

Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

VI Devices

Contents

* **1 Introduction, overview.**

Introduction
History of photonic crystals
The key concepts

* **2 Theory**

Main equations
Band structures and projected band structure
Plane wave expansion method
FDTD
Transfer matrices, FEM and other methods

* **3 Basic properties**

Mirror
Waveguide
Bends, splitters, couplers
Optical resonator
High quality factor cavities
Dispersion diagram and equifrequency surfaces
Superprism, negative refraction
Selfcollimation
Fourier analysis of Bloch waves

* **4 Fabrication techniques**

Epitaxy, patterning, etching
2D, III-V, Si, SOI
3D, Opals

* **5 Measurement techniques**

External light source
Internal light source
Advanced techniques

* **6 Applications**

Couplers
Polarizer and rotator
Modulator, routing
Add/Drop
Spectrometers and interferometers
Point defect photonic crystal lasers
Band-edge photonic crystal lasers

* **7 Emerging topics**

Integration with microfluidics systems
Biology
Slow light
Nano-beam
Optomechanic systems
Subwavelength structures
Slotted waveguides
Optical trapping
Sensors
Dynamic control
Non-reciprocal structures
Novel materials (chalcogenide, diamond, GaN,...)
Thermal photovoltaic
Topological transitions
...

Integrated optics

Planar integrated optics is now well developed

- Silica / doped silica
 - III-V semiconductors
 - LiNbO₃
 - Organic materials
-
- Phasar
 - Integrated spectrometers
 - Laser diode, amplifier
 - Non linear effects

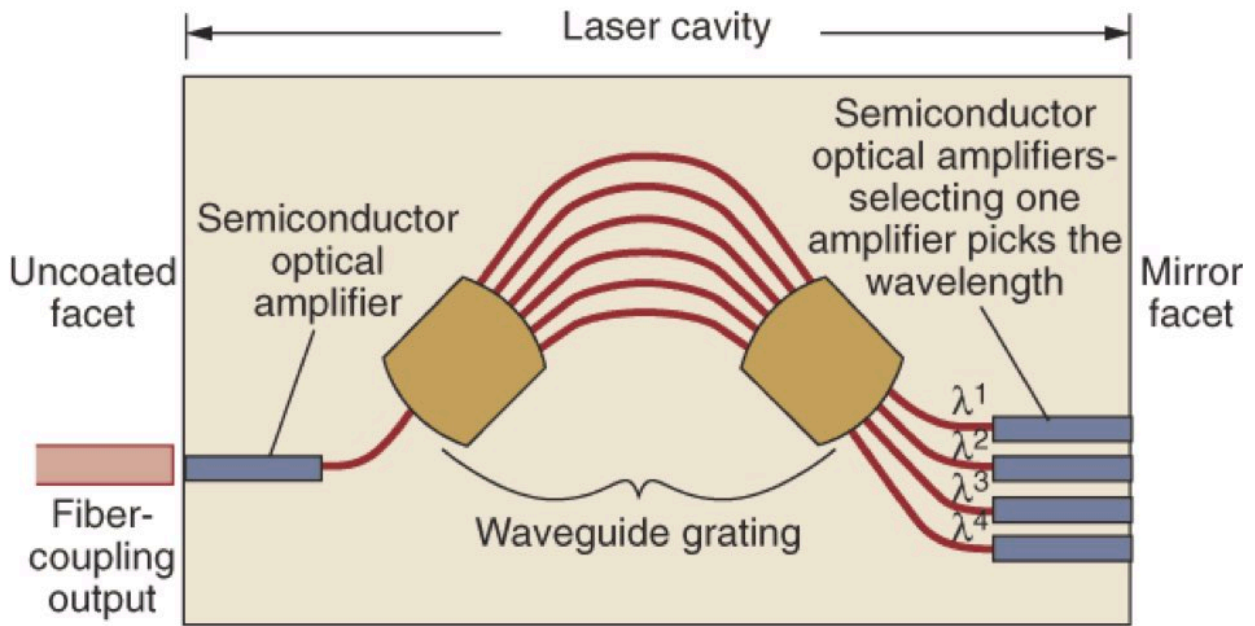
Integrated optics

But planar integrated optics did not follow the same trends as the integrated electronics (Moore's law)

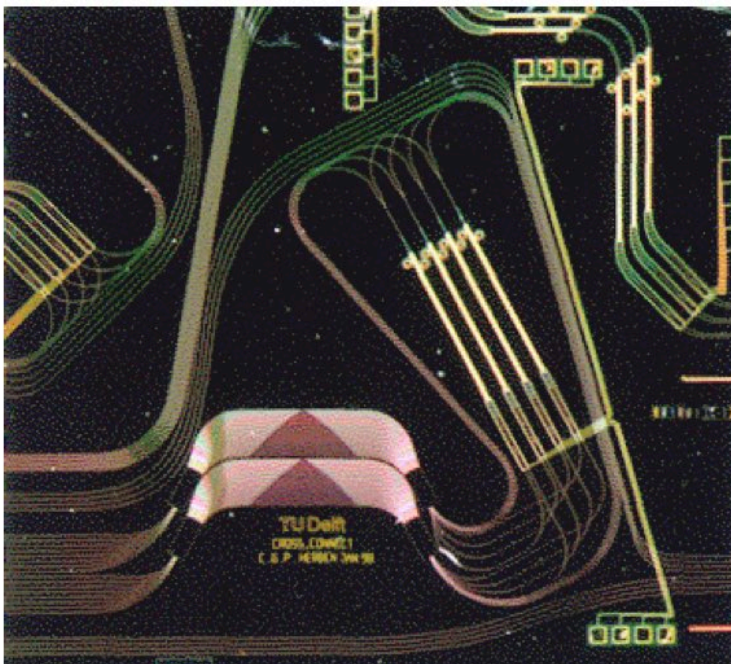
- Presently maximum of two or three functions for a limited number of channels are integrated on one chip
- Fabrication costs
- Smaller amounts
- Low fabrication yields
- Integrated circuits and optical fibres coupling issues
- Hybridisation of different technology

Nowadays the technology for an optical chip, compact and versatile, comparable to an electronic chip does not exist.

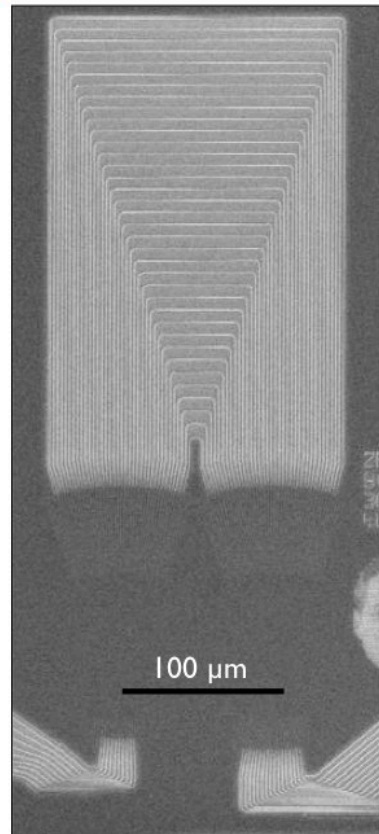
Integrated optics



Integrated optics



1mm



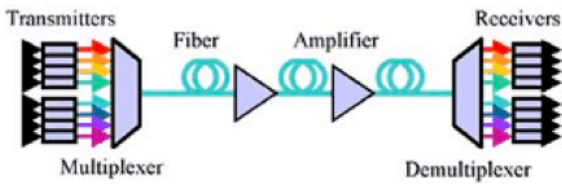
100 μm

C.G.P. Herben et al., IEEE PTL, 10, 678 (1998)

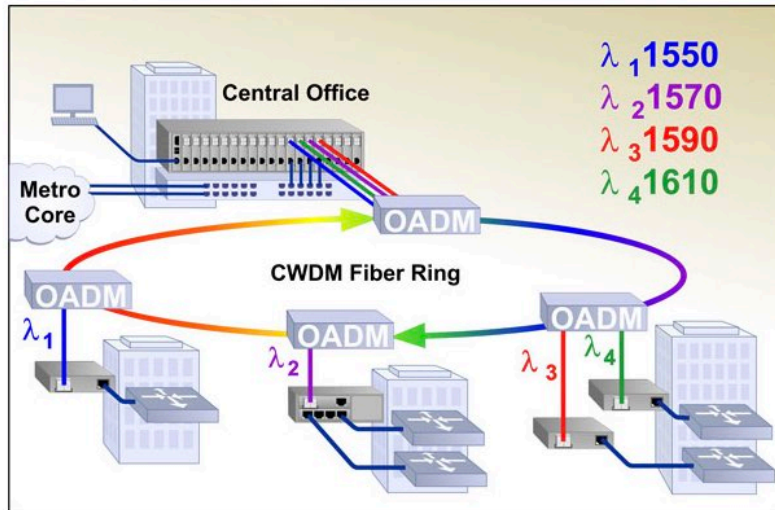
photonics.intec.ugent.be

Optical network

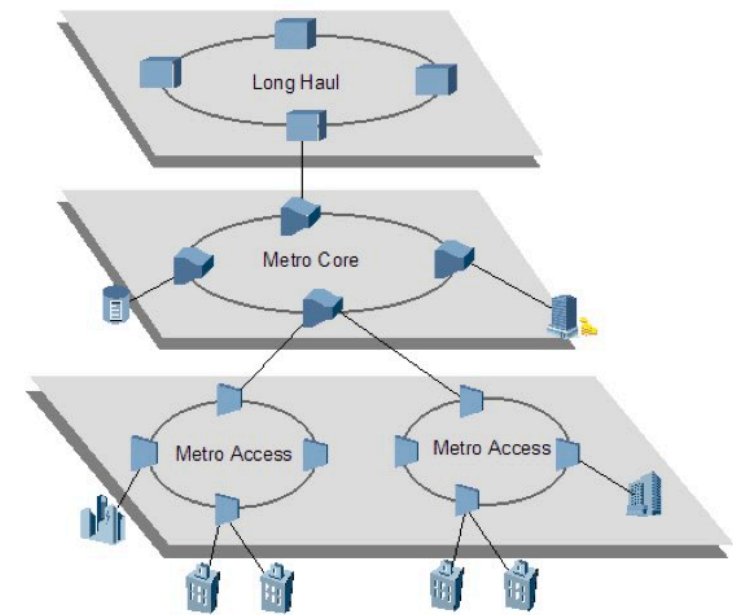
Wavelength multiplexing WDM (Wavelength Division Multiplexing)



Channel separation, 100, 50, 25 ... GHz
Number of channels 16, 32, 64, 128 ...



Optical network



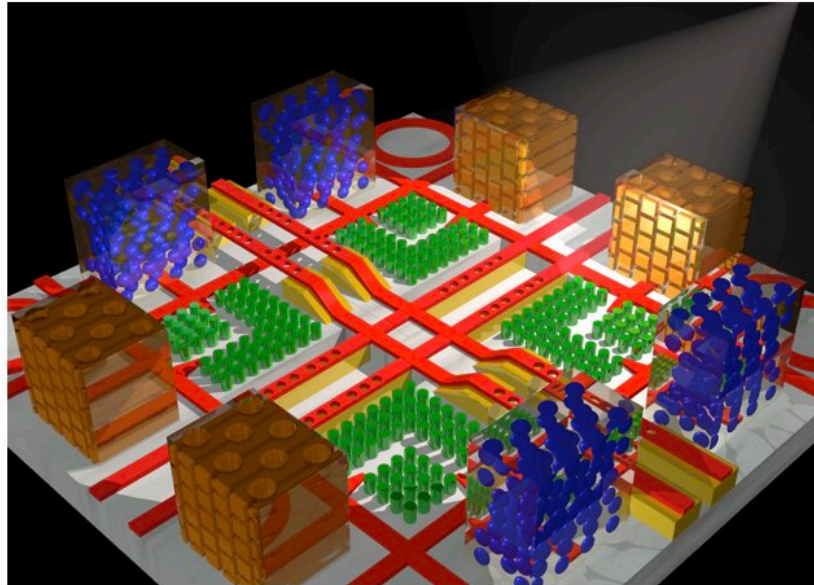
	Metro 6040		Metro 6100		BWS 320G/1600G		Multi-tenant building
	Internet data centre		Bank		Intelligent residential area		Enterprise



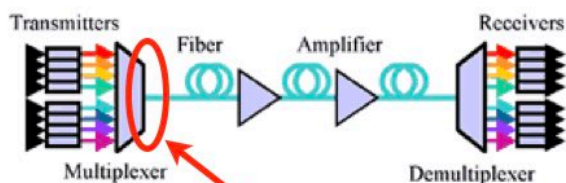
Integrated optics

In this context, photonic crystals generated great expectations

- Dense integration
- Miniaturisation
- Fabrication



Coupling



coupling issues between the outside world (a monomode telecom fibre not polarisation maintaining) and the modes of a nanophotonic device (photonic crystal or nanowire) :

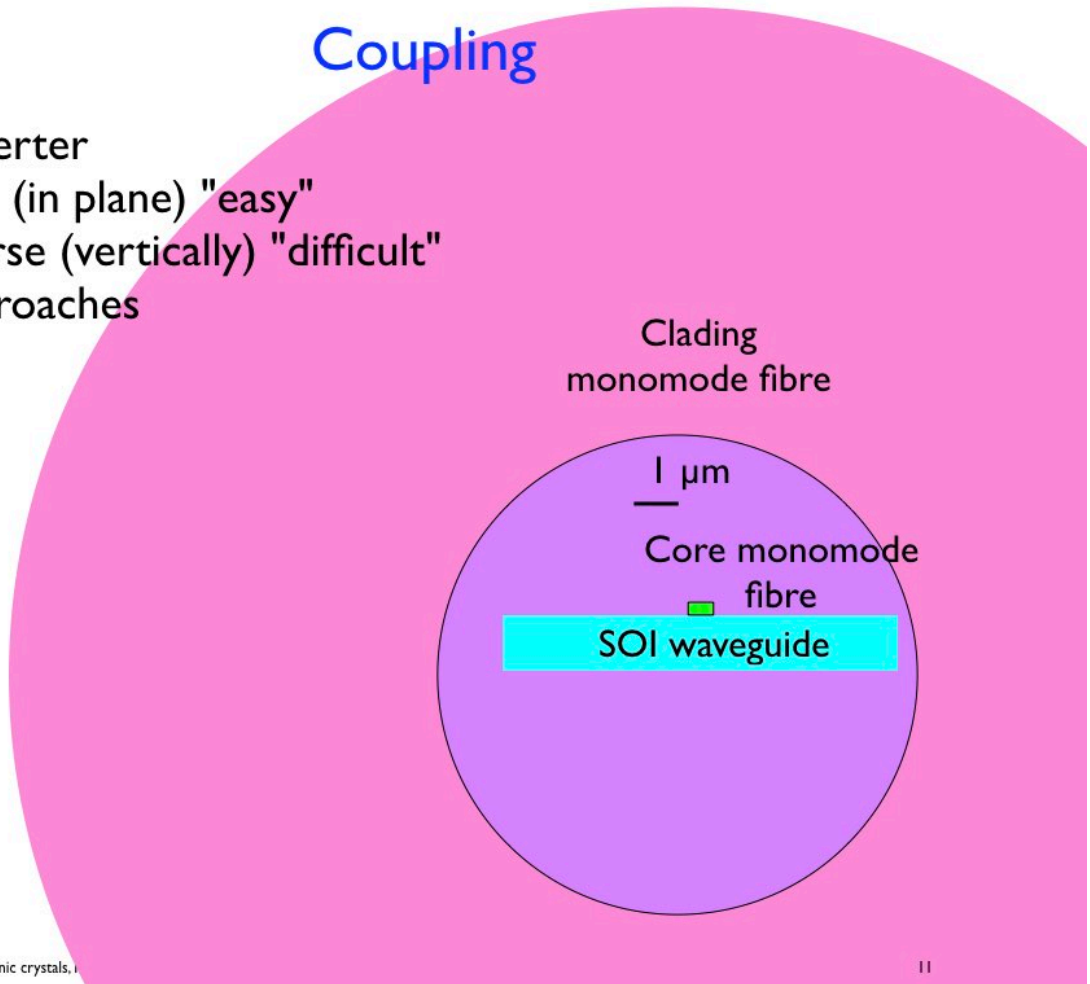
- Much smaller
- Very different optical mode shape
- Different numerical aperture
- Polarisation sensitive

Coupling

Mode converter

- Laterally (in plane) "easy"
- Transverse (vertically) "difficult"

