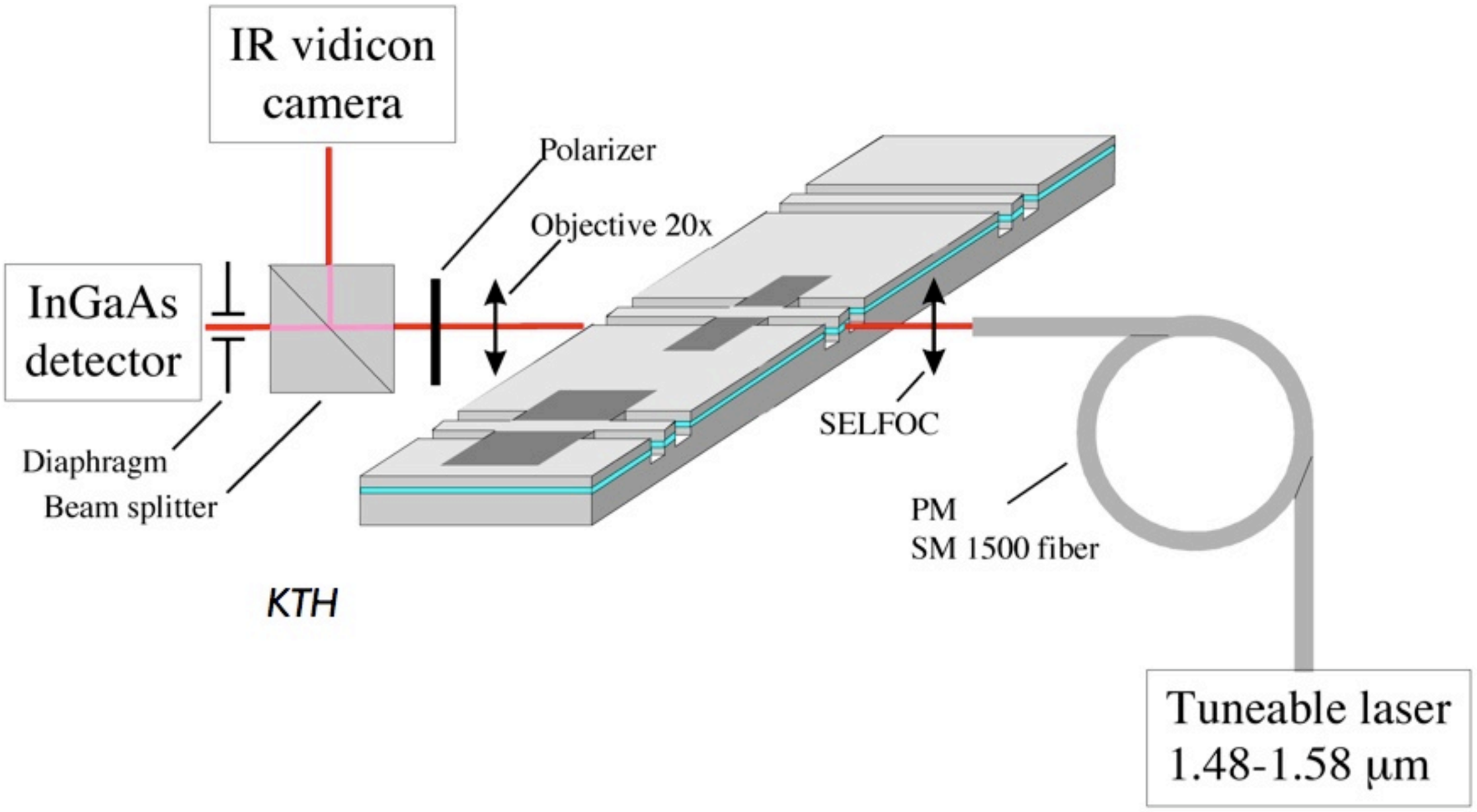
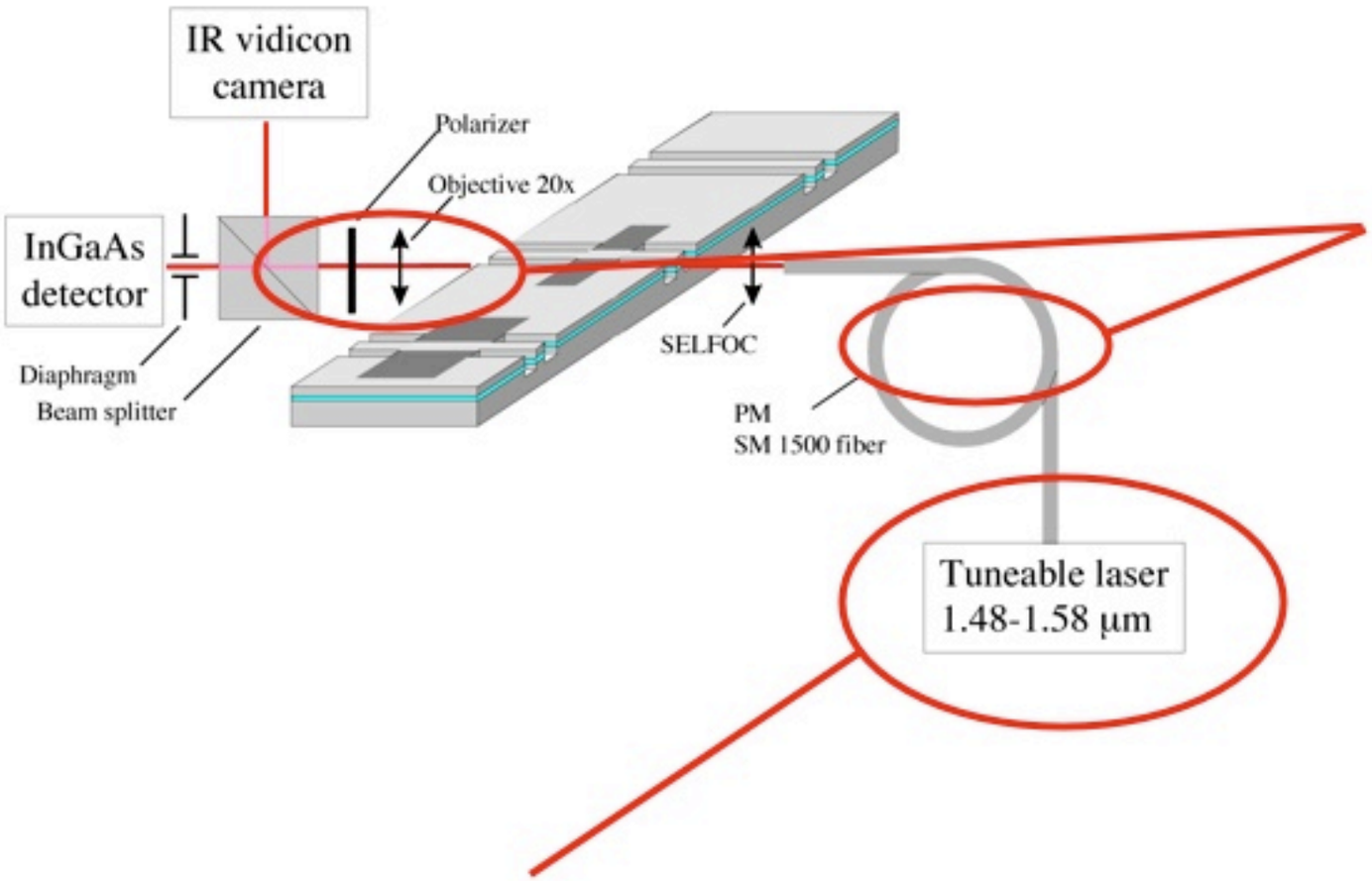
External source
End-Fire

Principle



External source
End-Fire

Principle



Light input or output :

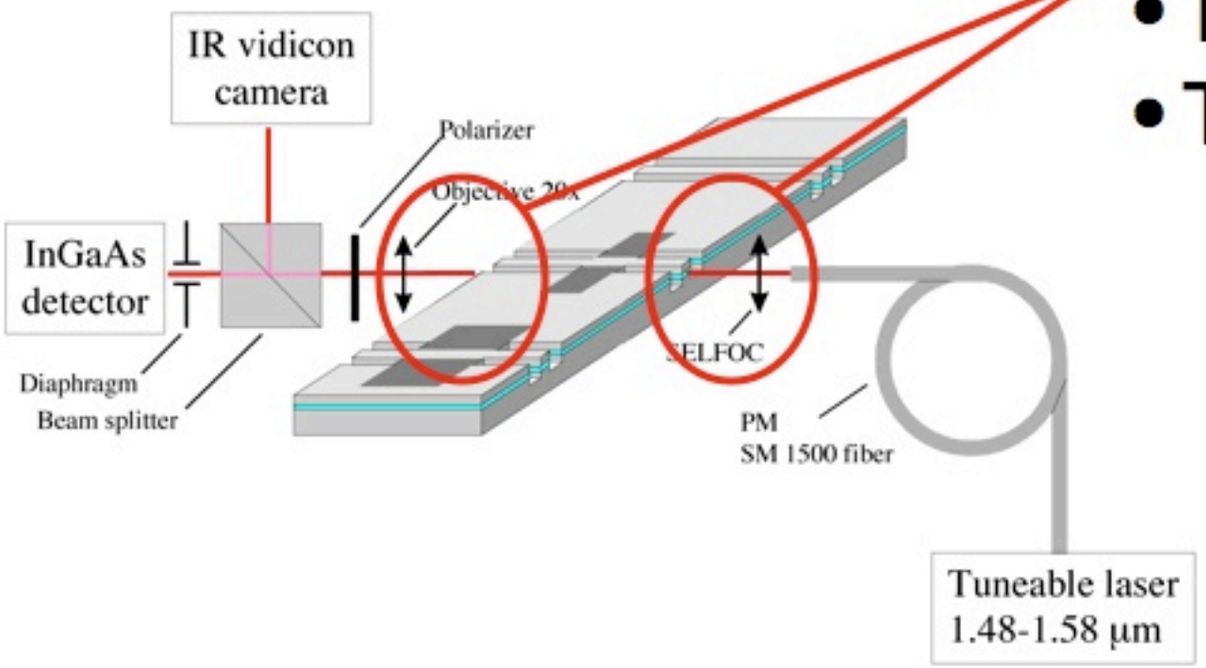
- Optical fiber, single mode
- Free space

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

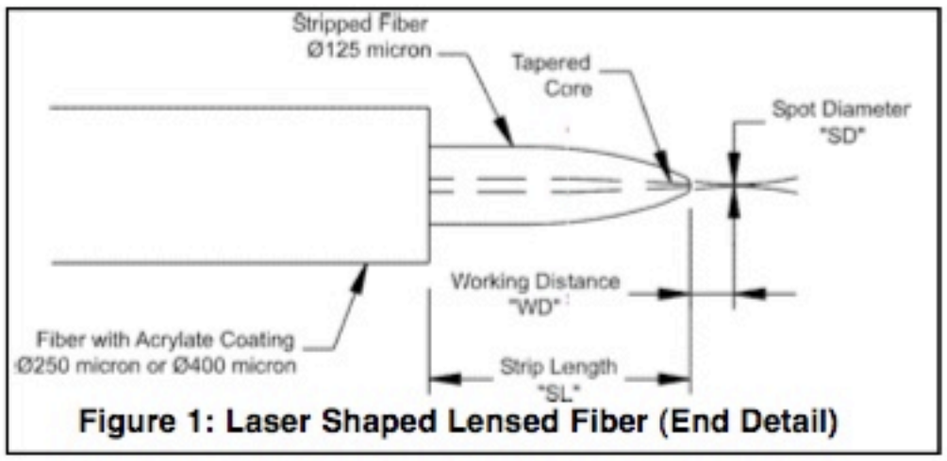


Figure 1: Laser Shaped Lensed Fiber (End Detail)

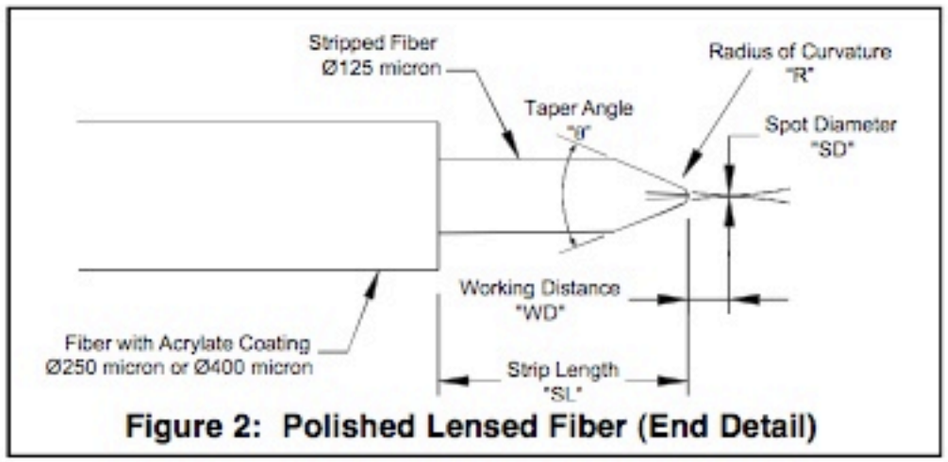
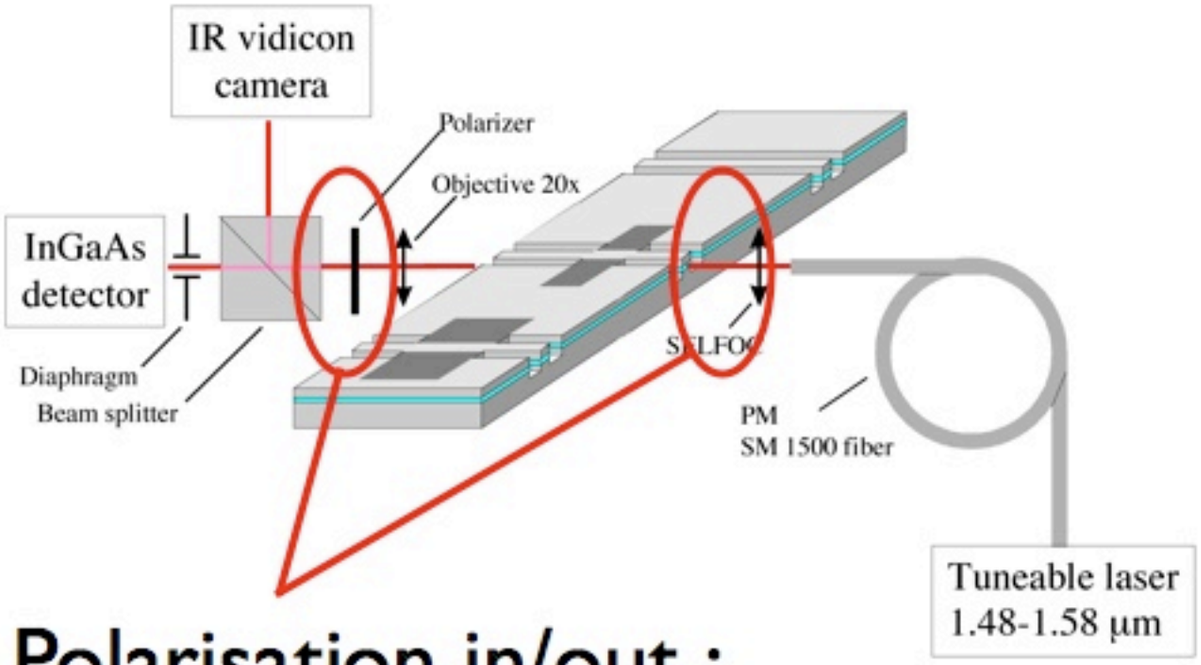


Figure 2: Polished Lensed Fiber (End Detail)

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

External source
End-Fire

Principle



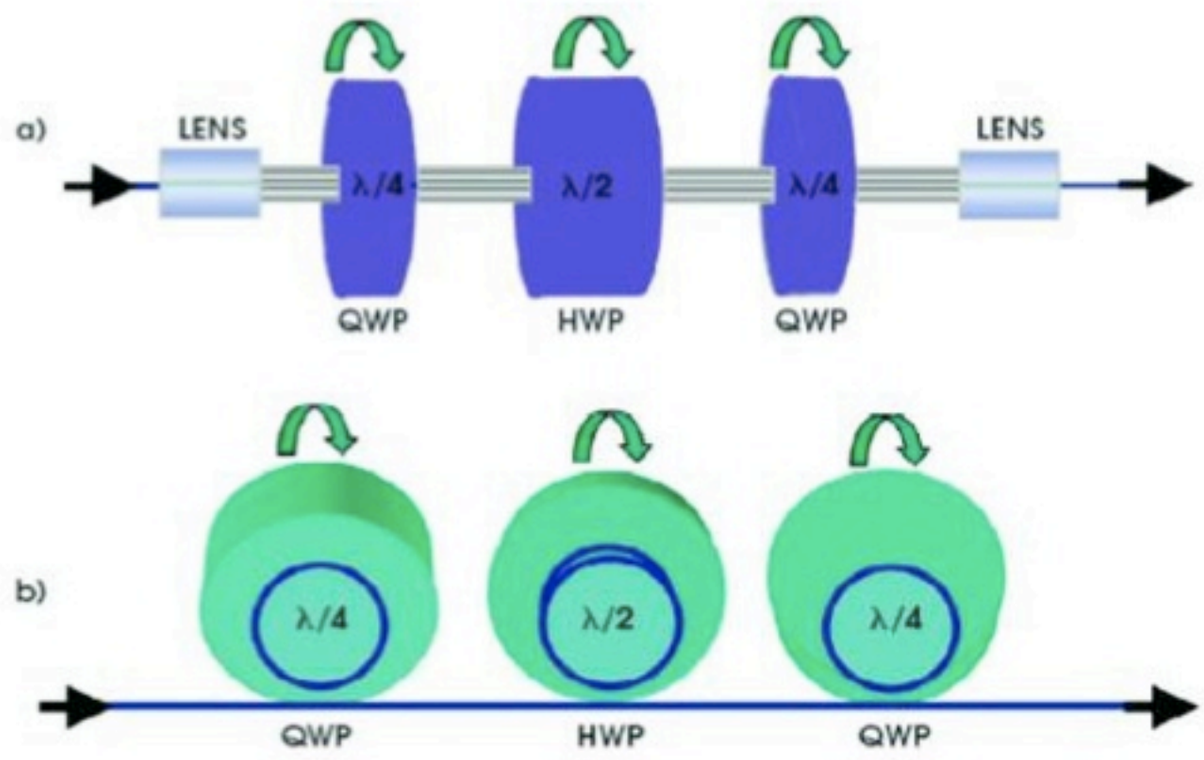


Figure 6. Polarization control using, a) multiple wave plates and, b) using multiple coiled fiber.

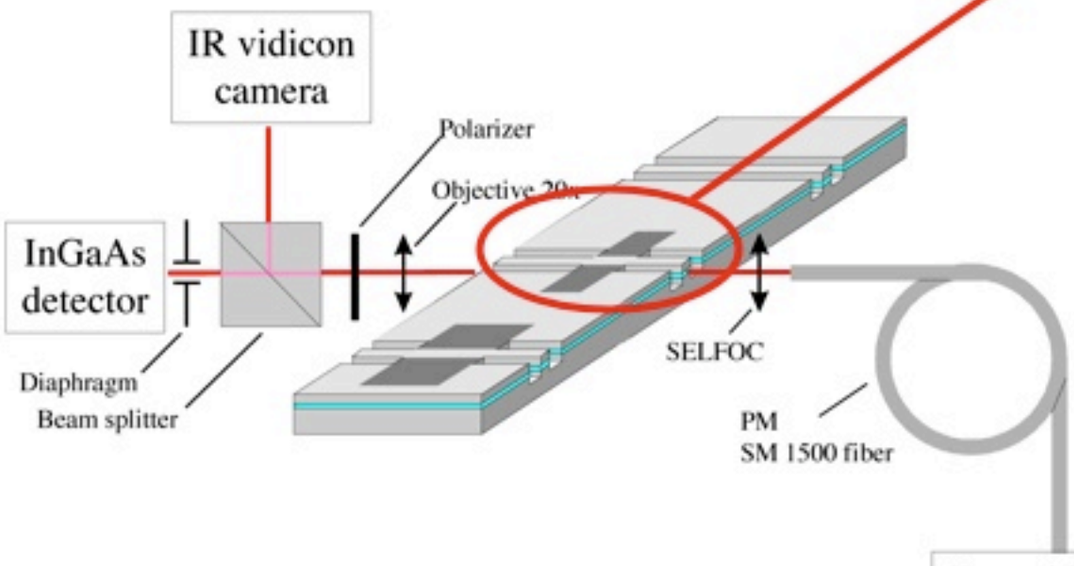
Newport App. Note 20

Polarisation in/out :

- Polarisation maintaining fibers
- Polarisation control
- Polarisation analysis
- Polariser, λ/2 and λ/4 retarding plates
- Coiled fibers
- Often reduced to a TE/TM control / analysis

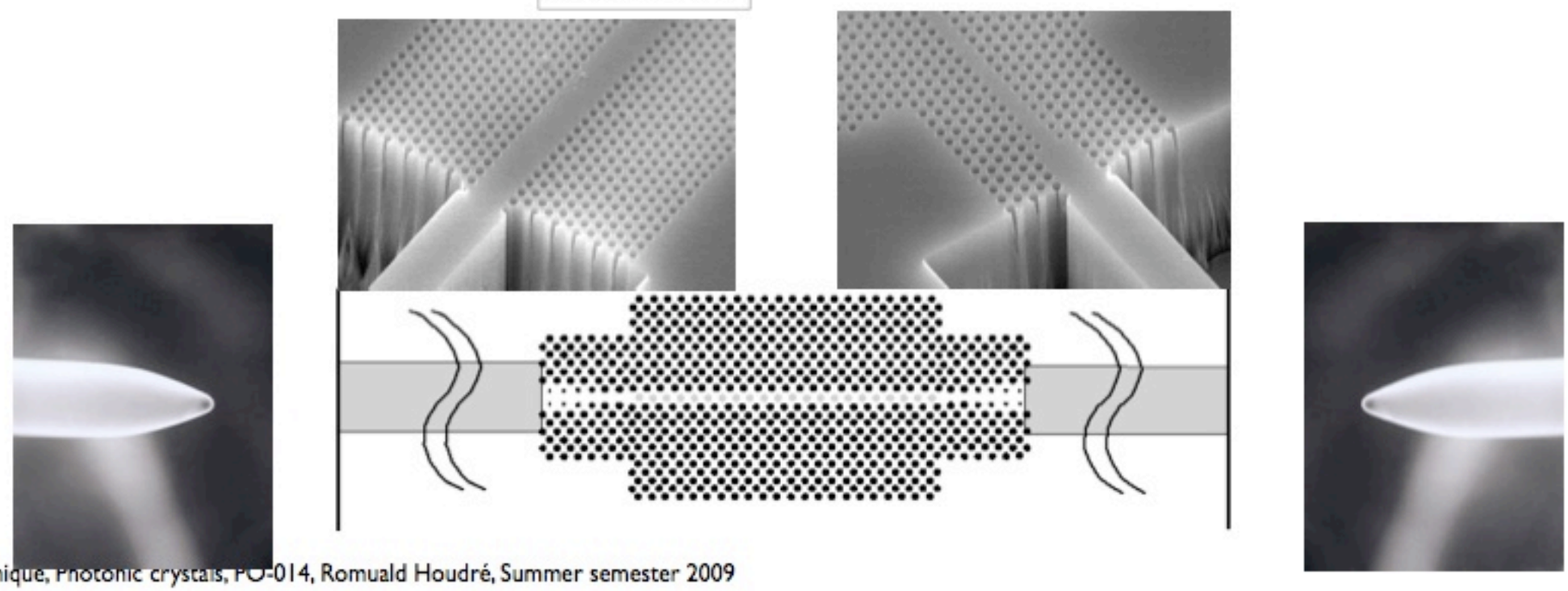
External source
End-Fire

Principle



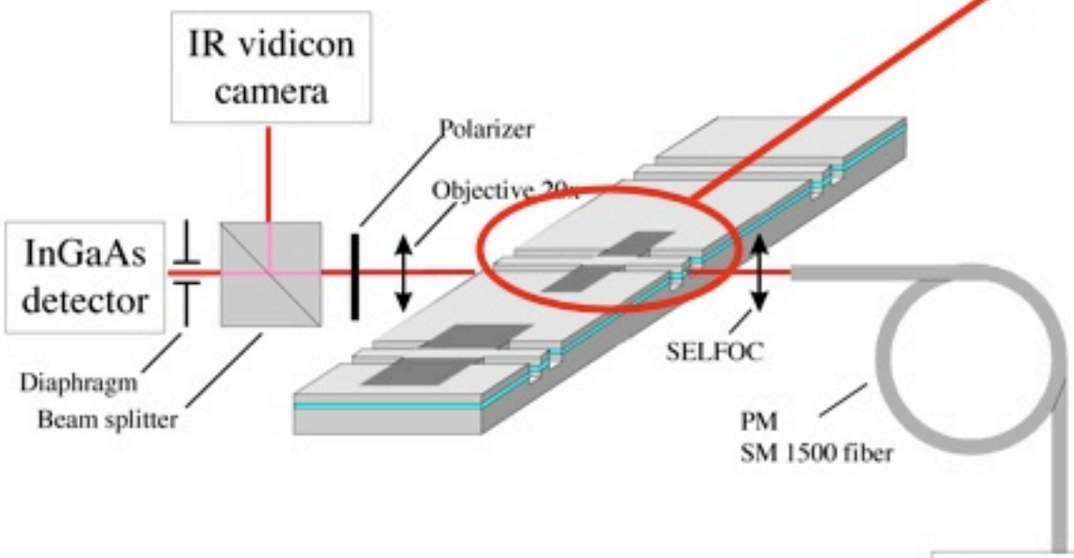
Sample :

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



External source
End-Fire

Principle



Sample :

- Access waveguide
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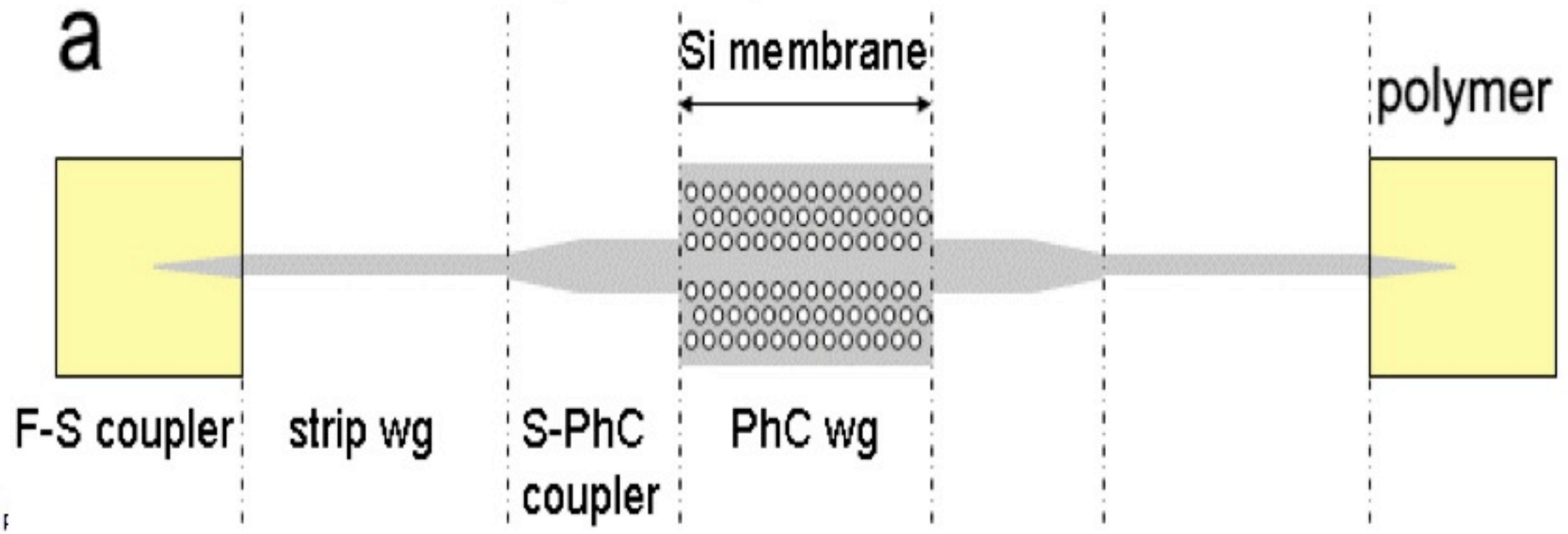
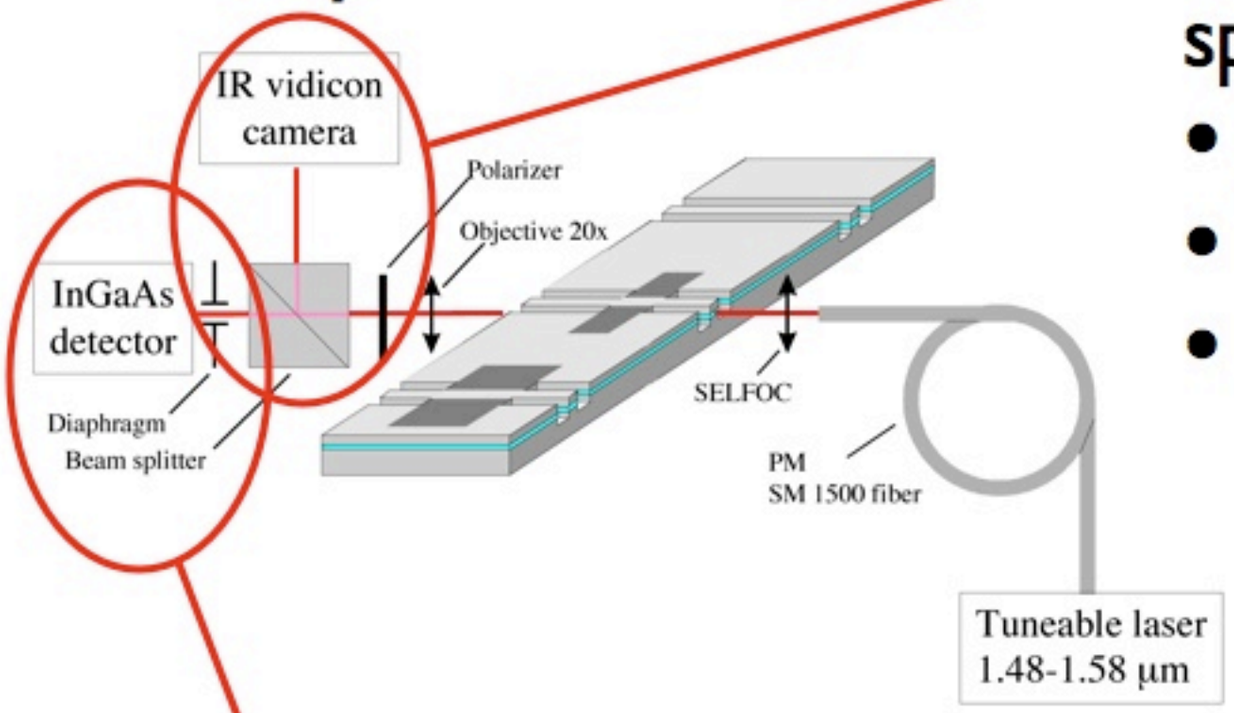
- PhC device



External source
End-Fire

Principle



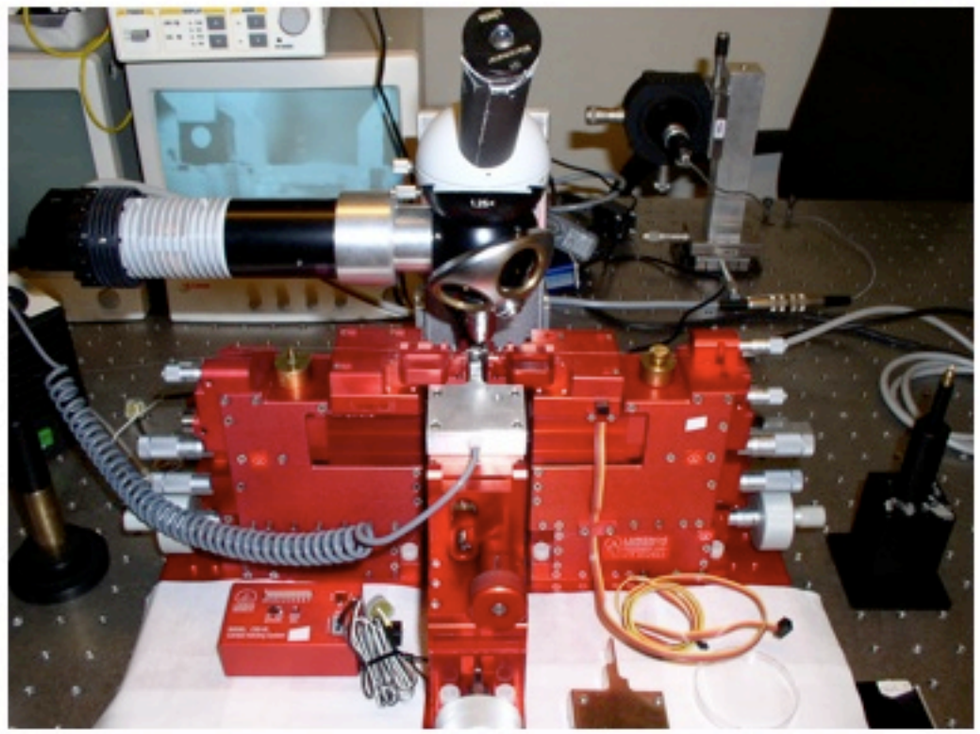
Imaging set-up if working in free space can be convenient

