The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964-2014

2572-1

Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

10 - 21 February 2014

Waveguide theory (and photonic circuit design)

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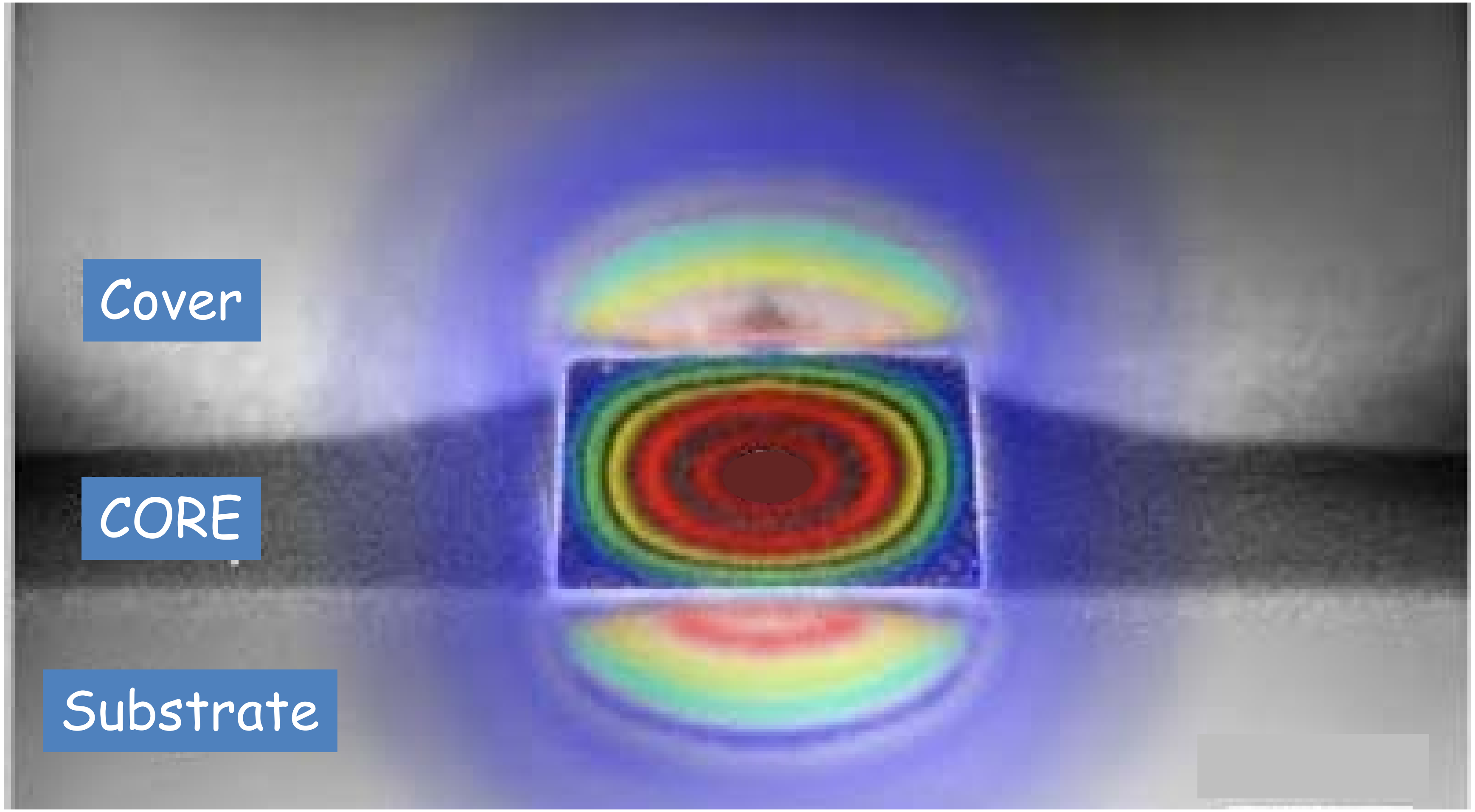
Waveguide theory and photonic circuit design