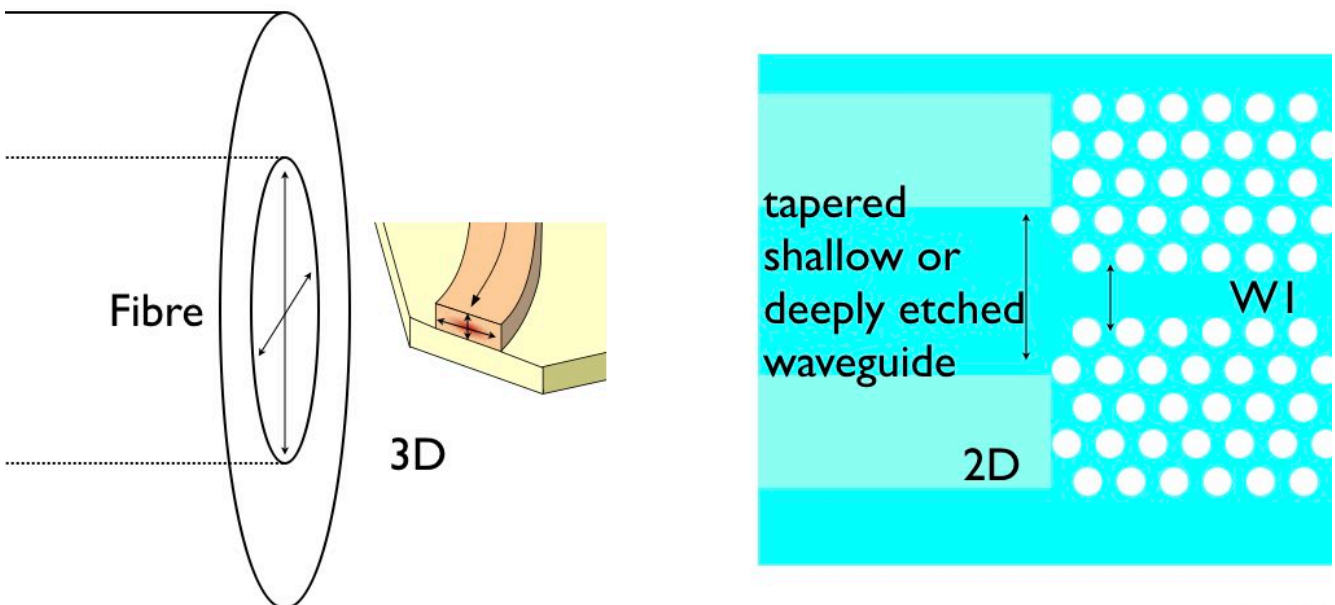
Several approaches



Coupling

Mode converter

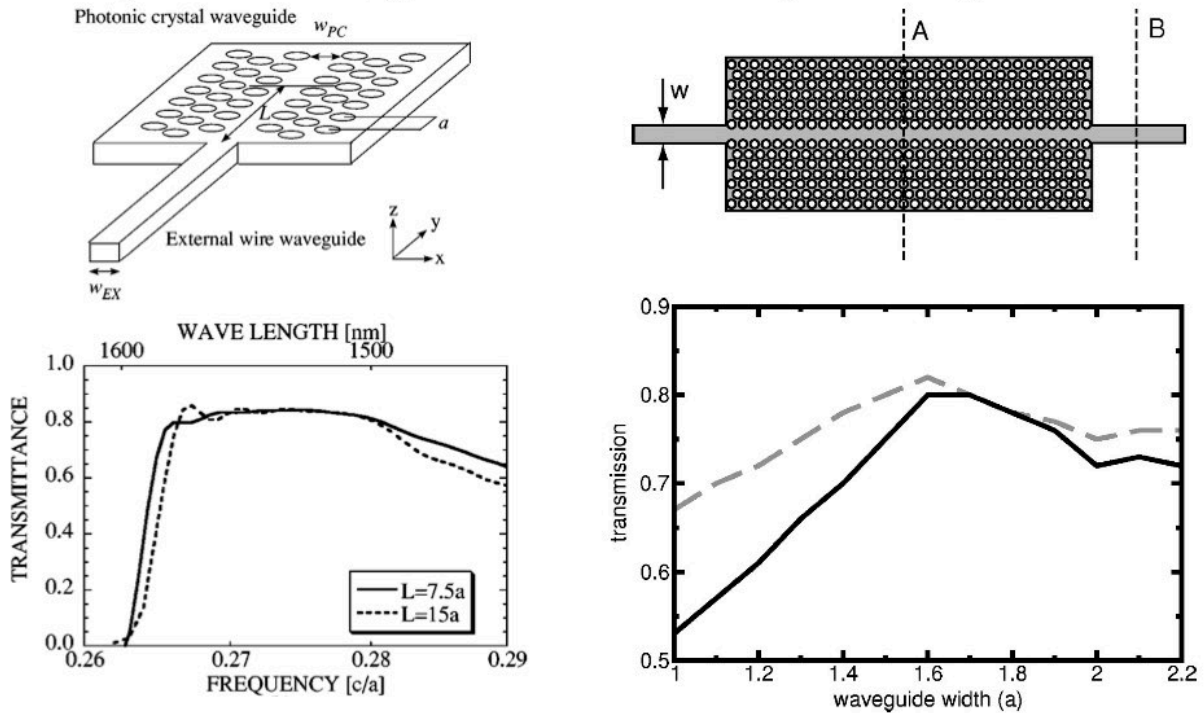
- 1 optical fibre, ridge waveguide, 3D
- 2 ridge waveguide, photonic crystal waveguide, 2D



Coupling

Direct coupling (butt coupling)

Fibre / guide : -30 dB, guide/CPh : 70-80 % (modelling)



E. Miyai et al., Appl. Phys. Lett., 81, 3730 (2002)

N. Moll et al., J. Appl. Phys., 93, 4986 (2003)

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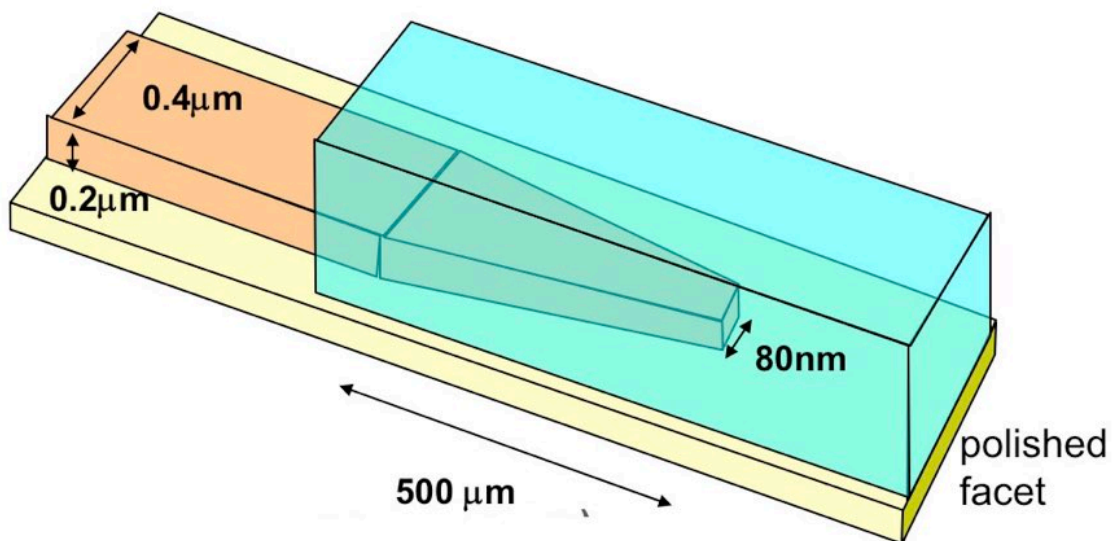
13 / 64



Coupling

Mode converter

3D, adapted solutions from industry and integrated optics



M. Notomi et al., Opt. Exp., 12, 1551 (2004)

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

G. Roelkens et al., Phot. Tech. Lett., 17, 2613 (2005)

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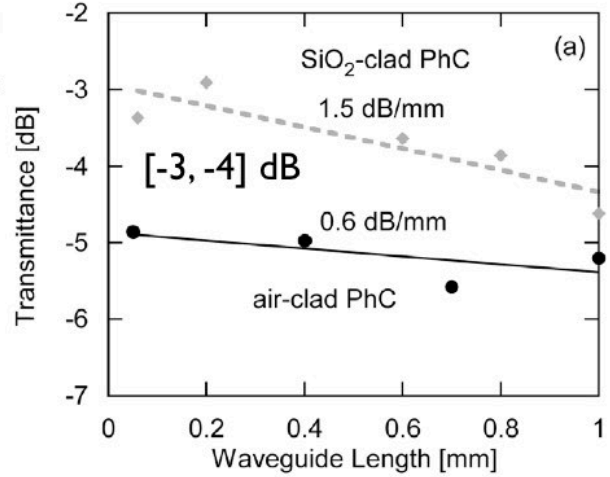
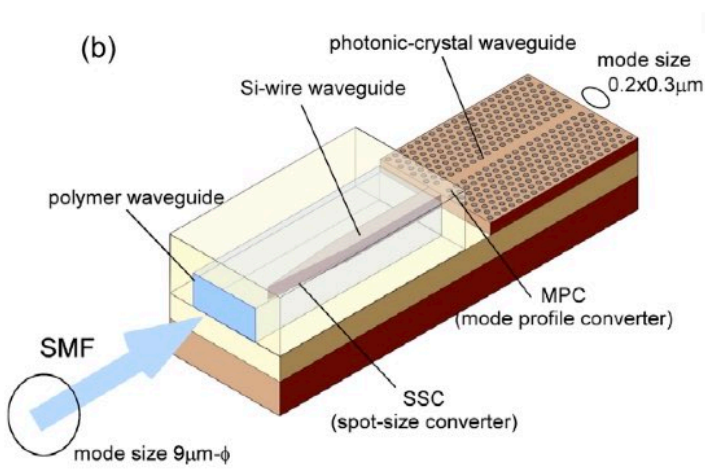
14 / 64



Coupling

Mode converter

3D, adapted solutions from industry and integrated optics



M. Notomi et al., *Opt. Exp.*, 12, 1551 (2004)

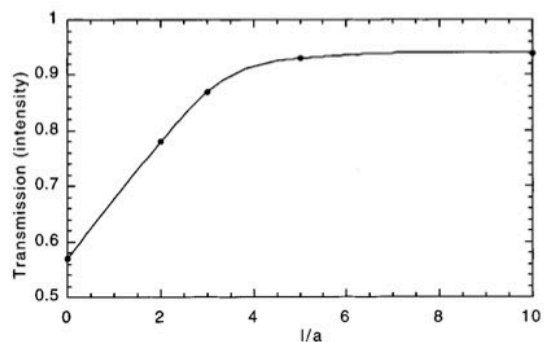
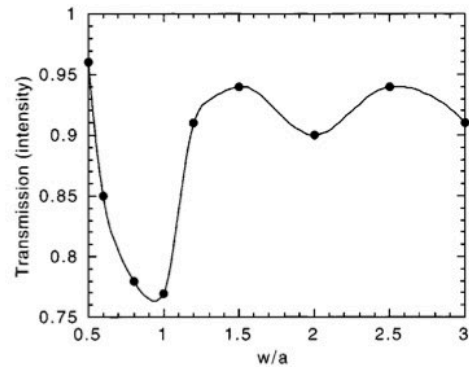
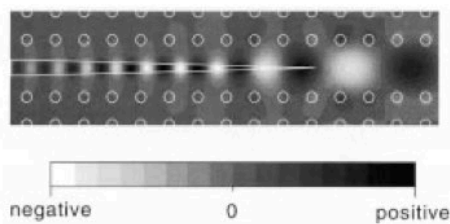
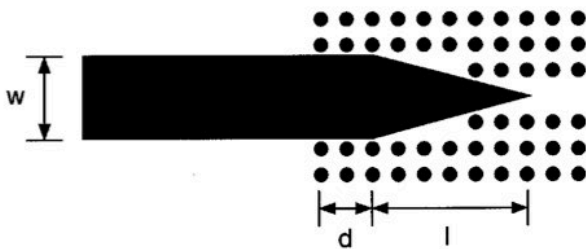
McNab et al., *Opt. Exp.*, 11, 2927 (2003)

G. Roelkens et al., *Phot. Tech. Lett.*, 17, 2613 (2005)

Coupling

Mode converter

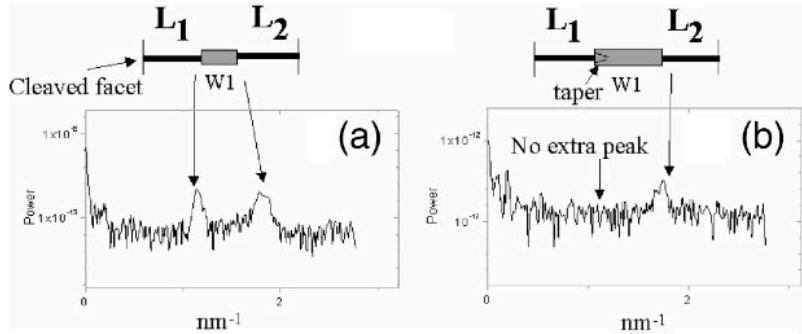
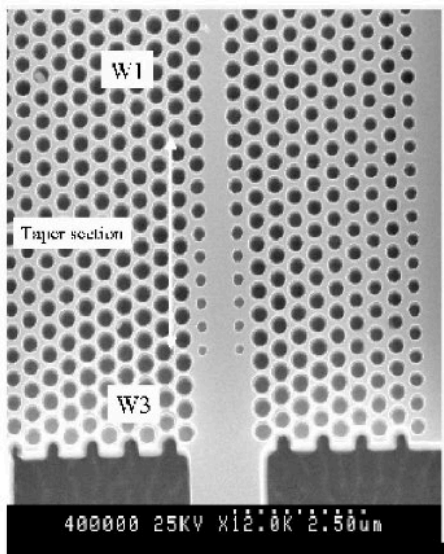
2D, many proposals



A. Mekis et al., *J. Light. Tech.*, 19, 861 (2001)

Coupling

Mode converter
2D, many proposals



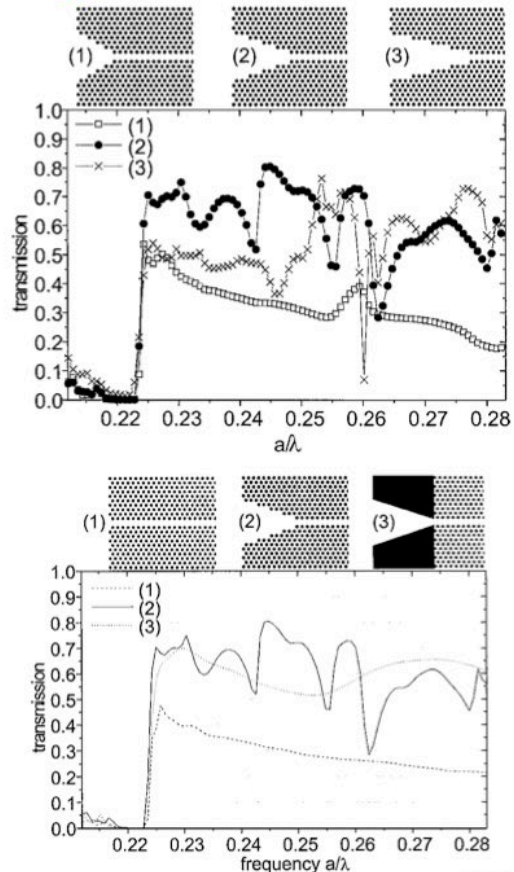
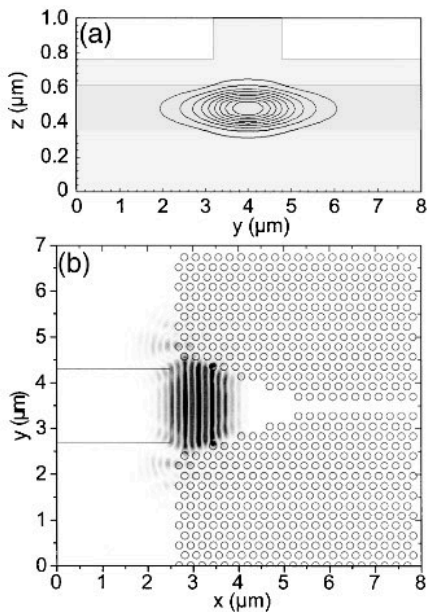
$$R < 1 - 6\%$$

A. Talneau et al., Opt. Lett., 27, 1522 (2002)

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Coupling

Mode converter
2D, many proposals



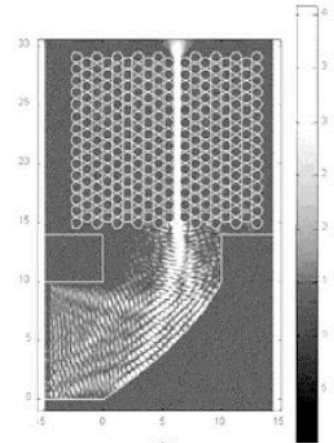
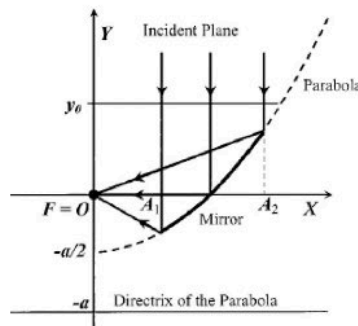
T. Happ et al., Opt. Lett., 26, 1102 (2001)

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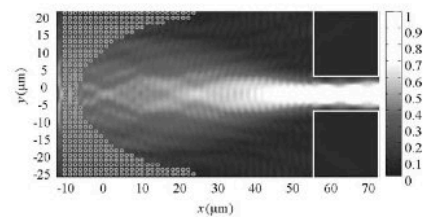
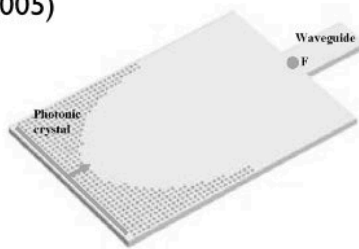
Coupling

Mode converter
2D, many proposals
see for example :

P. Sanchis et al., Opt. Exp., 10, 1391 (2002)
J. Jiang et al., Opt. Lett., 28, 2381 (2003)
W. Kuang et al., Opt. Lett., 27, 1604 (2002)
P.E. Barclay et al., Opt. Lett., 29, 697 (2004)
M.E. Potter et al., Opt. Exp., 10, 691 (2002)
D.W. Prather et al., Opt. Lett., 27, 1601 (2002)
C.C. Lin et al., Opt. Lett., 30, 1330 (2005)