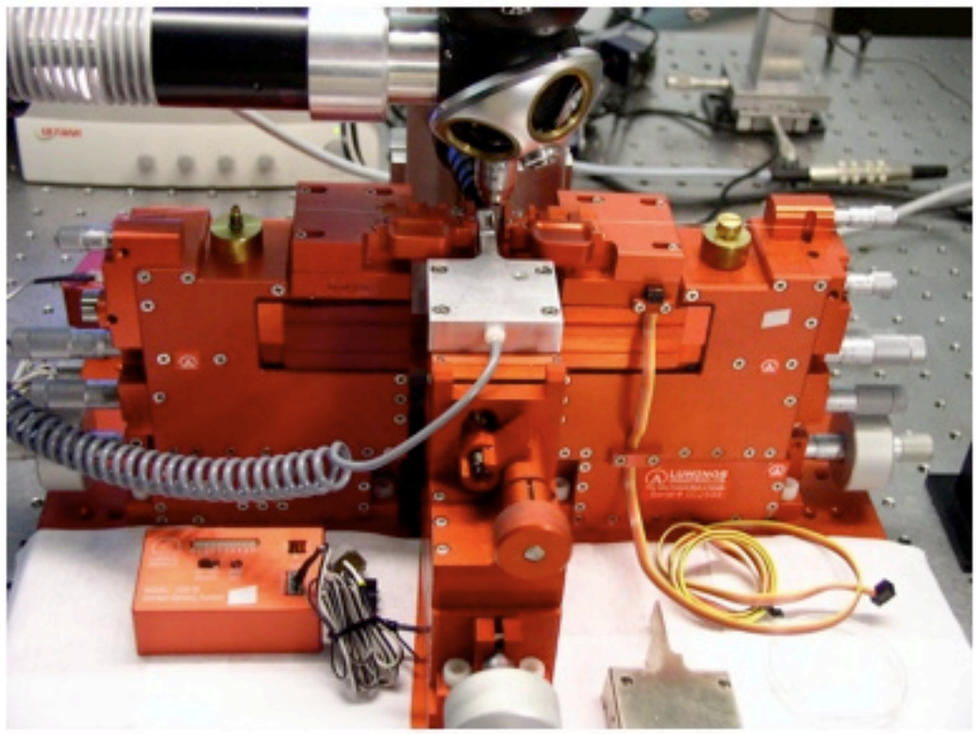
- Si CCD
- IR Vidicon
- IR InGaAs CCD

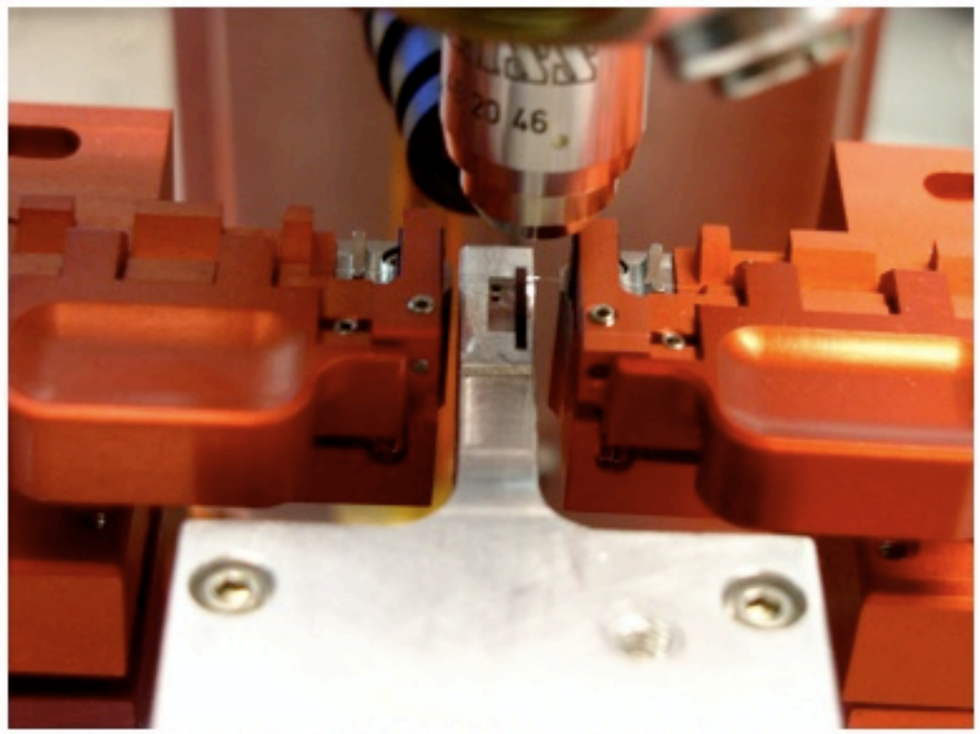
Detector

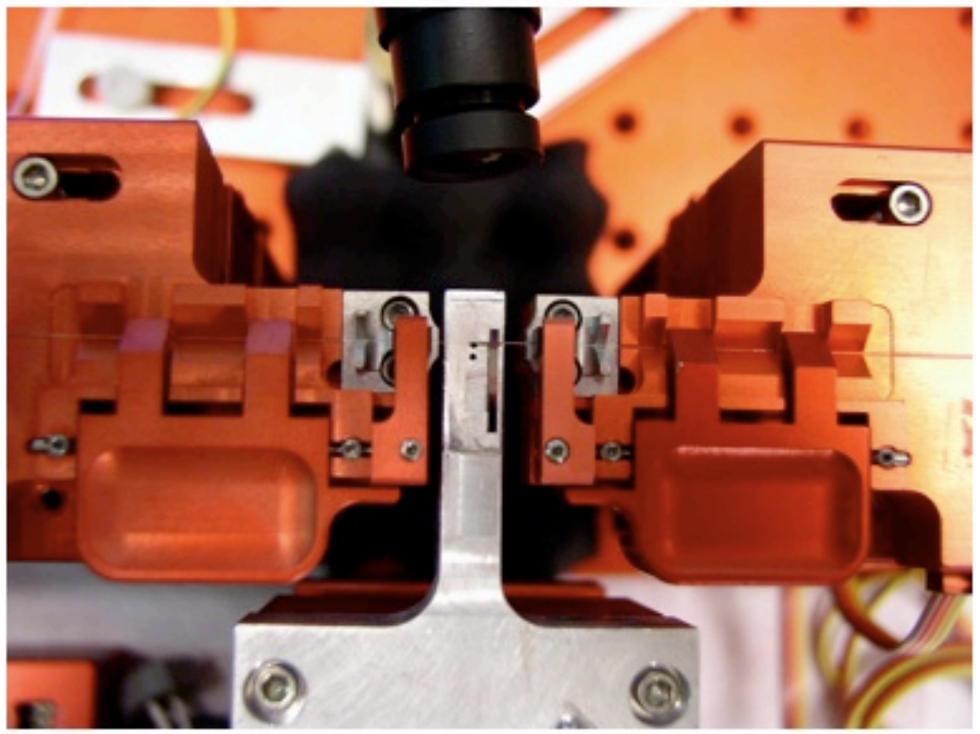
- Si
- InGaAs
- + spectrometer

External source
End-Fire



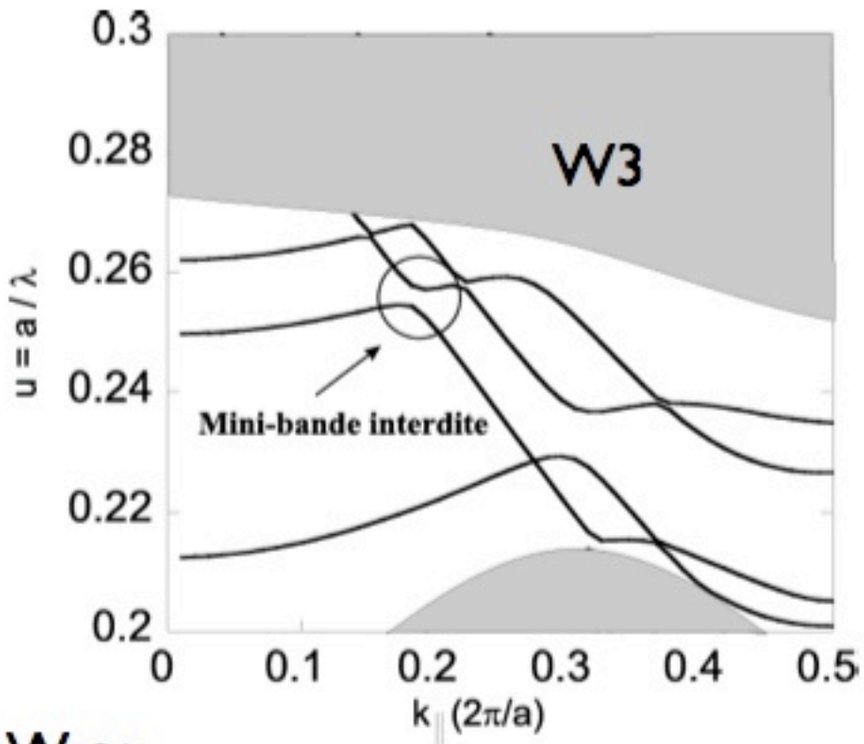


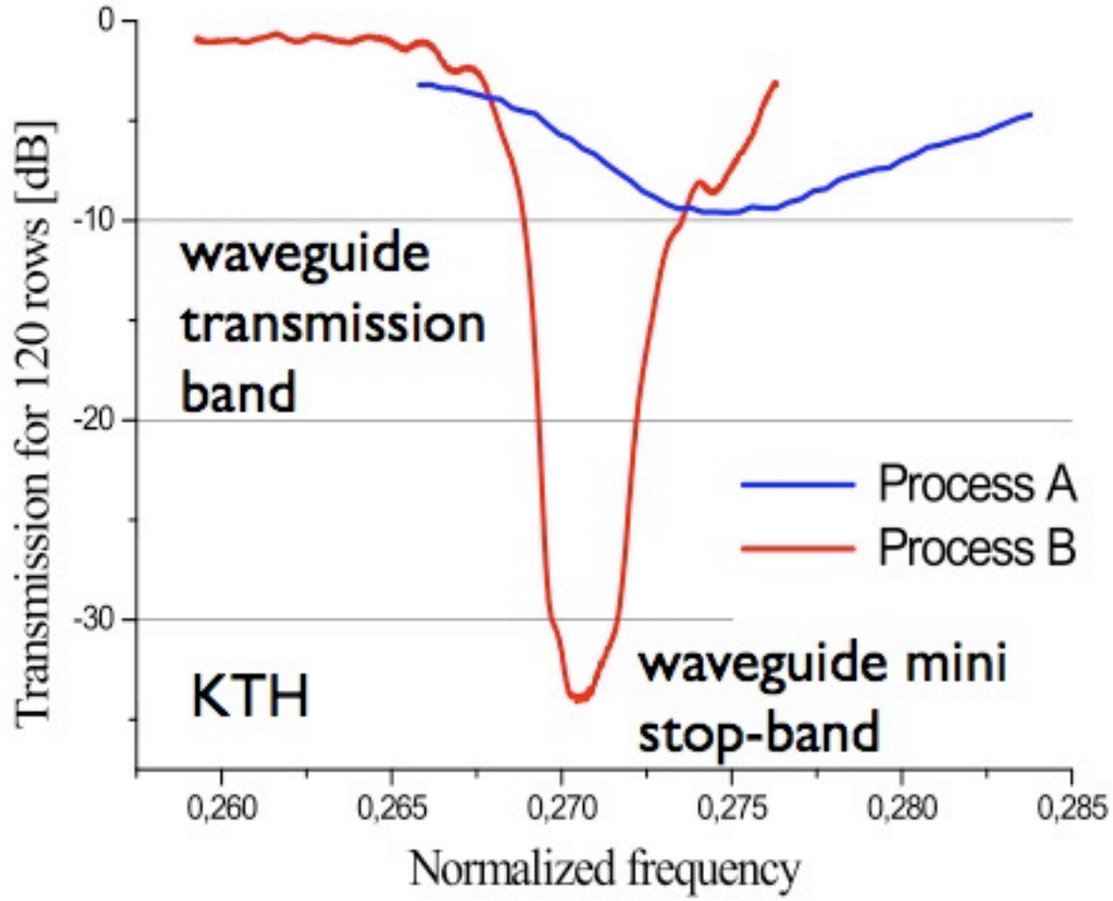




End-Fire

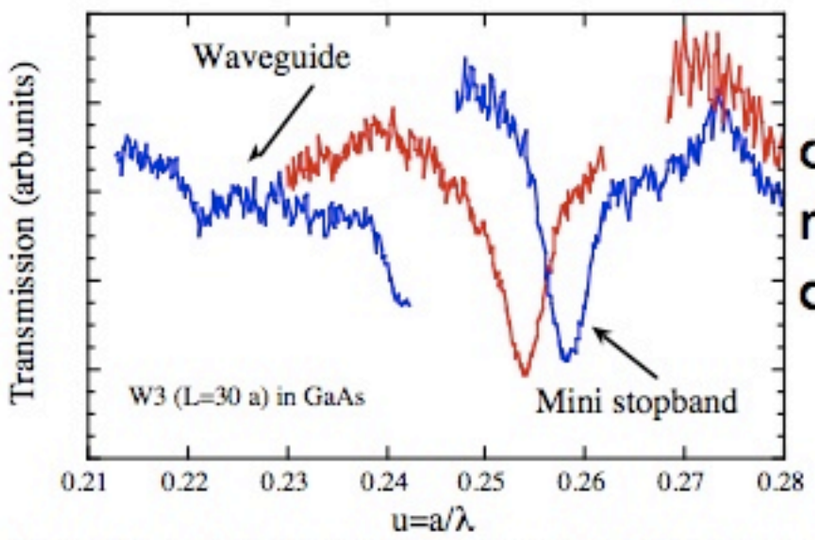
Transmission spectrum, ideal case



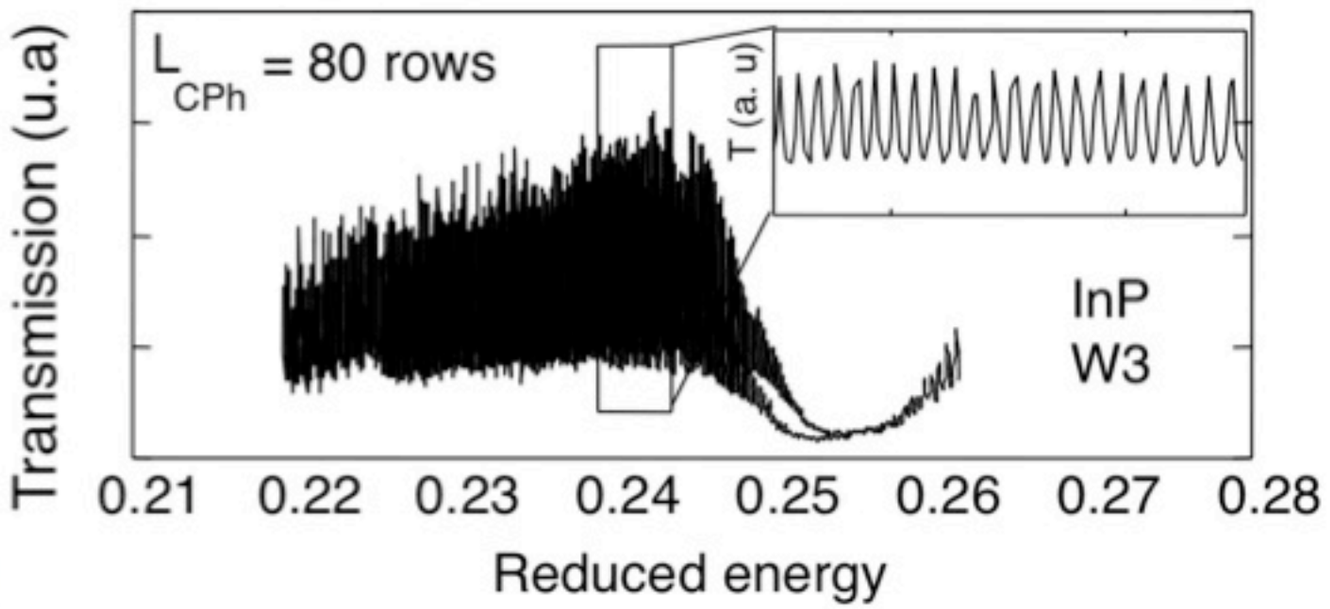


InP-based W3:W ≈

but more commonly :

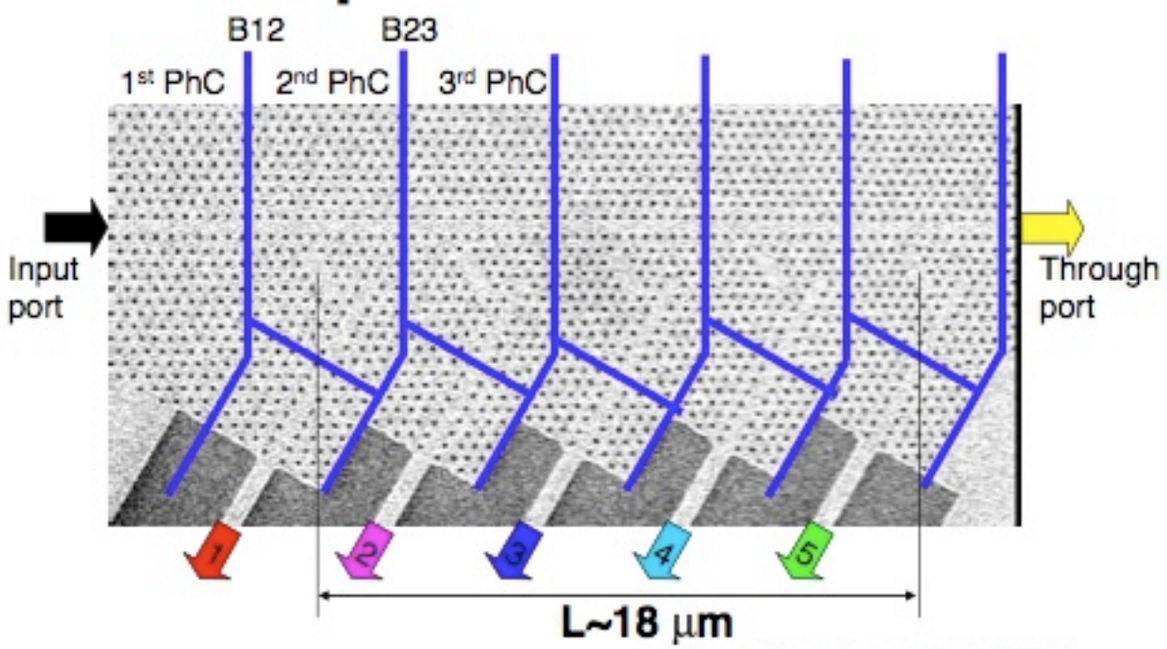


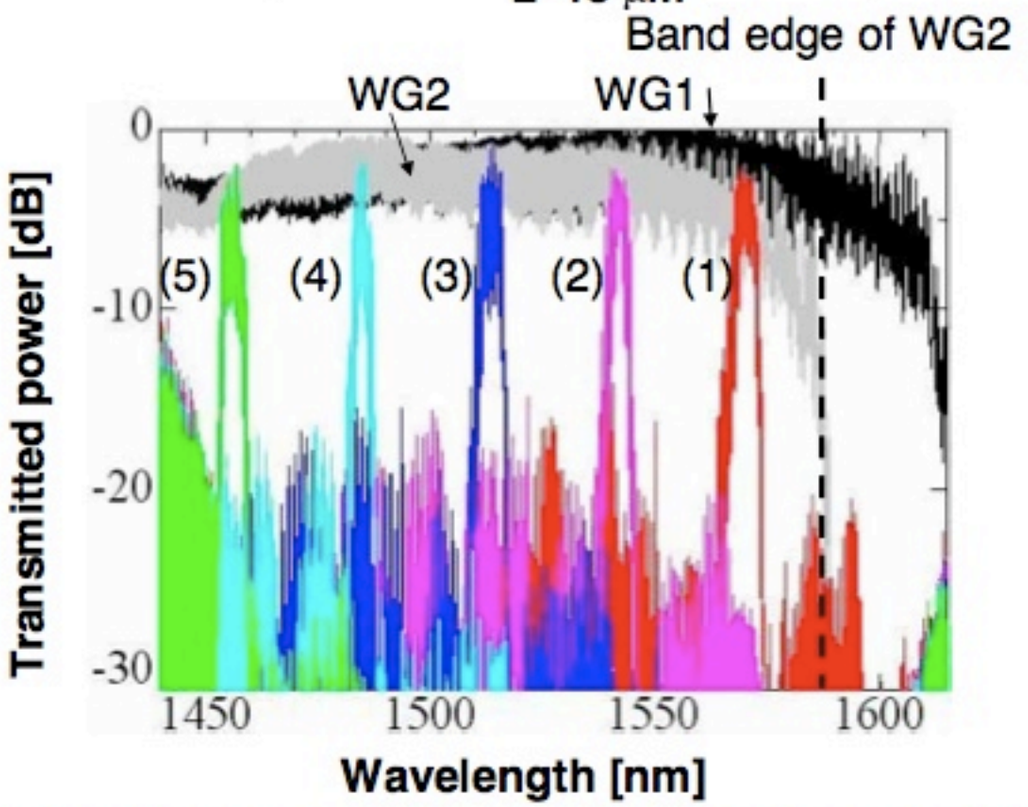
due to internal reflections and cavity fringes



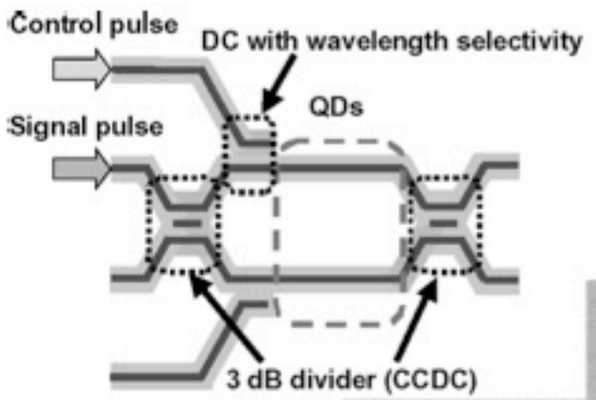
End-Fire

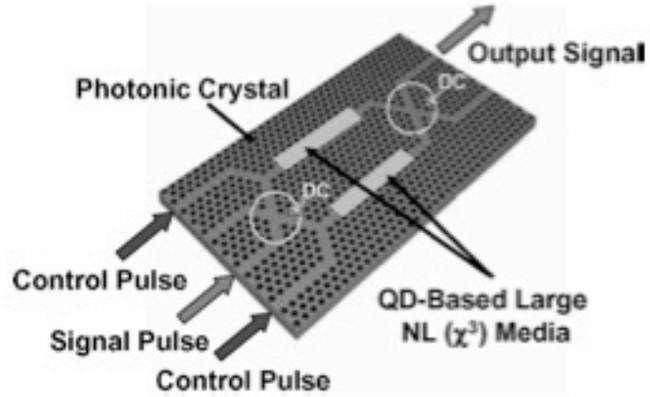
Examples, device characterisation

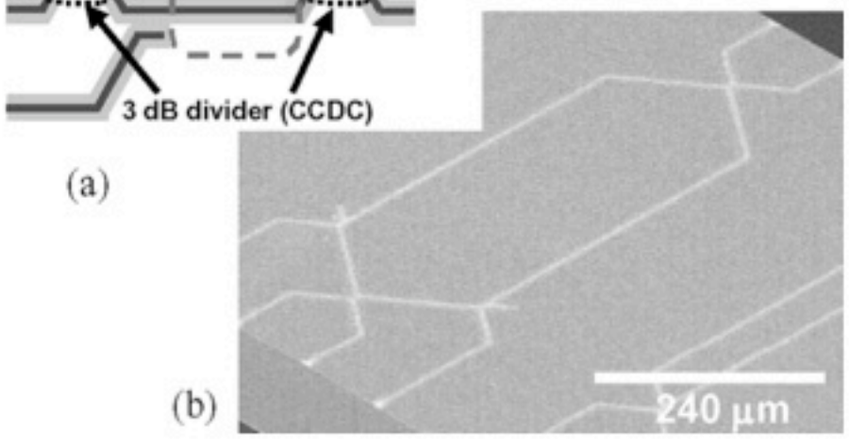


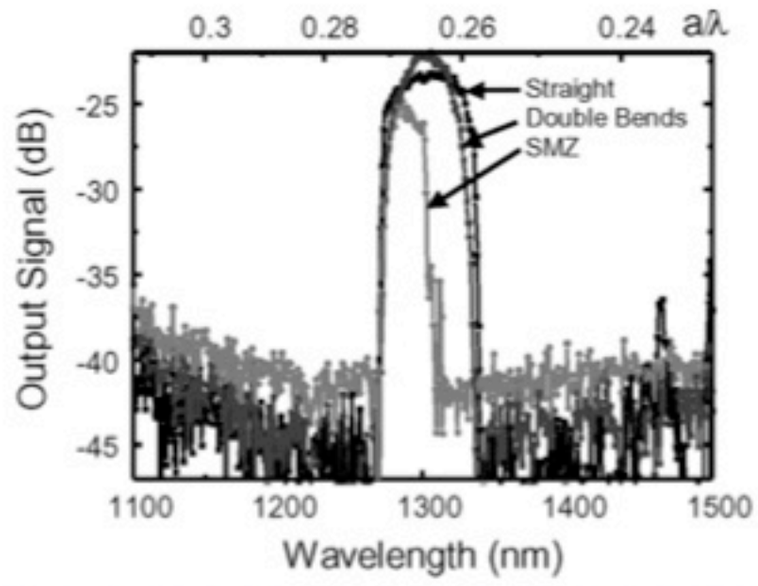


A. Shinya et al., Opt. Exp., 14, 12394, (2006)





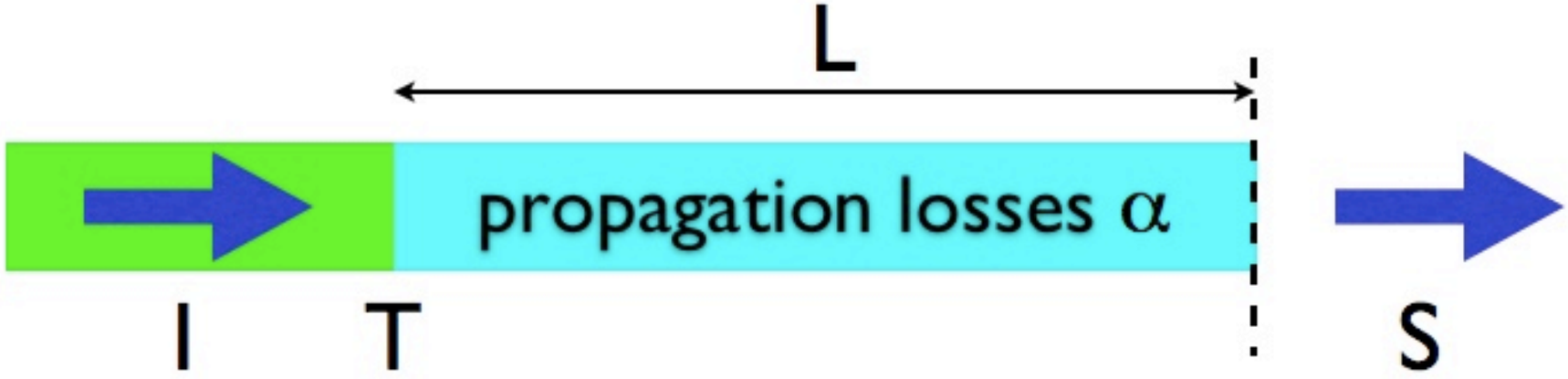


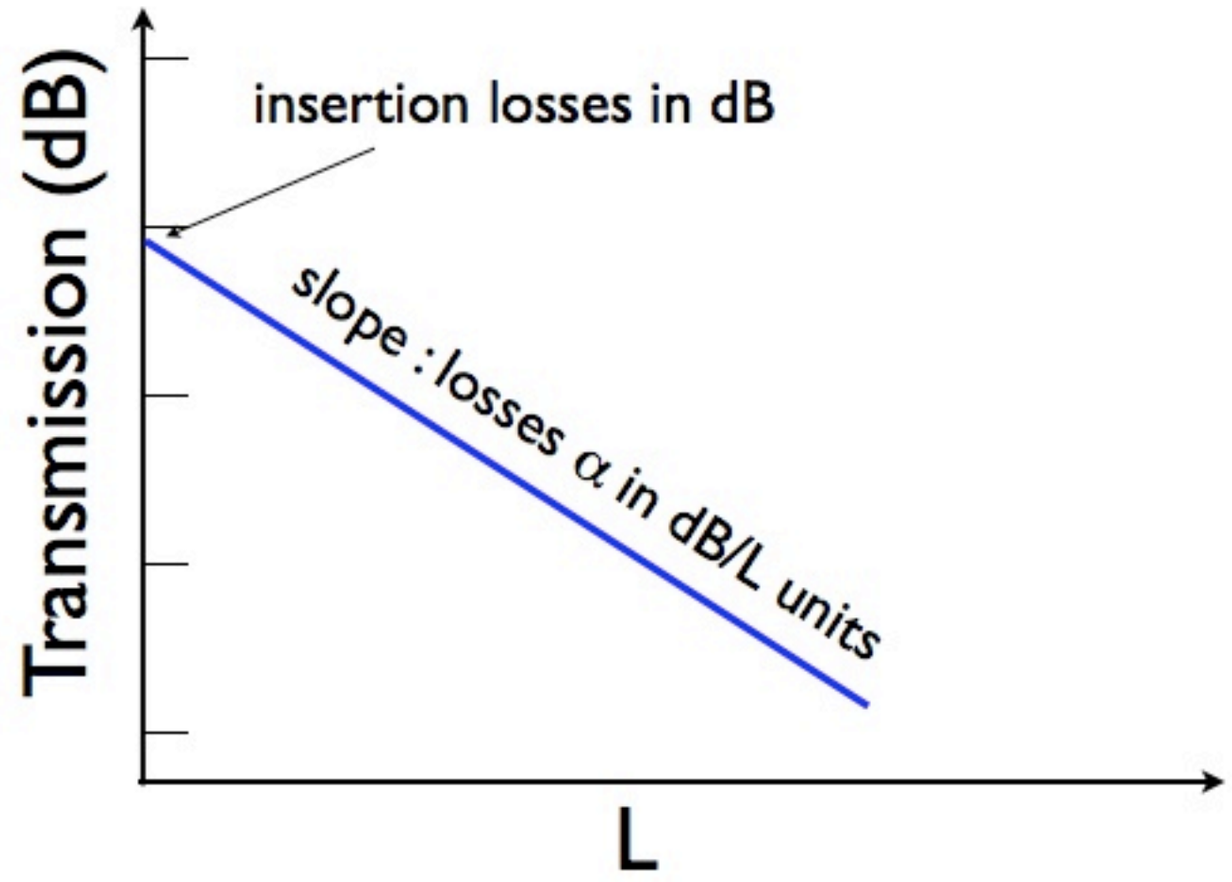


Y. Sugimoto et al., J. Sel. Area. Comm., 23, 1308, (2005)

Measurement of R,T and propagation losses

Cut-back method





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

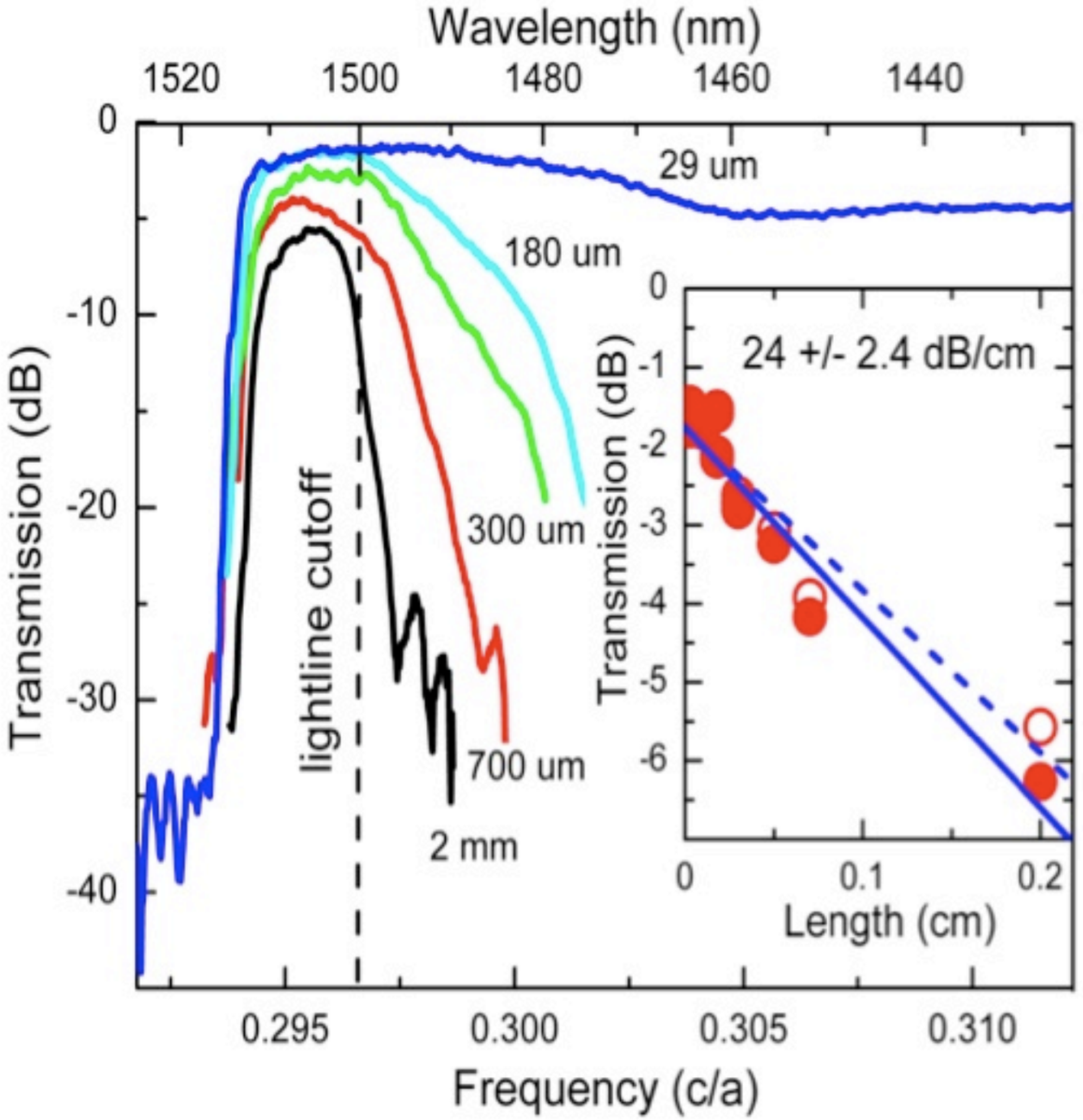
$$Ln\left(\frac{S}{I}\right) = Ln(T) - \alpha L$$