- Waveguides (no theory…)
- The role of index contrast in waveguides (survey of technologies, type of waveguides, index contrast…)
- Bends and advanced topics on bends (the matched bend,...)
- The dark side of integrated optical waveguides (backscatter, xtalk, losses, spurious modes, the (ng-neff) role….)
- An excursus on ring resonators: history, spectral characteristics, applications, ...
- Circuits: MZ, rings, higher order filters, delay lines, …
- The circuit approach (building Blocks, Circuit simulators and few slides on Aspic, our circuit simulator that will be used at the end of the course for hands-on session).
- The structure of generic foundries and available generic foundries

WAVEGUIDES



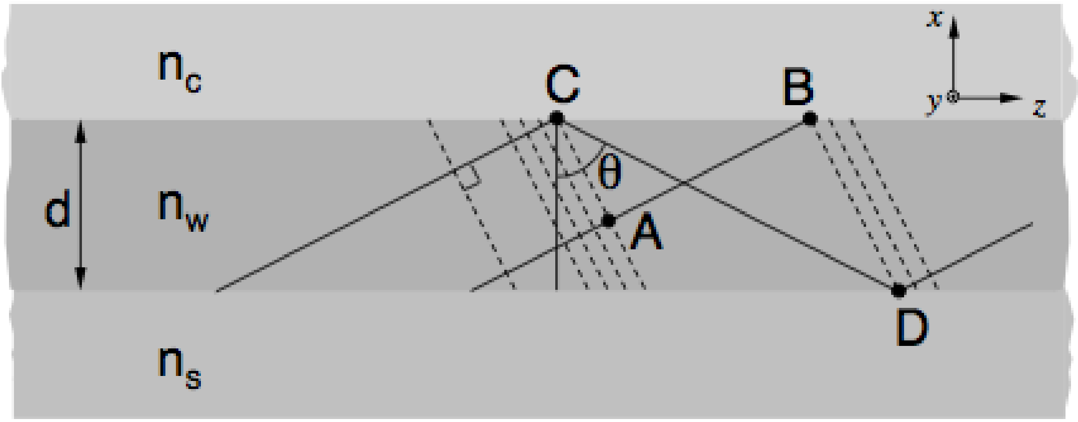
WAVEGUIDES

$n_2 > n_1$

n_1

Impedance $\eta = \sqrt{\frac{\mu}{\epsilon}}$

Ray Optics (forget…)



Electromagnetic Theory (Maxwell Equations)
- rigorous -
(Jiri Ctyroky, next week)

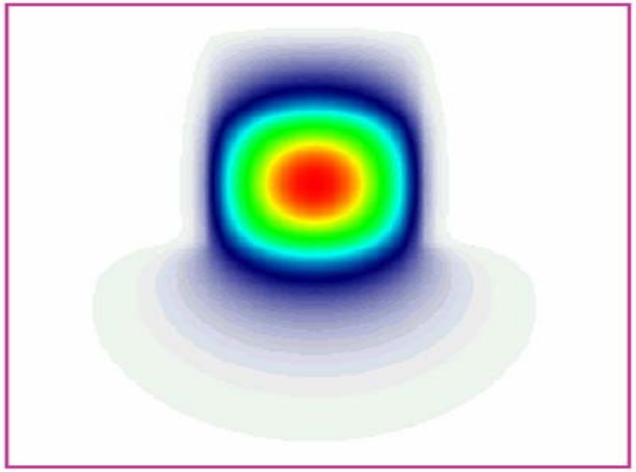
WAVEGUIDES

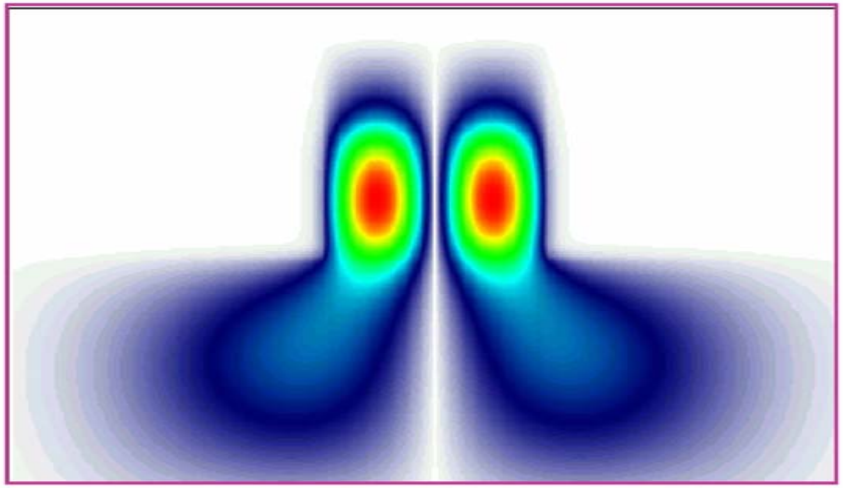
$$\mathbf{E}(x,y) = \sum_m a_m \mathbf{e}_m(x,y) + \int_0^\infty a(\beta)\mathbf{e}_R(\beta;x,y)d\beta,$$