(a) D.W. Prather et al. (b)

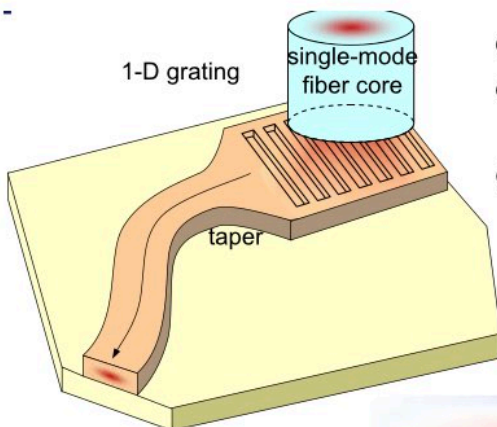


(a) (b)

But few convincing demonstrations

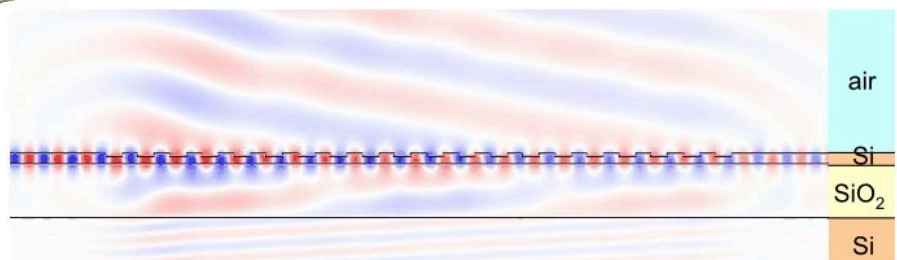
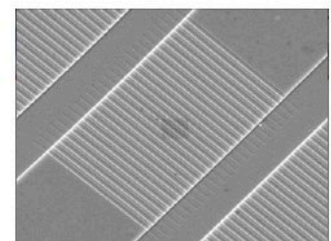
Coupling

1D grating
another approach adapted from industry and integrated optics



coupling $\approx 30\%$ (exp. 2006) - 80% (modelling)
over $\Delta\lambda \approx 100\text{ nm}$ à 1500 nm

Optimisation :
depth of each slit
back reflector

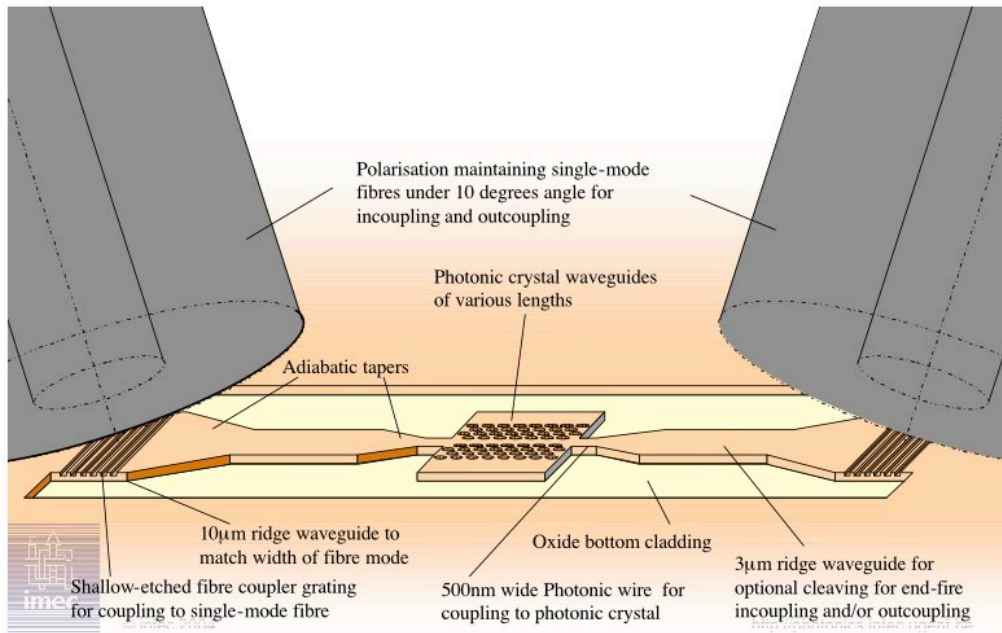


D. Taillaert et al., J. Quant. Elect., 38, 949 (2002) and photonics.intec.ugent.be

Coupling

ID grating

another approach adapted from industry and integrated optics



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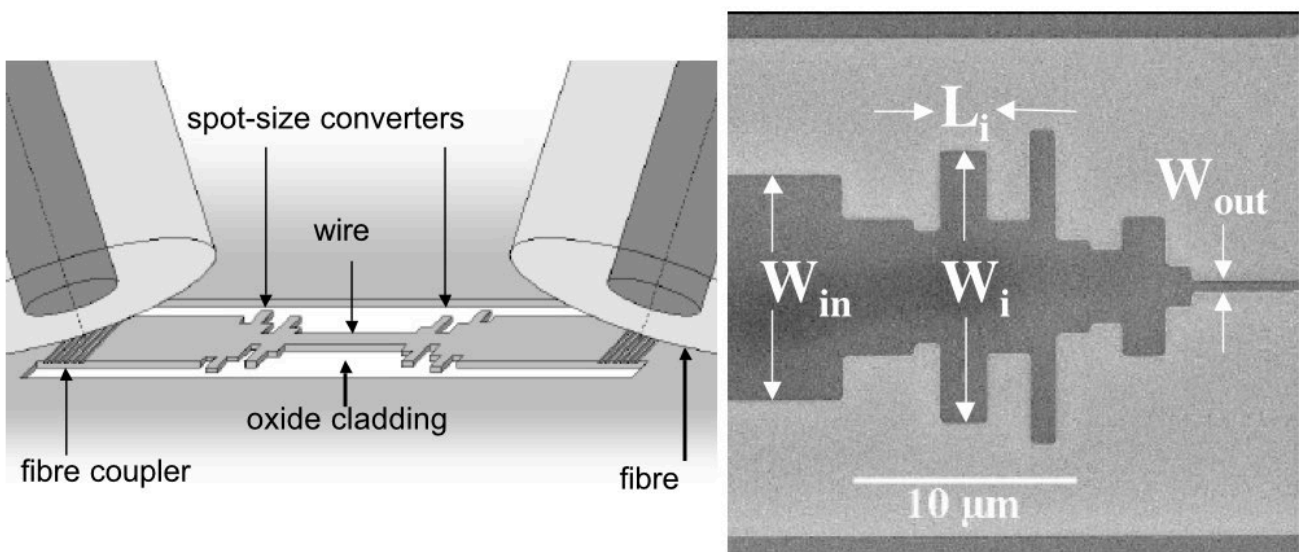
21 / 64



Coupling

ID grating

another approach adapted from industry and integrated optics



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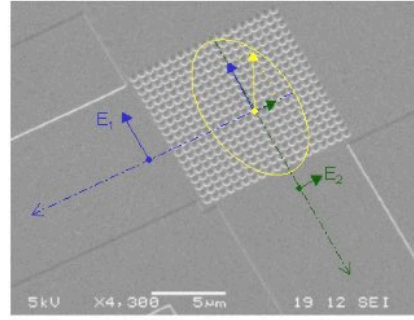
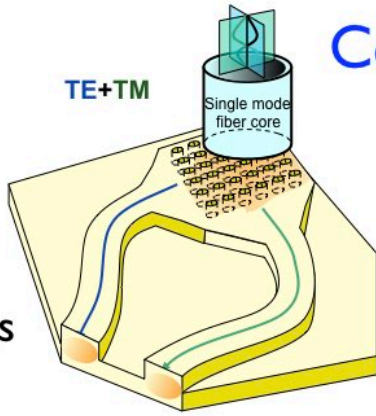
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22 / 64

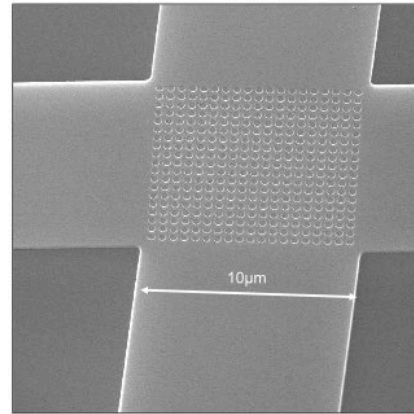
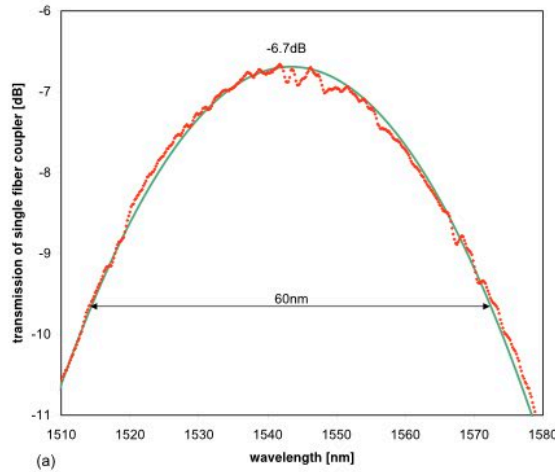


Coupling

2D gratings



$T = 20\%$



W. Bogaerts et al., *Opt. Exp.*, 15, 1567 (2007) and photonics.intec.ugent.be

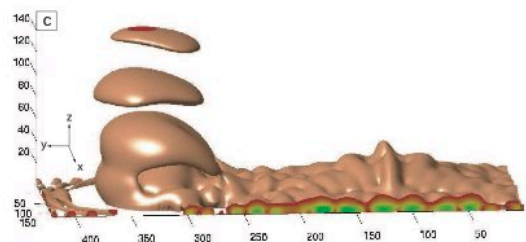
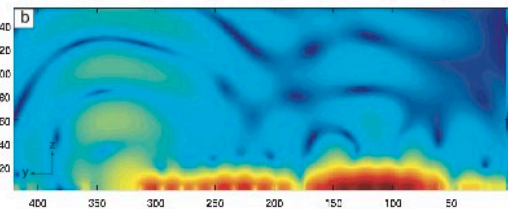
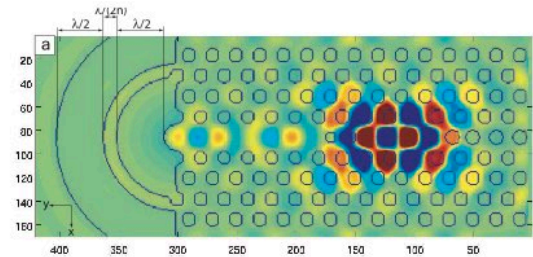
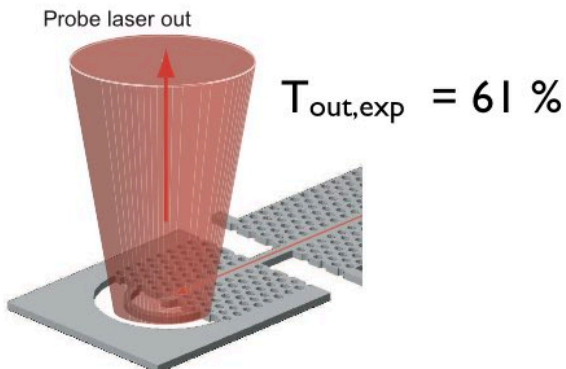
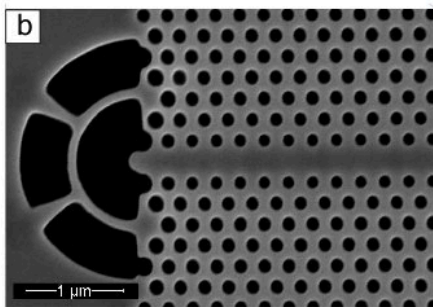
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23 / 64



Coupling

Other grating design - I



A. Faraon et al., *Opt. Exp.*, 16, 12154 (2008)

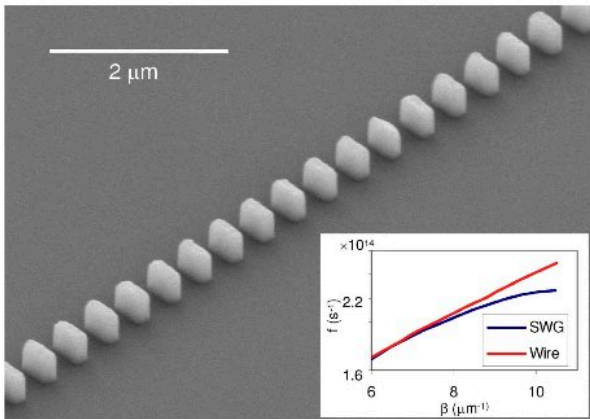
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24 / 64

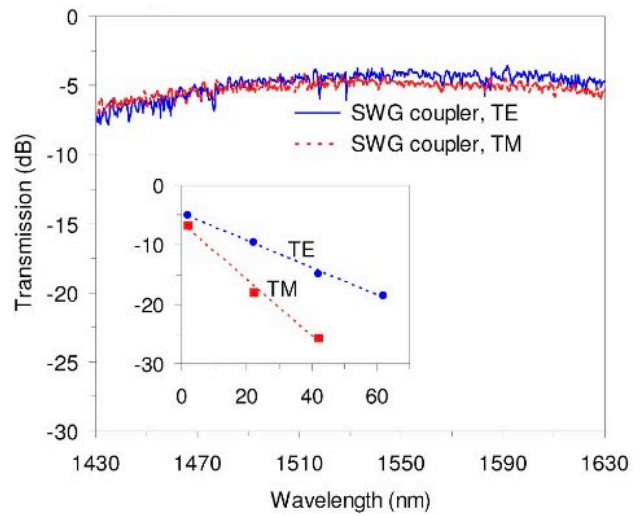
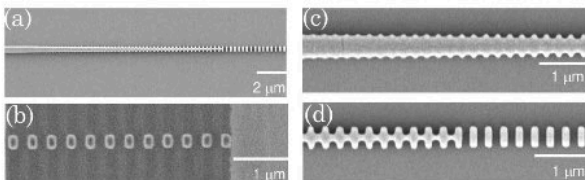


Coupling

A recent successful approach: Subwavelength grating waveguides



+ SU-8 or SiO₂ encapsulation



Coupling losses < -0.9 dB

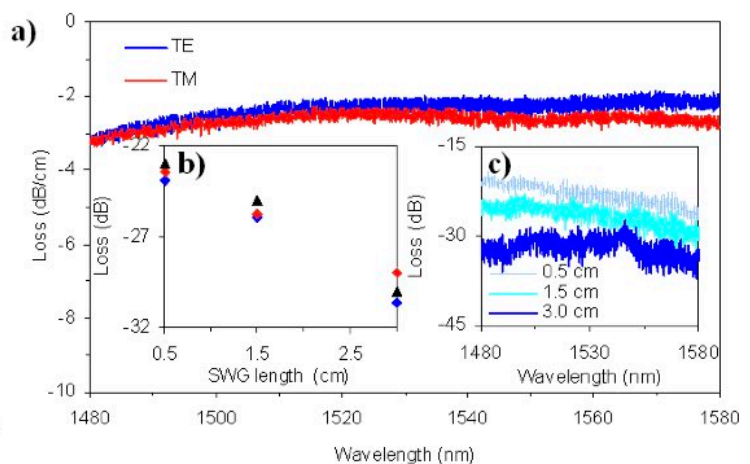
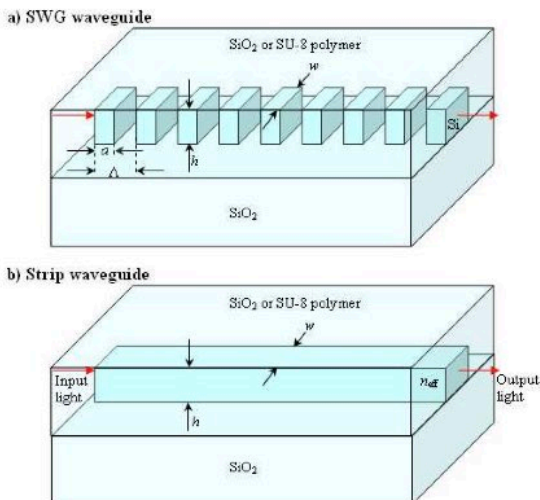
P. Cheben et al., *Opt. Lett.*, 35, 2526 (2010)

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Coupling

Note: the same approach is used for

Waveguiding



Propagation losses \approx -2.1 dB/cm

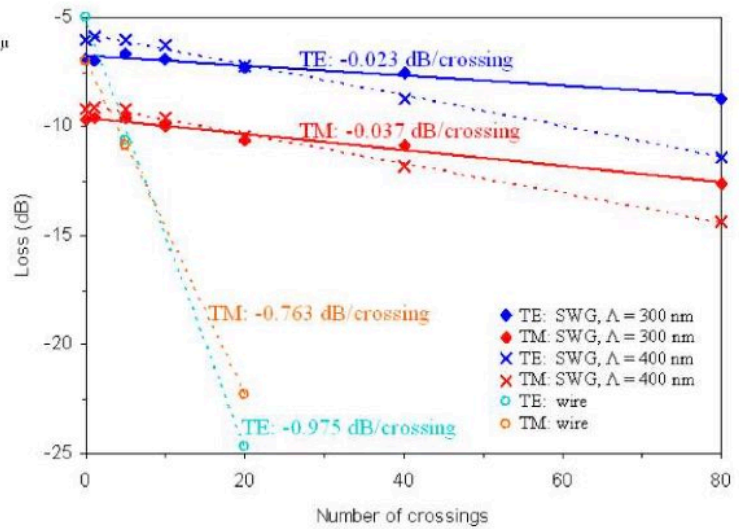
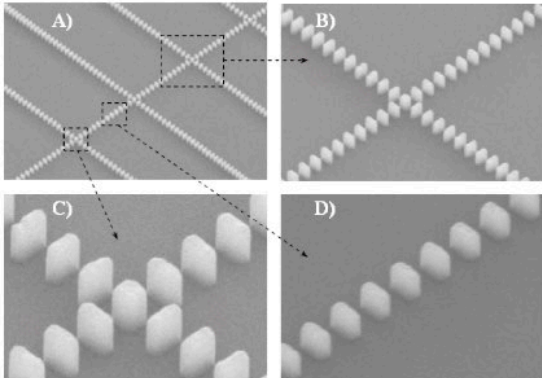
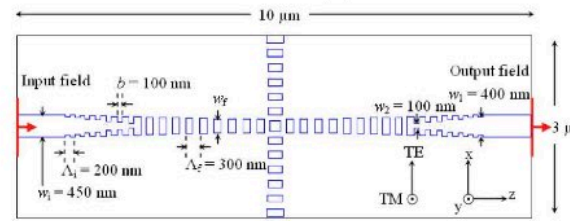
P. Bock et al., *Opt. Exp.*, 18, 20251 (2010)