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

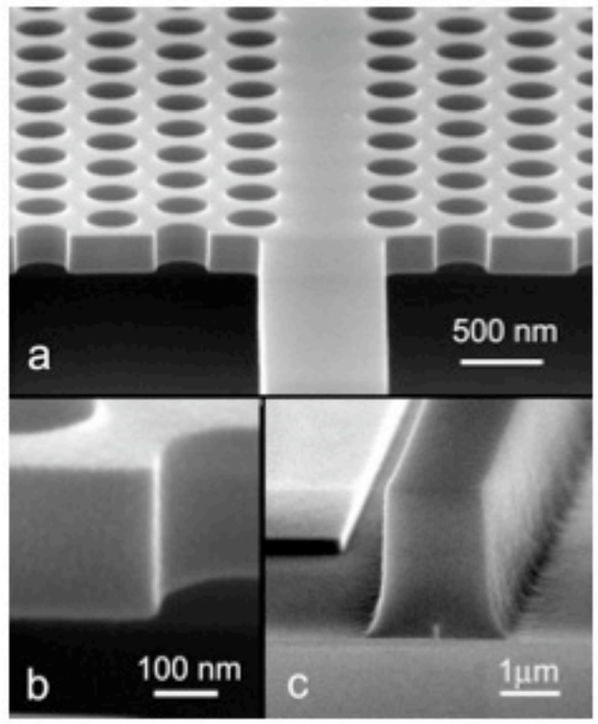
$$A_{dB/cm} = 10\frac{\alpha_{cm^{-1}}}{Ln(10)} = 4.34\,\alpha_{cm^{-1}}$$

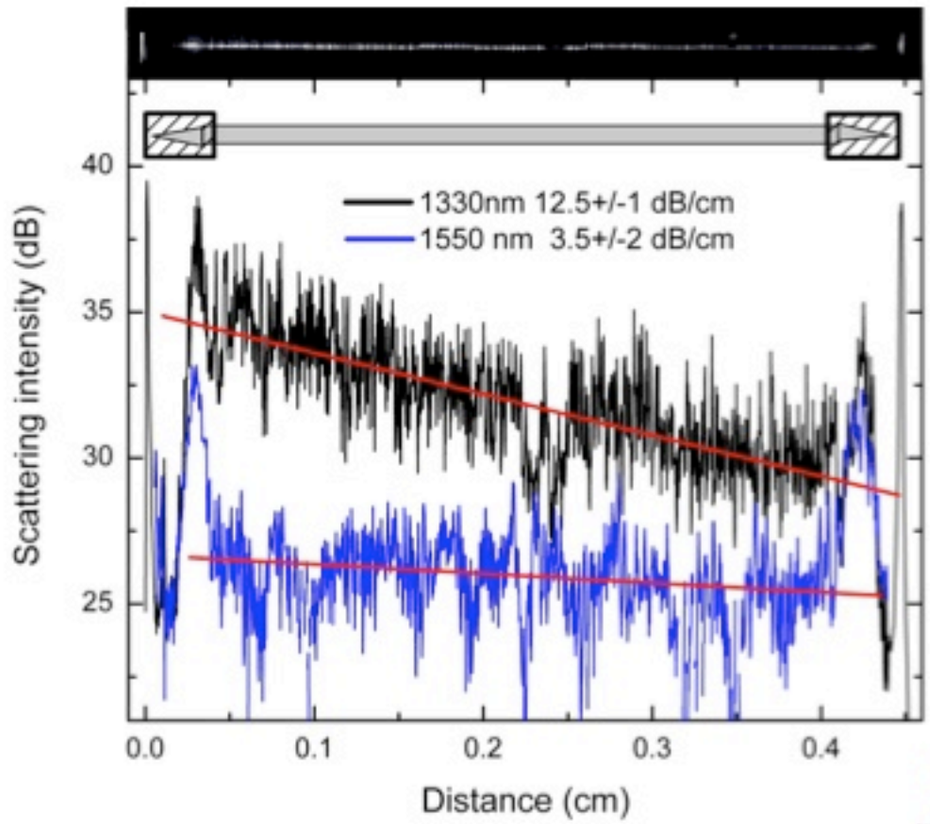
Measurement of R,T and propagation losses

Cut-back method, examples



SOI

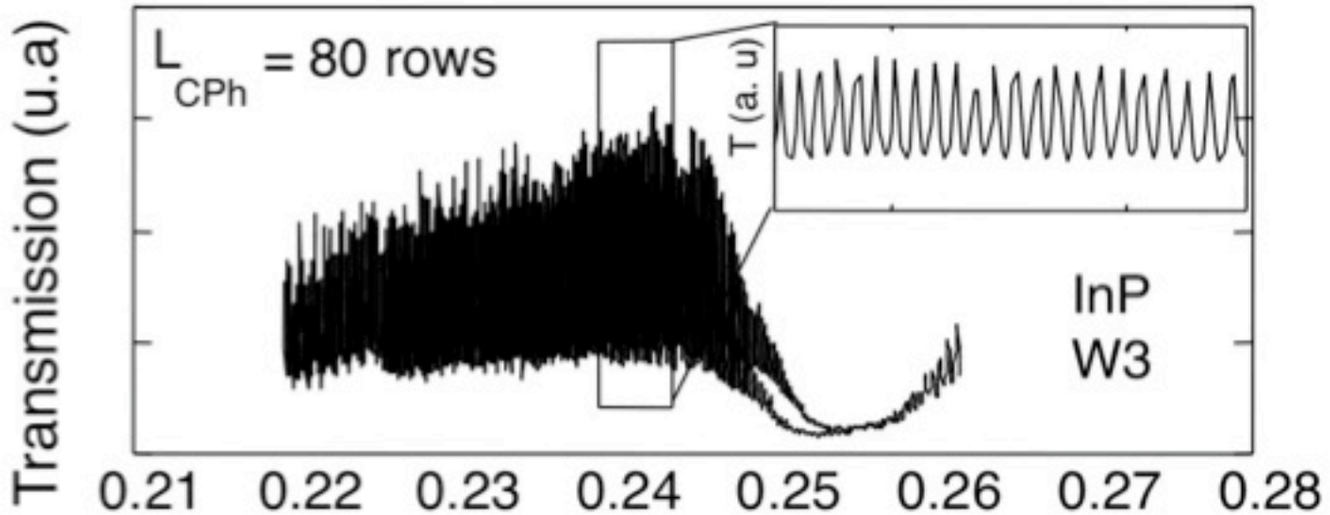




S. J. McNab et al., Opt. Exp., 11, 2927, (2003)

End-Fire

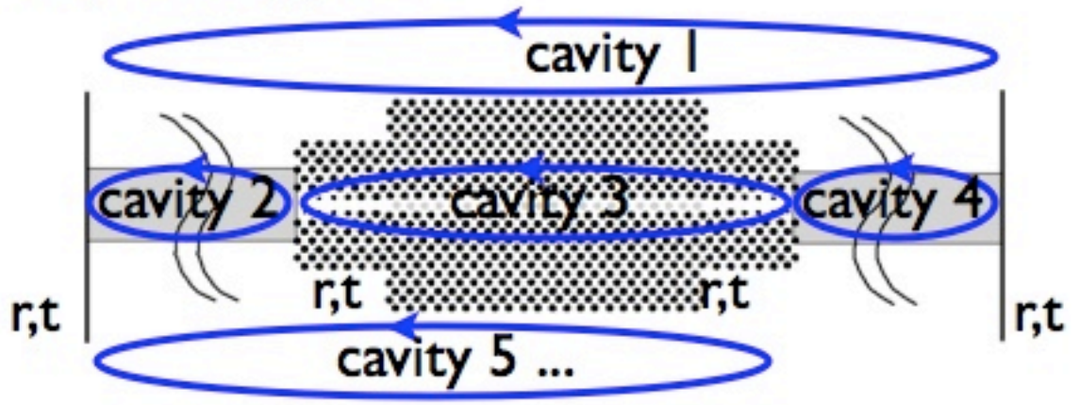
Transmission spectrum, parasitic reflections



Reduced energy

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

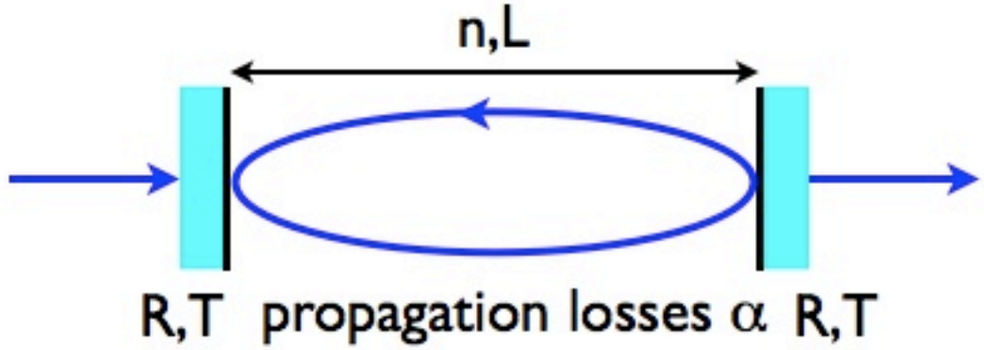
$$T_{FP} = \frac{T^2}{1 + R^2 e^{-2\alpha L} - 2\mathrm{Re}^{-\alpha L}\cos(\frac{4\pi nL}{\lambda})}$$

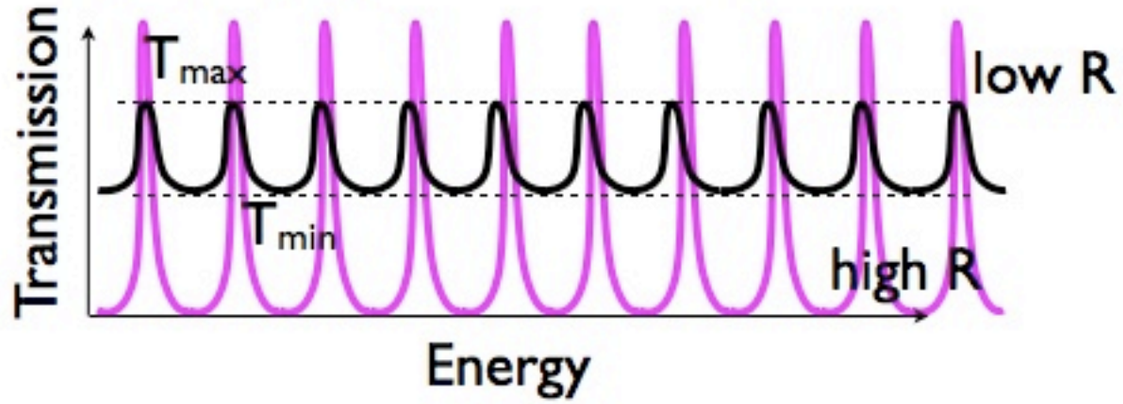
$$T_{\min} = \left(\frac{T}{1+\mathrm{Re}^{-\alpha L}}\right)^2 \quad T_{\max} = \left(\frac{T}{1-\mathrm{Re}^{-\alpha L}}\right)^2$$

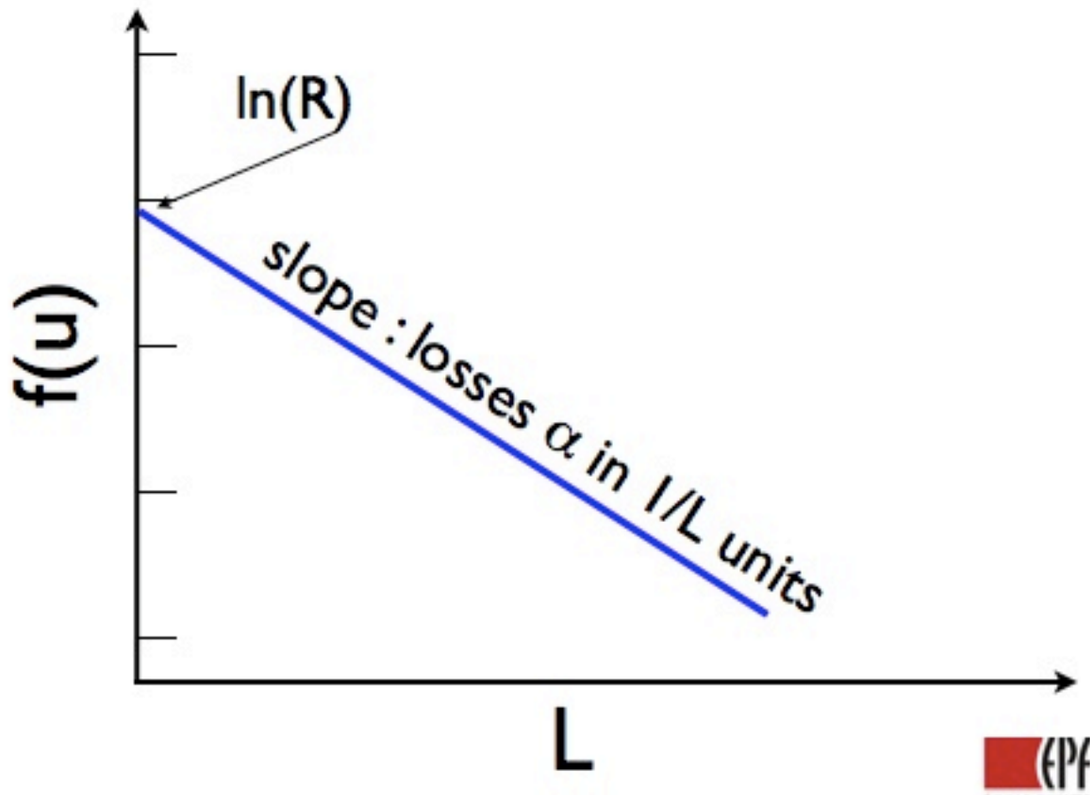
$$u = \sqrt{\frac{T_{\min}}{T_{\max}}} = \sqrt{\frac{P_{\min}}{P_{\max}}}$$

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

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

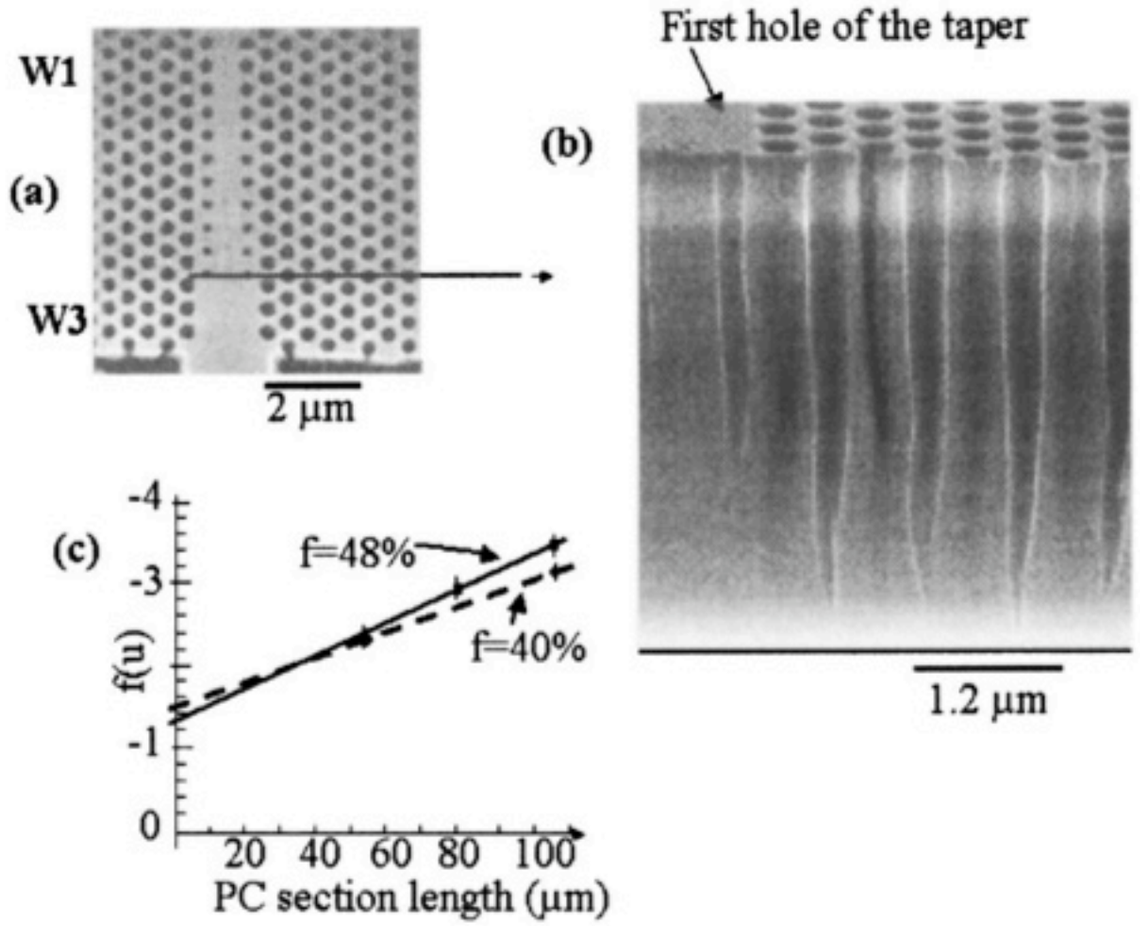






Measurement of R,T and propagation losses

Example



InP

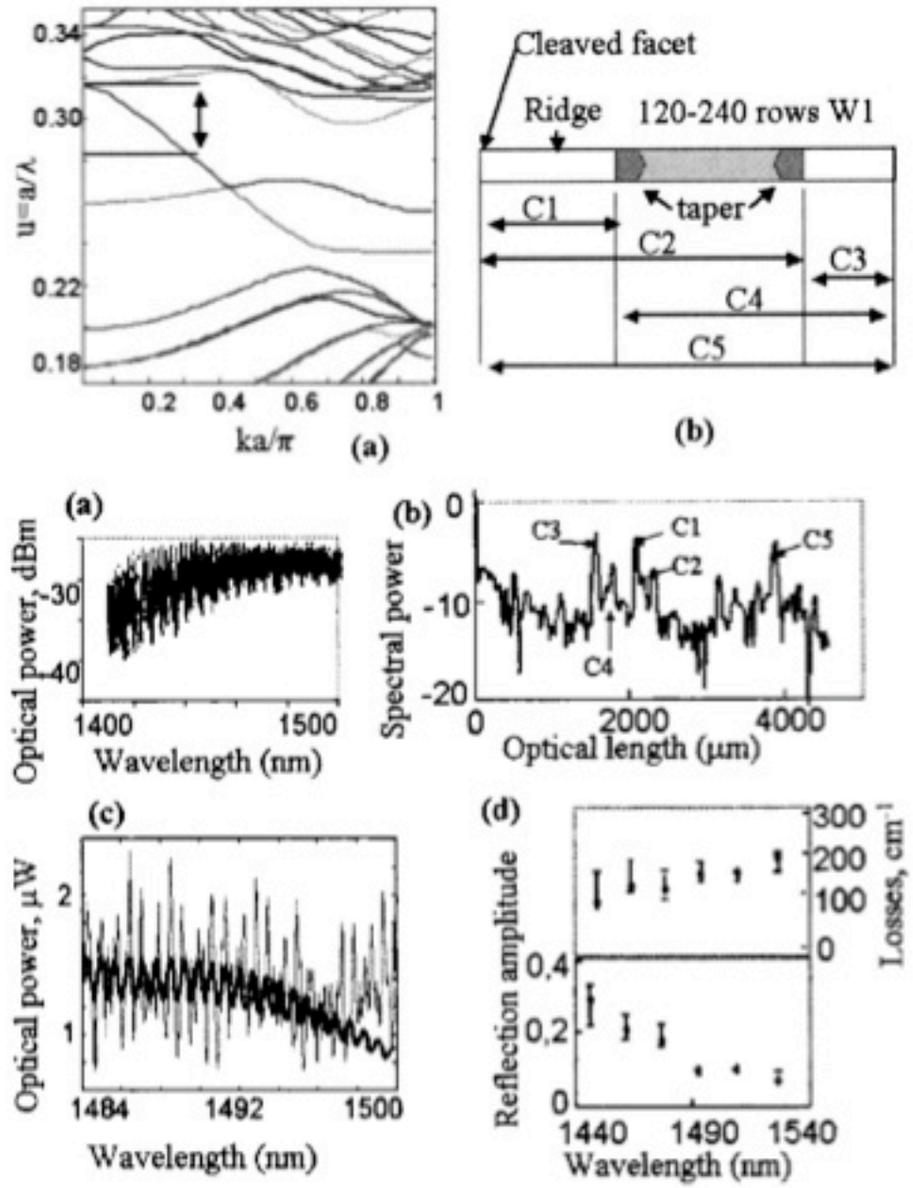


FIG. 3. 120 rows long $W1$–PCW with taper access: (a) transmitted power spectrum, (b) spectral power on the 1484–1500 nm window, (c) unfiltered (thin line) and filtered (bold line) transmitted power with a filter suited to $C1$ cavity, and (d) taper reflection and propagation losses as a function of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

The method has also been used in the case of several coupled cavities with Fourier filtering

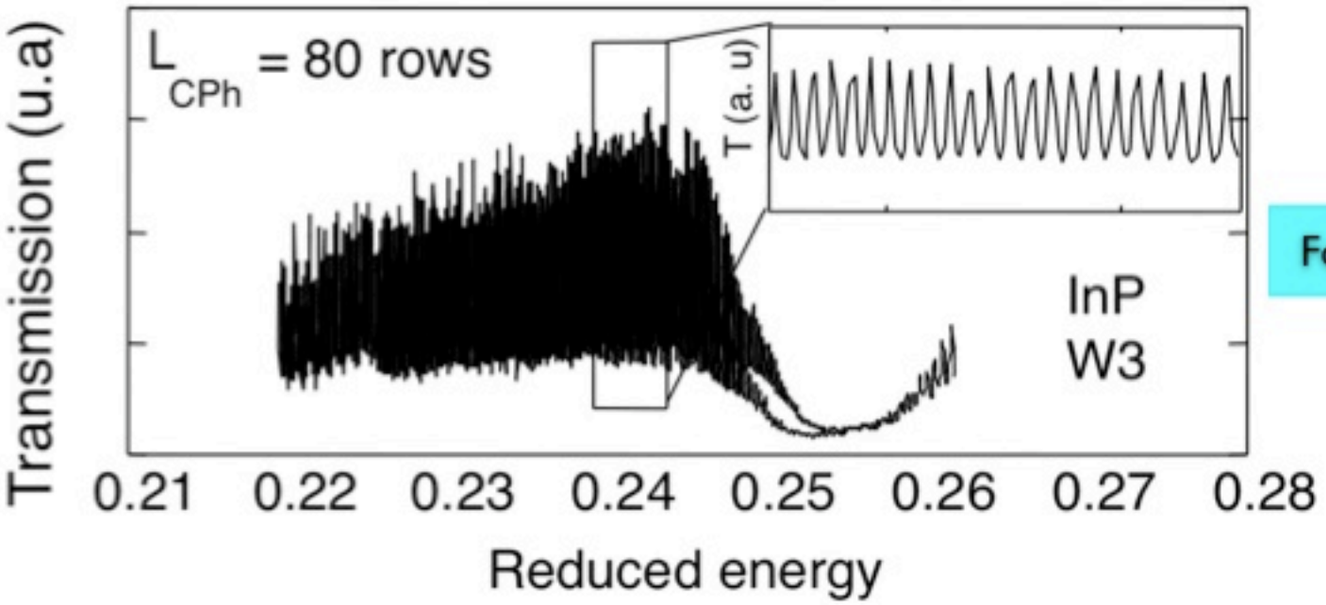
Exact theoretical model is missing

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

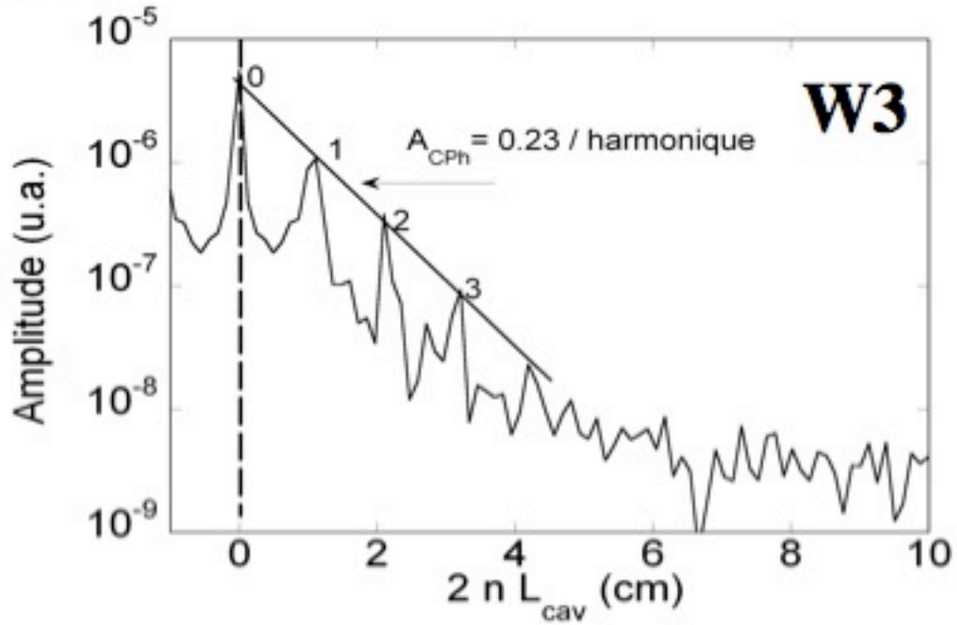
Measurement of R,T and propagation losses