Guided modes

Radiative modes
(plane waves)

Dielectric waveguides are between free space and metallic waveguides





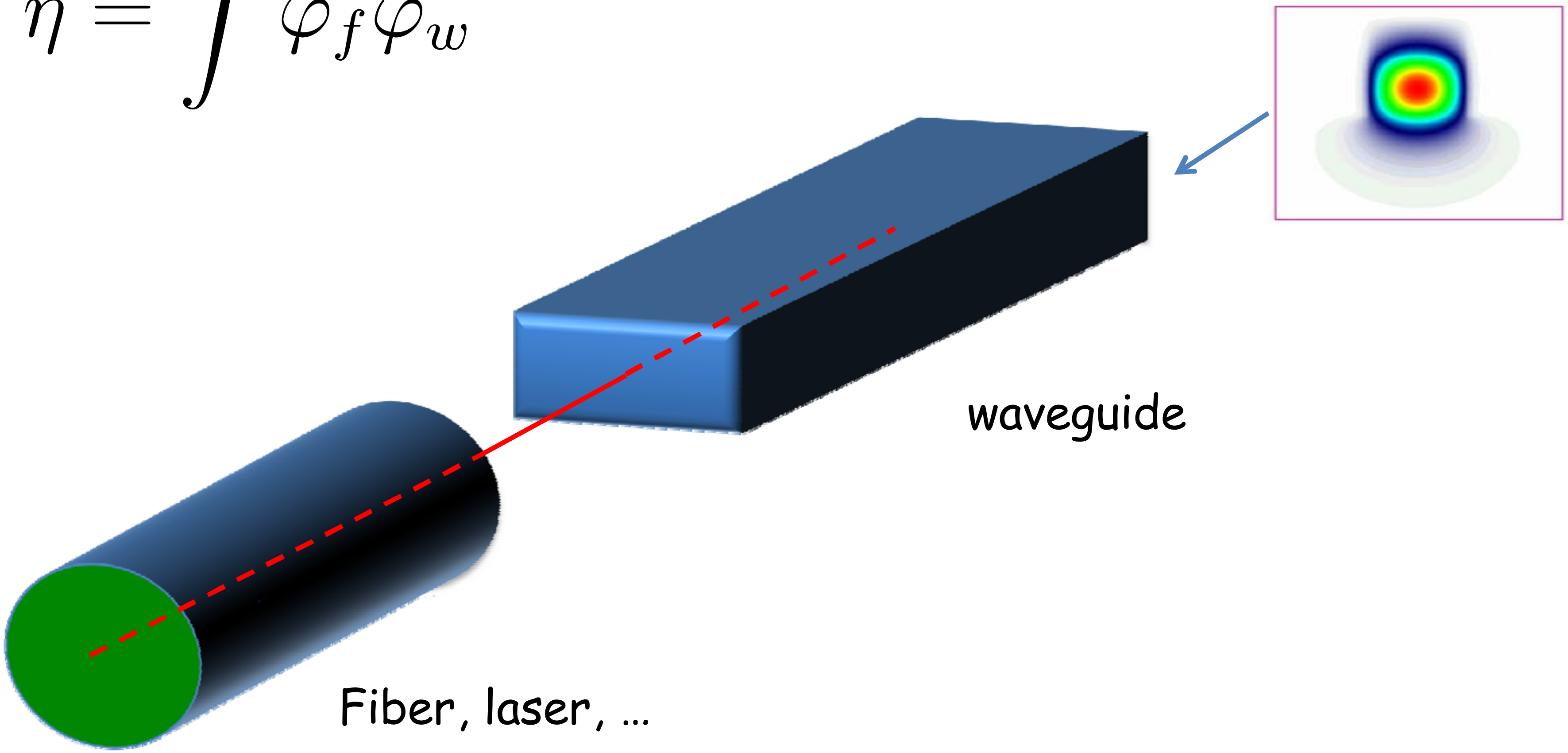
Characteristics of the modes

Guided modes are

- orthogonal (in space and in time)
- do not exchange power
- z independent (do not change the shape)
- solution of the wave equation
- Propagate as exp(-jβz)
- Attenuate as exp (-αz)
- Each mode has his α, β, n_g...
- Depend on the cross section
- Have a cutoff wavelength (if asymmetric)
- ...