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Coupling

Note: the same approach is used for

Waveguides crossing



Crossing losses ≈ -0.023 dB
Crosstalk < -40 dB

P. Bock et al., Opt. Exp., 18, 16146 (2010)

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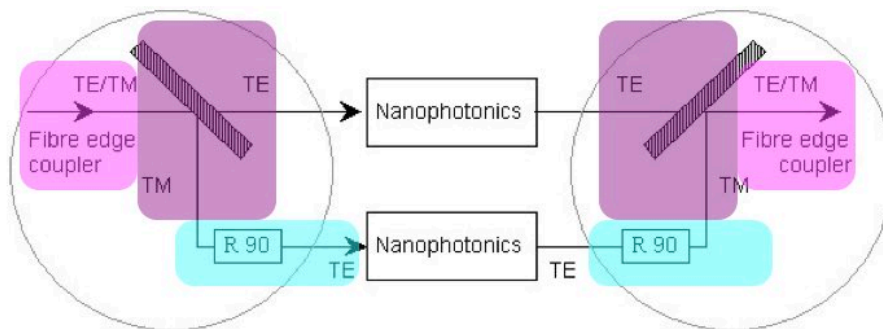
27 / 64



Coupling

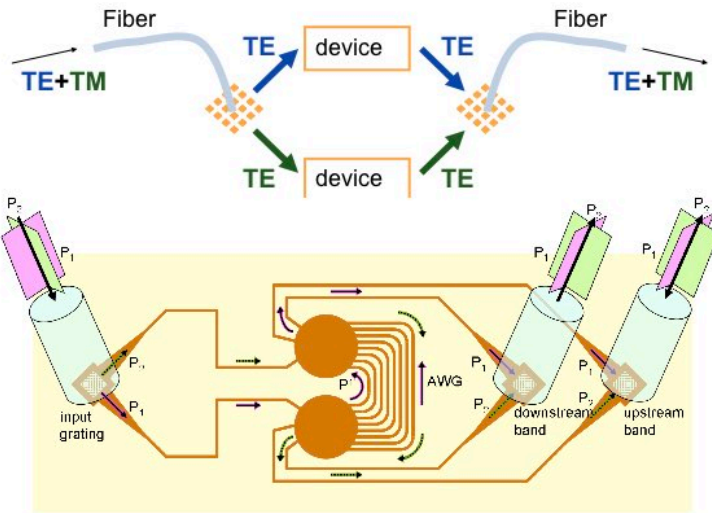
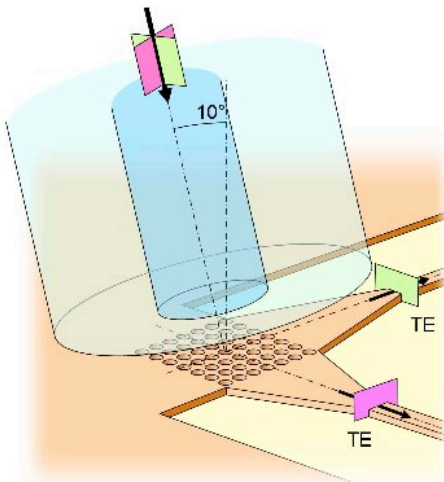
Polarisation diversity :

- Each signal delivered by the input optical fibre has a different polarisation state
- This polarisation state may even change with time
- Nanophotonic devices (photonic crystal included) are all polarisation sensitive)



Coupling

Polarisation diversity



Insertion losses [-6dB -2dB]

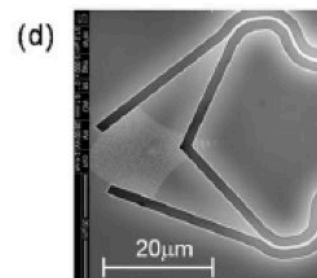
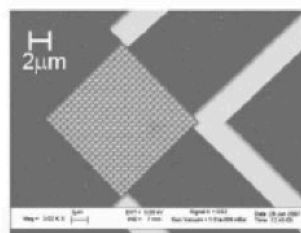
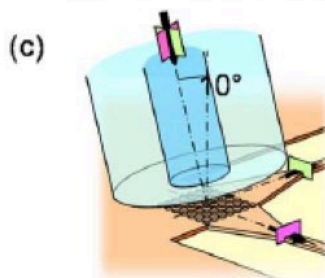
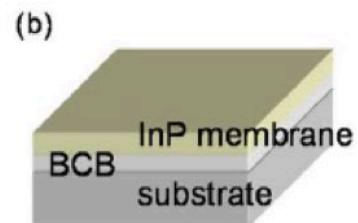
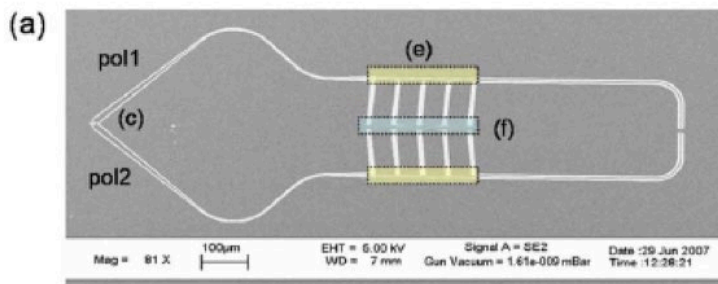


W. Bogaerts et al., *Opt. Exp.*, 15, 1567 (2007) and photonics.intec.ugent.be
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Coupling

Polarisation diversity

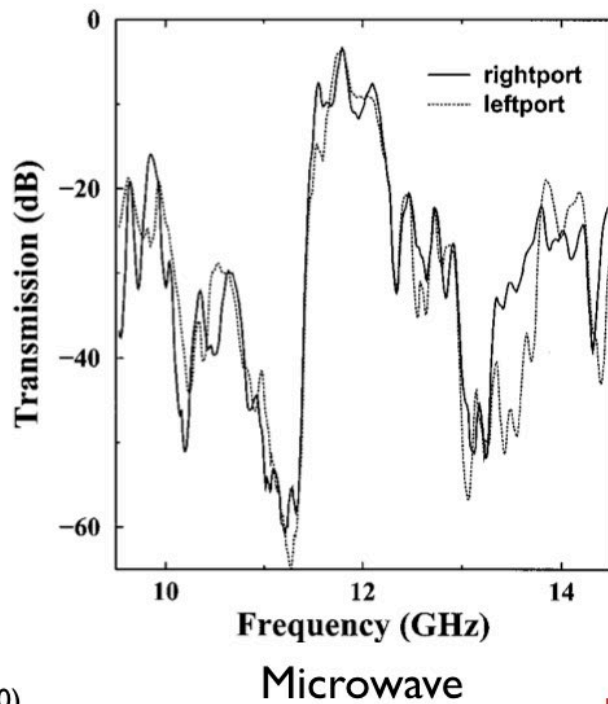
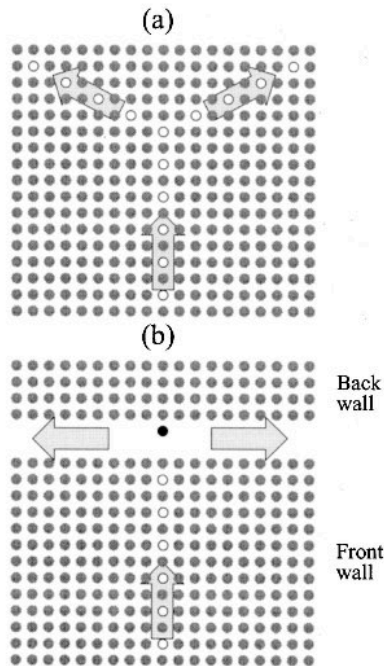
Integrated with demultiplexer and photodetector



F. Van Laere et al., *J. Light. Tech.* 27, 417 (2009)

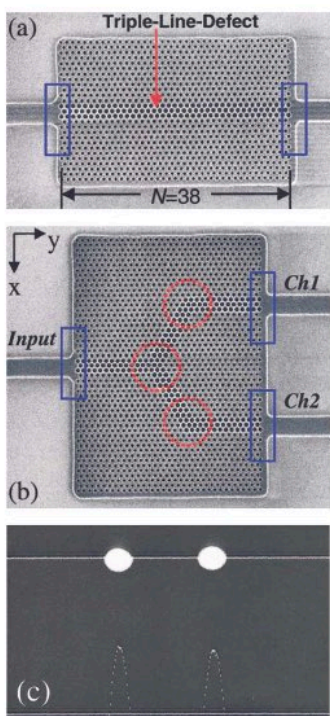
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Passive devices : Divider & Couplers

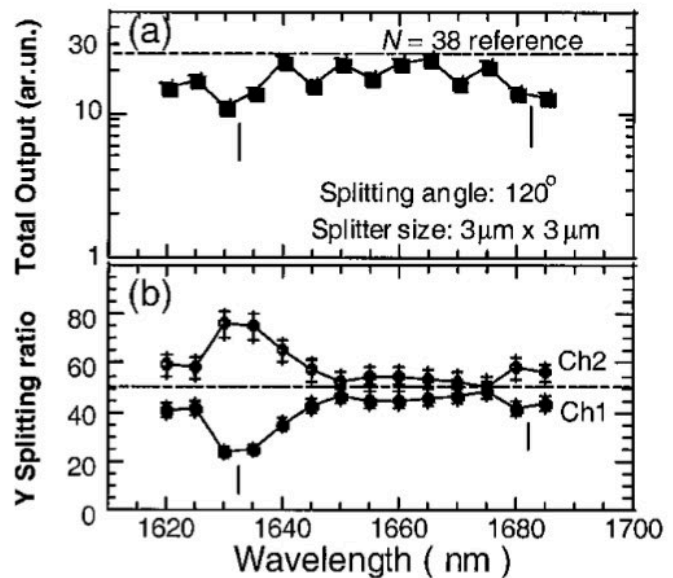


M. Bayindir et al., Appl. Phys. Lett., 77, 3902 (2000)
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Passive devices : Divider & Couplers

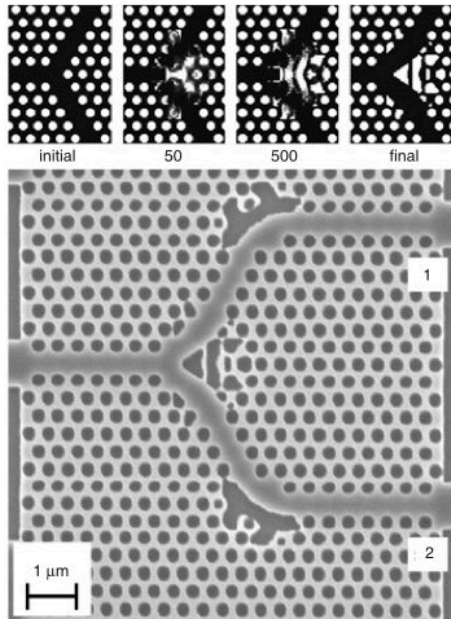


membrane GaAs
0.5-1 dB losses
1640-1680 nm

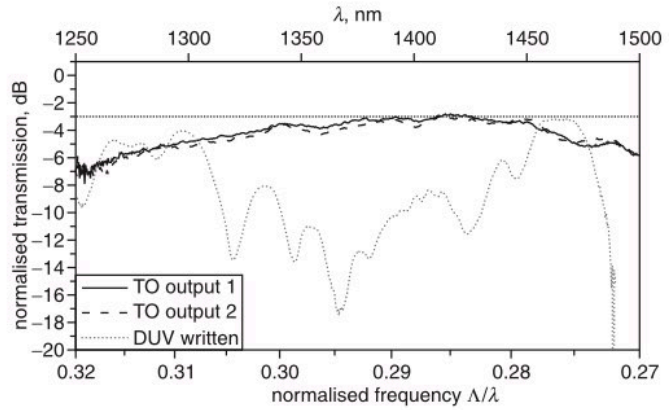


M. Bayindir et al., Appl. Phys. Lett., 77, 3902 (2000)
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Passive devices : Divider & Couplers



Same type of issues in bends



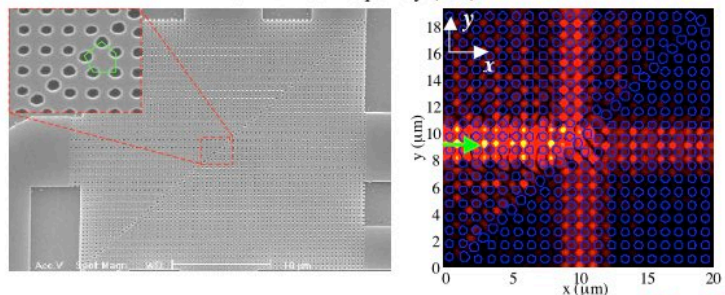
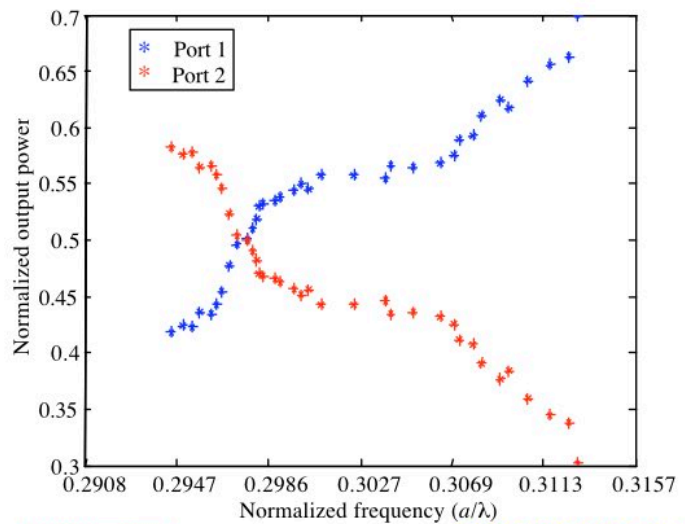
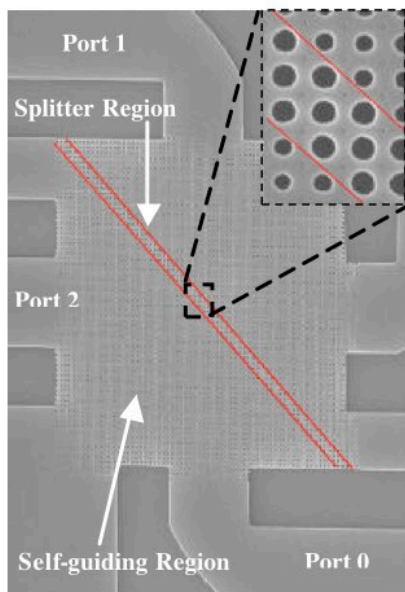
P.I. Borel et al., *El. Lett.*, 41, 69 (2005)
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Also : M. Ayre et al., *IEEE J. Sel. Areas. Comm.*, 23, 1390 (2005)



Passive devices : Divider & Couplers

Selfcollimation
2 et 3 ports

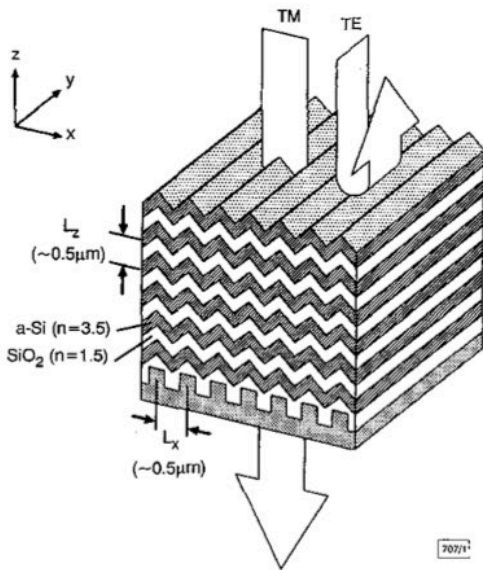


D.M. Pustai et al., *Opt. Exp.*, 12, 1823 (2004)

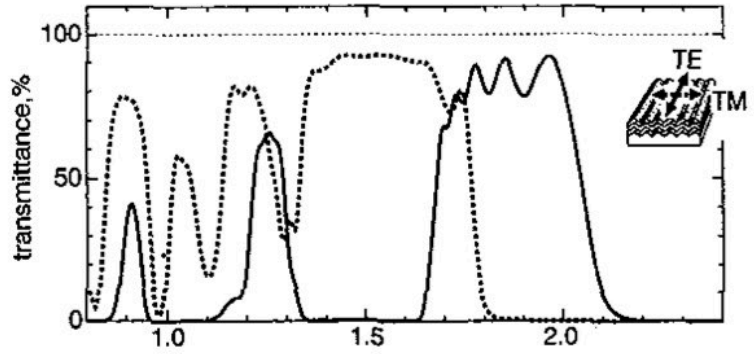
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017