Hofstetter method

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



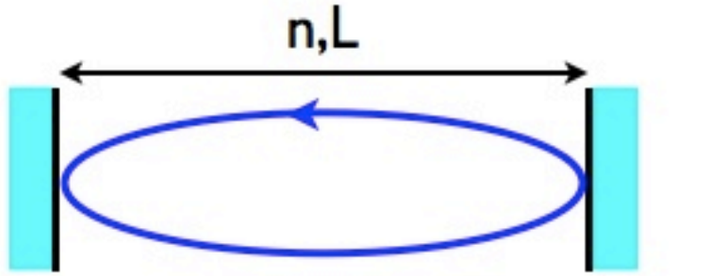
Fourier



Amplitude decay of the harmonic n

A_r = attenuation after n single passes

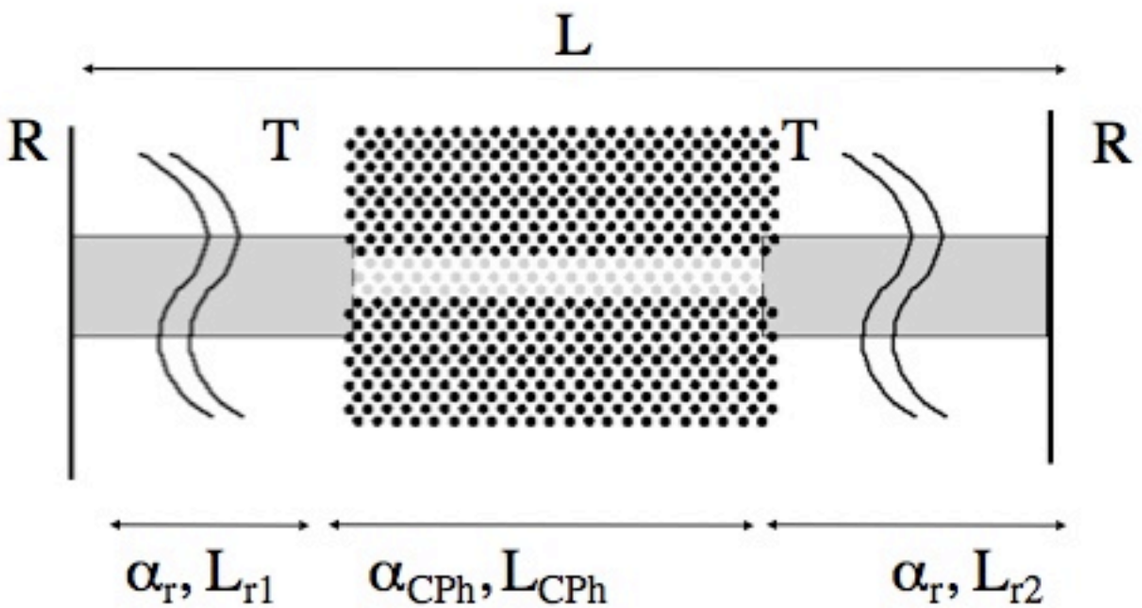
$$A_{r,n} = R^n e^{-n\alpha L}$$



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

Measurement of R,T and propagation losses

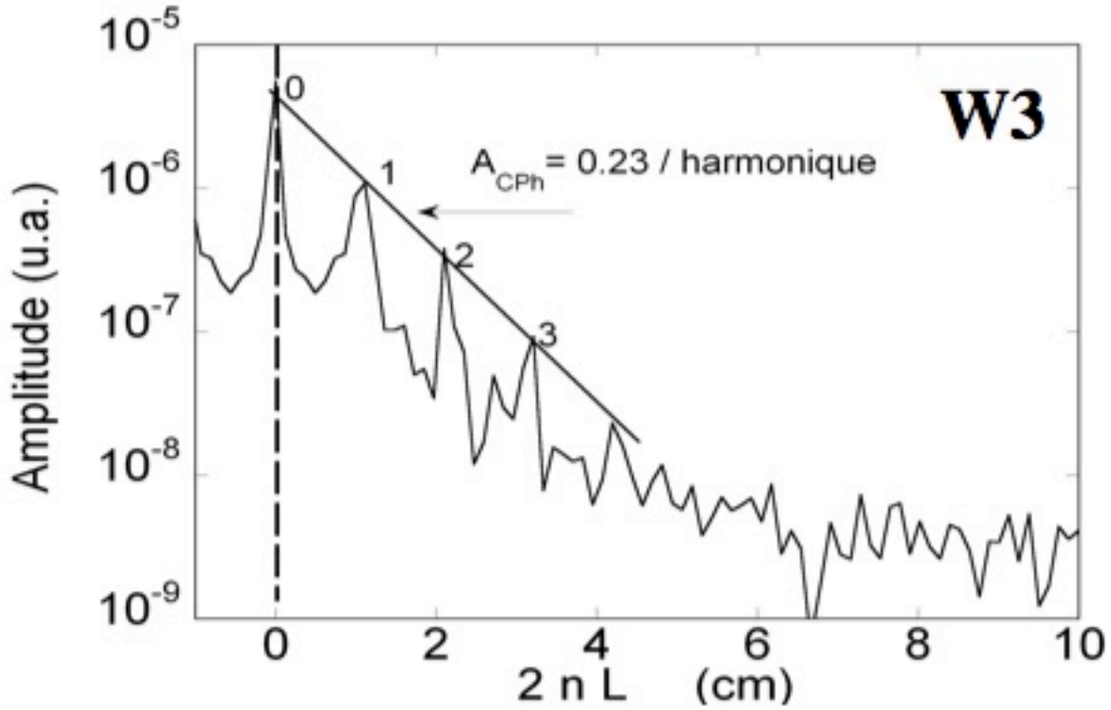
Hofstetter method

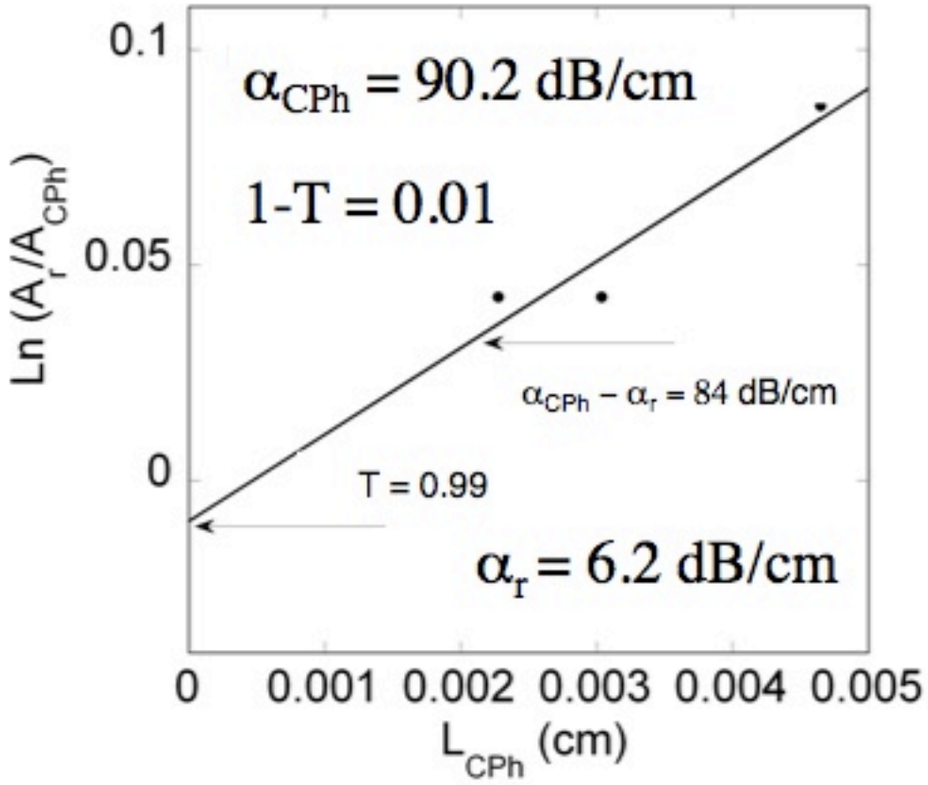


$$A = R.T^2 e^{-\alpha_{CPh} L_{CPh}} e^{-\alpha_R (L_{r1} + L_{r2})}$$

after division by a reference waveguide

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





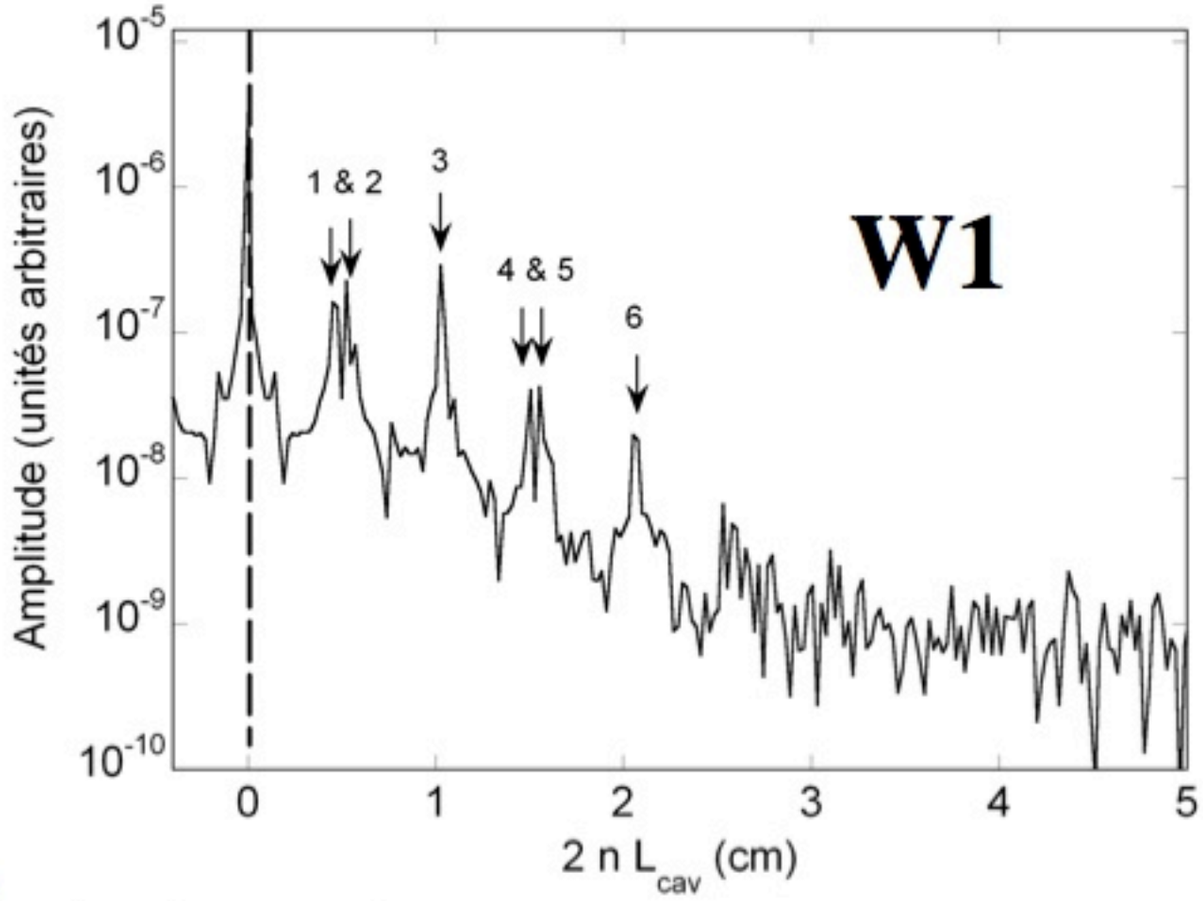
D. Hofstteter et al., Opt. Lett., 22, 1381, (1997) and IEEE J. Quant. Elect., 34, 1914, (1998)

Measurement of R,T and propagation losses

Hofstetter method

Internal reflections lead to multiple cavities

$$L_r$$

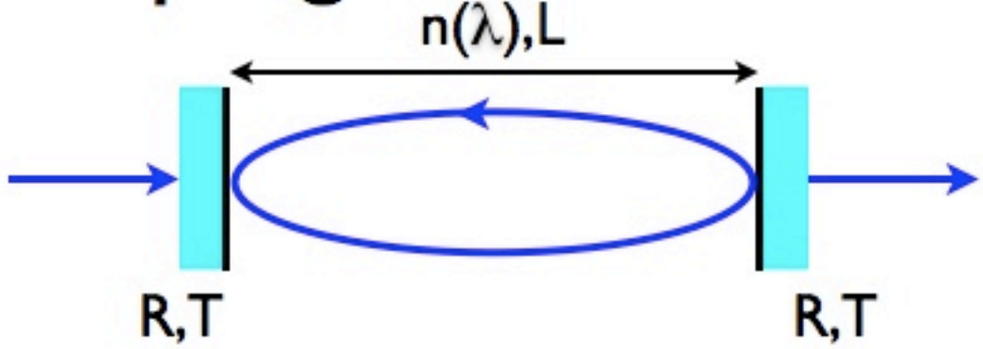


- harmonics 1 and 4 : L_{r1}
- harmonics 2 and 5 : L_{r2}
- harmonics 3 and 6 : L_r

Dispersion curve

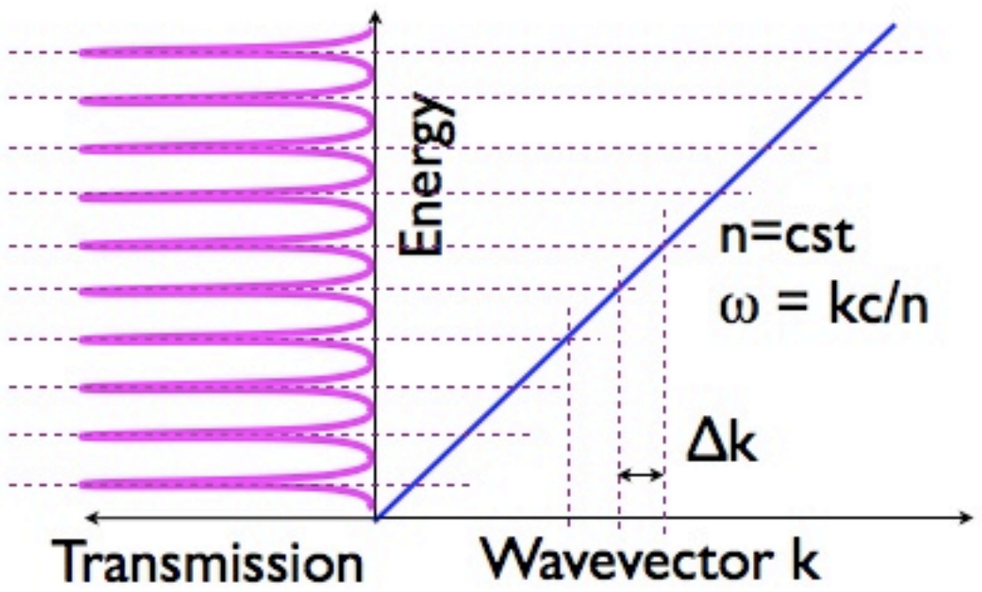
Fabry-Perot fringes and k-space sampling

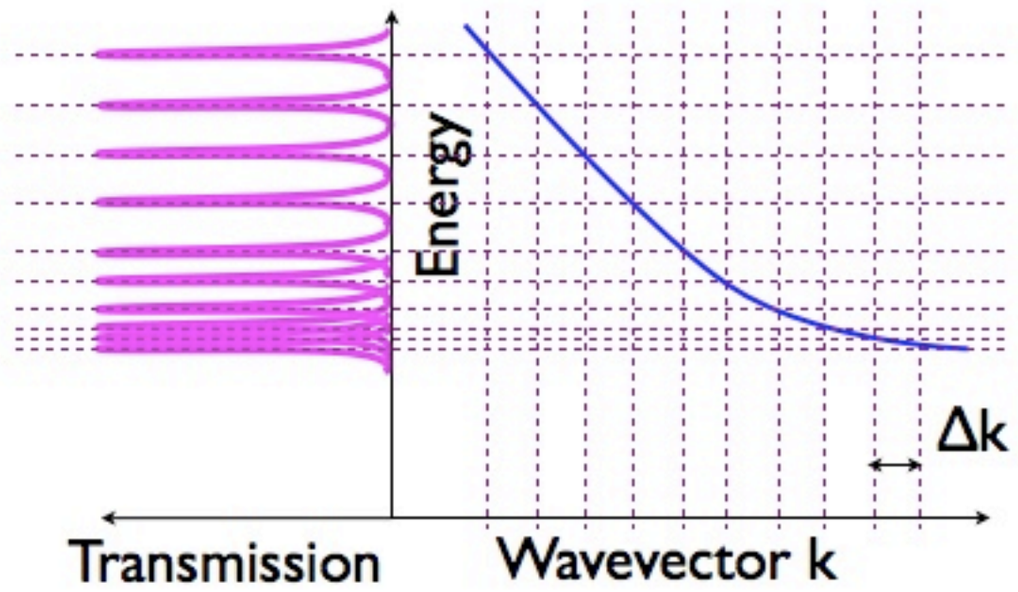
Fabry-Perot fringes equally spaced in energy ?



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

resonances equally spaced in k $\Delta k = \pi/L$

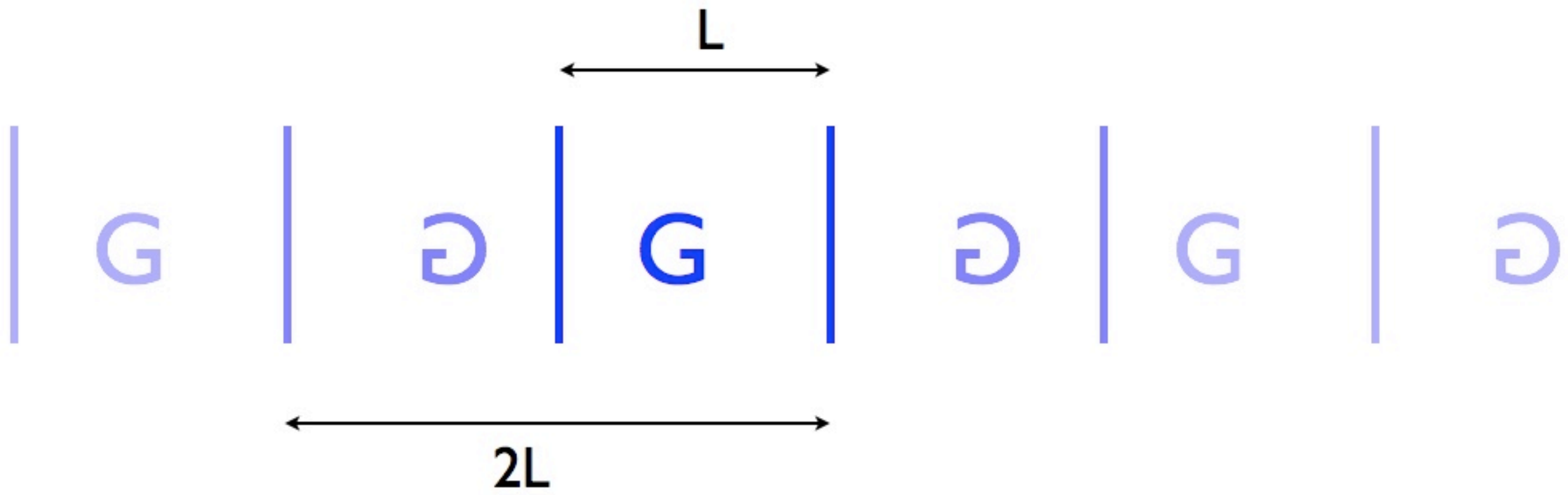




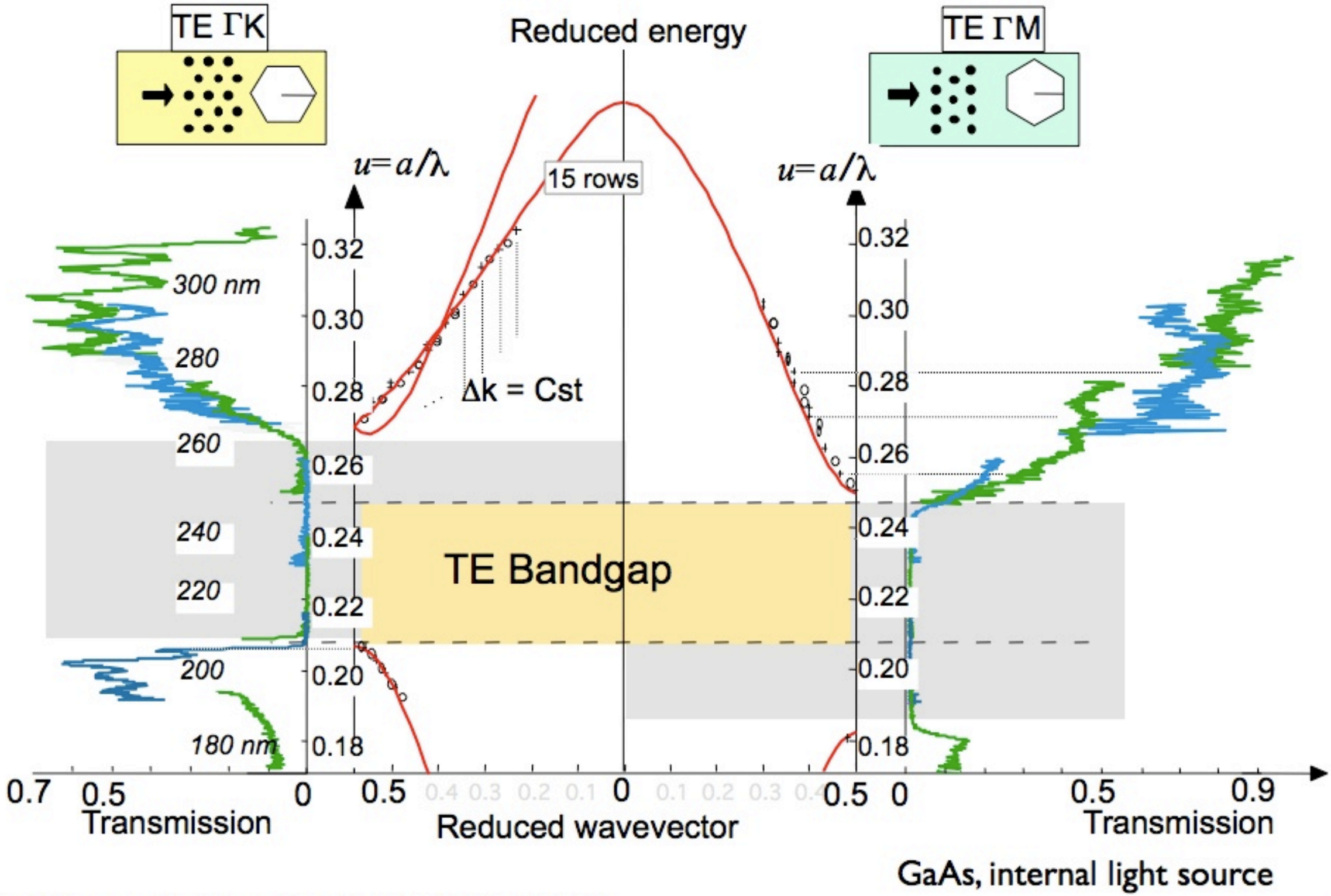
Note: sampling in Δk exact k values are more difficult to determine

Echantillonage

Une manière plus visuel de décrire cela consiste développer les images des miroirs, ce qui donne un objet de période 2L donc une périodicité en $2\pi/2L=\pi/L$



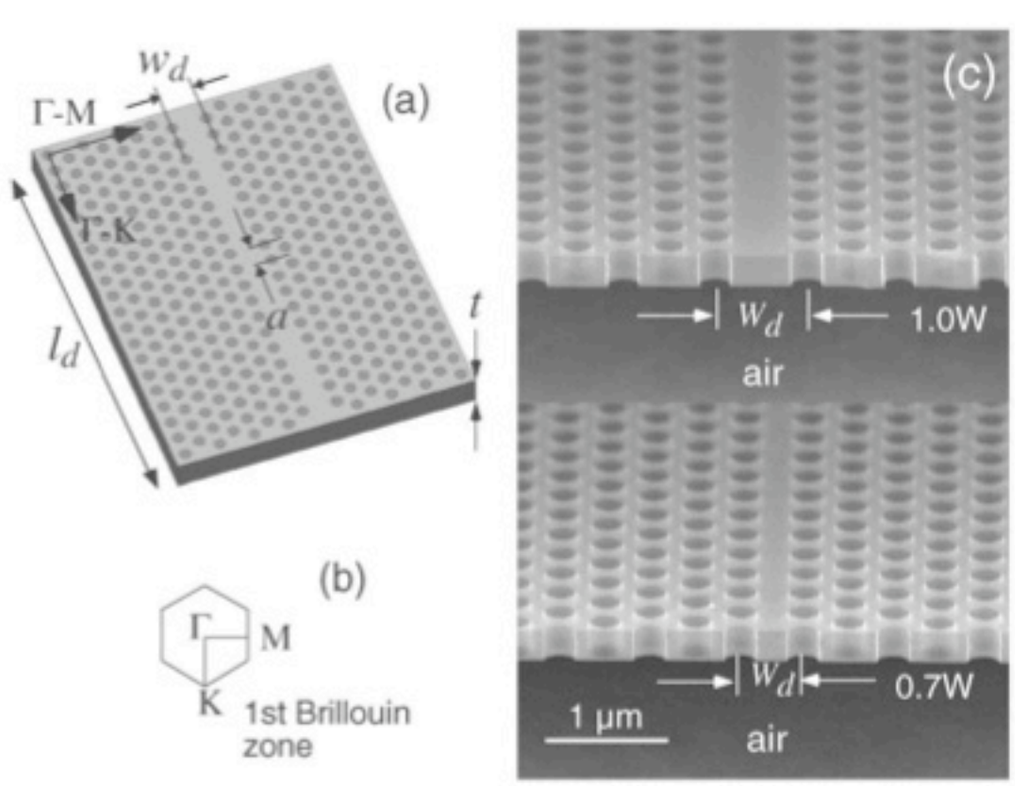
Dispersion curve measurement

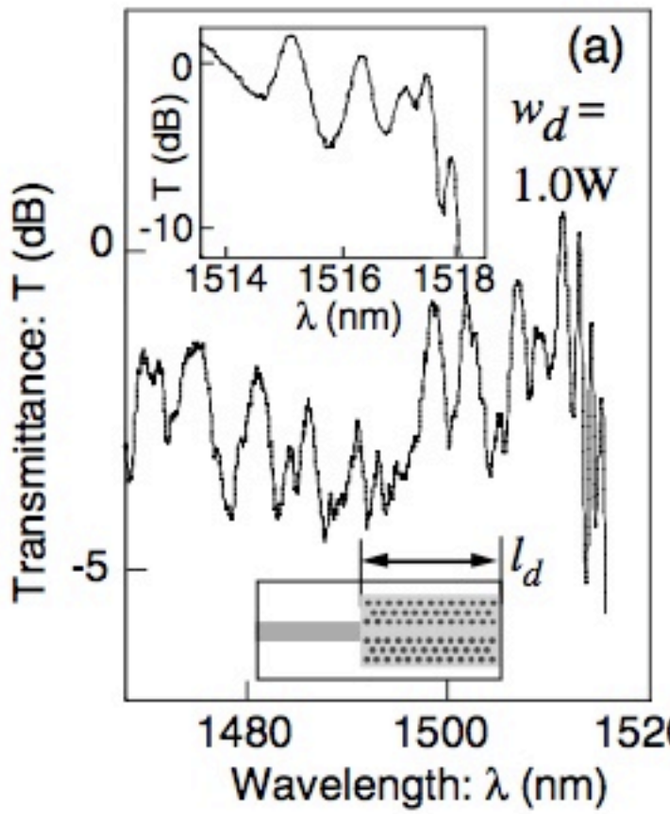


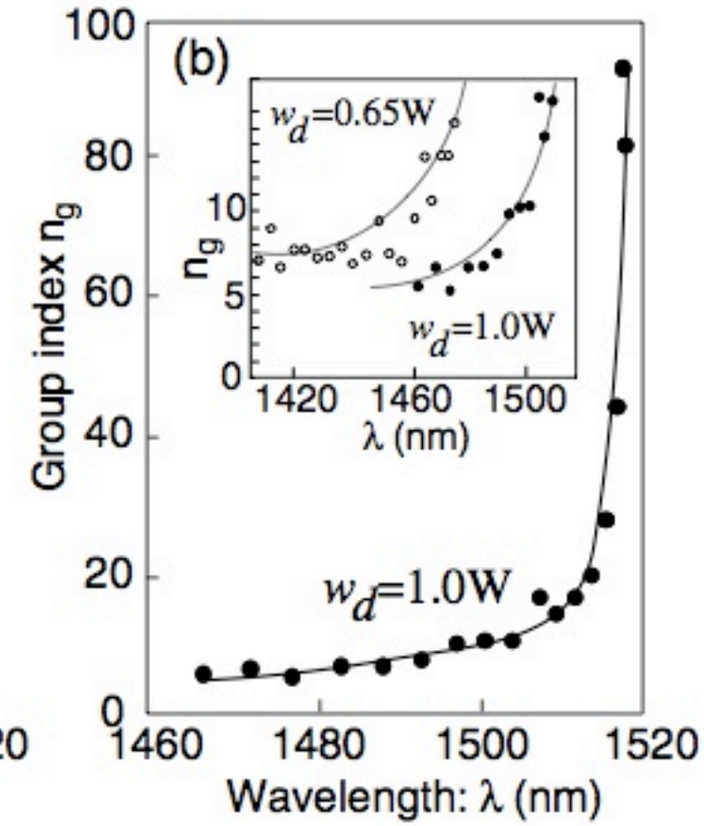
GaAs, internal light source

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

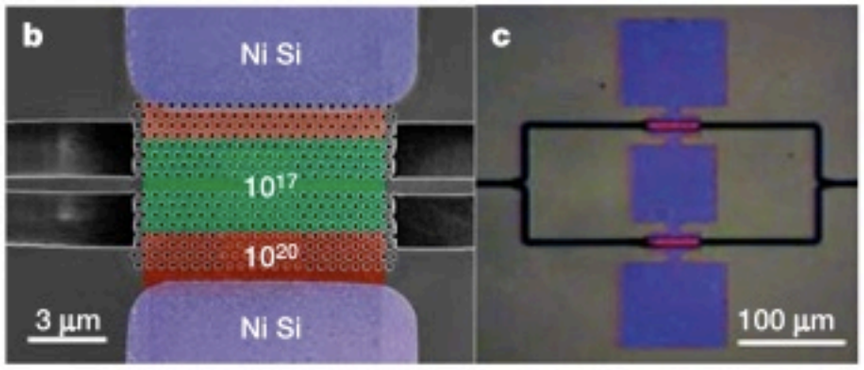


Figure 3 | Active electrically tunable MZI with lateral electrical contacts to photonic crystal waveguides. **a**, Time averaged magnetic field energy

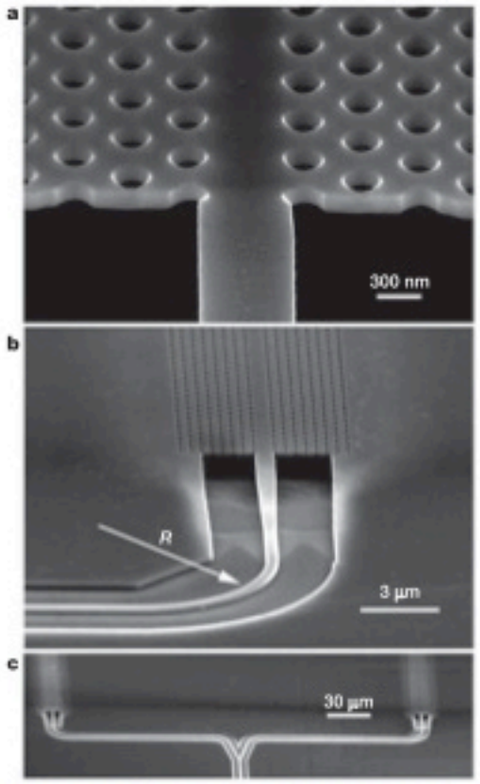
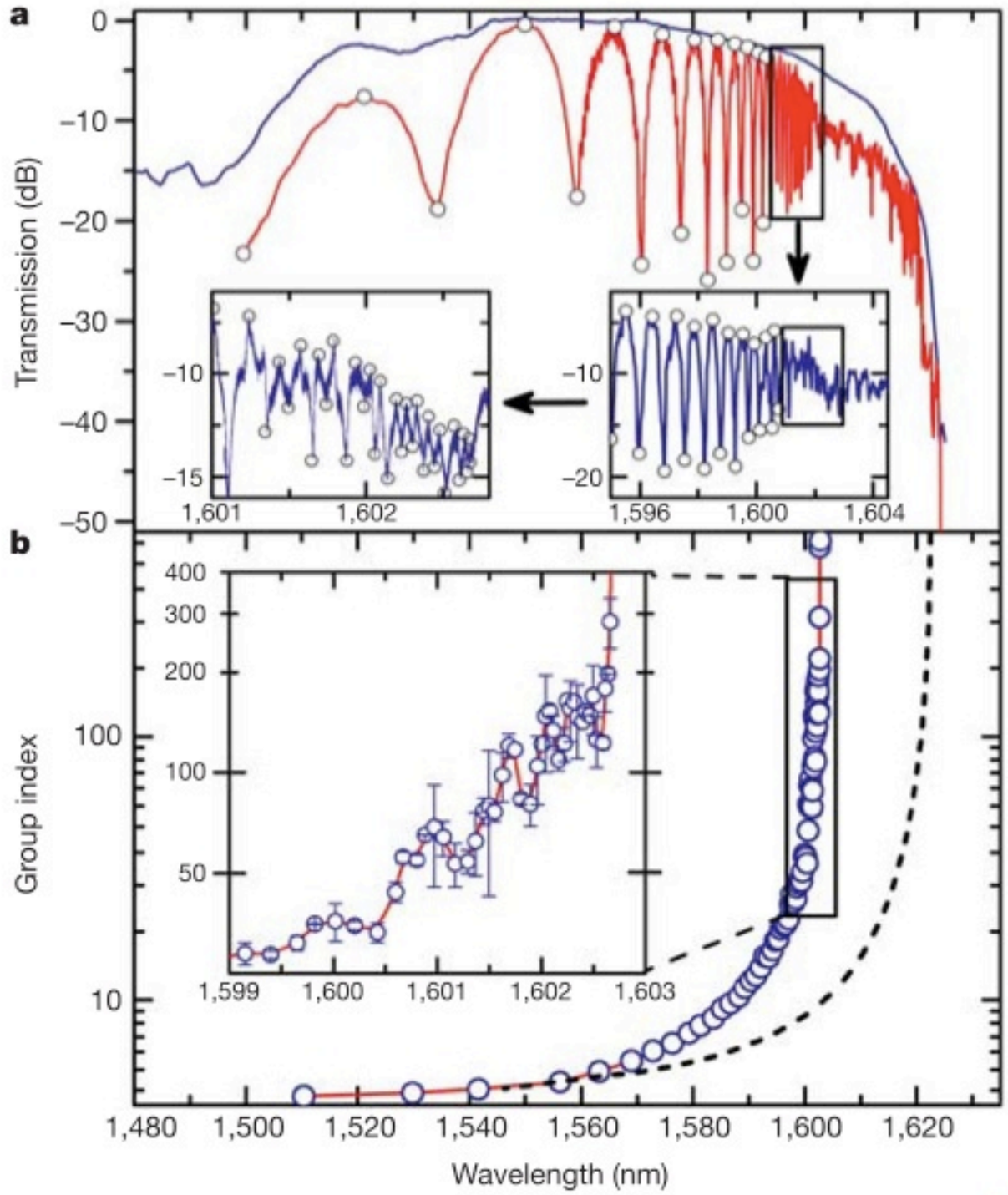