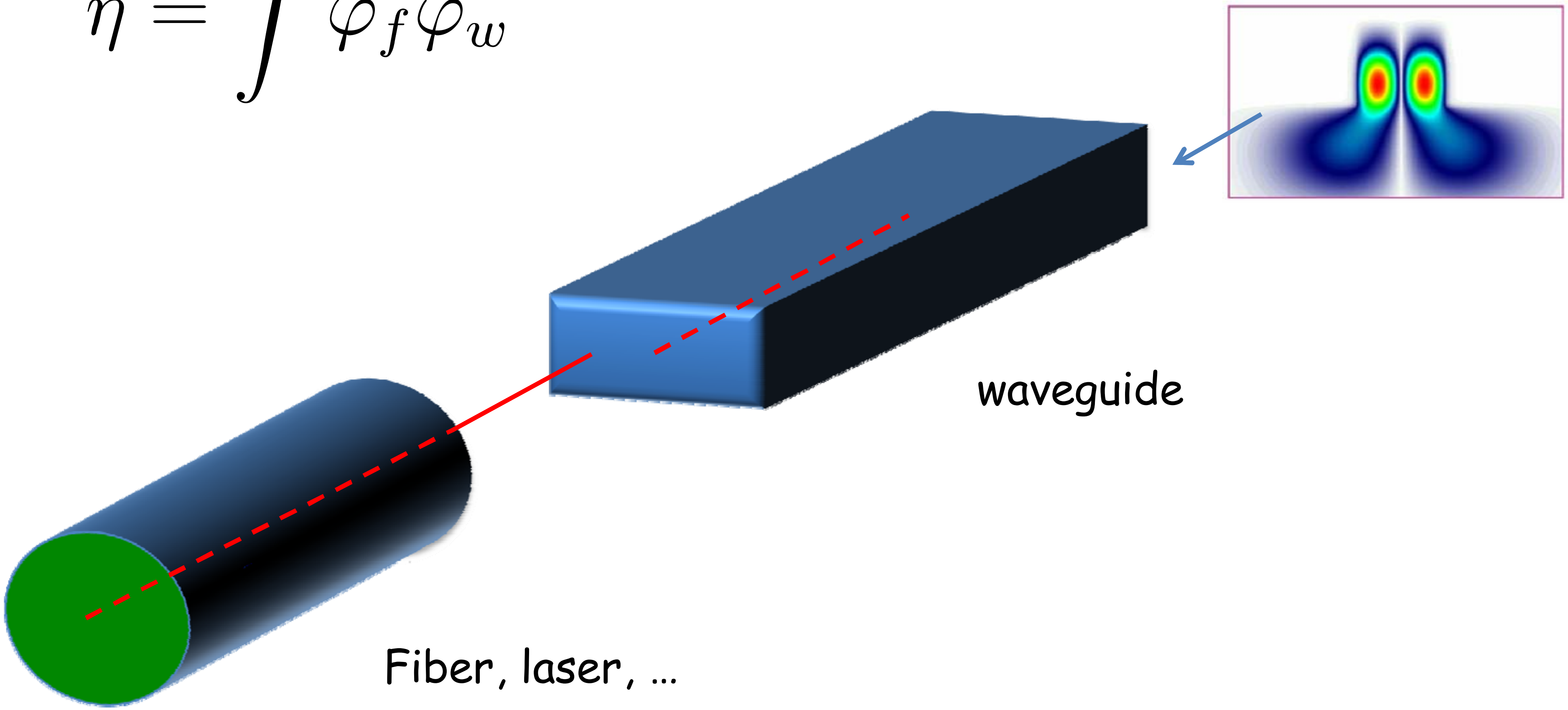
Existing modes and Excited modes

$$\eta = \int \varphi_f \varphi_w$$



Existing modes and Excited modes

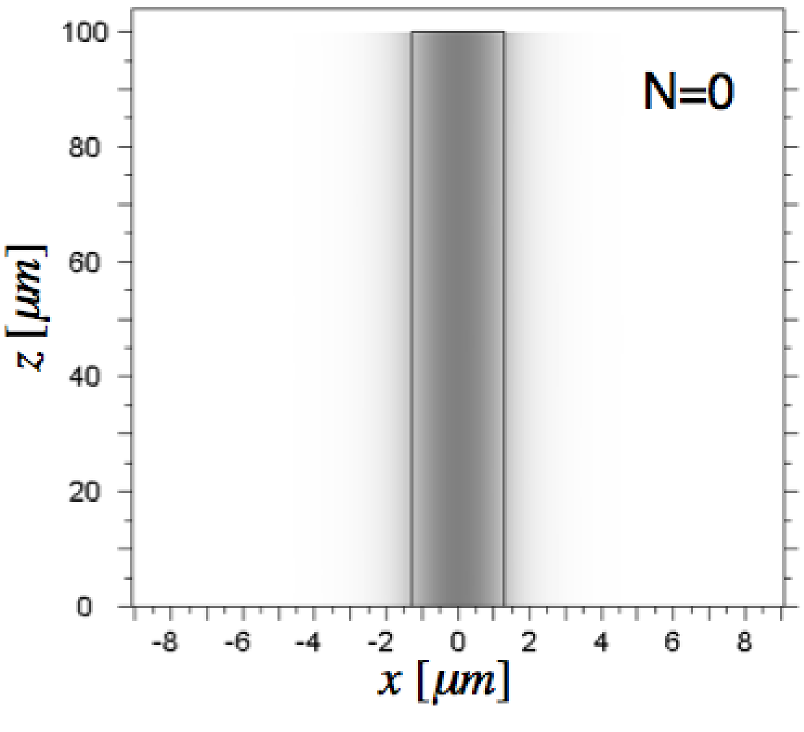