Passive devices : Polarisation splitter



A rare example of a device using 3D photonic crystals

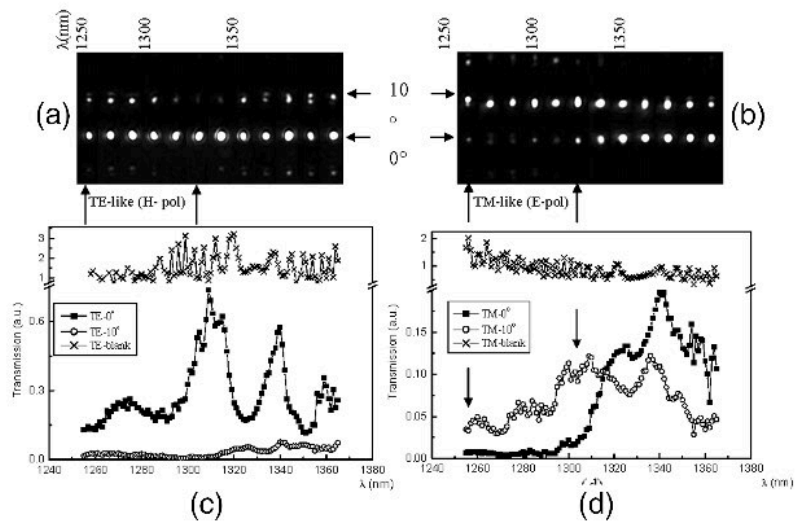
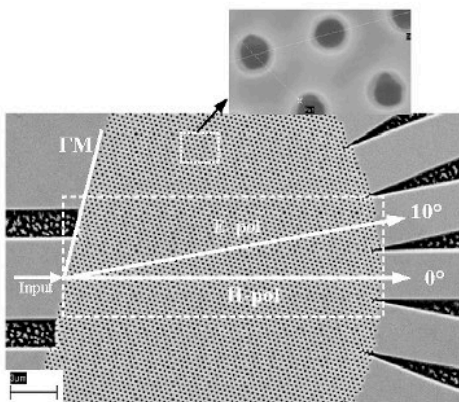


Y. Ohtera et al., *El. Lett.*, 35, 1271 (1999)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Polarisation splitter

Selfcollimation



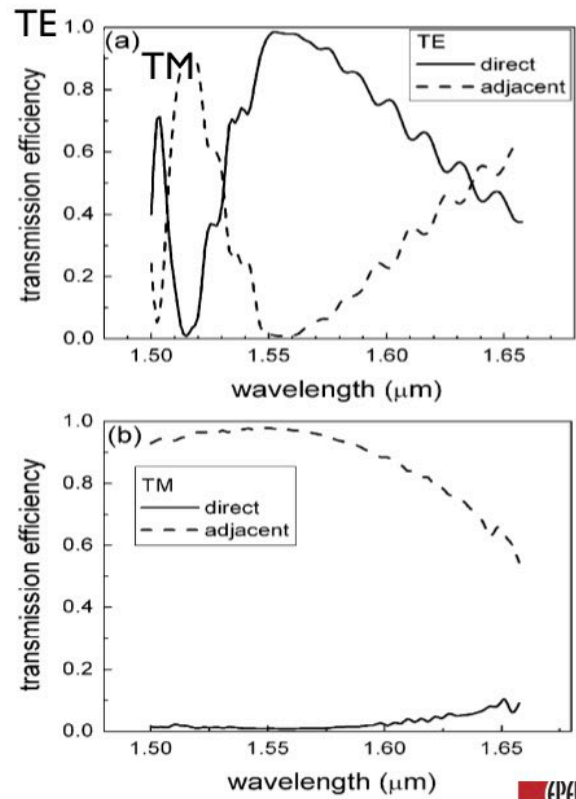
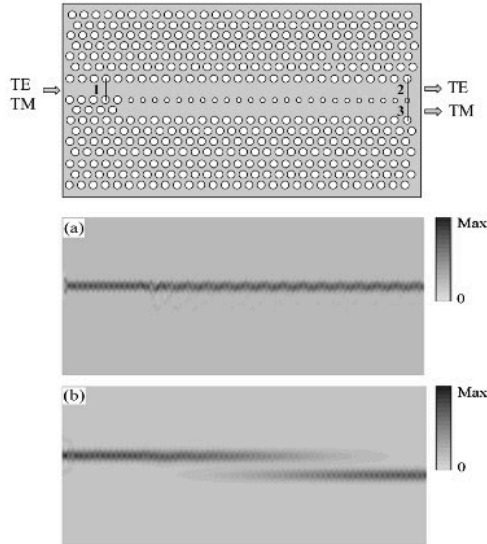
No quantitative data

L. Wu et al., *Opt. Lett.*, 29, 1620 (2004)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Polarisation splitter

Codirectional coupler
Modelling only



T. Liu et al., Phot. Tech. Lett., 17, 1435 (2005)

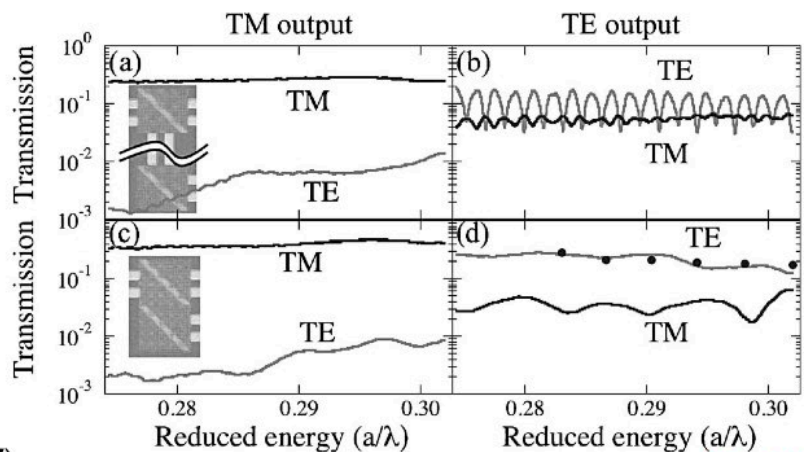
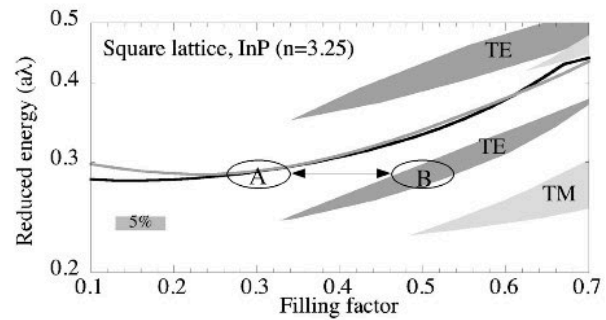
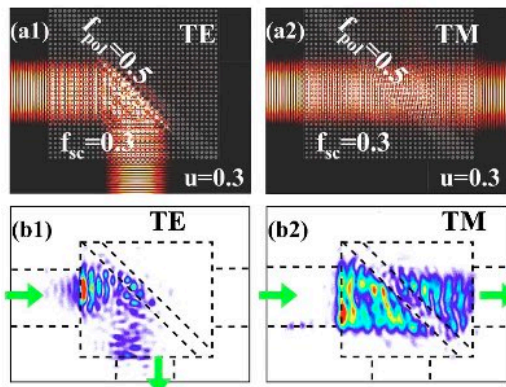
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37 / 64



Passive devices : Polarisation splitter

Selfcollimation
T = 30-35 %
Rejection 0.2-4 %



V. Zabelin et al., Opt. Lett., 32, 530 (2007)

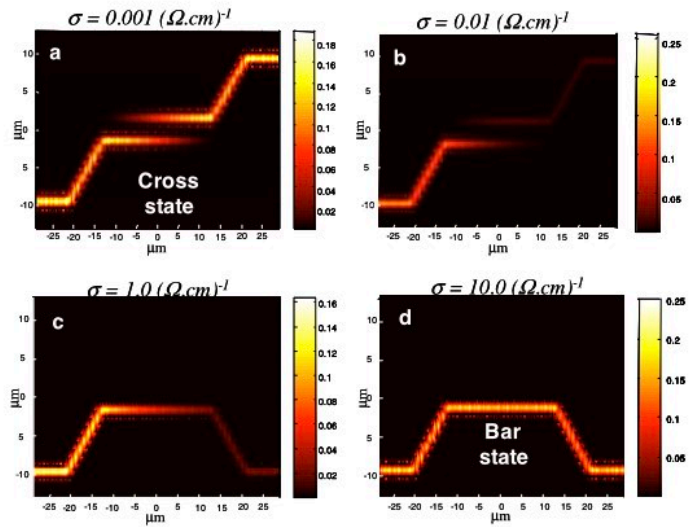
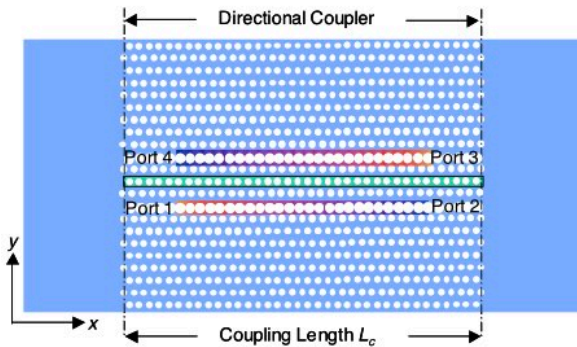
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38 / 64



Passive devices : Modulator & Router

Modulation of the conductivity by free carriers injection
Modelling only

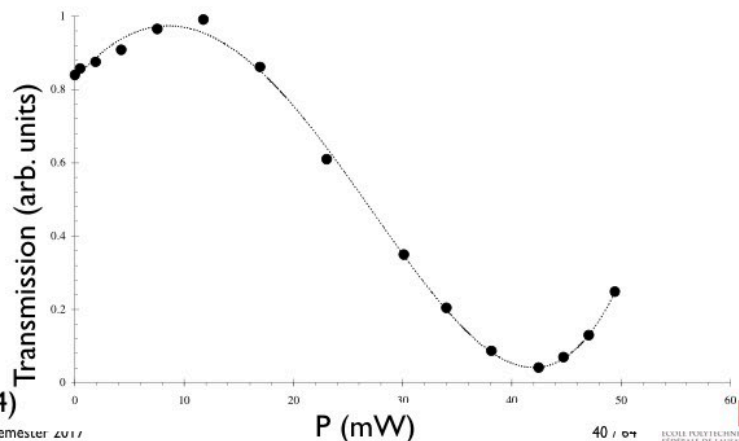
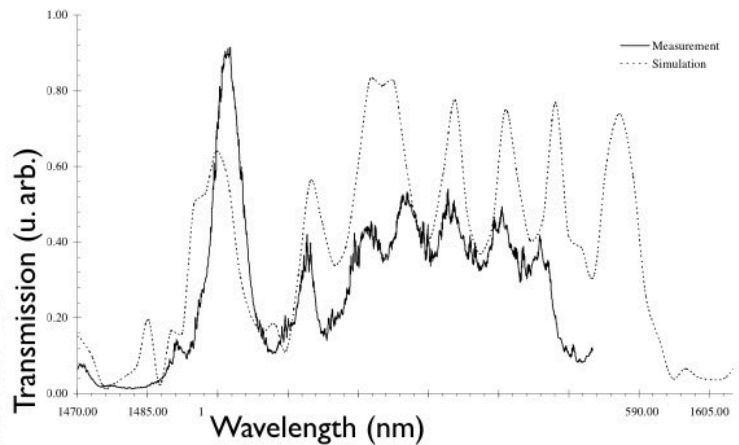
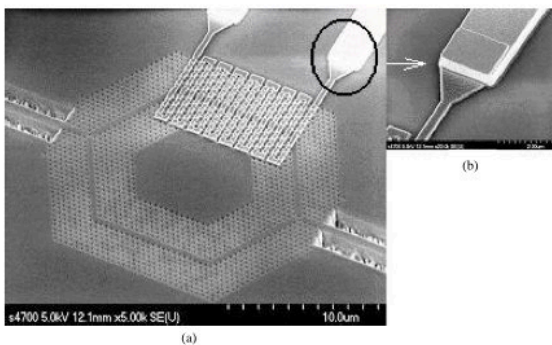


A. Sharkawi et al., Opt. Exp., 10, 1048 (2002)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Modulator & Router

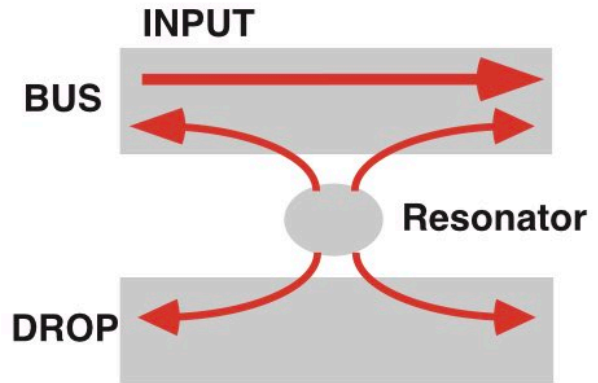
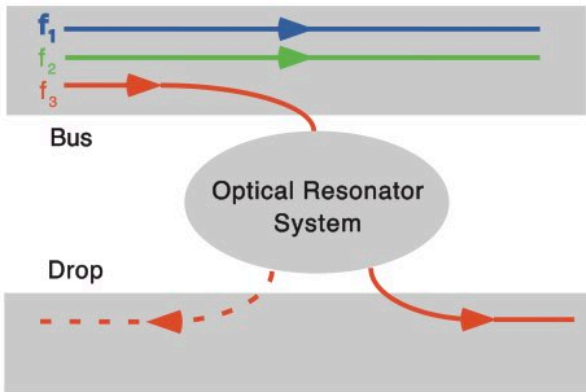
Thermo-optics effects
No quantitative data



E.A. Camargo et al., Opt. Exp., 12, 588 (2004)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Add-drop filter



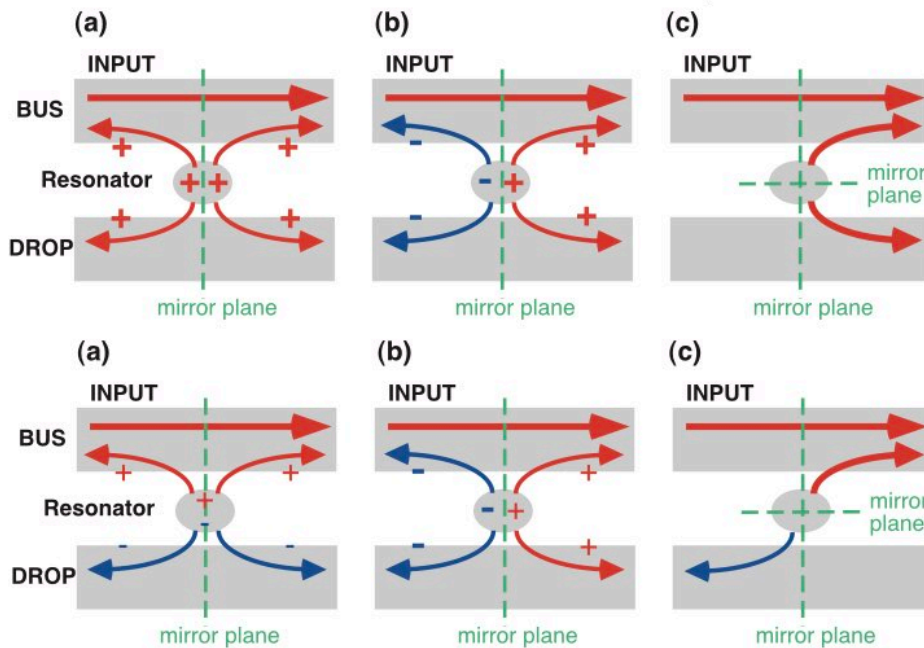
I cavity mode

S. Fan et al., Opt. Exp., 3, 4 (1998)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Add-drop filter

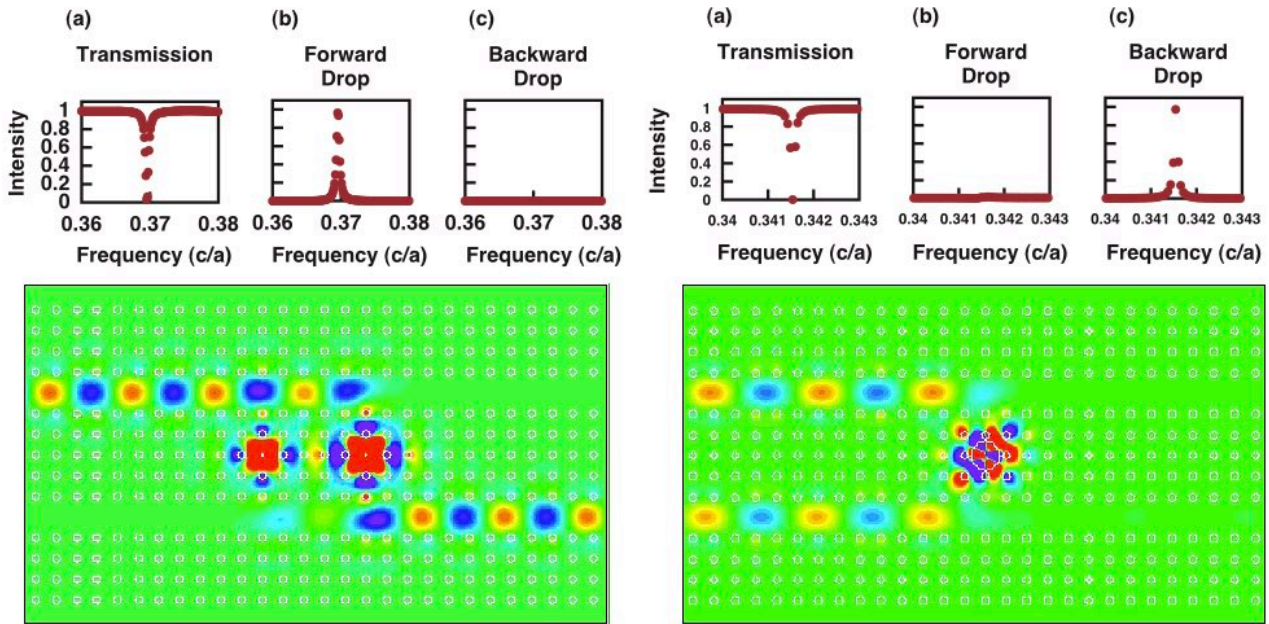
2 degenerated modes are needed to achieve directivity