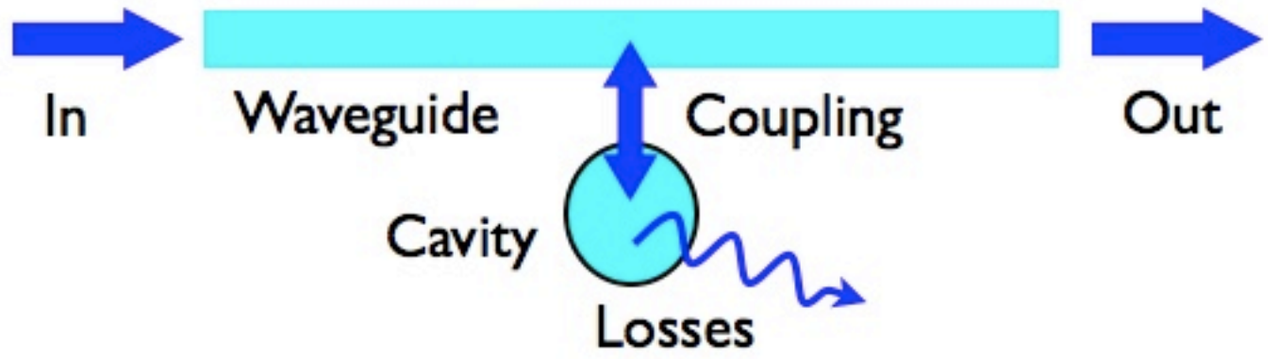
Figure 1 | SEM images of a passive unbalanced Mach–Zehnder interferometer using photonic crystal waveguides. **a**, Input section of the



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

Optical cavities, high quality factor

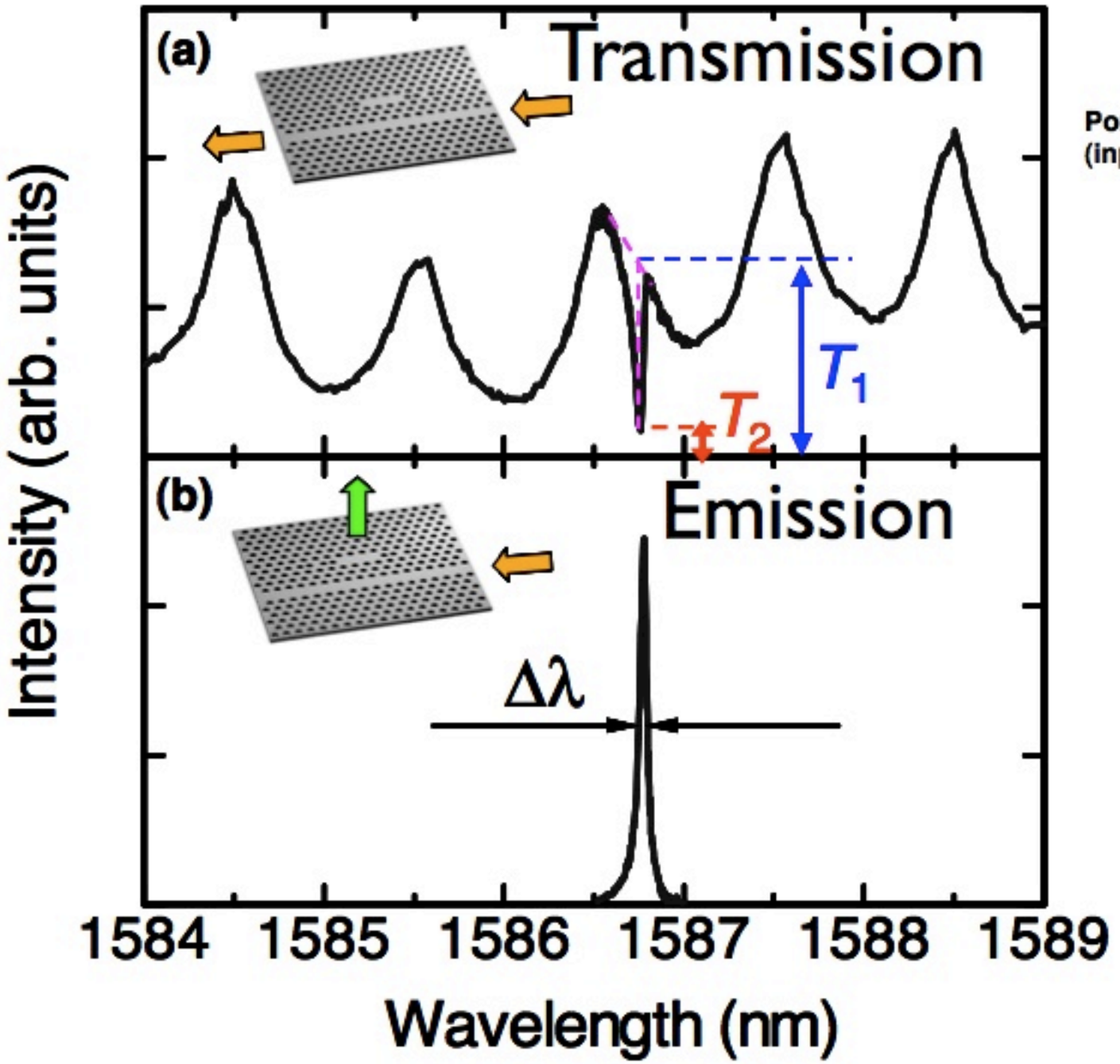
Measurement of the cavity requires coupling to a probe which affect the Q

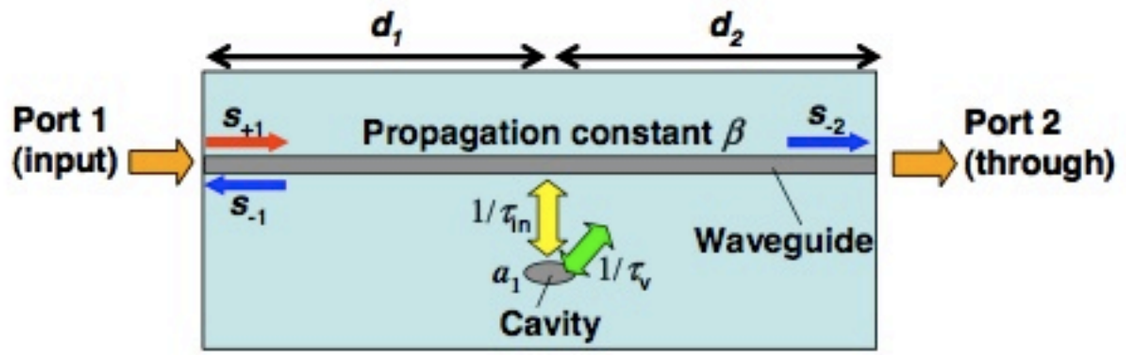


- Intrinsic Q = Q_{int}, unloaded cavity, coupling only to free space radiation and material losses, defects
- Coupling Q = Q_{probe}, additional losses due to the measurement
- Measured Q = Q_{meas}, loaded cavity

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

Optical cavities, high quality factor



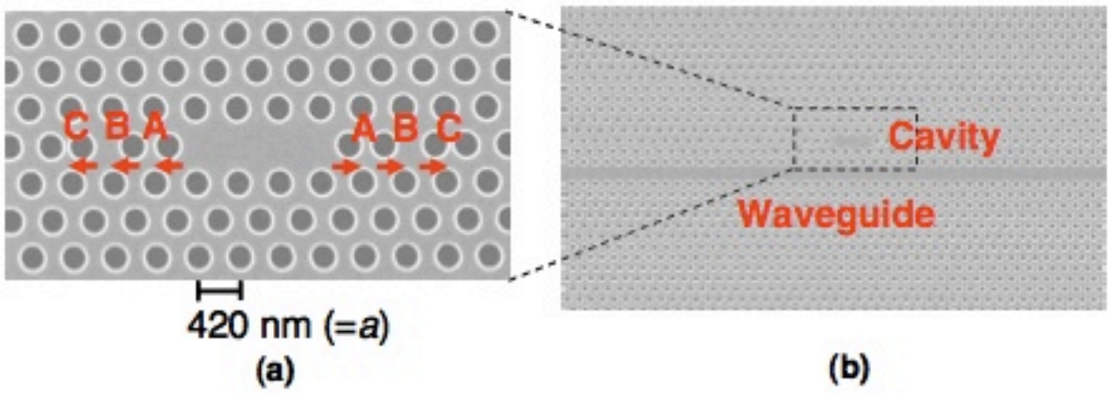


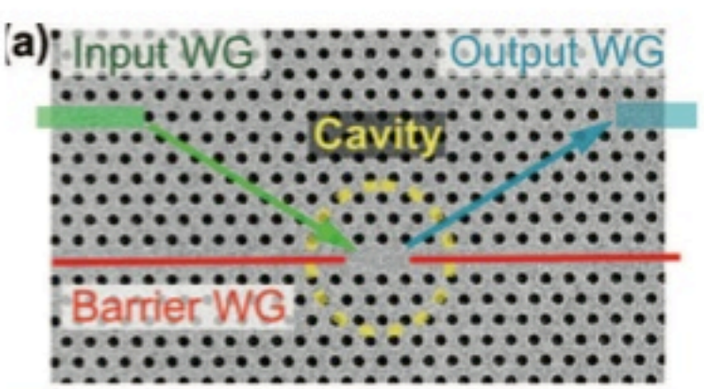
$$T = \frac{T_2}{T_1}$$

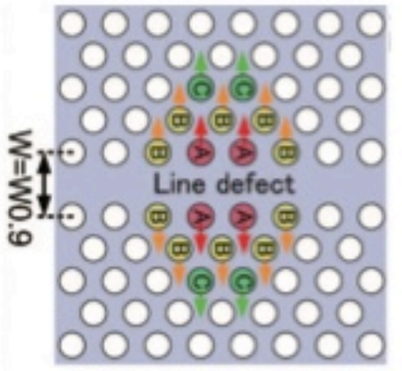
$$Q_{int} = \frac{Q_{meas}}{\sqrt{T}}$$

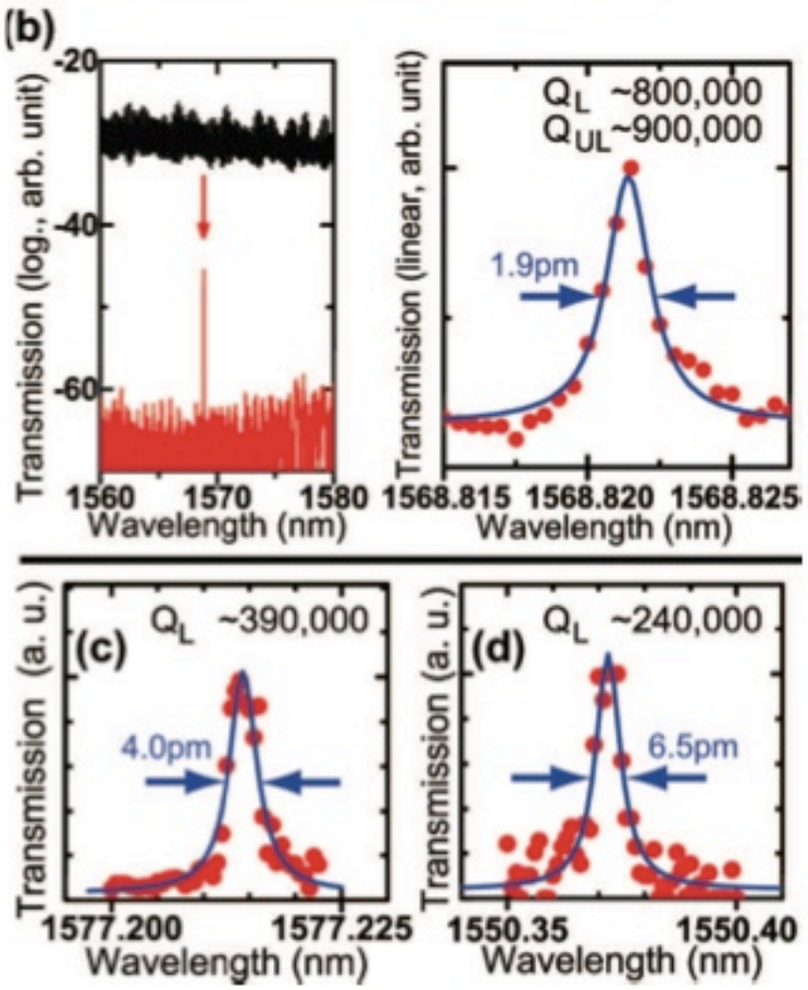
Y. Akahane et al., Opt. Exp., 13, 1202, (2005)

Optical cavities, high quality factor







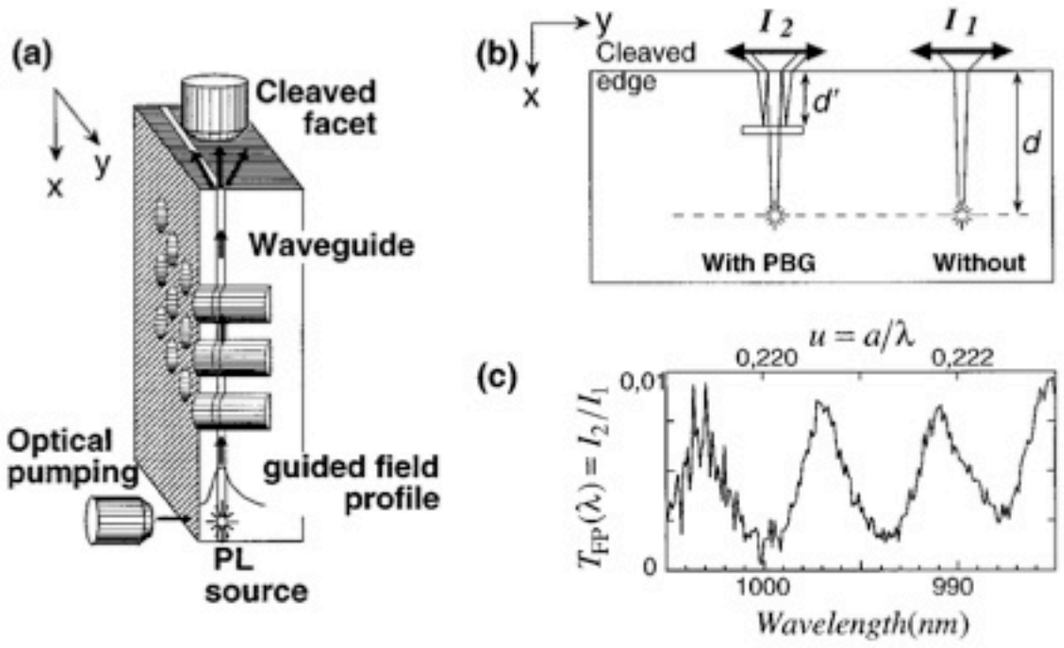


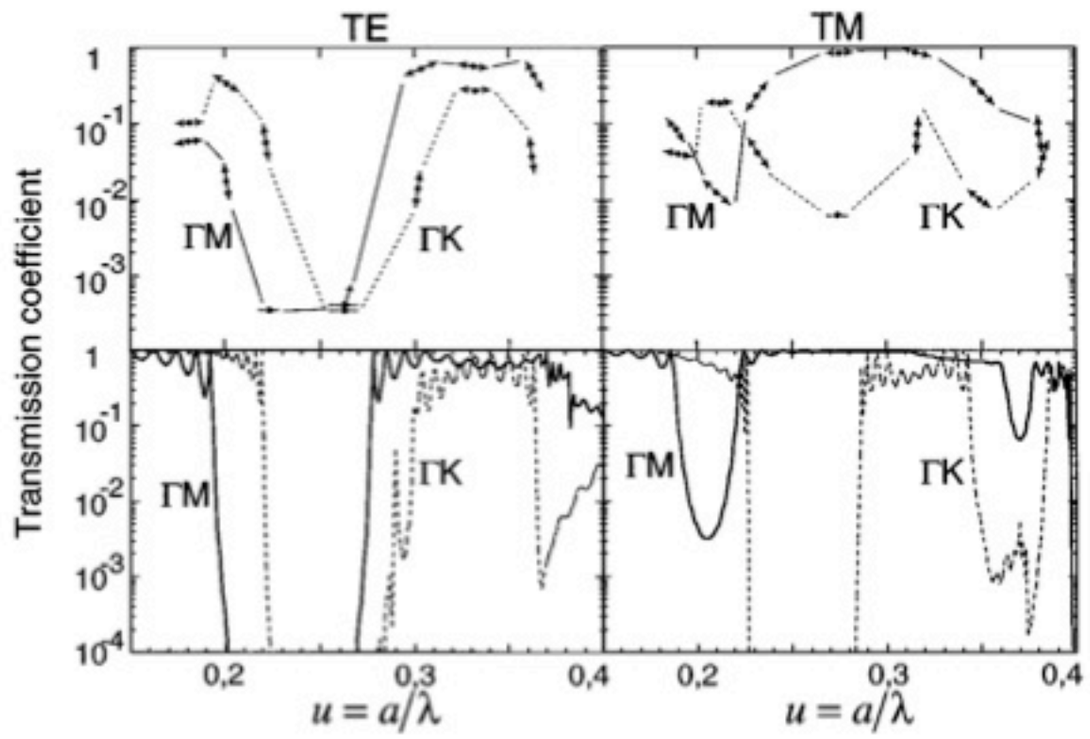
Y. Akahane et al., Opt. Exp., 13, 1202, (2005) E. Kuramochi et al., Appl. Phys. Lett., 88, 041112, (2006)

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





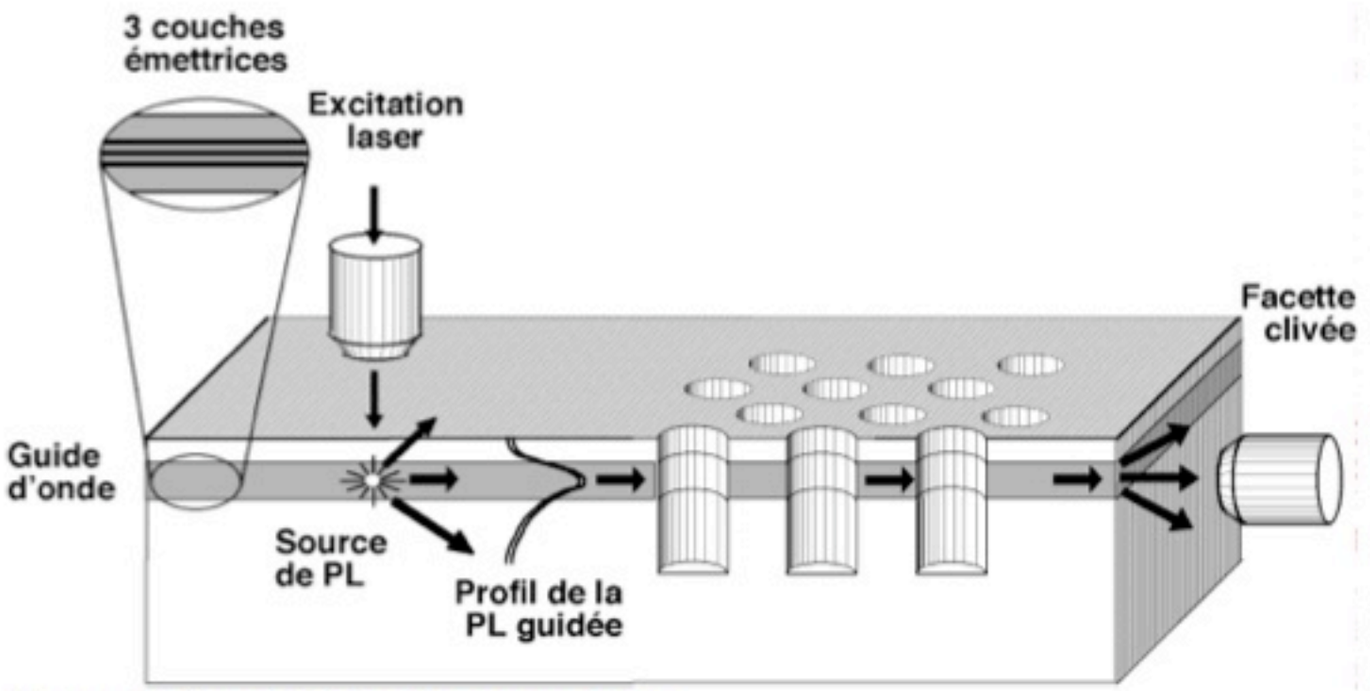
D. Labilloy et al., Phys. Rev. Lett., 79, 4147, (1997)