$$\eta = \int \varphi_f \varphi_w$$



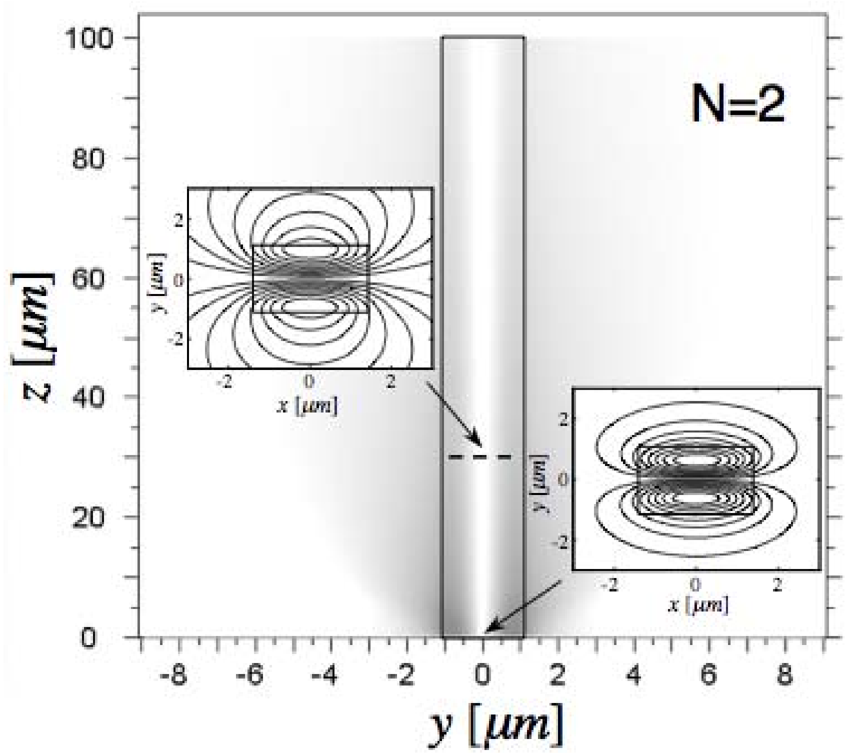
Leaky modes

Leaky modes or quasi-mode are packets of radiative modes
Behave as badly guided modes