S. Fan et al., Opt. Exp., 3, 4 (1998)

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Passive devices : Add-drop filter



+ long literature

All these structures are very sensitive to fabrication fluctuations

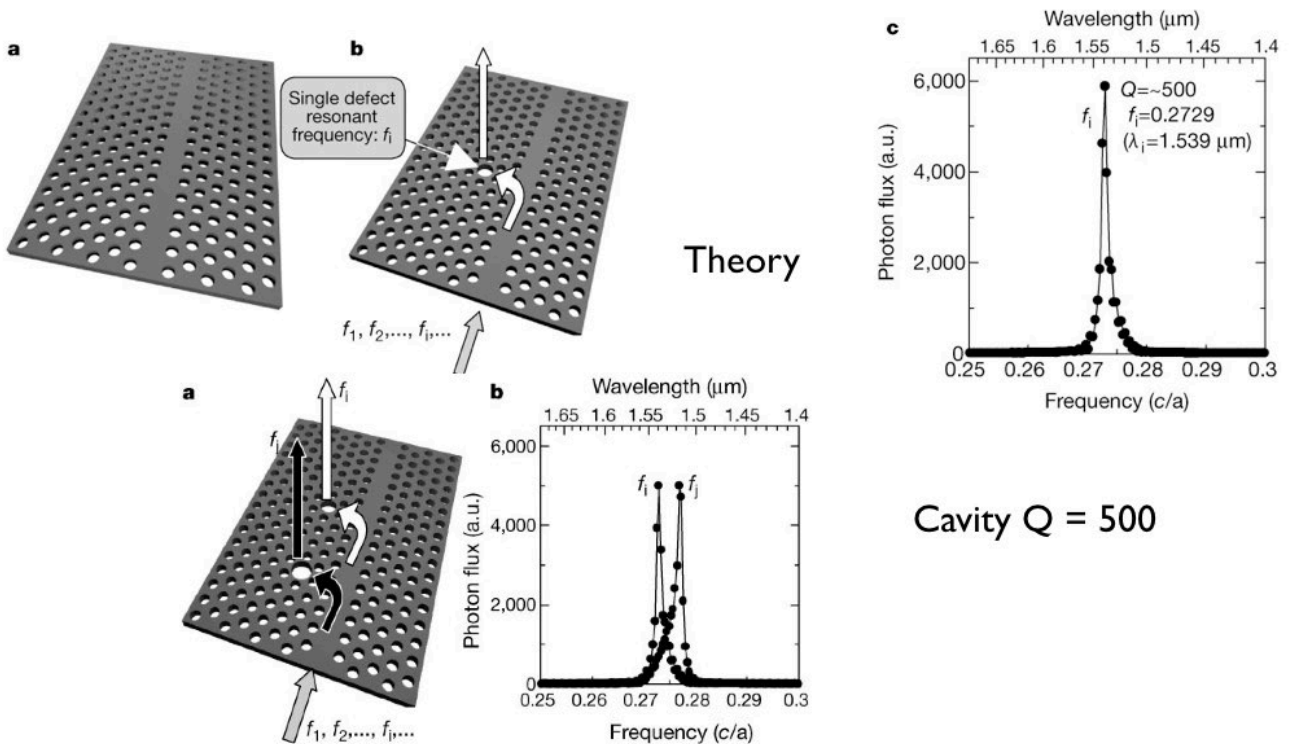
S. Fan et al., Opt. Exp., 3, 4 (1998)

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43 / 64



Passive devices : Spectrometer & Demultiplexer



Cavity $Q = 500$

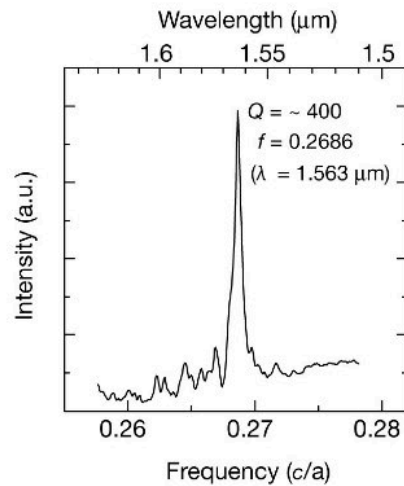
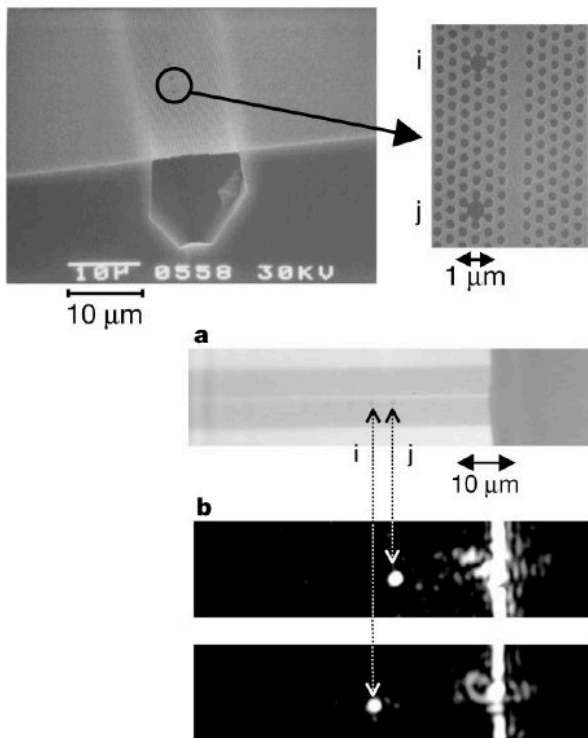
S. Noda et al., Nature, 407, 608 (2000)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

44 / 64



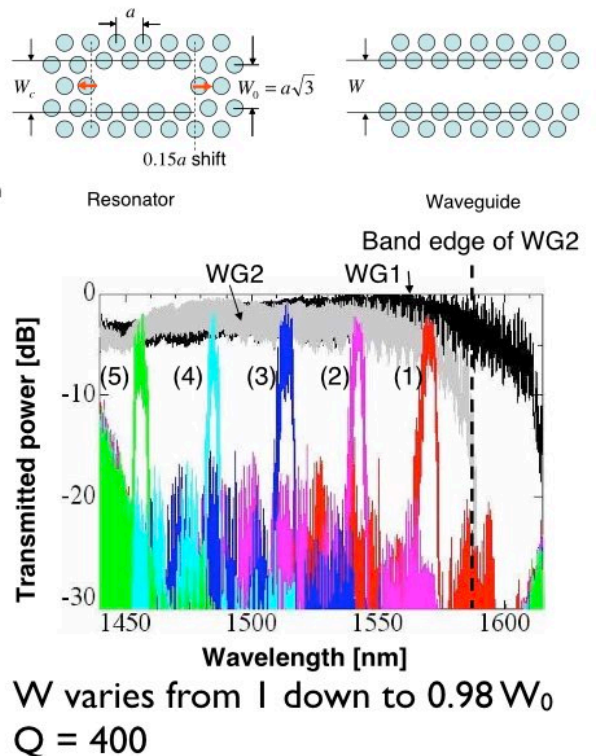
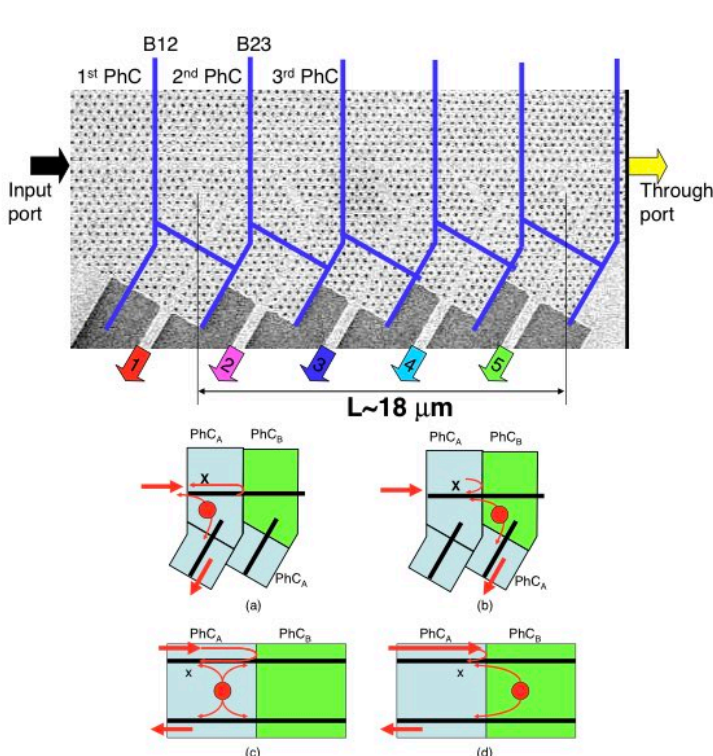
Passive devices : Spectrometer & Demultiplexer



Experimental
 $\Delta a = \text{a few nm !}$
 $Q = 400$

S. Noda et al., Nature, 407, 608 (2000)
 Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Spectrometer & Demultiplexer

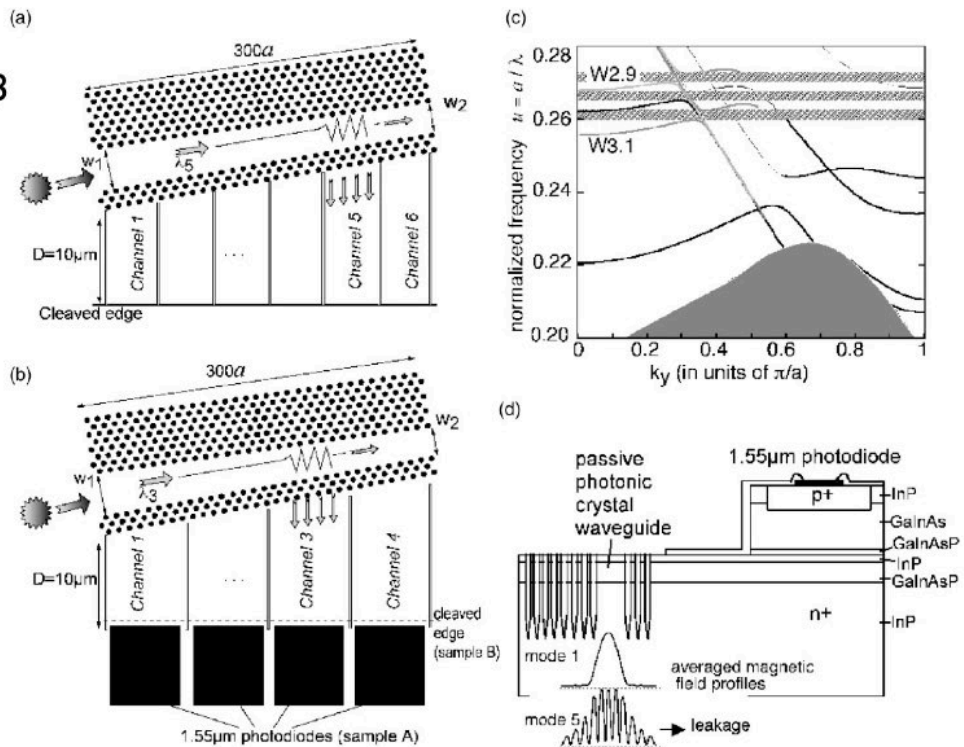


A. Shinya et al., Opt. Exp., 14, 12394 (2006)
 Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

see also A. Shinya et al., Opt. Exp., 13, 4202 (2005)
 46 / 64 EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Passive devices : Spectrometer & Demultiplexer

"Sieve"
Miniband W3



E. Viasnoff-Schwoob et al., Appl. Phys. Lett., 86, 101107 (2005)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

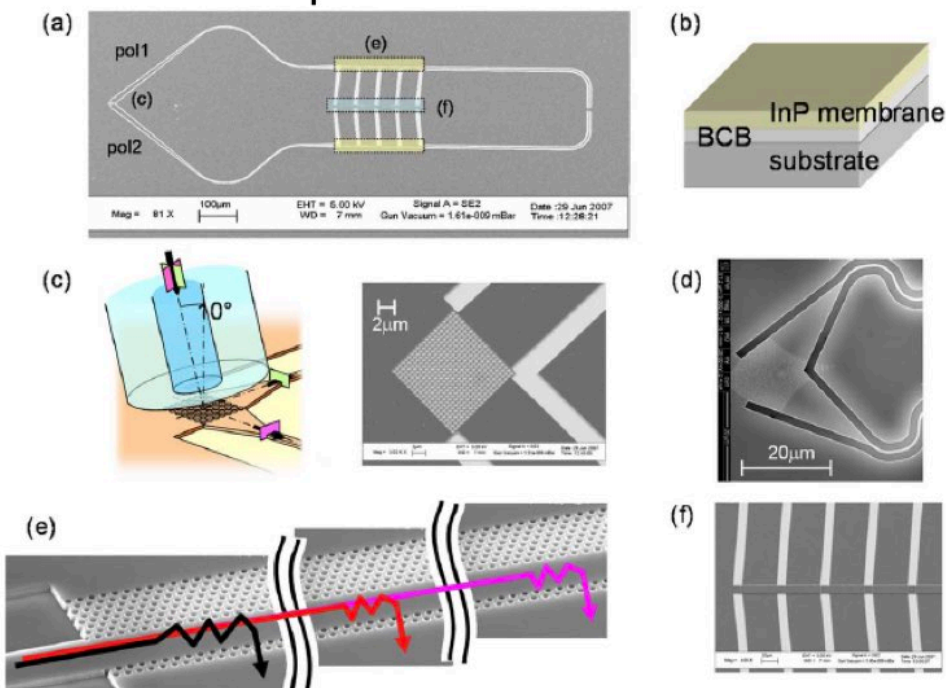
47 / 64



Passive devices : Spectrometer & Demultiplexer

Polarization diversity

Integrated with a demultiplexer and a detector



F. Van Laere et al., J. Light. Tech. 27, 417 (2009)

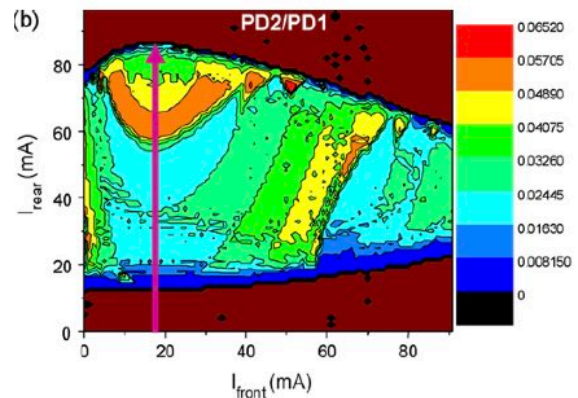
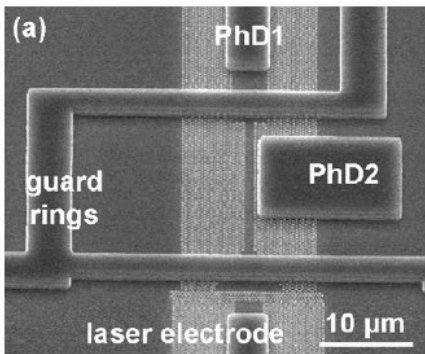
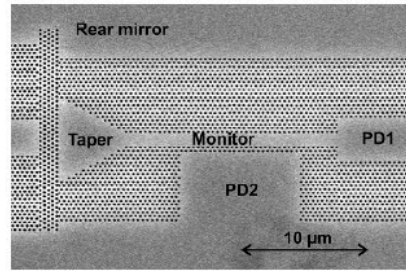
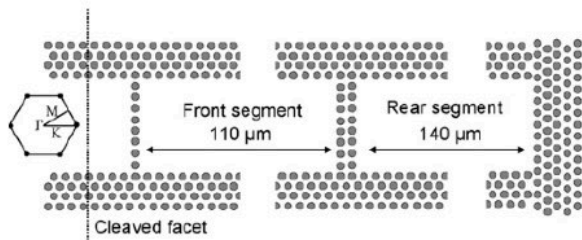
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48 / 64