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

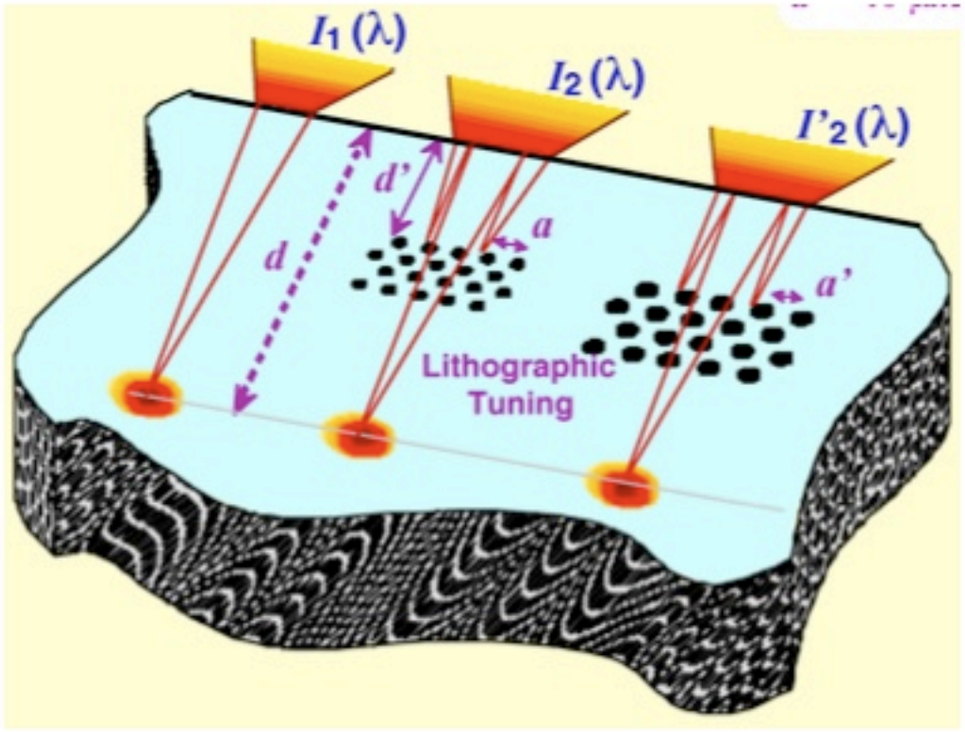
ILS

Principle: Insert light emitters inside the planar waveguide

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



D. Labilloy PhD dissertation



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

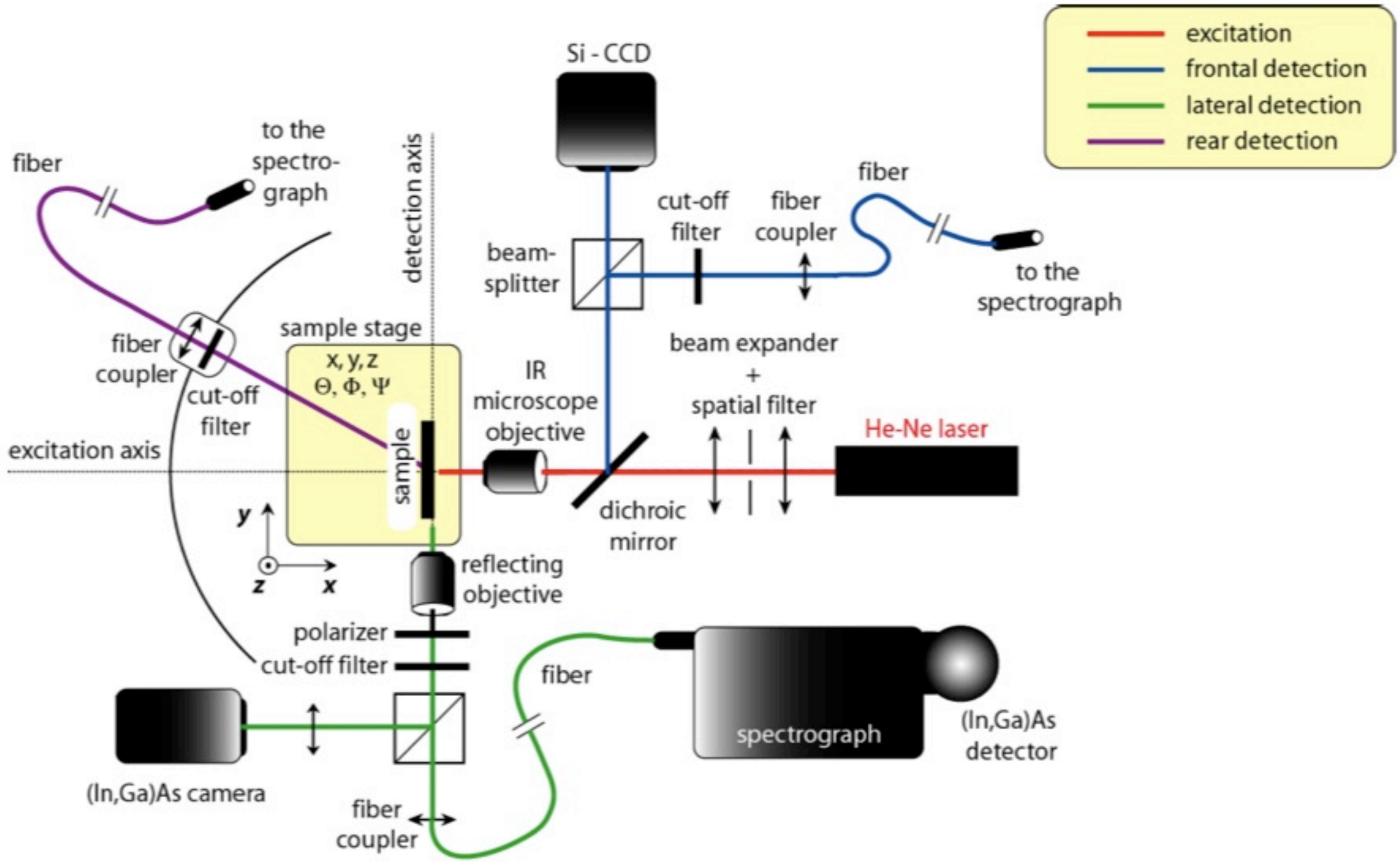
And make use of lithographic tuning

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

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

ILS

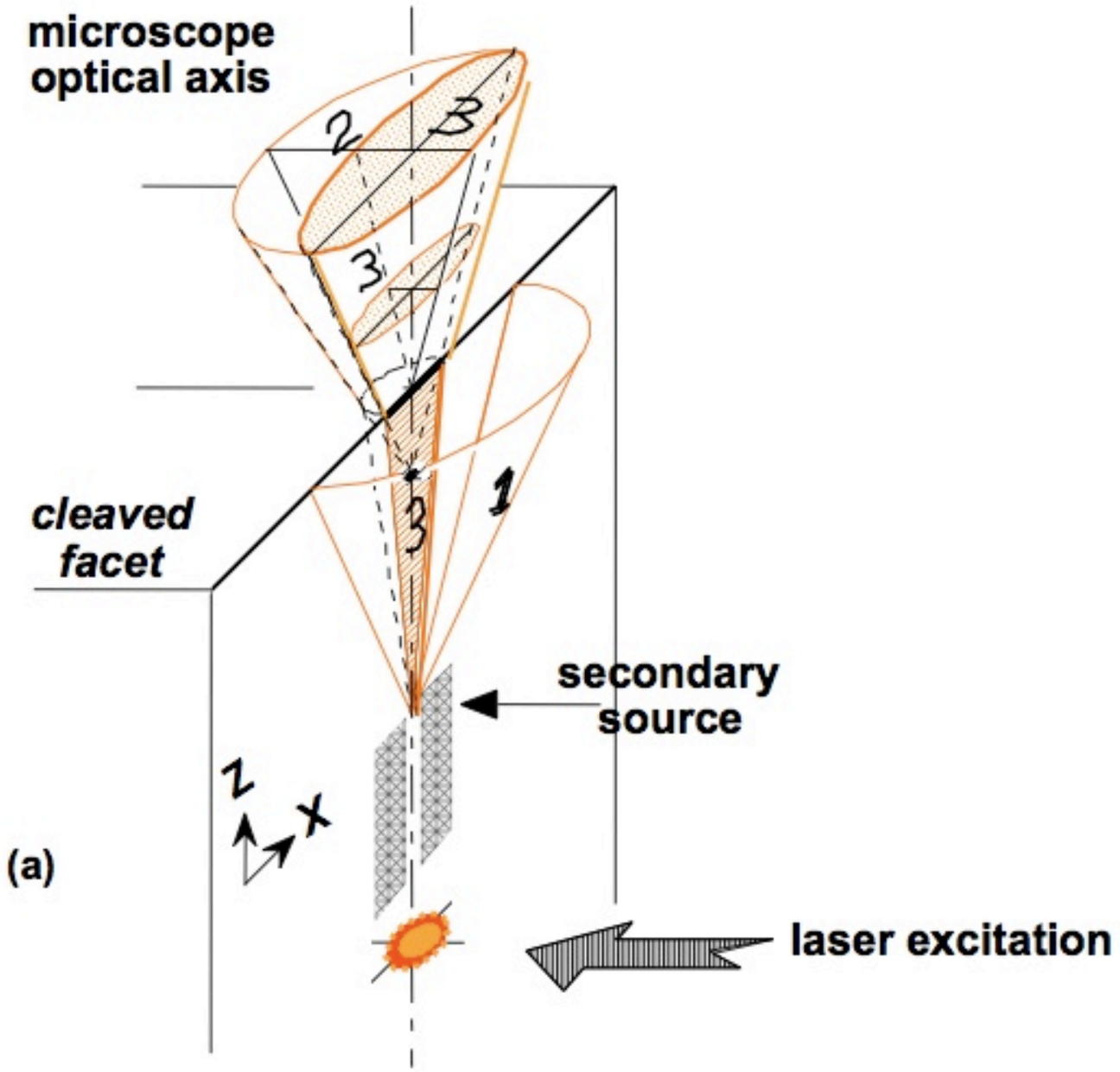
Experimental set-up

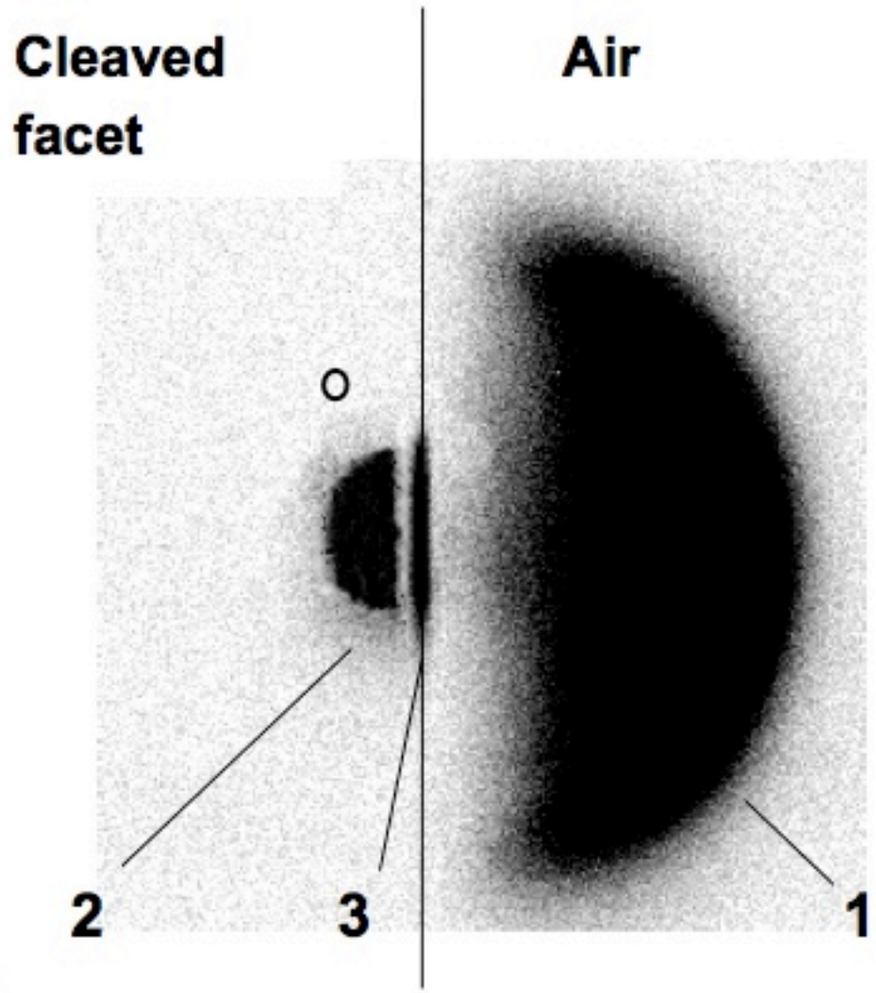


R. Ferrini et al., J. Quantum Electron., 38, 786, (2002)

ILS

Experimental set-up,
as usual real life is a bit more complex

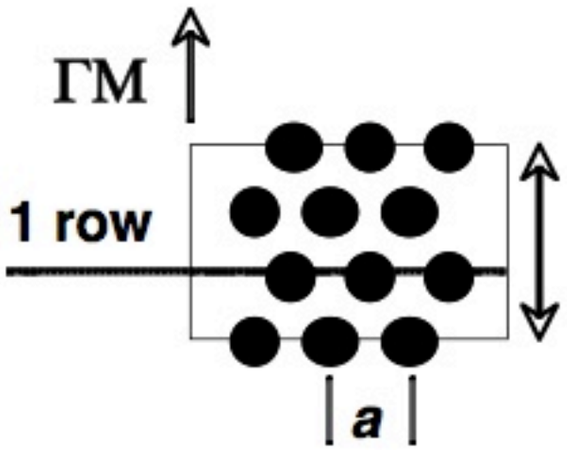




H. Benisty et al., J. Quantum Electron., 38, 770, (2002)

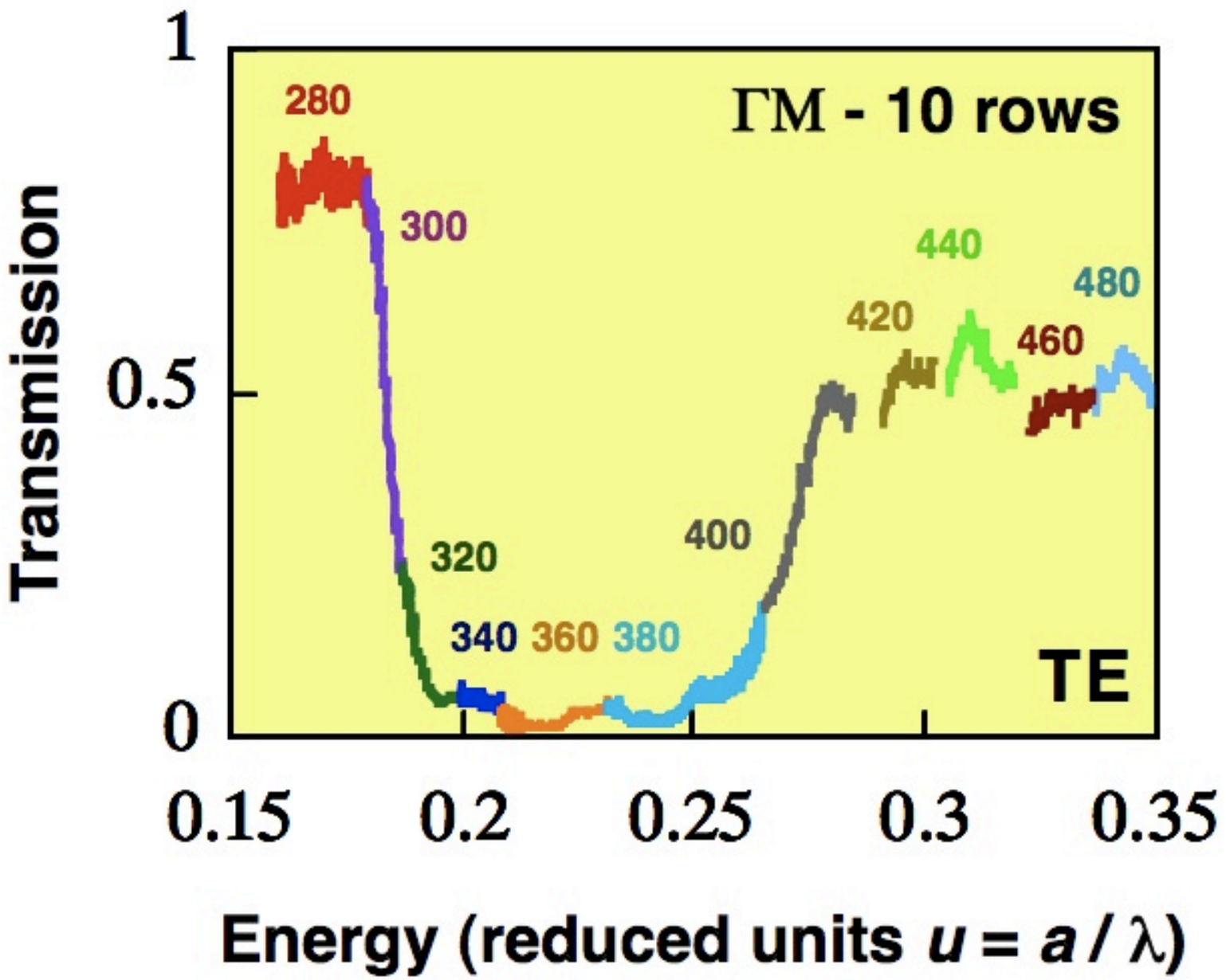
Transmission spectrum

Examples



TE polarization

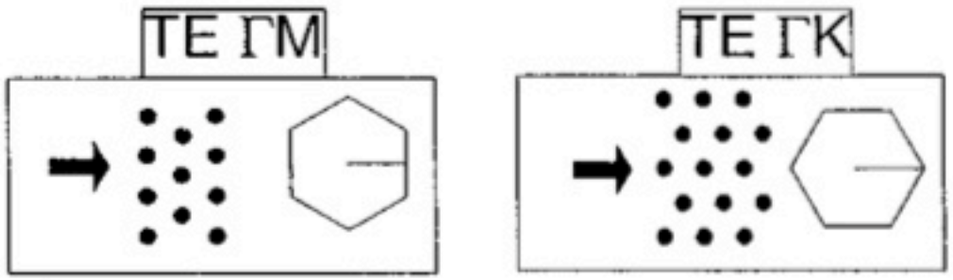
InP/(Ga,In)(As,P) QW
λ=1.55μm f=30%



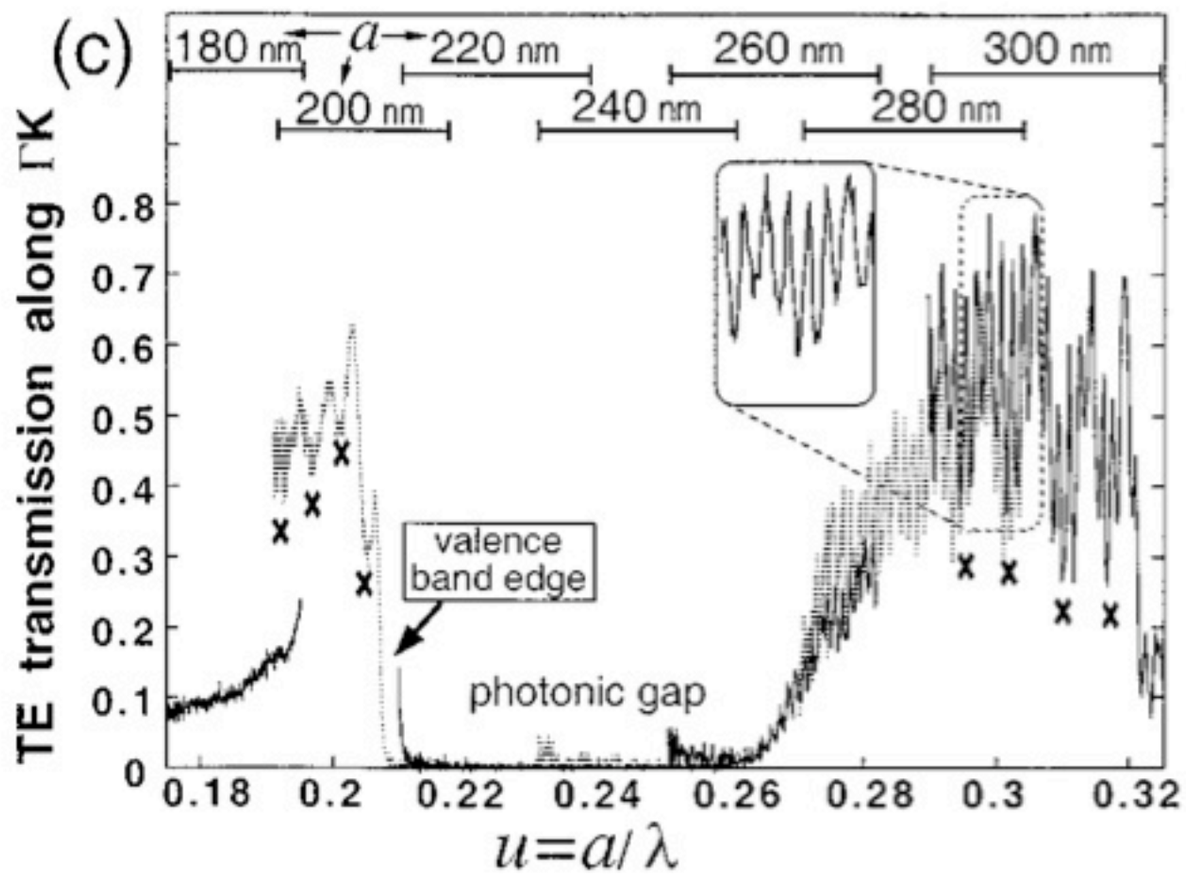
R. Ferrini et al., J. Quantum Electron., 38, 786, (2002)

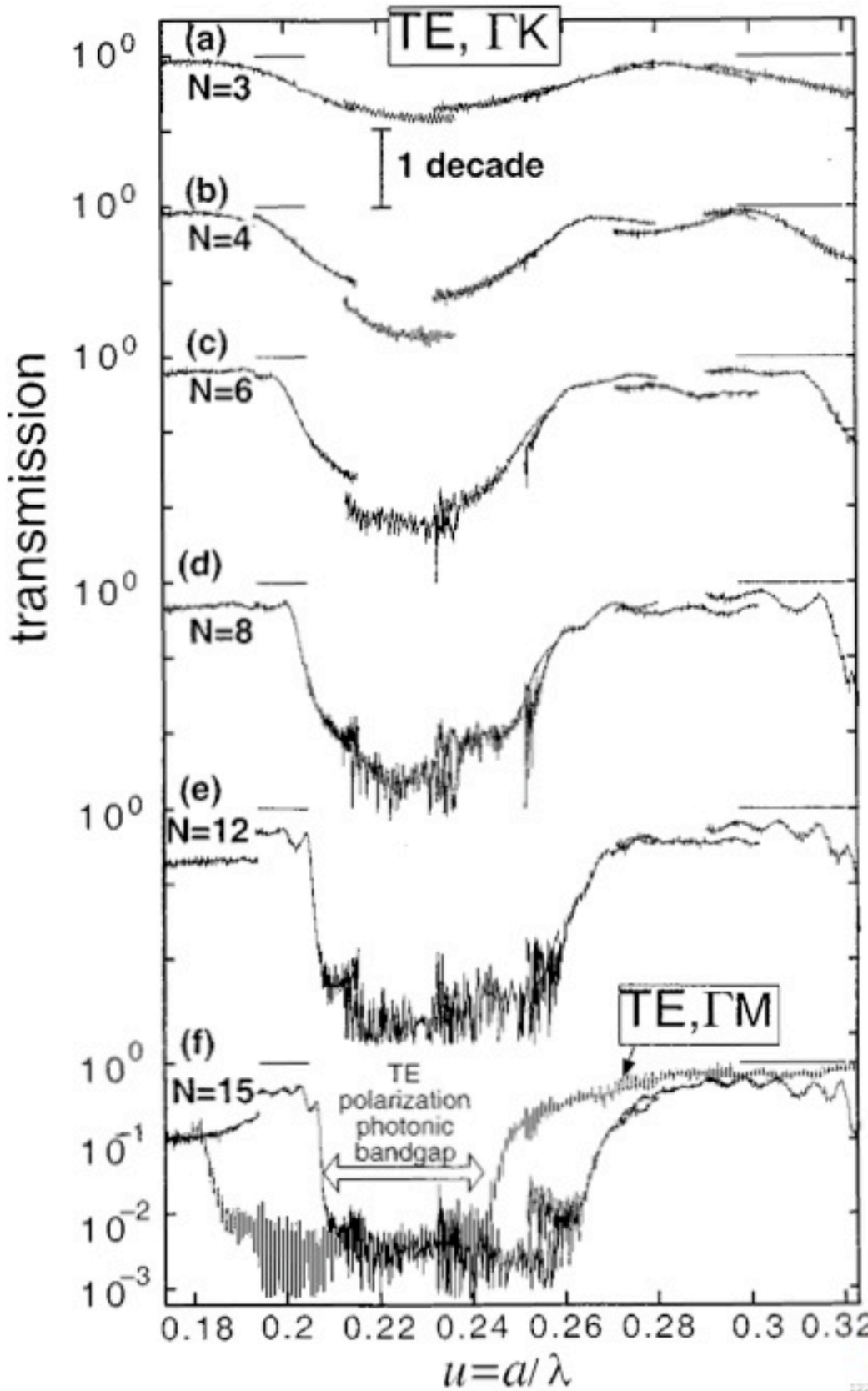
Transmission spectrum

Examples



Triangular lattice of holes in GaAs based planar waveguide

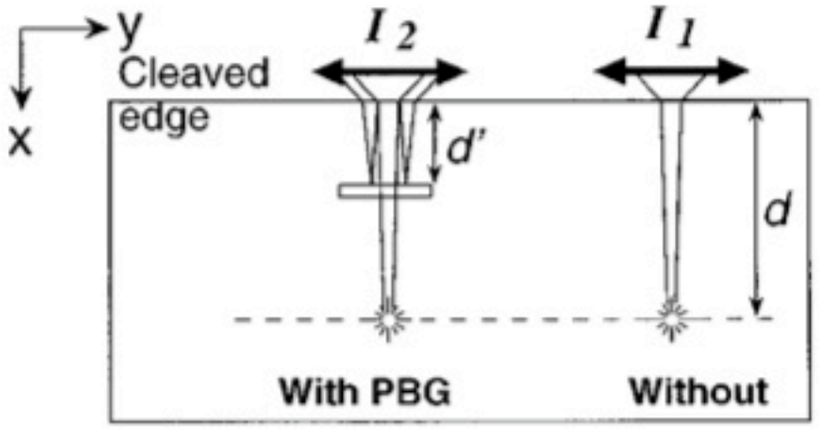


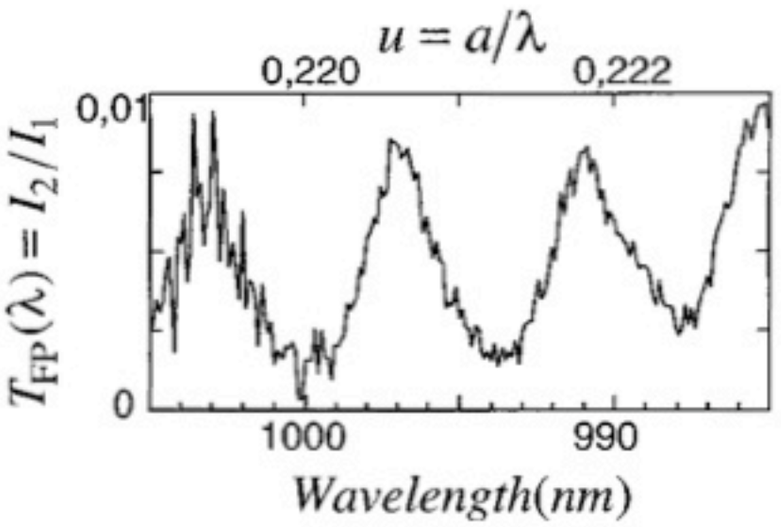


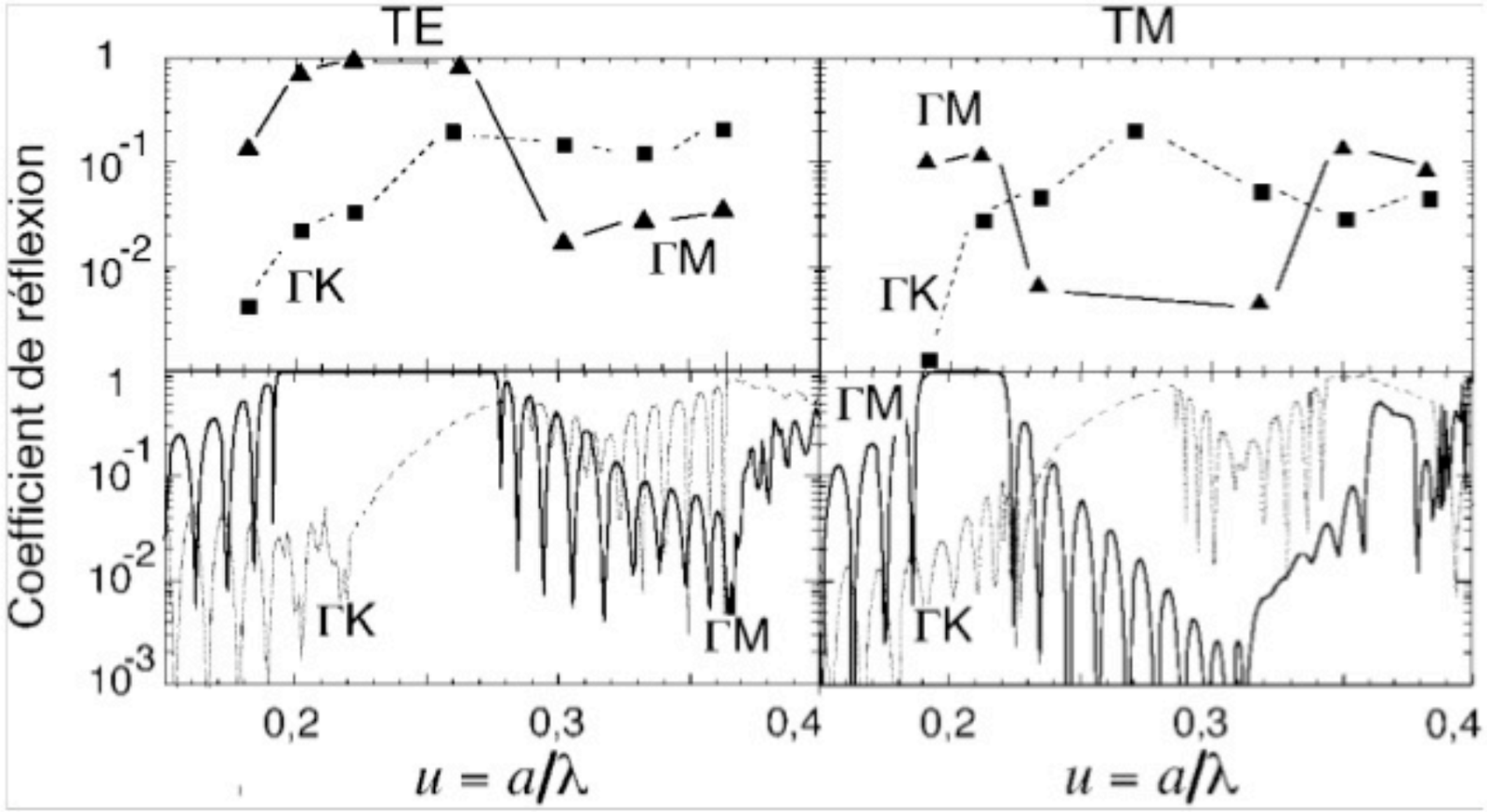
D. Labilloy et al., Phys. Rev. B, 59, 1649, (1999)

Reflectivity spectrum

Make use of the cavity fringes PhC / cleaved facet





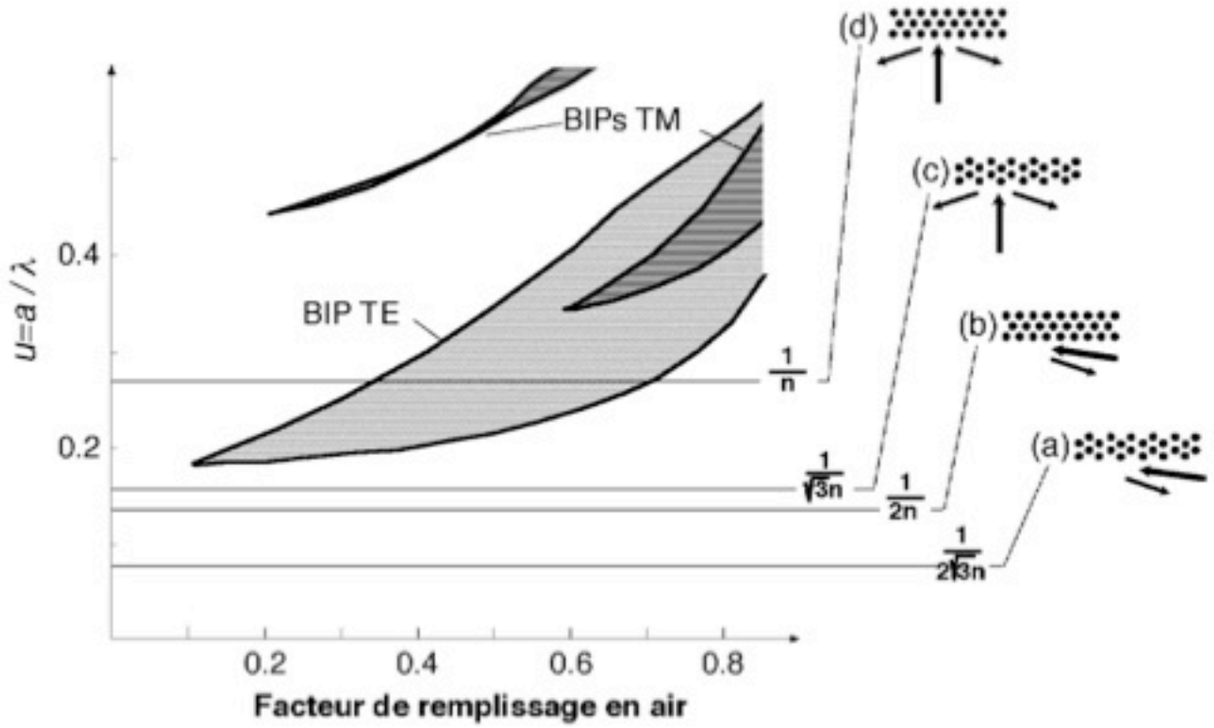


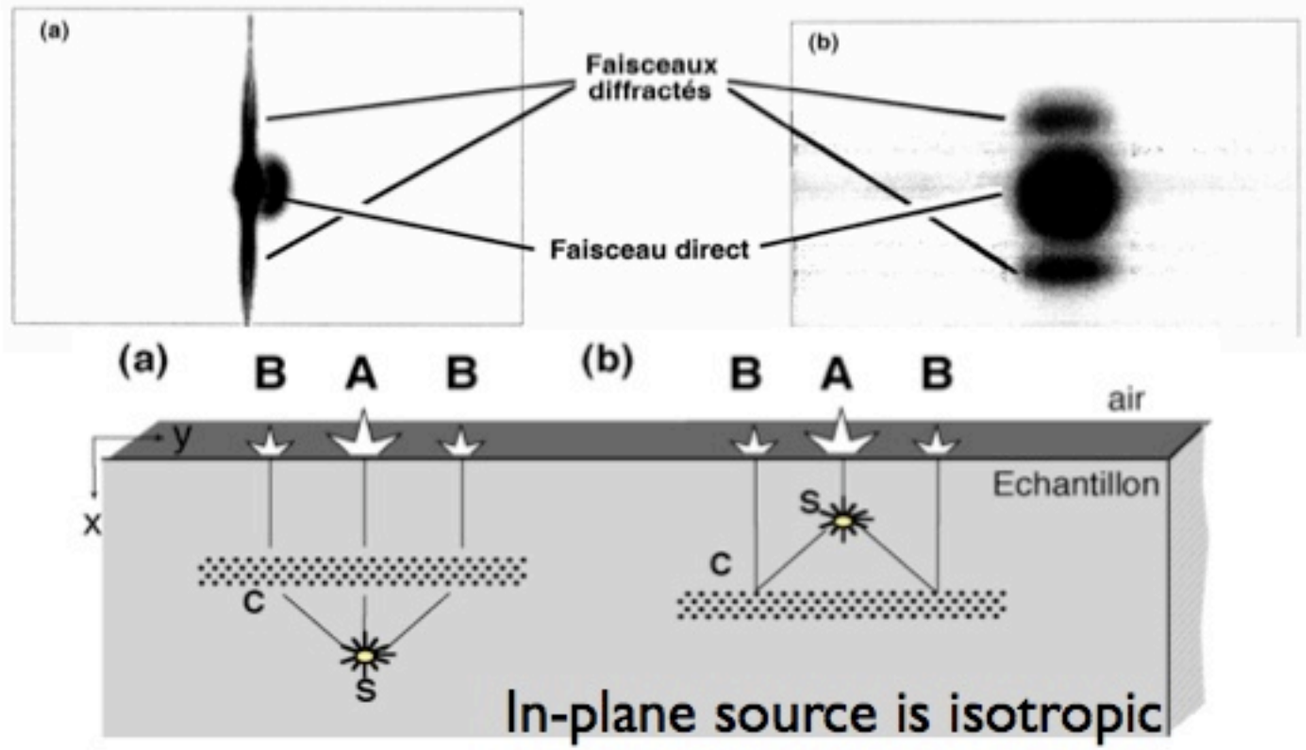
D. Labilloy et al., Phys. Rev. Lett., 79, 4147, (1997)

D. Labilloy PhD dissertation

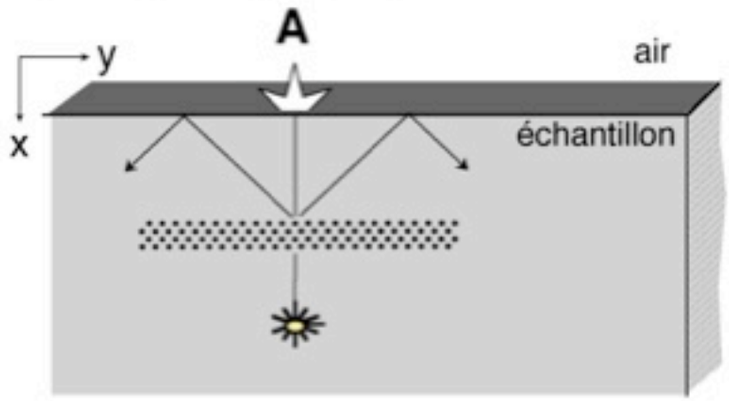
Diffraction

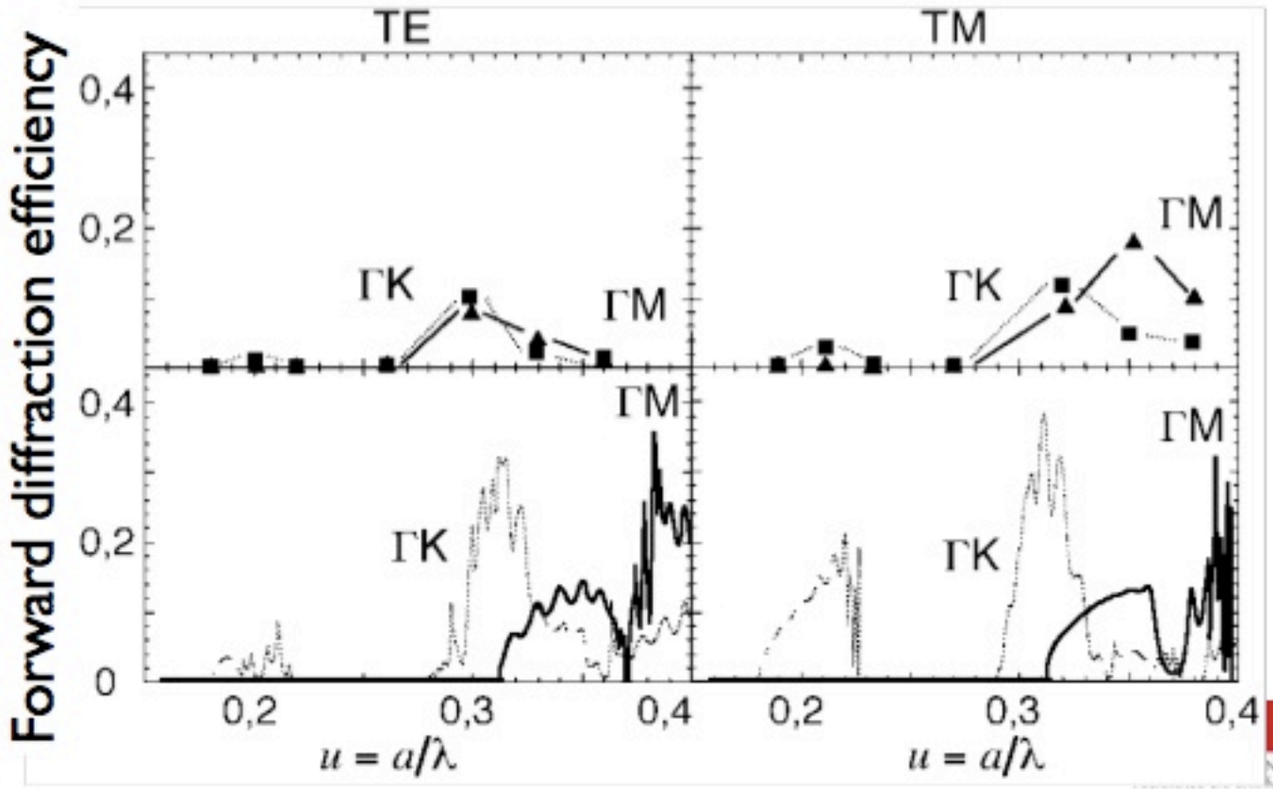
Measurement of light diffration at the PhC interface





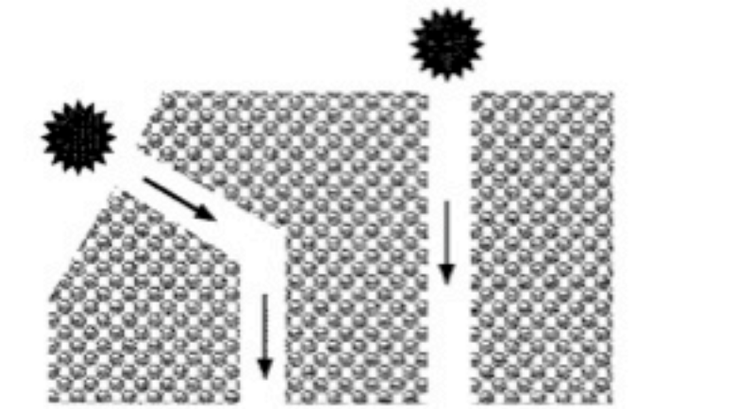
Diffraction cut-off frequencies, normal incidence