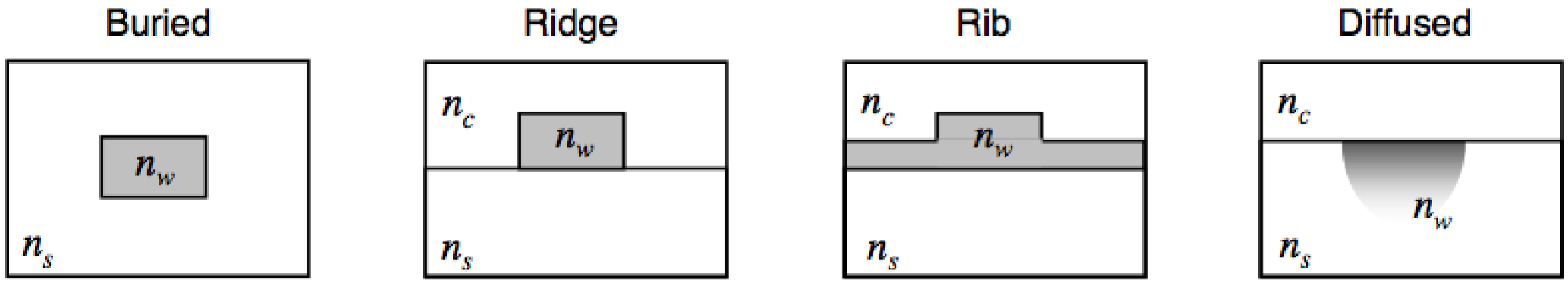
Guided mode



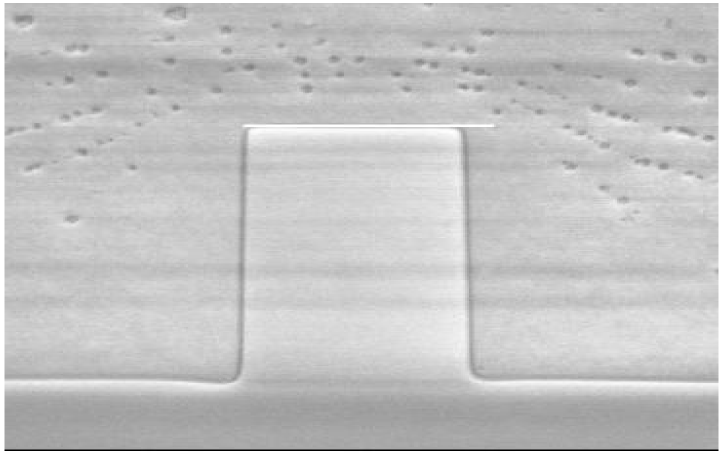
Leaky mode

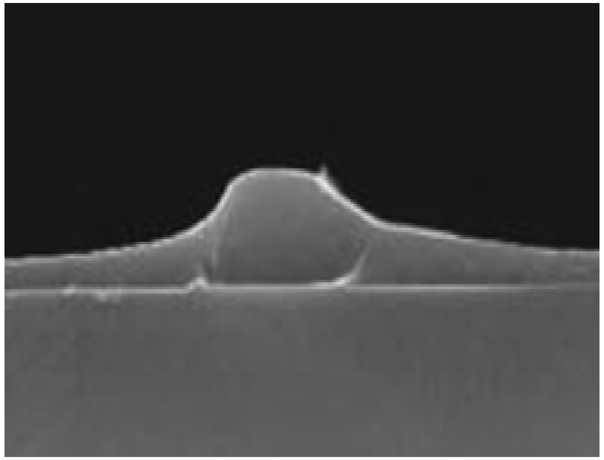


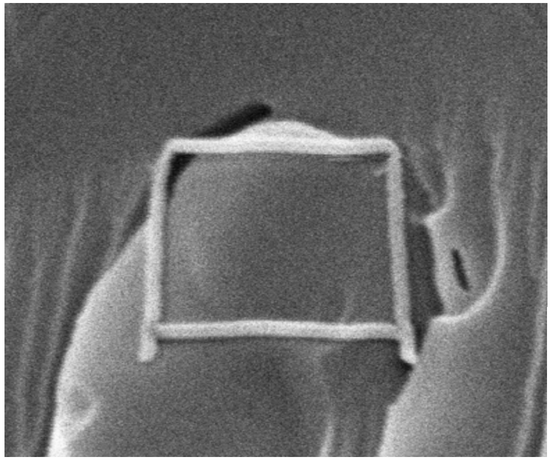
WAVEGUIDES

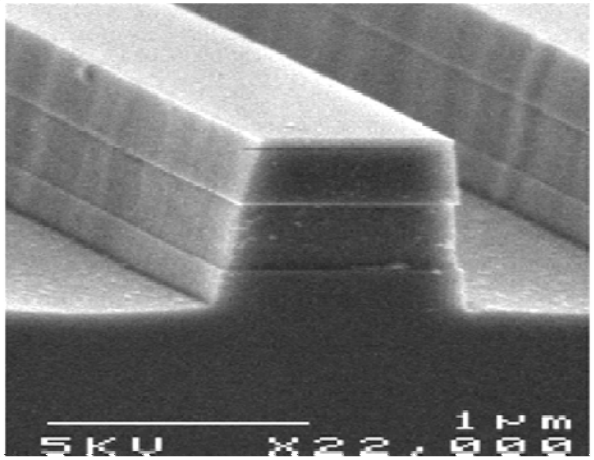


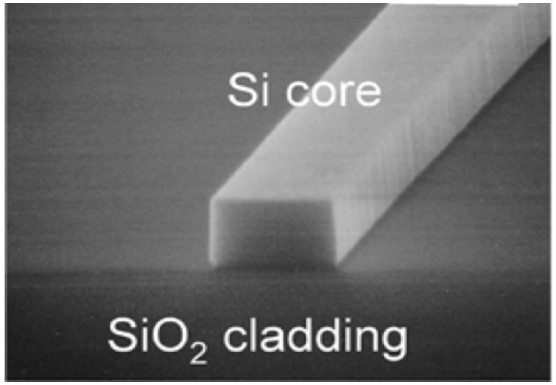
WAVEGUIDES



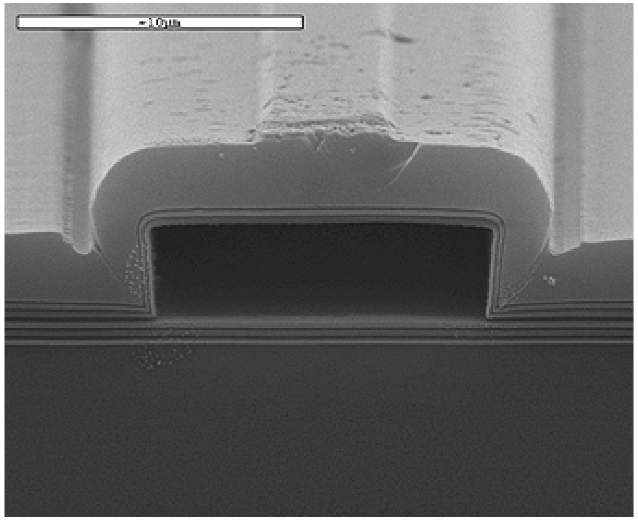