Passive devices : Spectrometer & Demultiplexer

Integration with a tuneable laser and wavelength monitoring

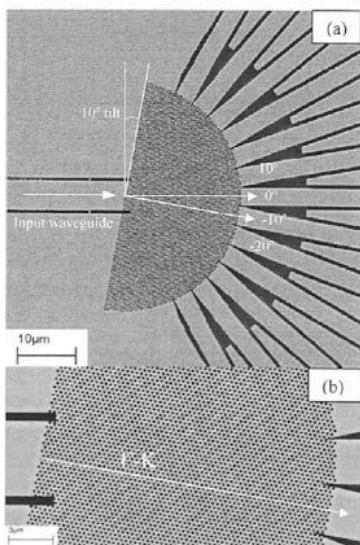


H. Hofmann et al., Photon. Nanostruct. Fundam. Appl. 6, 205 (2008)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Passive devices : Superprism

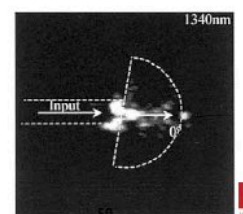
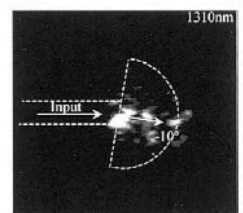
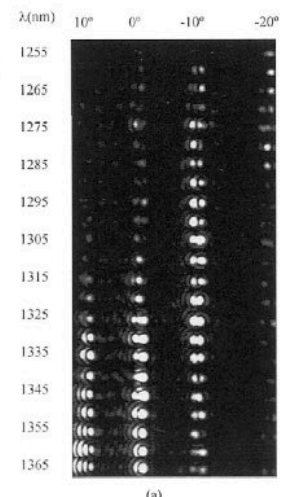
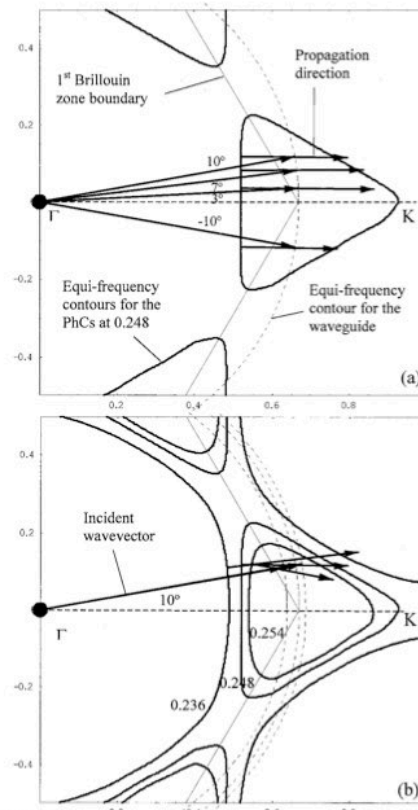
M. Notomi, Phys. Rev. B, 62, 10696 (2000)



Superprism + selfcollimation
 $\Delta\theta = 20^\circ$ over $\Delta\lambda = 25$ nm
at 1300 nm

L. Wu et al., J. Light. Tech., 83, 5121 (2003)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

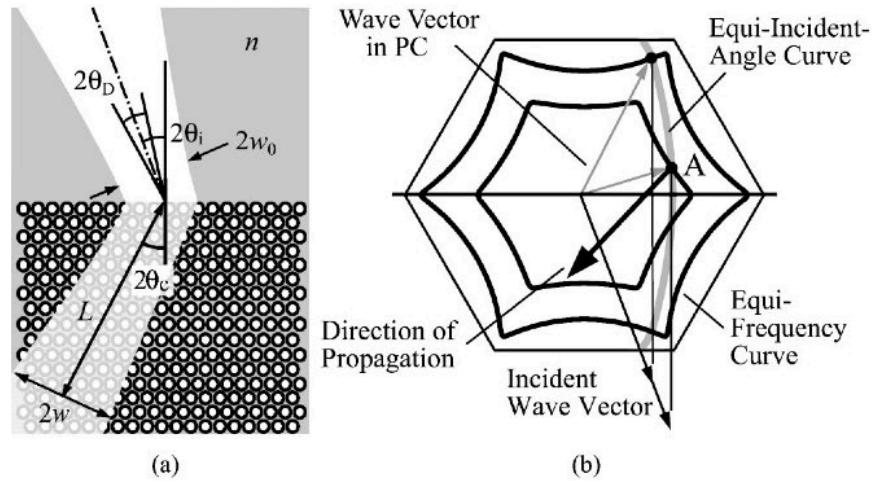


Passive devices : Superprism

When considering also the optical extend of the beam (size and divergence)

Resolution is strongly limited by the device size

$$Q = 3700, L = 100 \mu\text{m}$$

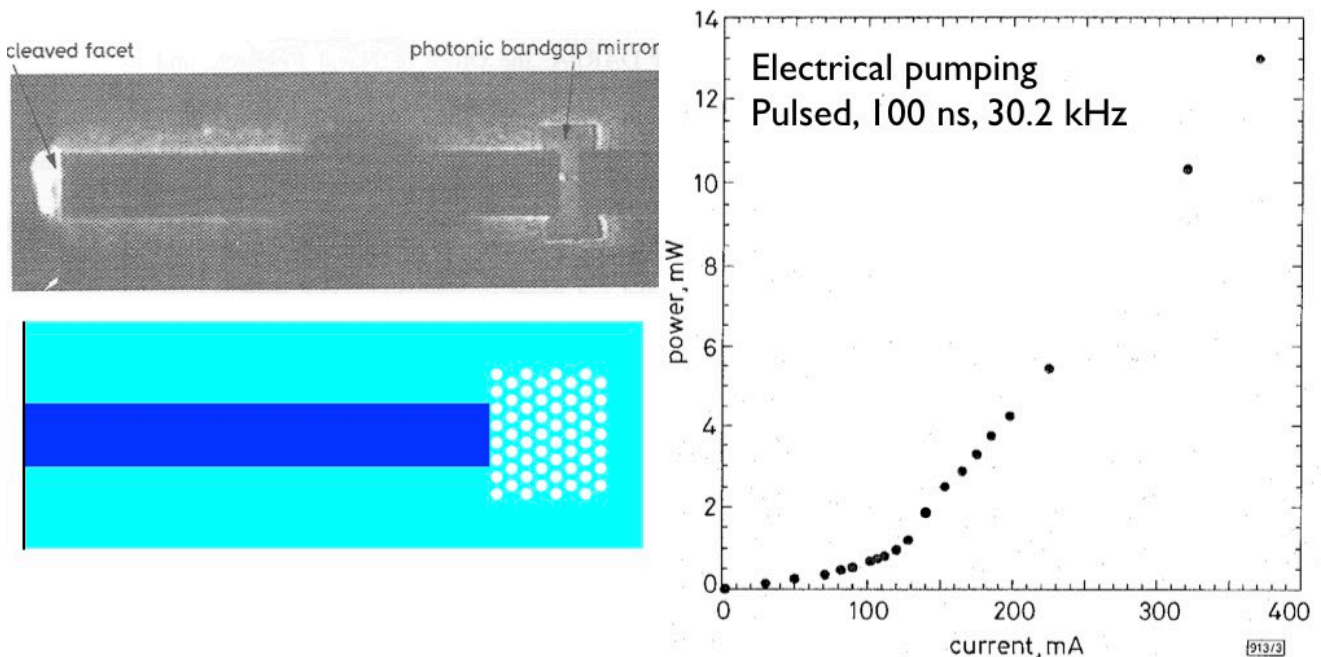


T. Baba et al., Appl. Phys. Lett., 81, 2325 (2002)

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Lasers

First laser using photonic crystals as mirrors

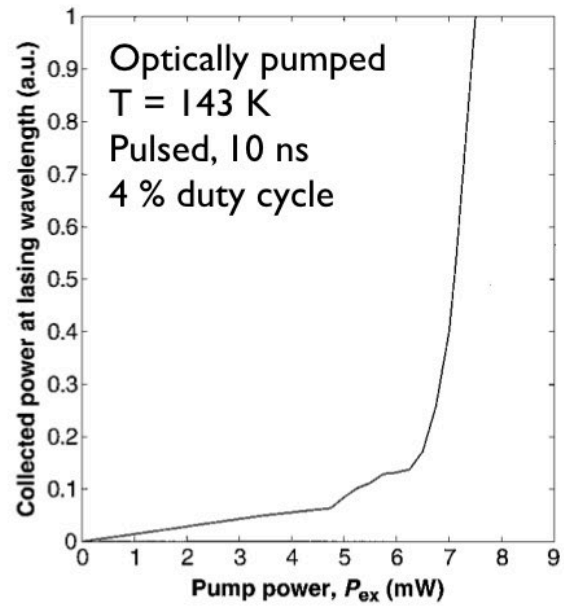
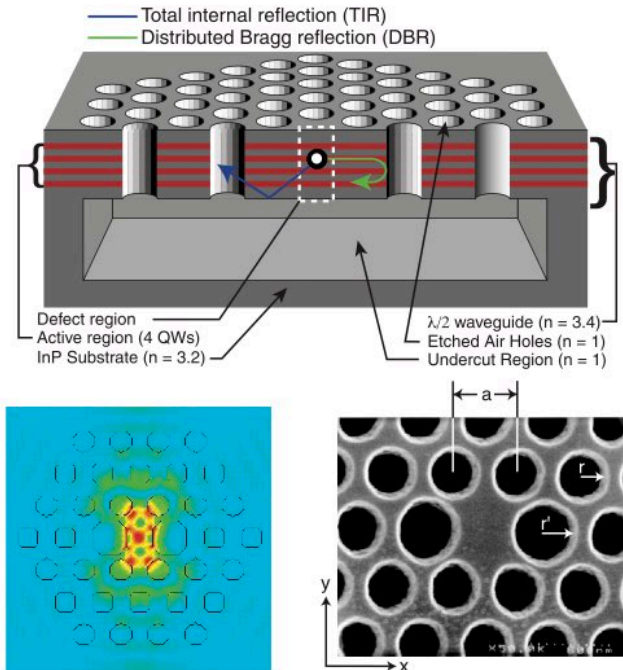


J. O'Brien et al., El. Lett., 32, 2243 (1996)

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

Lasers

First single mode photonic crystal laser



O. Painter et al., Science., 284, 1819 (1999)

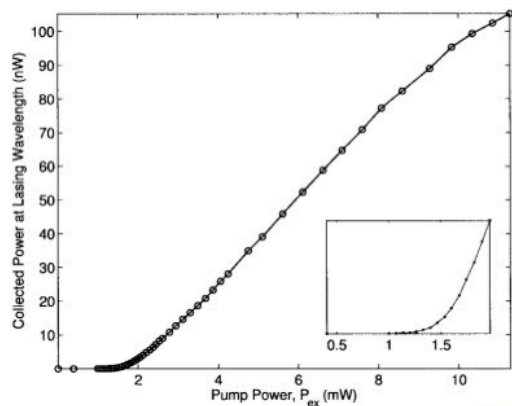
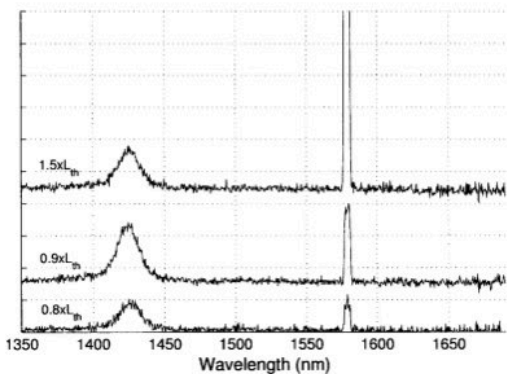
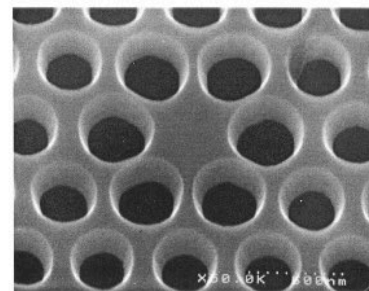
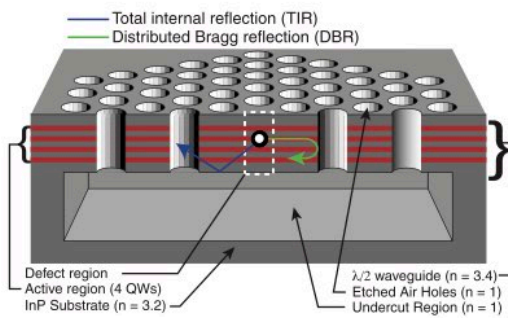
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53 / 64



Lasers

First room temperature photonic crystal laser



O. Painter et al., J. Light. Tech., 17, 2082 (1999)

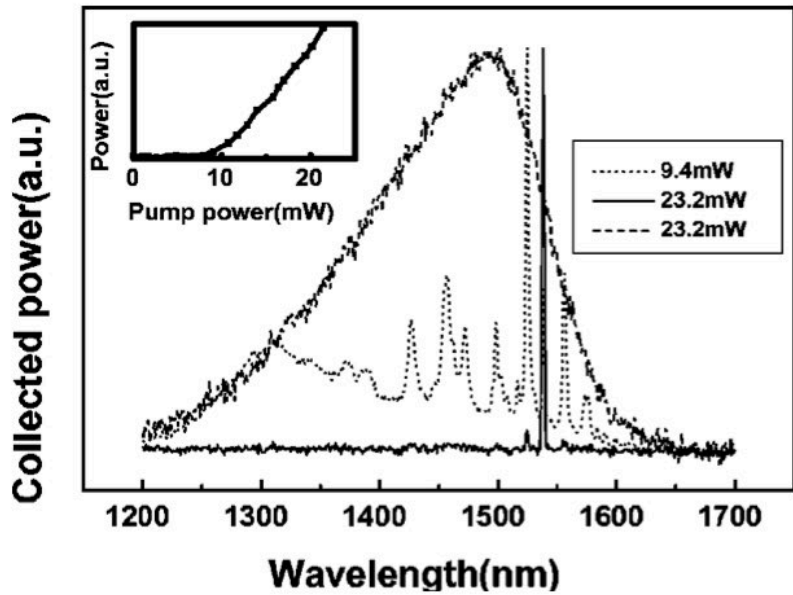
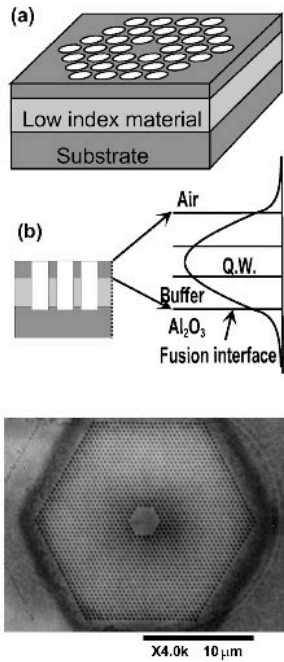
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54 / 64



Lasers

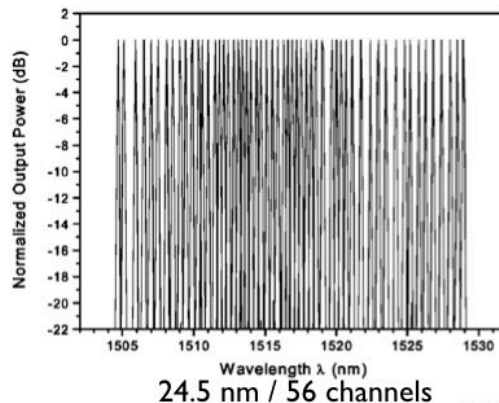
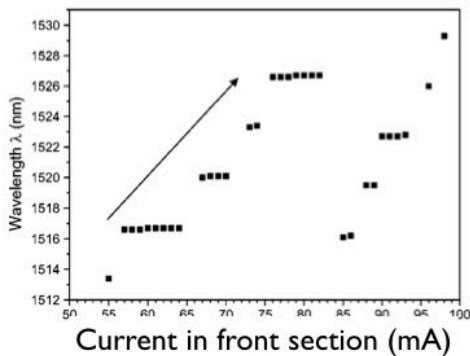
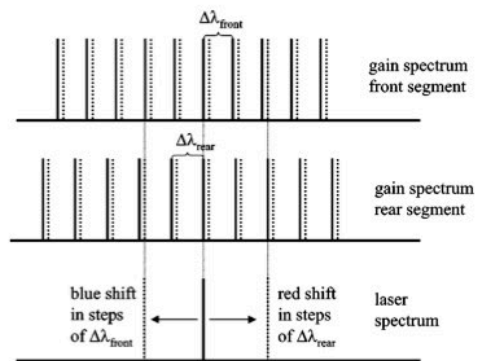
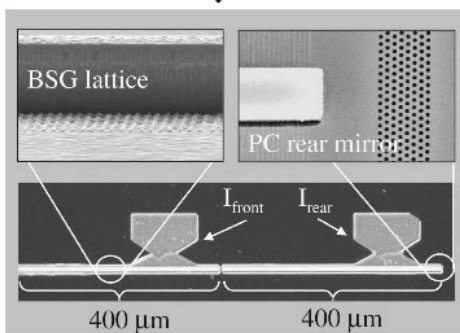
Room temperature and CW
Optical pumping, AlOx