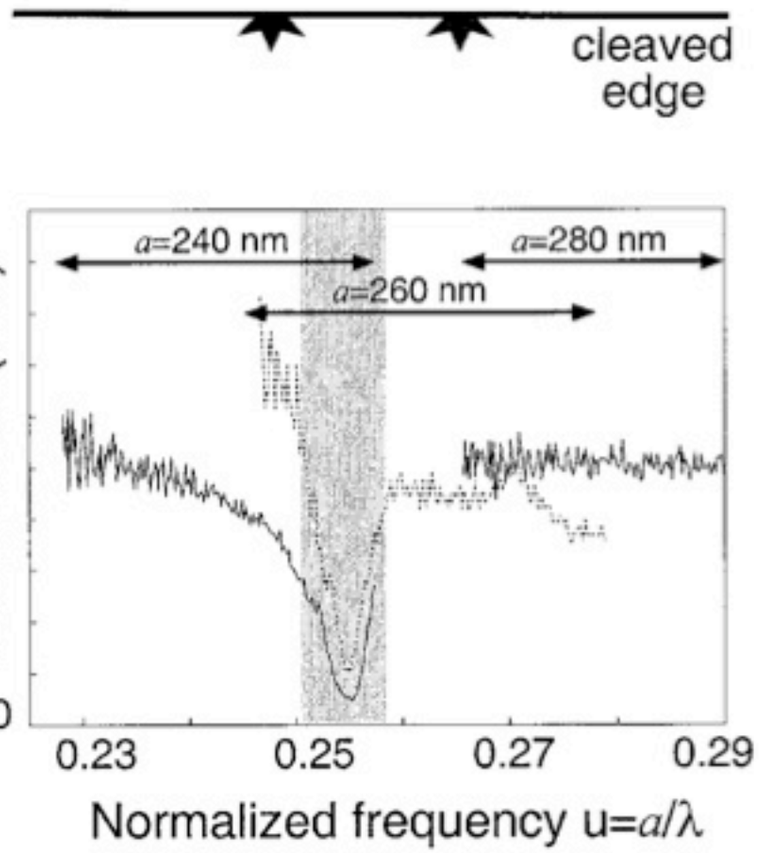


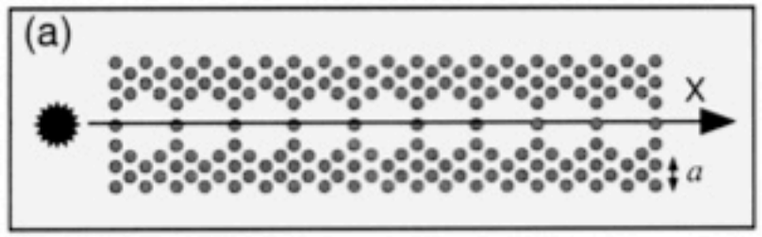


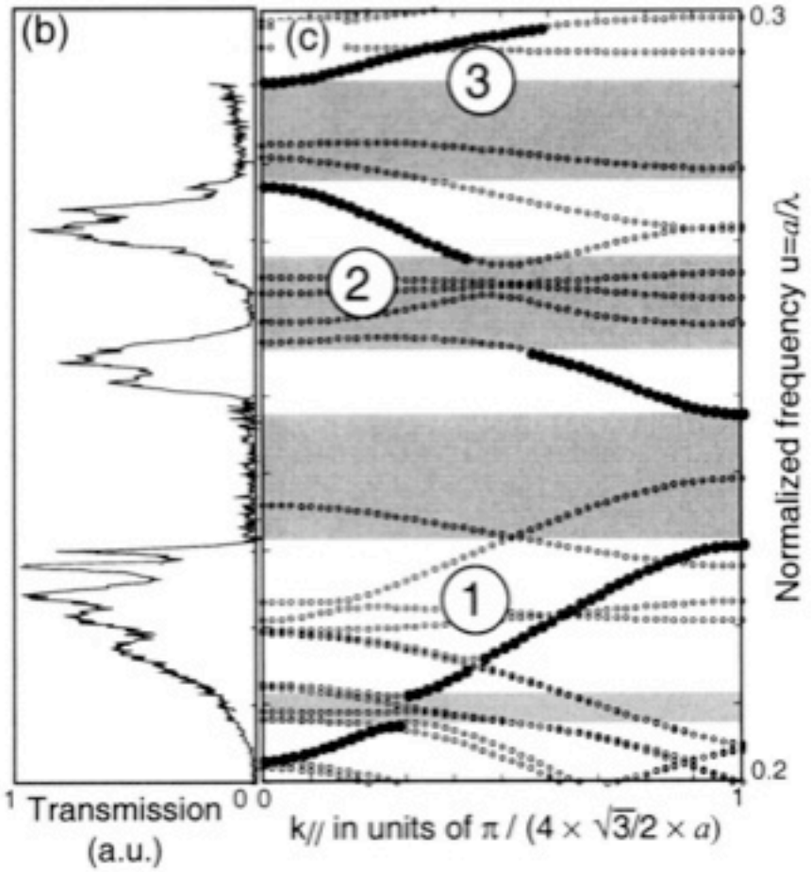
D. Labilloy PhD dissertation

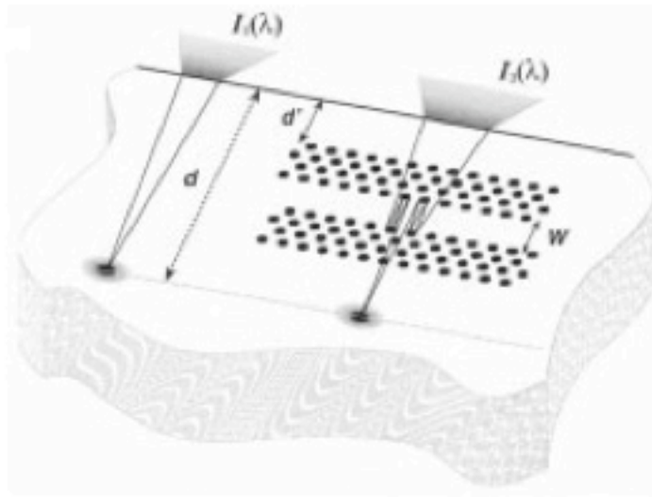
Waveguides, bends and Fabry-Perot cavities

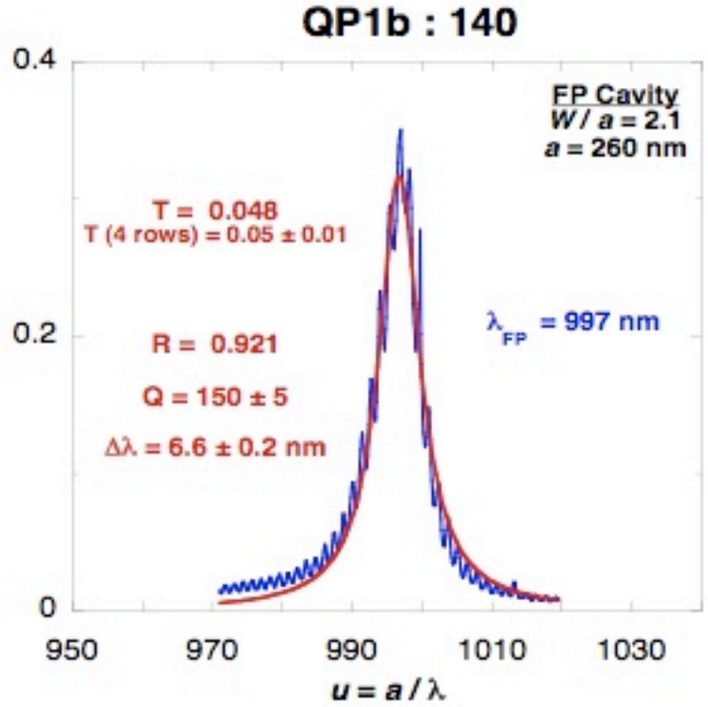












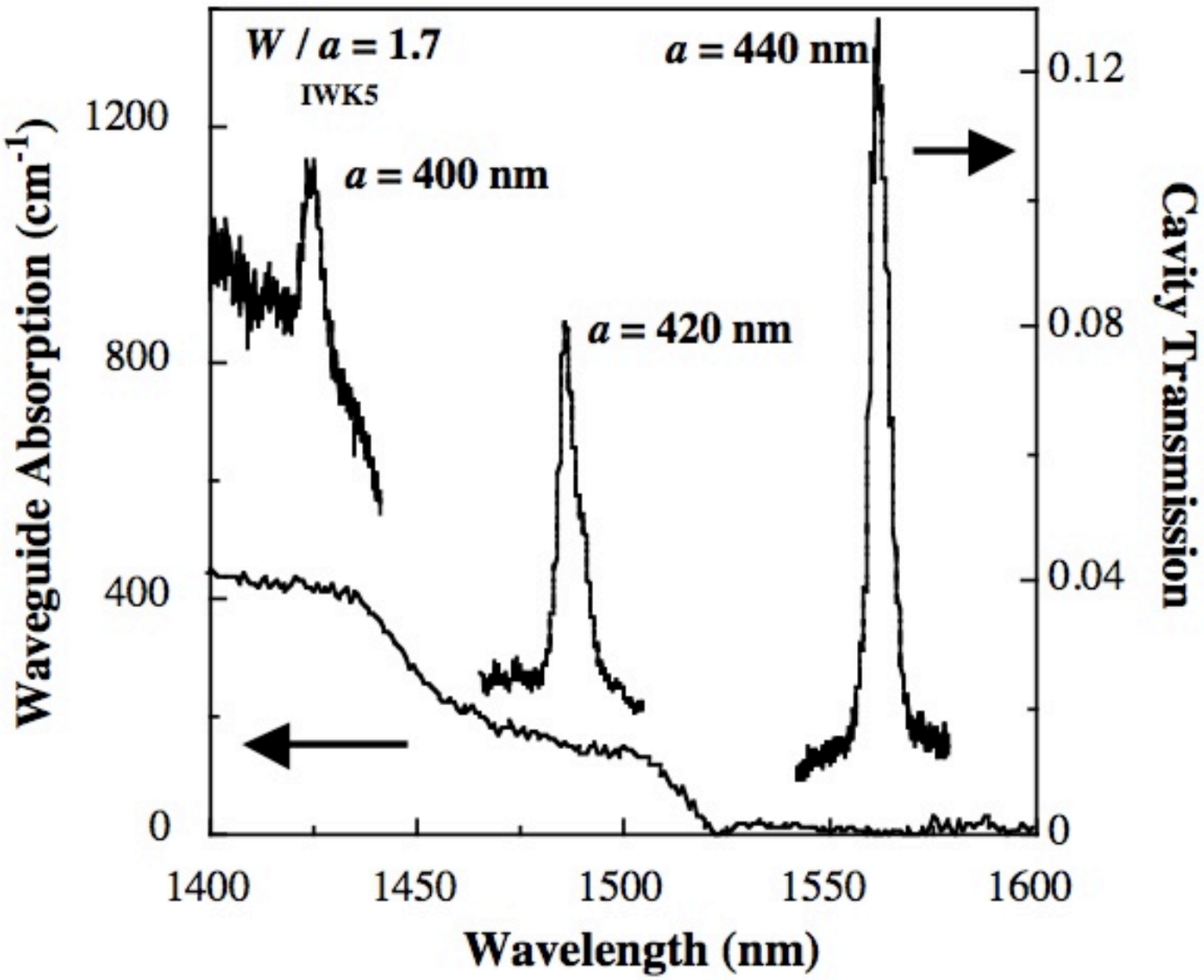
S. Olivier, Opt. Lett., 26, 1019, (2001)

S. Olivier, J. Light. Tech., 20, 1198, (2002)

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

Limitation

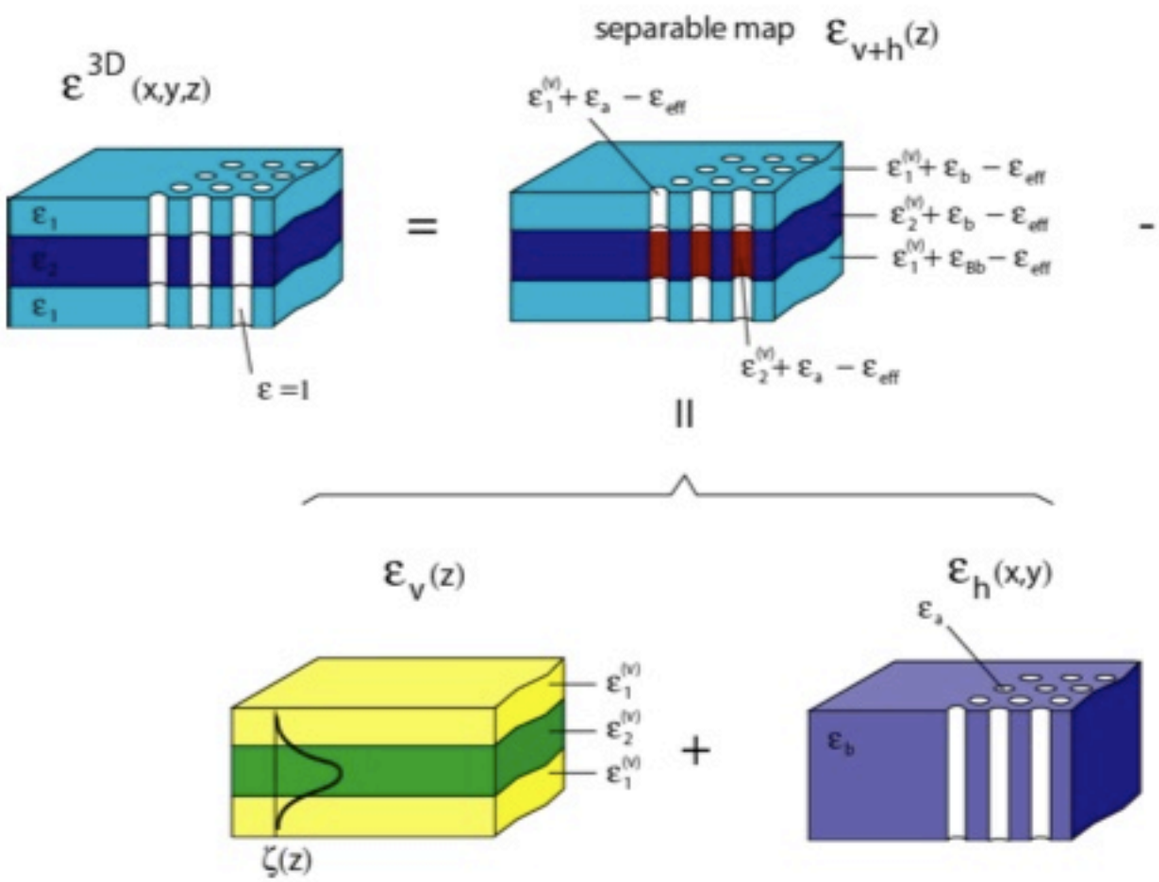
QW or QD absorption in the waveguide

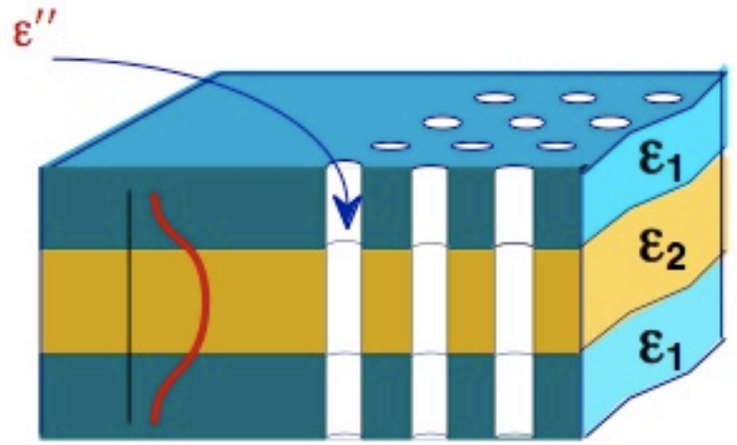


Out of plane scattering and losses

Phenomenological model

- For data analysis out of plane scattering can be cast into a phenomenological imaginary dielectric constant ε'' in air
- Intrinsic losses



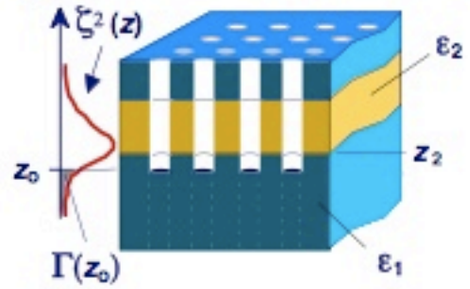


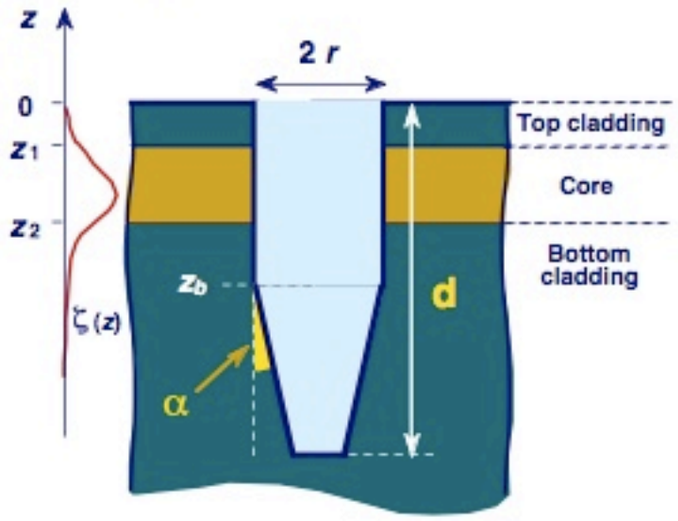
H. Benisty et al. Appl. Phys. Lett. 76, 532, (2000).

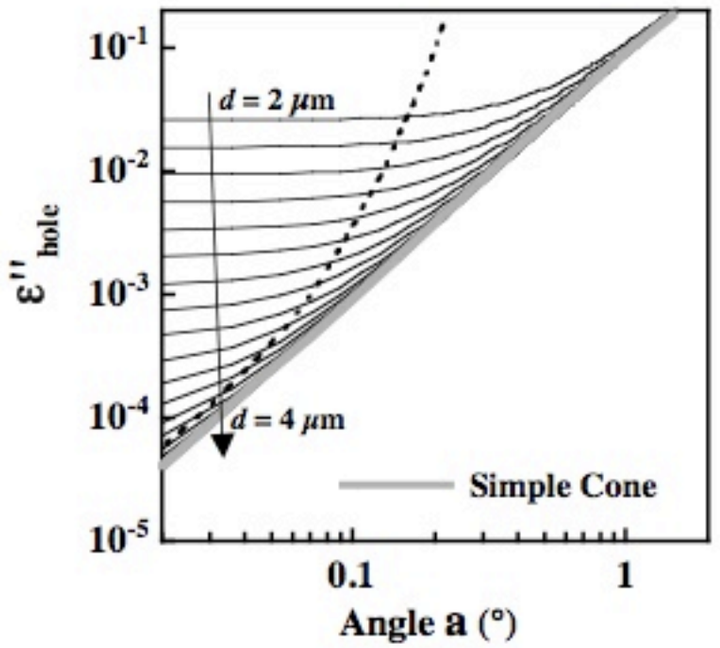
Out of plane scattering and losses

Phenomenological model

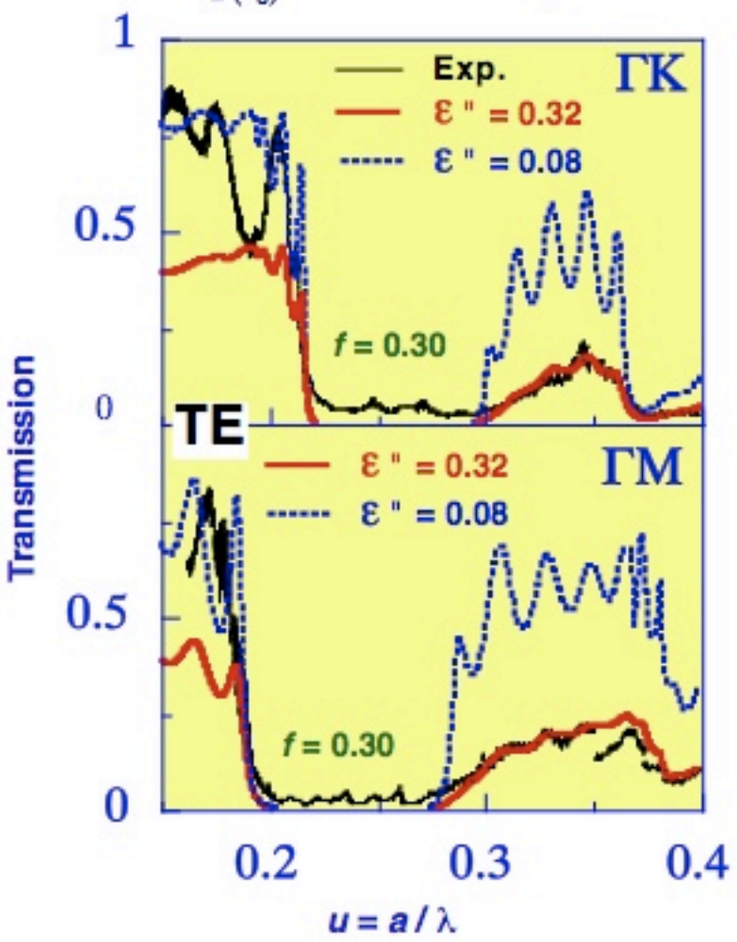
- Extrinsic losses, strongly correlated with hole shape, depth and in-plane disorder

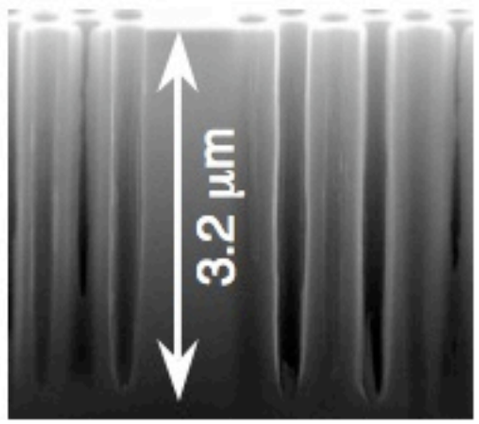


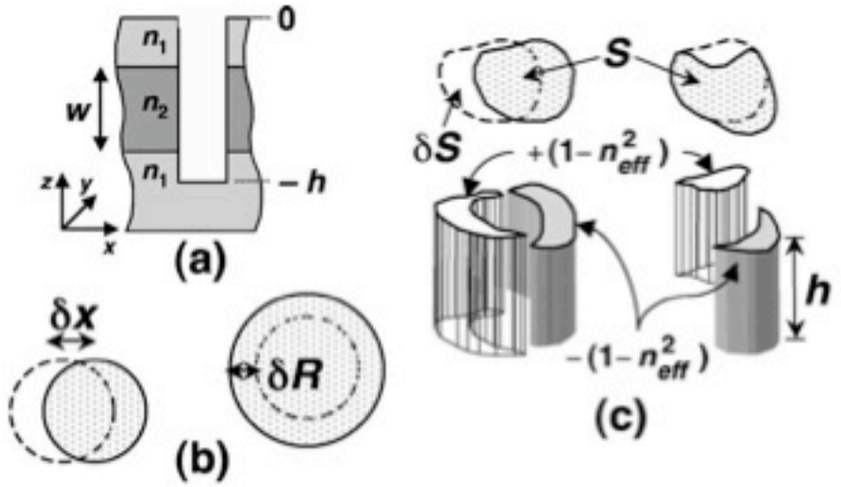




R. Ferrini et al., Appl. Phys. Lett. 82, 1009, (2003)







R. Ferrini et al., J. Opt. Soc. Am. B 20, 469, (2003)

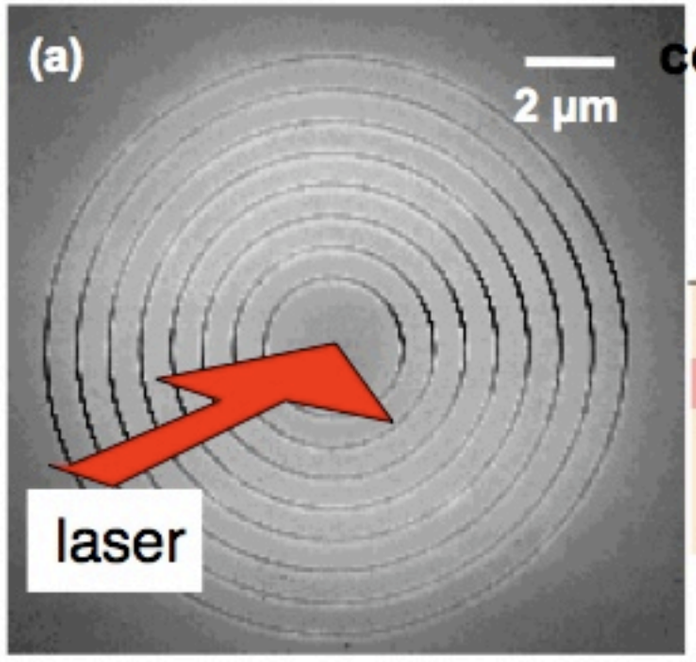
R. Ferrini et al., Opt. Lett. 31, 1426, (2006)