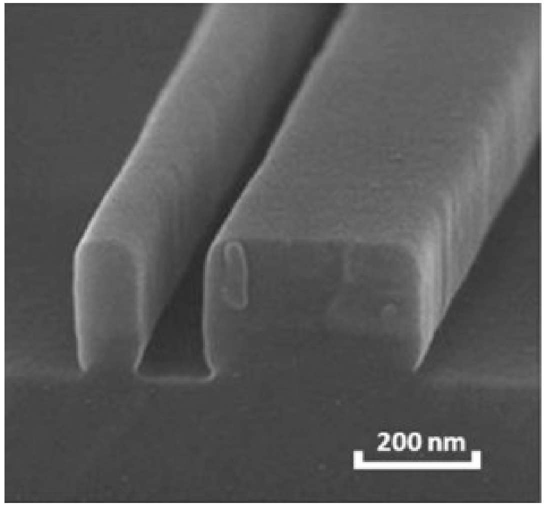




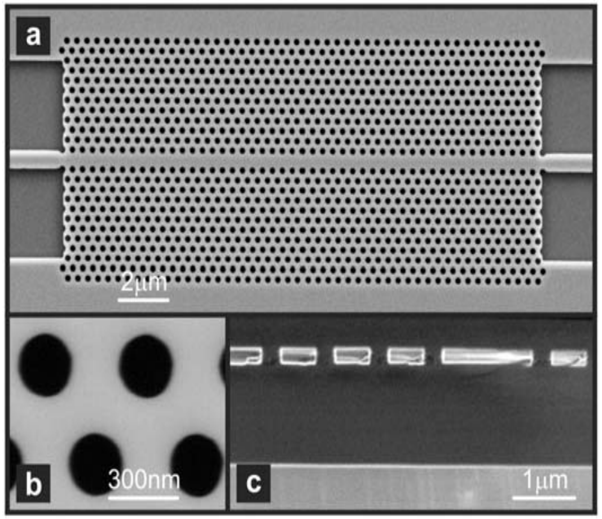
Other Waveguides



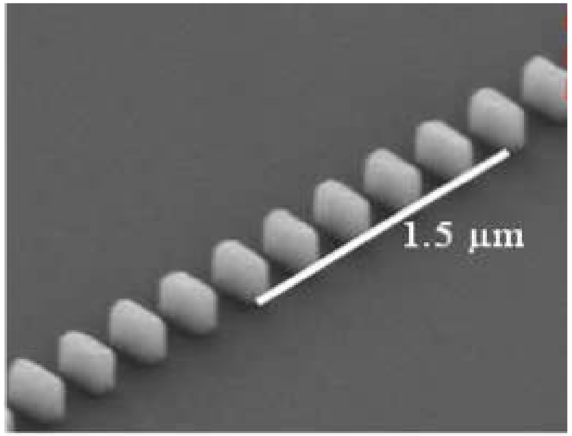
Hollow waveguide



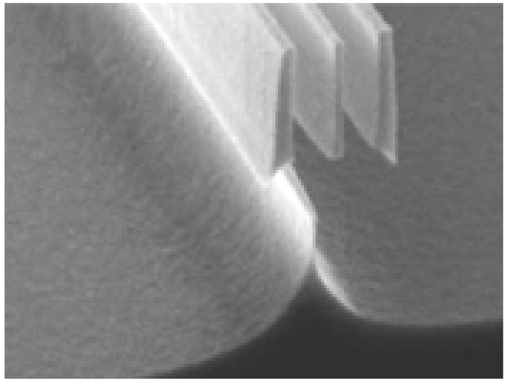
Slot waveguide



Photonic Crystal waveguide



Segmented waveguide



Good for sensing !

The characteristics of an Optical Waveguide