J.K. Hwang et al., Appl. Phys. Lett., 76, 2982 (2000)
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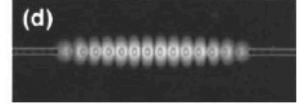
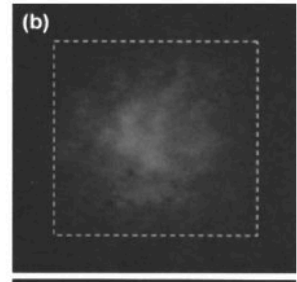
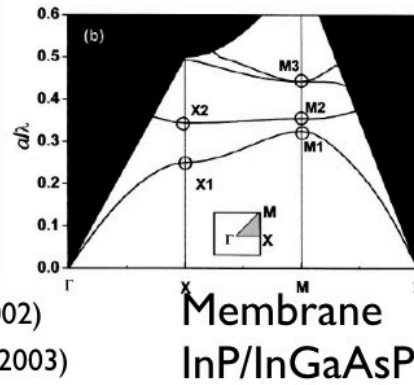
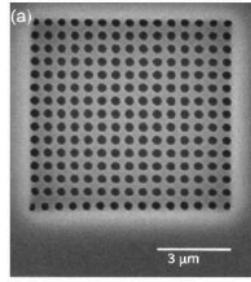
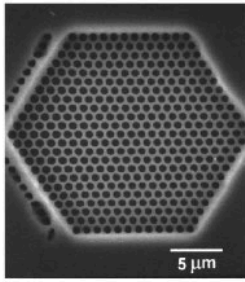
Lasers

Hybrid tuneable laser. Vernier effect with two cavities controlled with current injection



S. Mankhopf et al., Appl. Phys. Lett., 82, 2942 (2003)
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

2D distributed feedback lasers (DFB)



H.Y. Ryu et al., Appl. Phys. Lett., 80, 3476 (2002)
 S.H. Kwon et al., Appl. Phys. Lett., 83, 3870 (2003)

Laser "without" cavity
 Gain enhancement

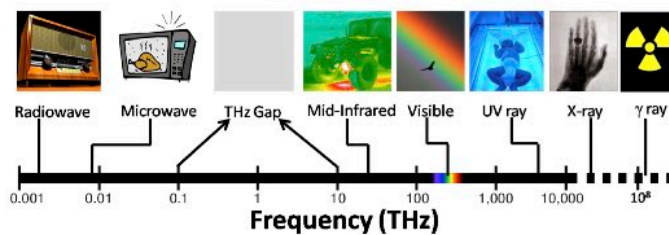
Low threshold
 Reduced dimensions
 Better mode control
 In-plane or vertical emission

- Distributed feedback laser
- Band edge laser
- Slow light mode laser

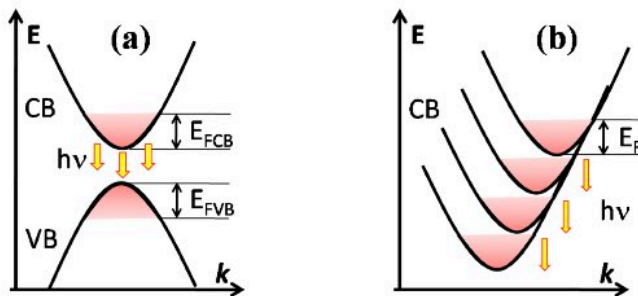
Three languages for very similar objects

2D distributed feedback lasers (DFB)

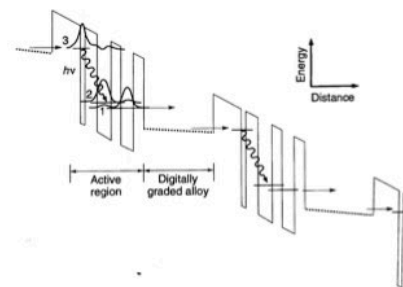
Application in the THz range ($1 \text{ THz} \approx \lambda = 300 \mu\text{m}$)



Quantum Cascade structures




Intersubband transitions



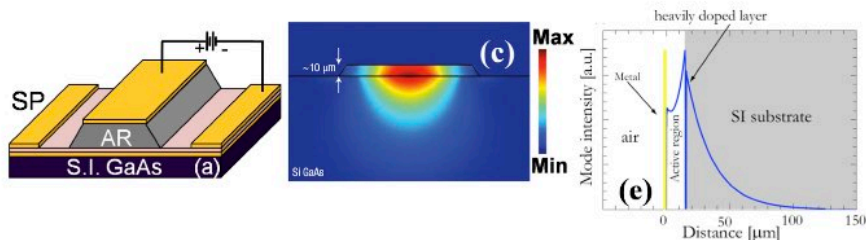
- TM polarized
- ➔ PhC crystal structure
- ➔ In-plane waveguide

2D distributed feedback lasers (DFB)

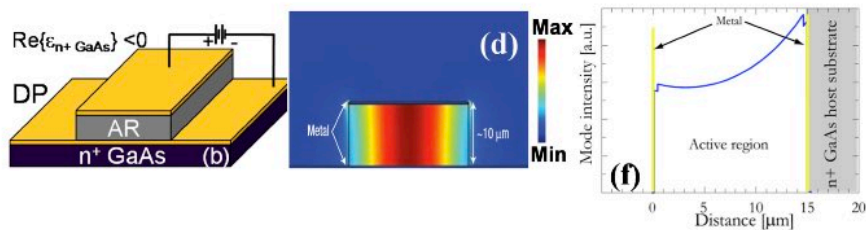
In-plane waveguide

Index guiding as in NIR 

Single plasmon



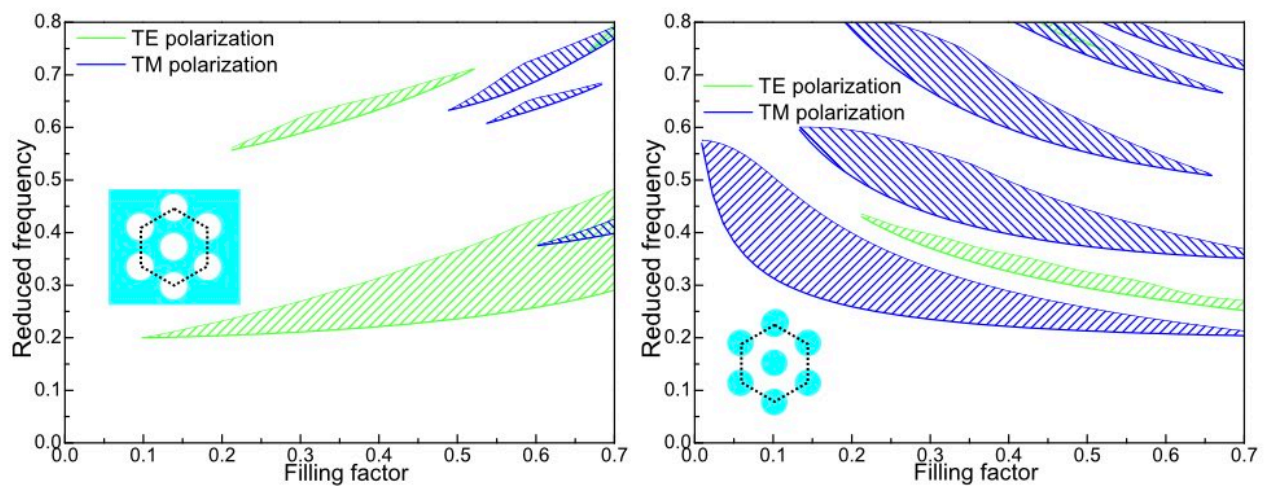
Double plasmon (metal-metal waveguide)



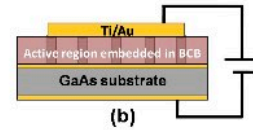
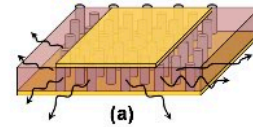
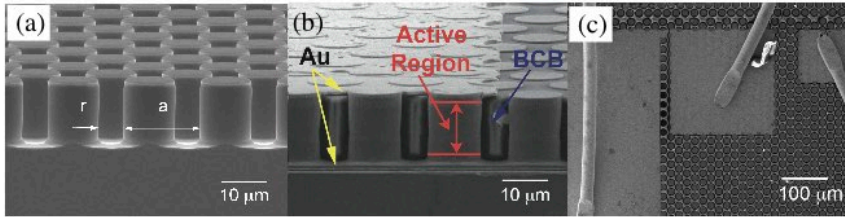
2D distributed feedback lasers (DFB)

PhC crystal structure

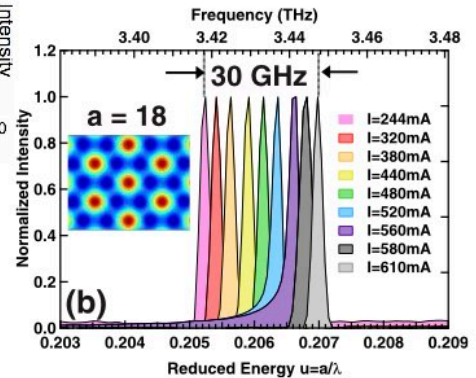
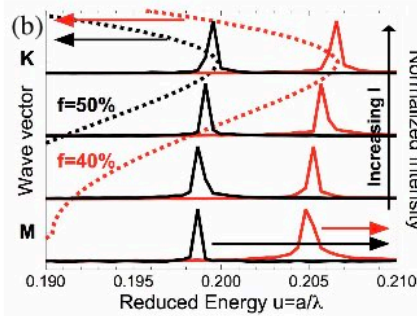
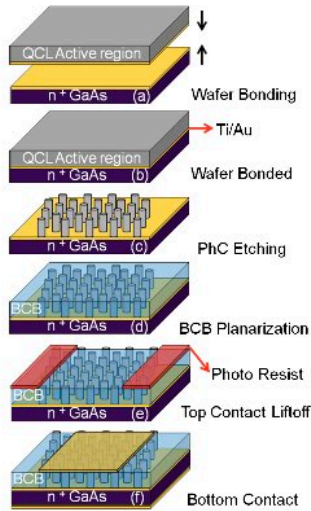
Rather lattice of pillars than holes



2D distributed feedback lasers (DFB)



Single mode
Losses reduction
Tuneability

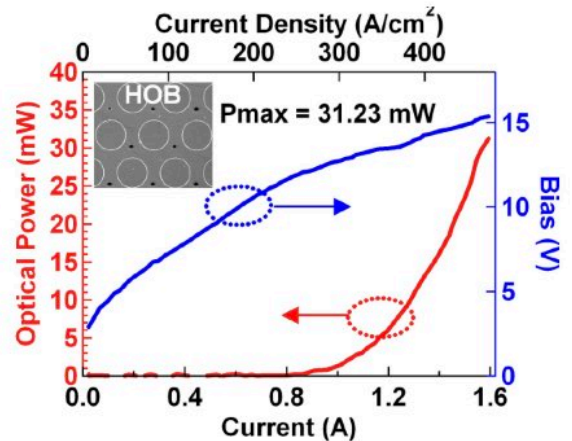
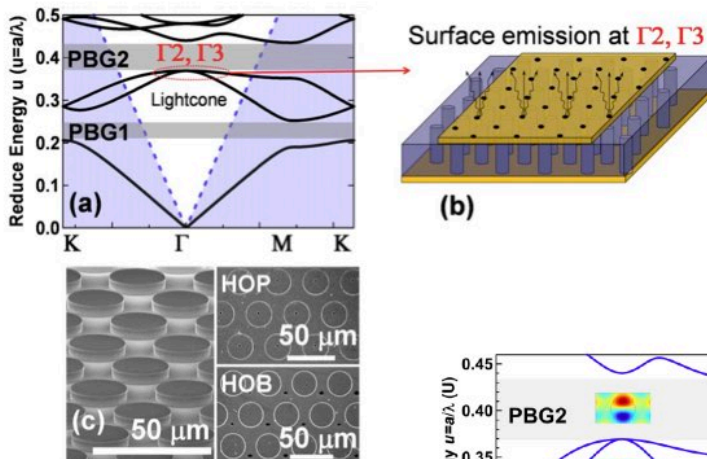


A very challenging process

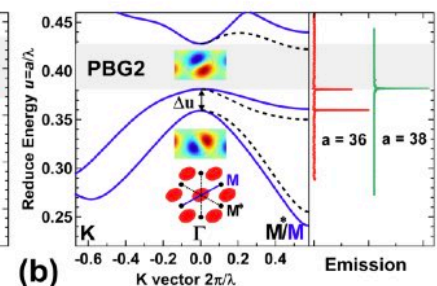
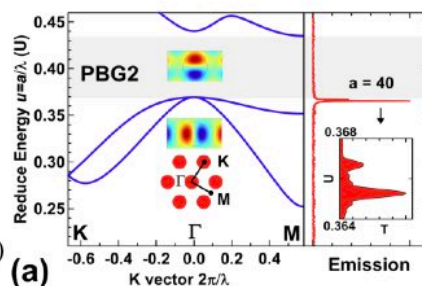
H. Zhang et al., *Opt. Exp.*, 15, 16818 (2007) & H. Zhang et al., *J. Appl. Phys.*, 108, 093104 (2010)
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

2D distributed feedback lasers (DFB)

Surface emitting version



See also
L. Sirigu et al., *Opt. Exp.*, 16, 5206 (2008)
B. S. Williams *Nat. Photonics* 1, 517 (2007)
R. Colombelli et al., *Science* 302, 1374 (2003)
M. Bahriz et al., *Opt. Exp.* 15, 5948 (2007)
A. Benz et al., *Opt. Exp.* 15, 12418 (2007)



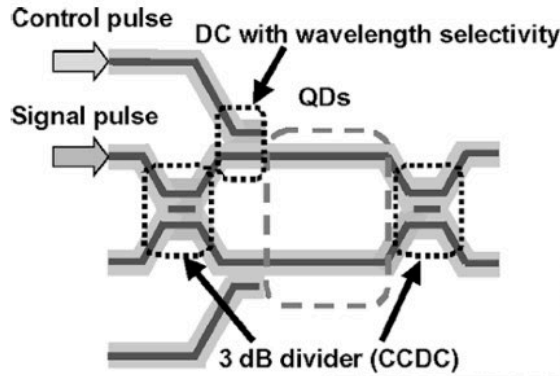
H. Zhang et al., *Opt. Exp.*, 19, 10707 (2011)

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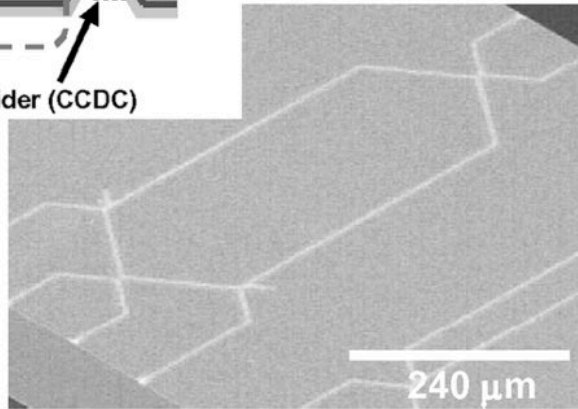
Circuits

FESTA Project (J)

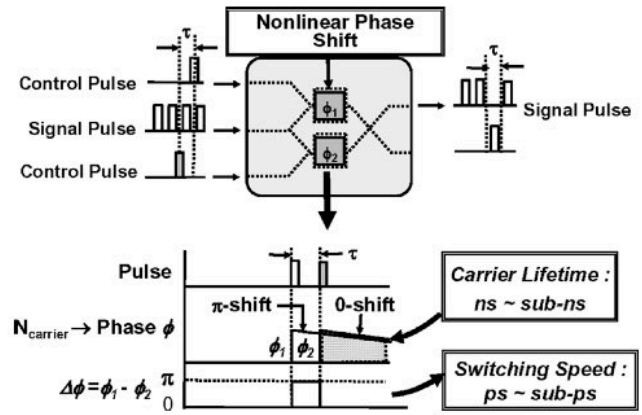
Example of a complex circuit



(a)



(b)



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

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Circuits

FESTA Project (J)

Example of a complex circuit

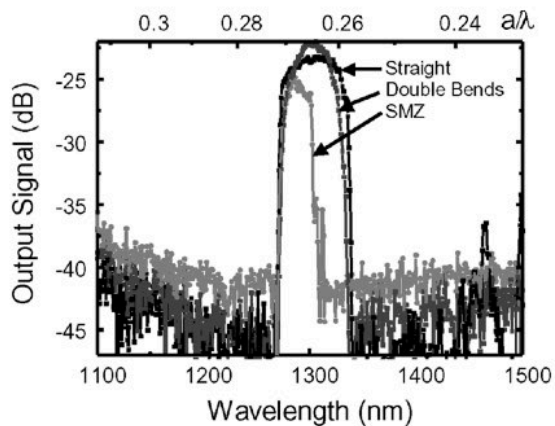
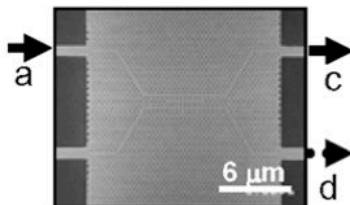
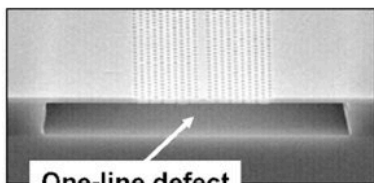
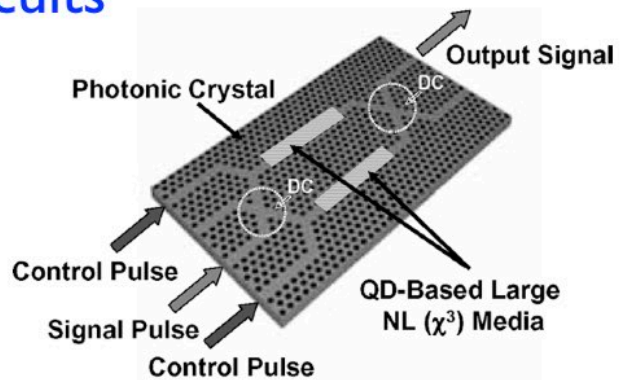
Couplers, bends ...

GaAs membrane

Quantum dots

Non-linear effects

Each building block fully characterised



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

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