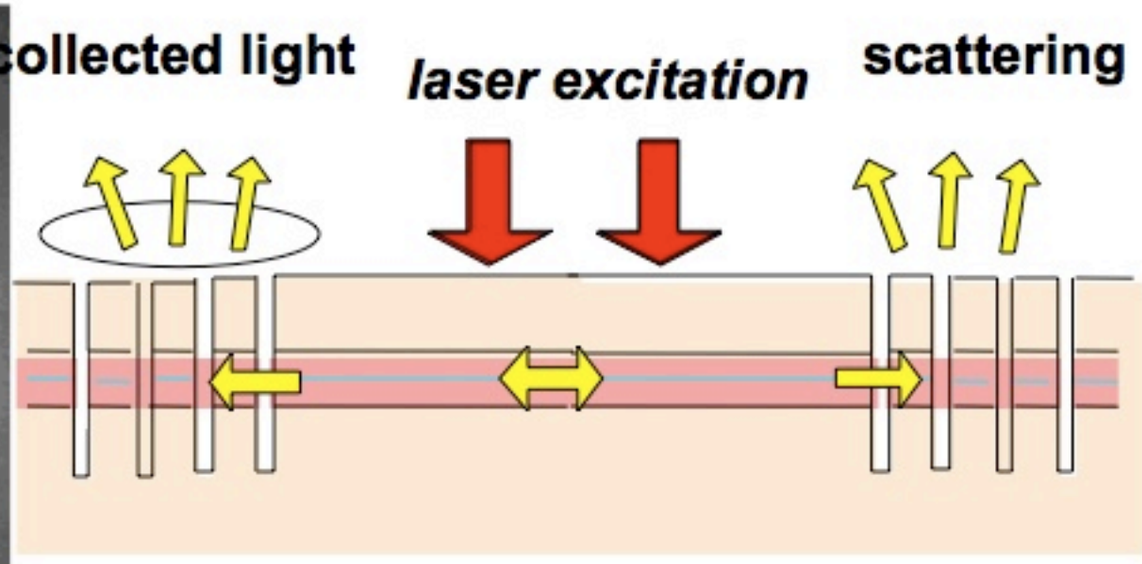
Photoluminescence

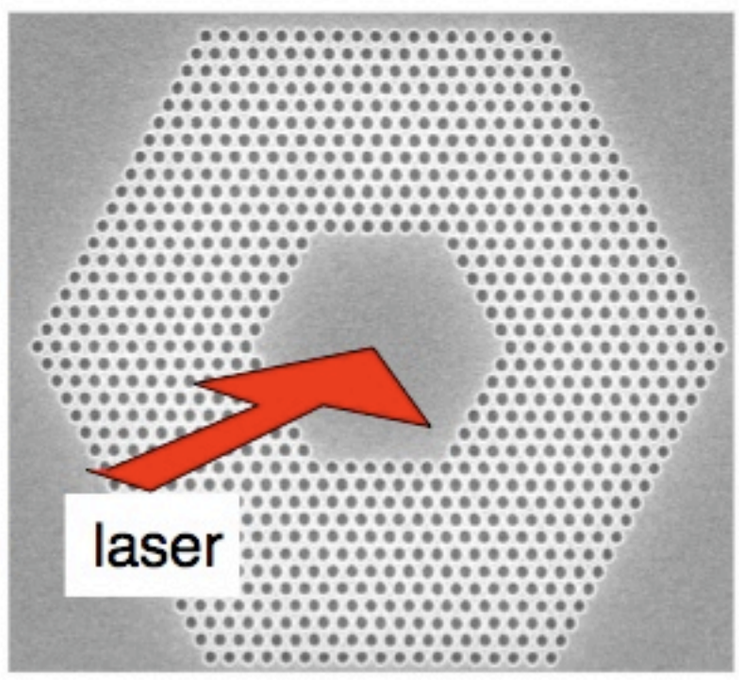
Light source inside the PhC structure

- PhC defect
  - Point defect, optical cavity

Front photoluminescence emission

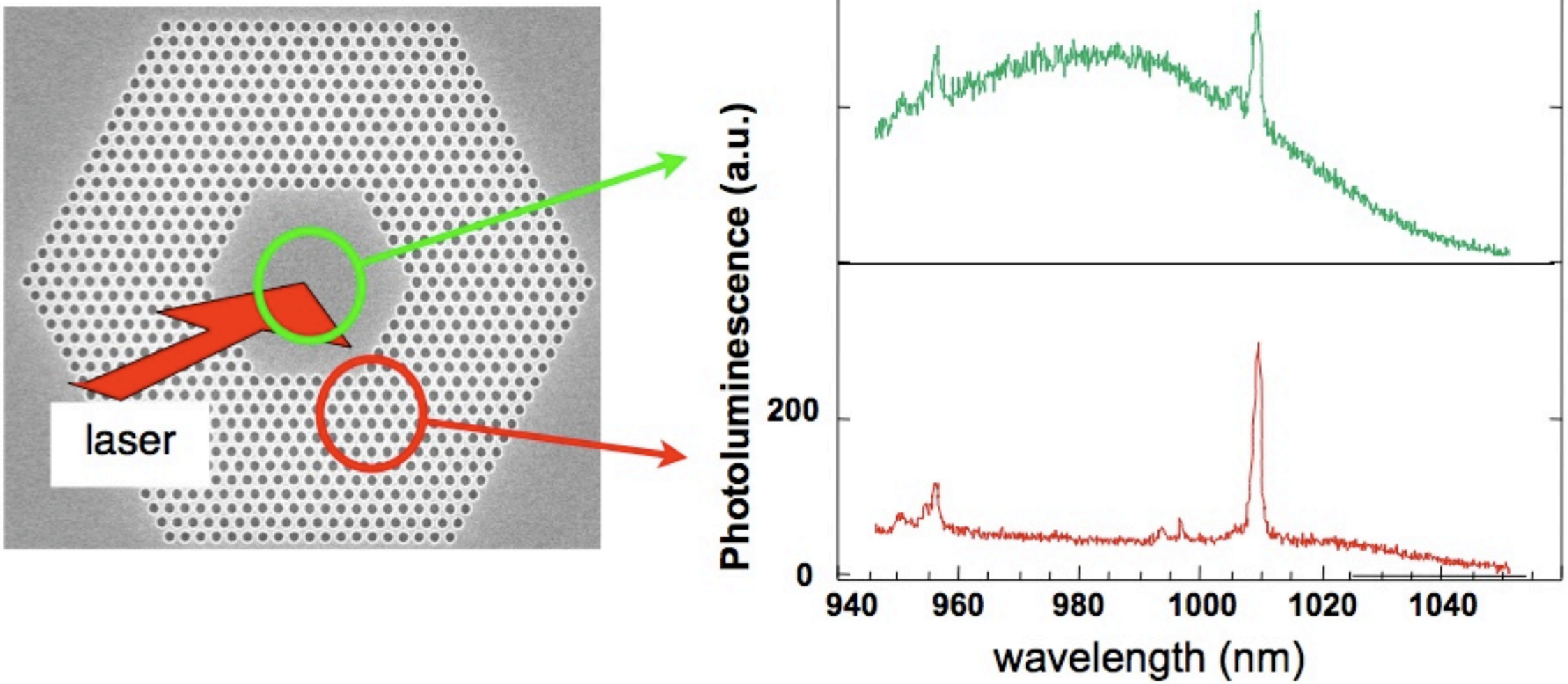






Photoluminescence

Mode spectroscopy

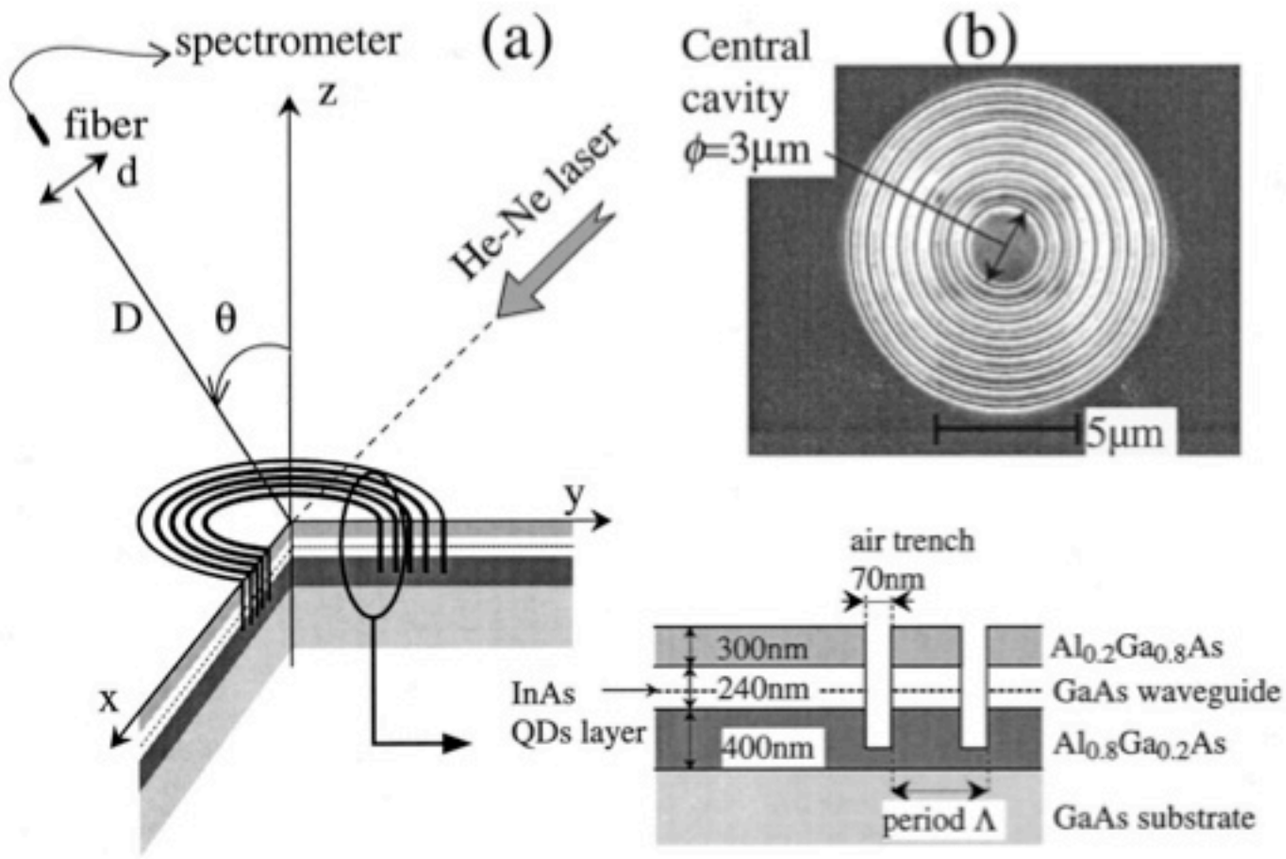


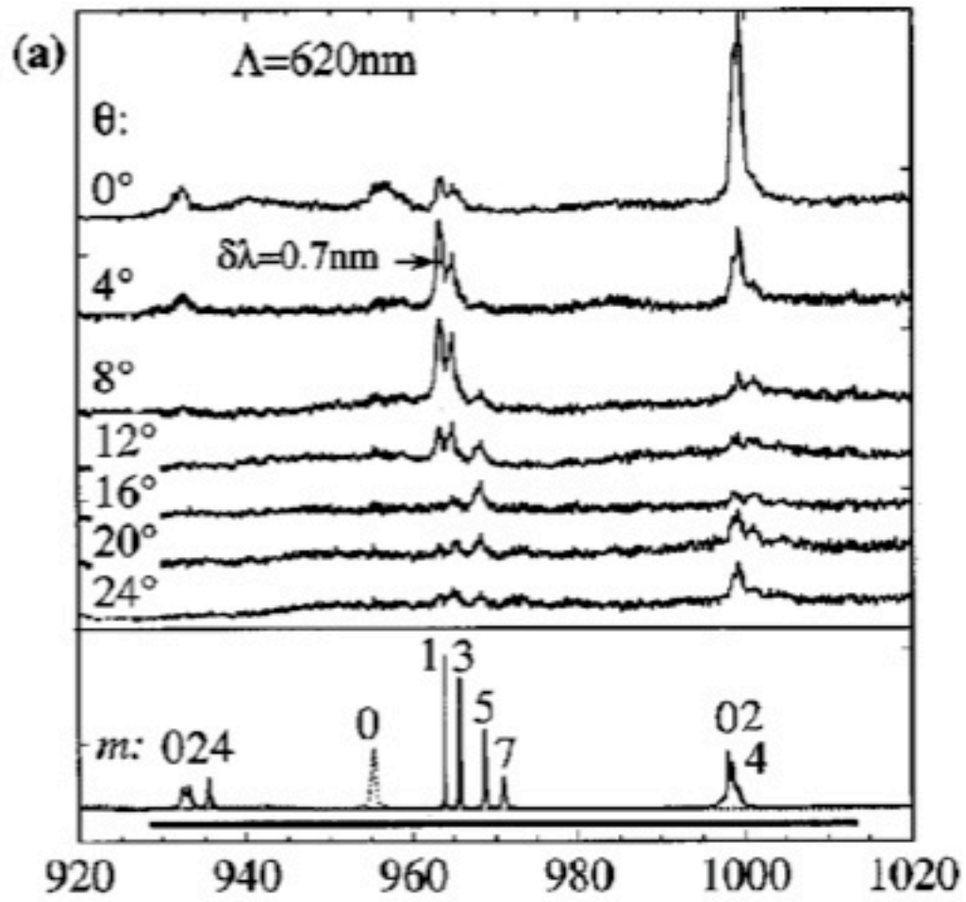
C.J.M. Smith et al., JOSA B, 17, 2043, (2000)

Photoluminescence

Mode spectroscopy

Coupled with angular resolution



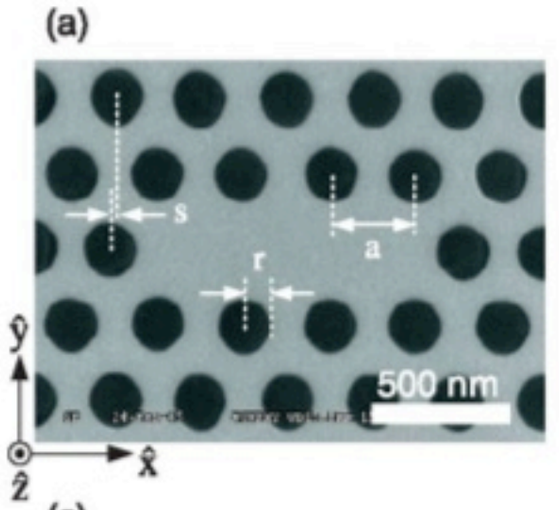


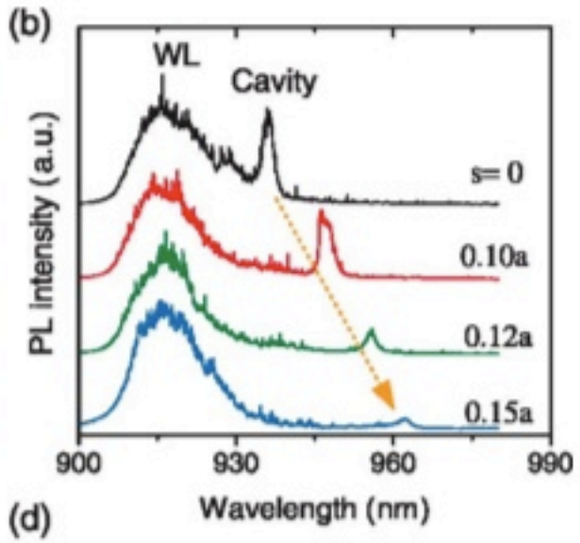
D. Ochoa et al., Phys. Rev. B, 61, 4806, (2000)

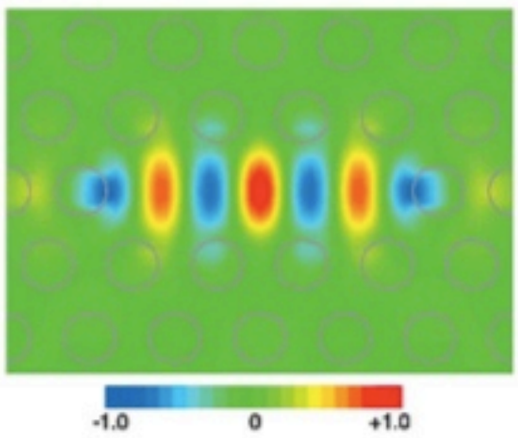
Photoluminescence

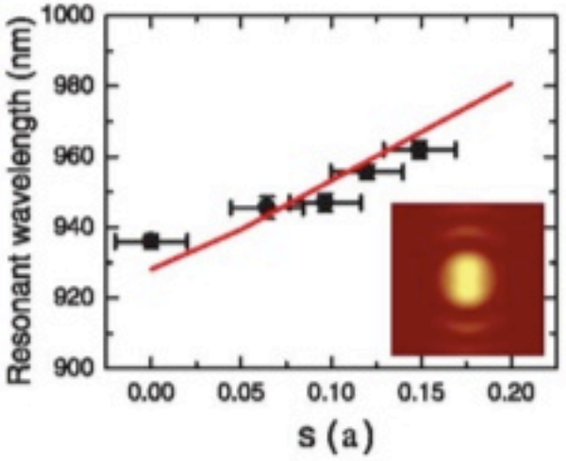
Time resolved

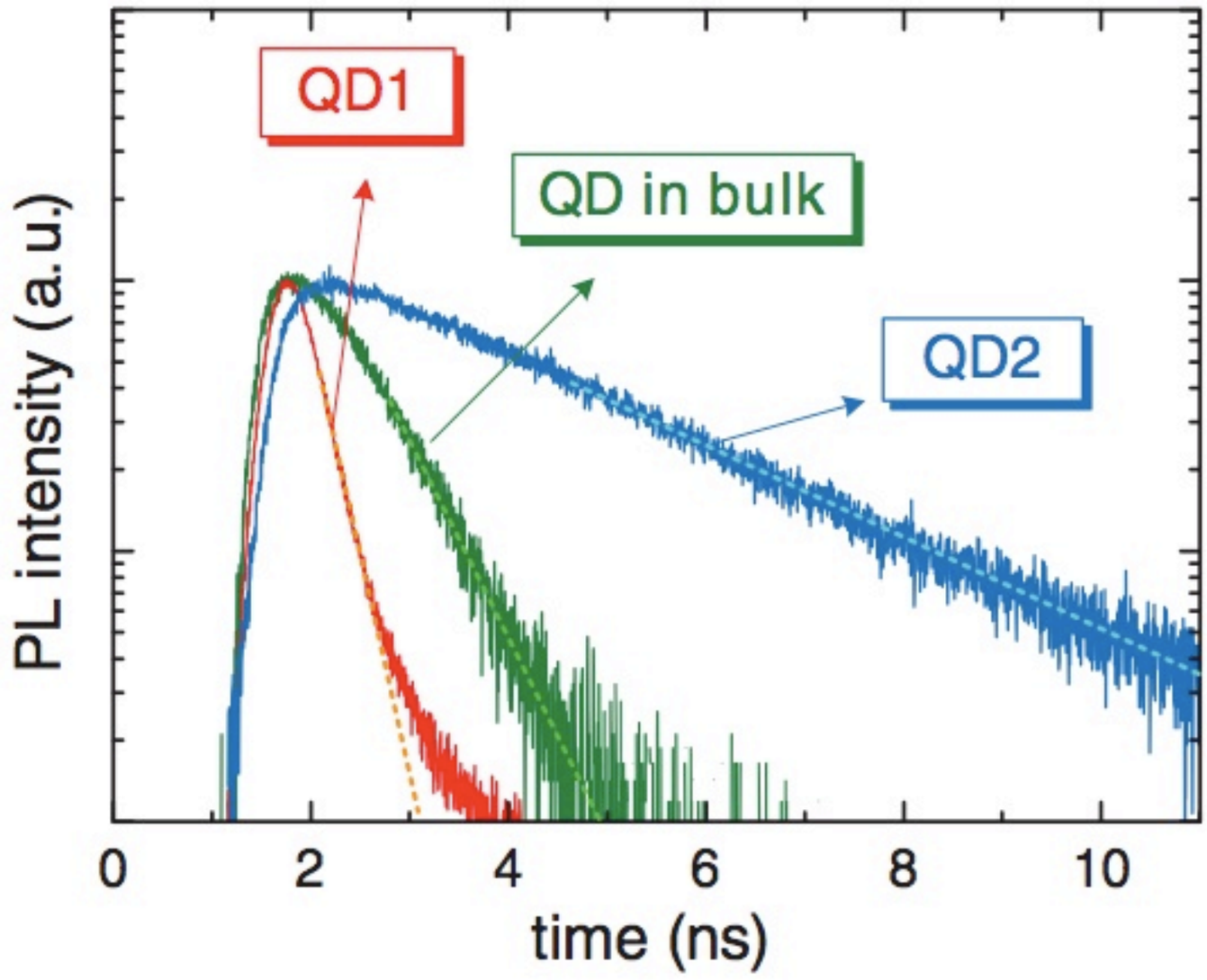
Life time modification, Purcell effect, emission enhancement and inhibition











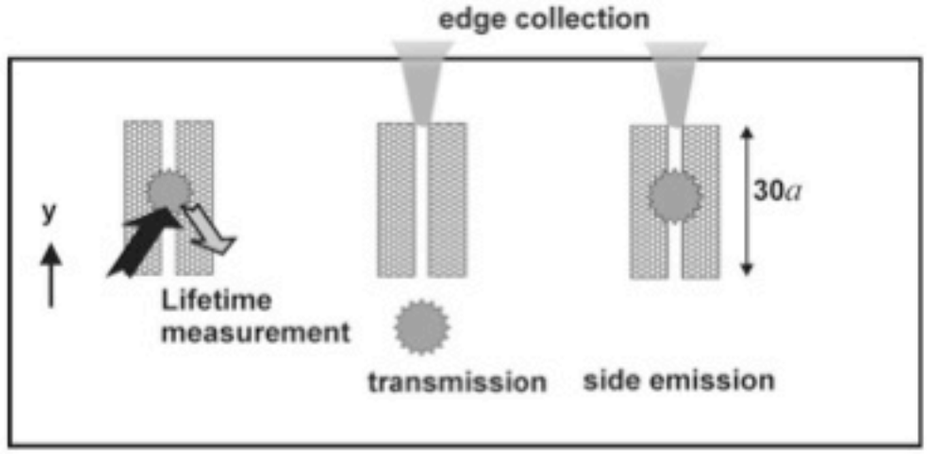
Wen-Hao Chang et al., Phys. Rev. Lett. 96, 117401, (2006)

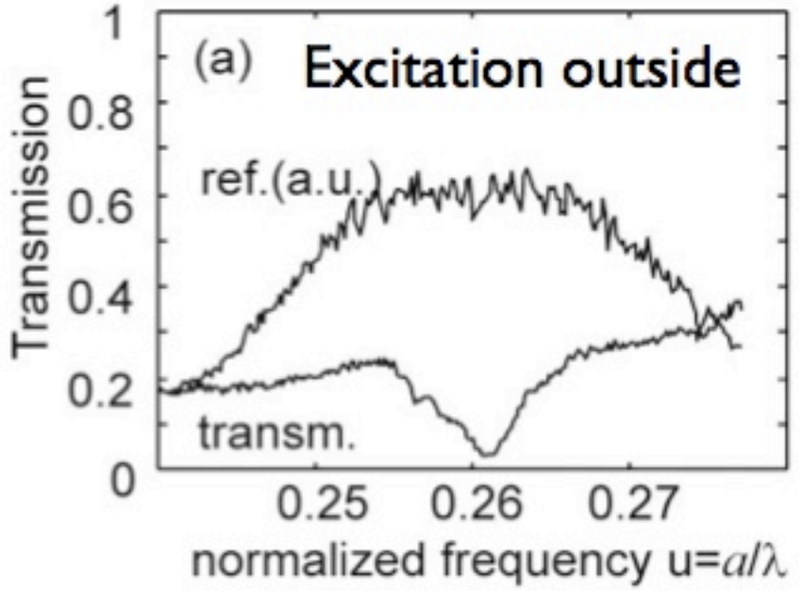
Photoluminescence

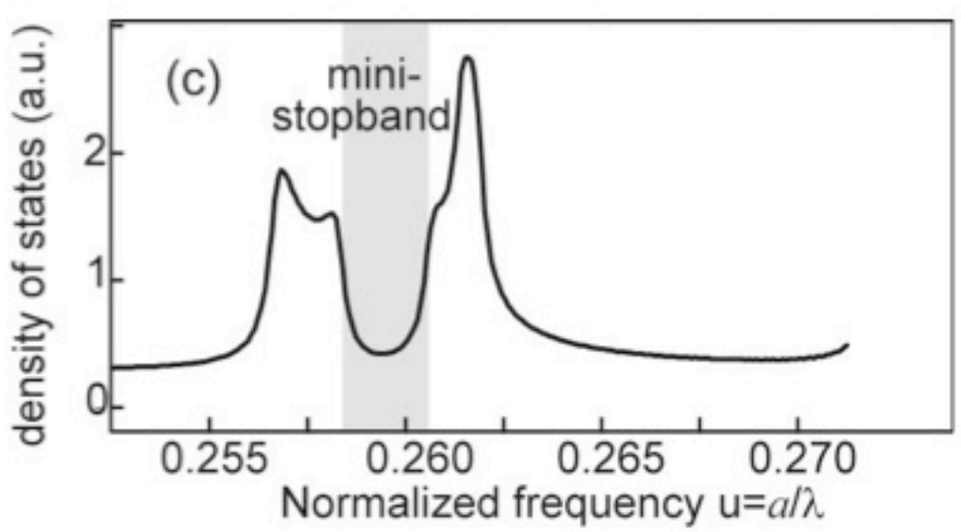
Light source inside the PhC structure

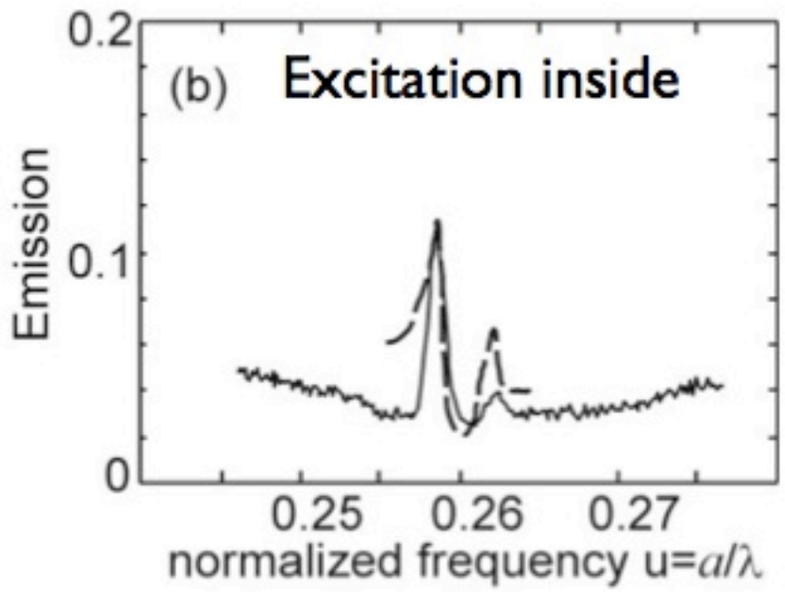
- PhC defect
  - Line defect, waveguide

Probing the density of states singularities









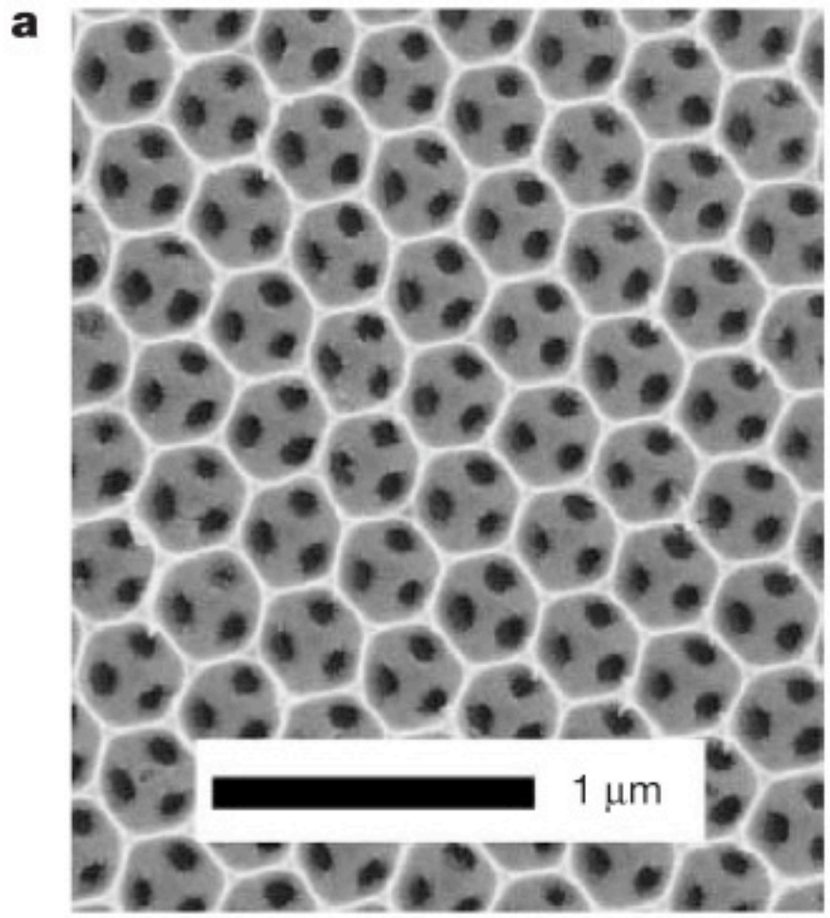
E.Viasnoff-Schwoob et al., Phys. Rev. Lett., 95, 183901, (2005)

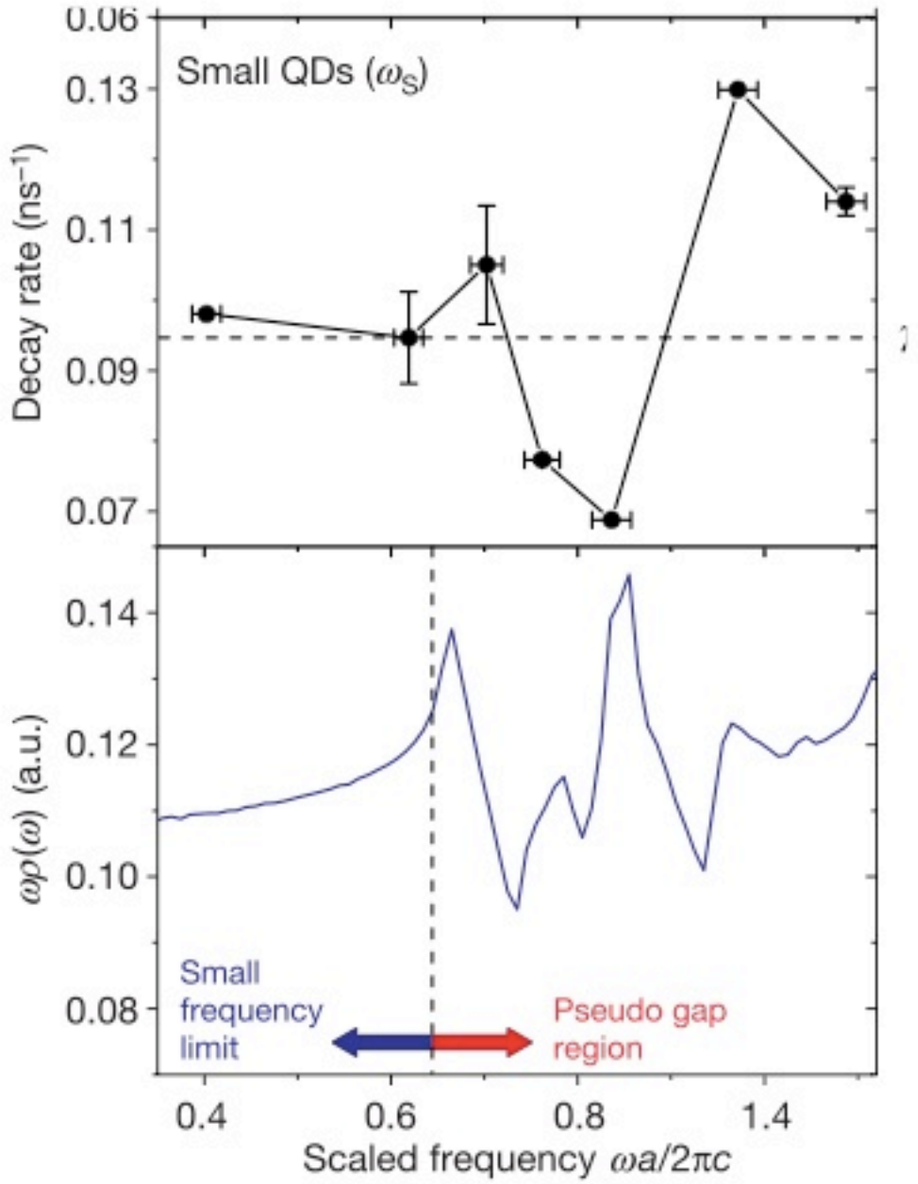
Photoluminescence

Light source inside the PhC structure

- Bulk 3D PhC

Probing the local density of states singularities, lifetime modification





CdSe nanocrystals in inverted opals

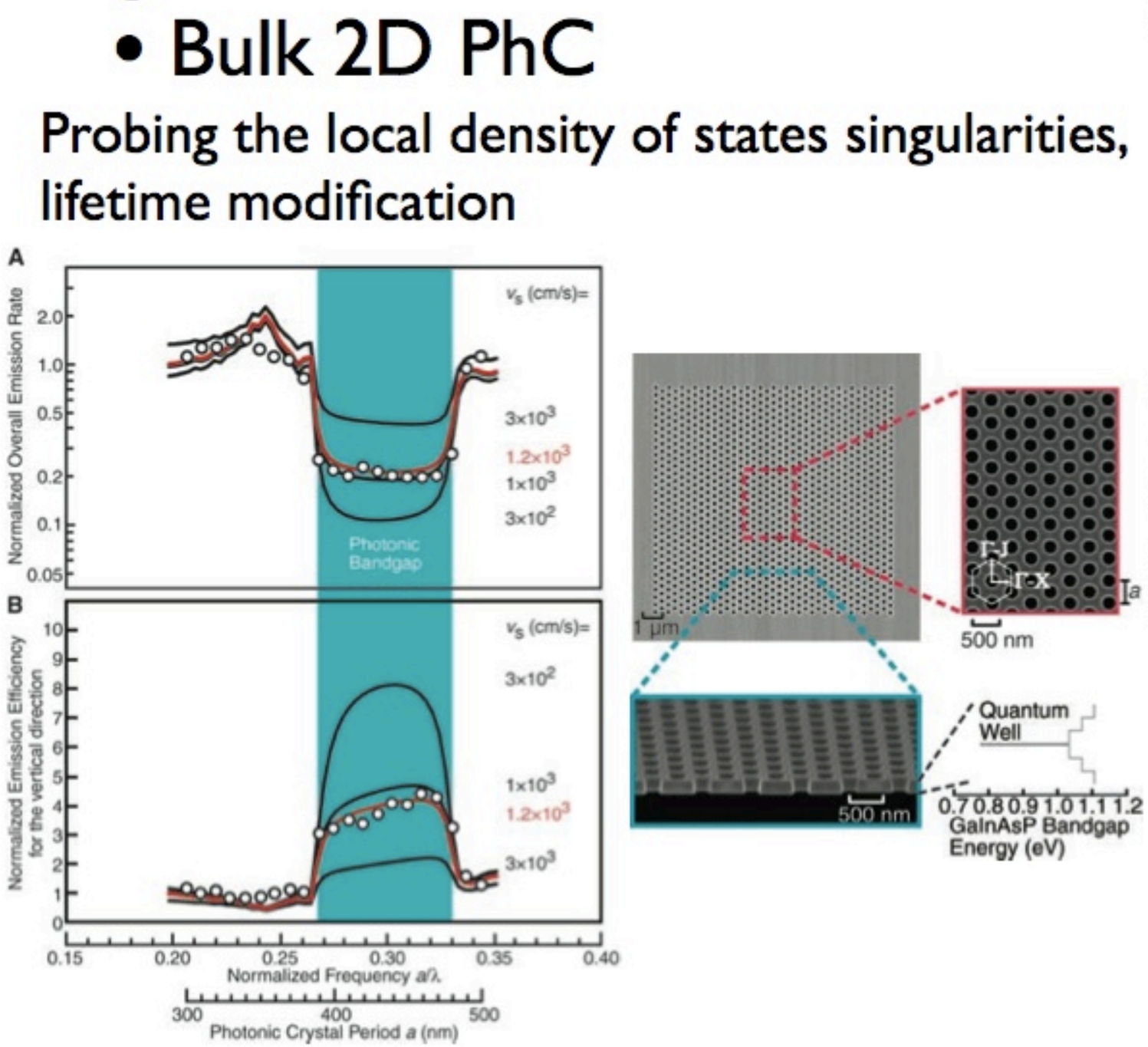
P. Lodahl et al., Nature, 430, 654, (2004)

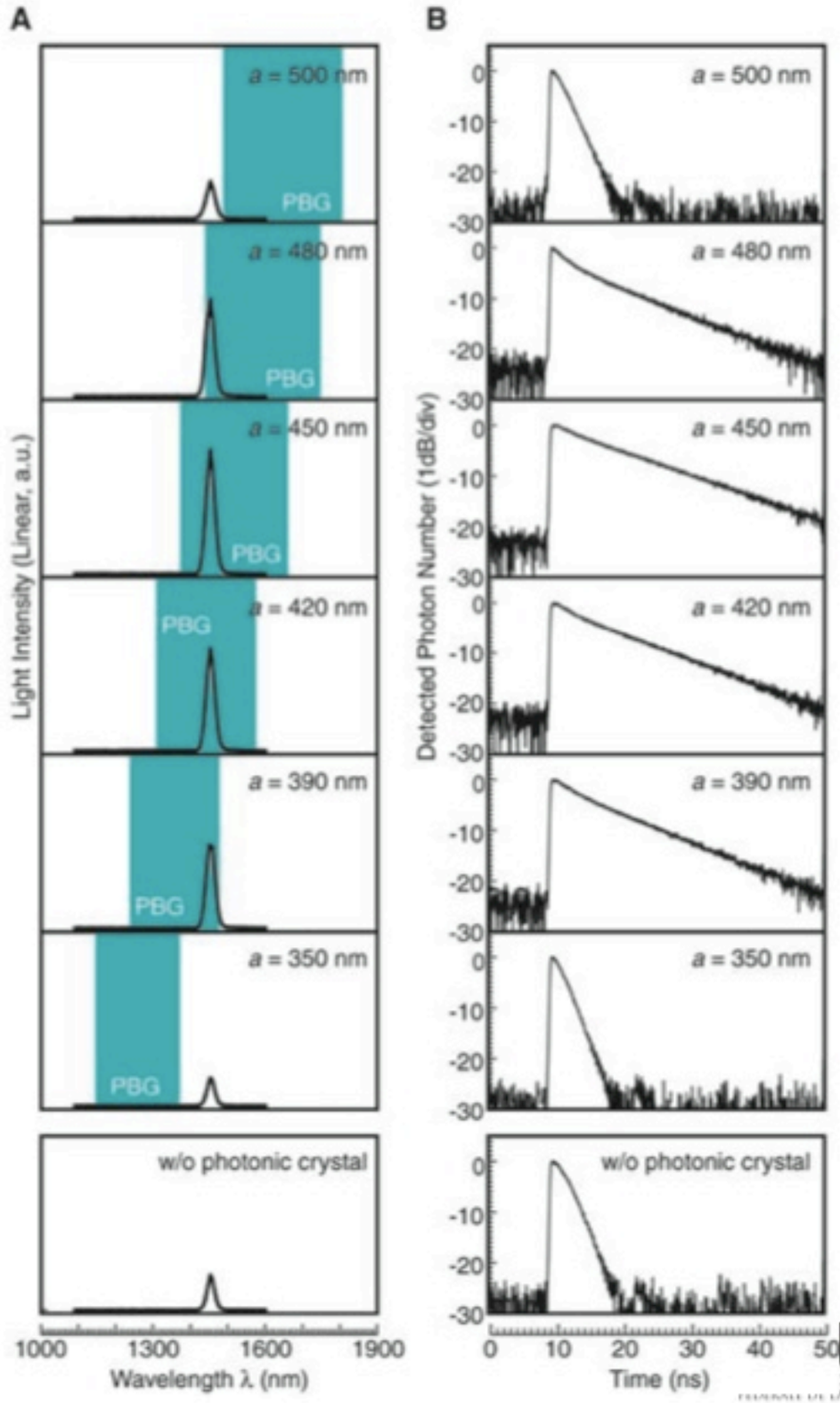
Photoluminescence

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)