Single mode (why? …always?)

Low loss (dB/cm?, dB/μm?; fibers 0.2 dB/km !)

Low (high) polarization dependence

Small bending radius

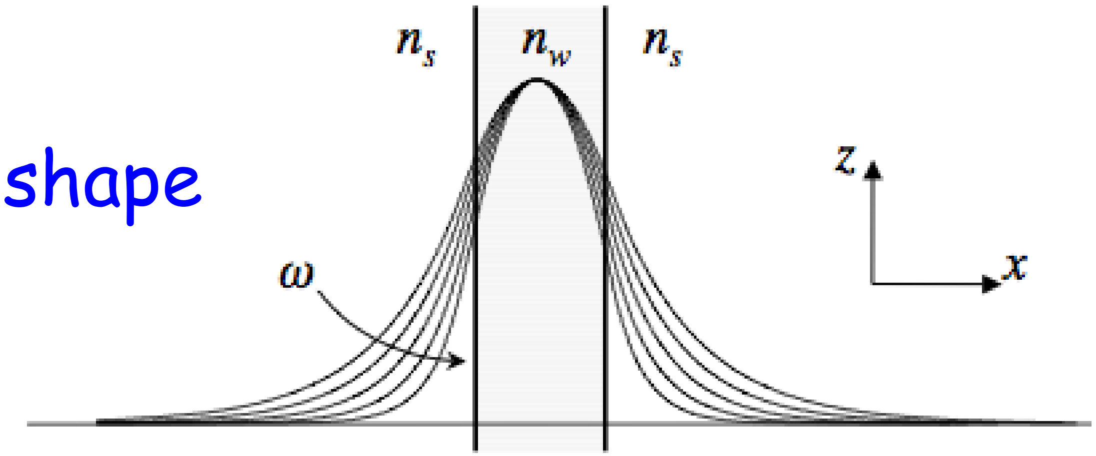
Large mode (for efficient fiber coupling)

Active controls (thermooptic, electrooptic, carriers….)

Nonlinearities ?

The characteristics of an Optical Waveguide

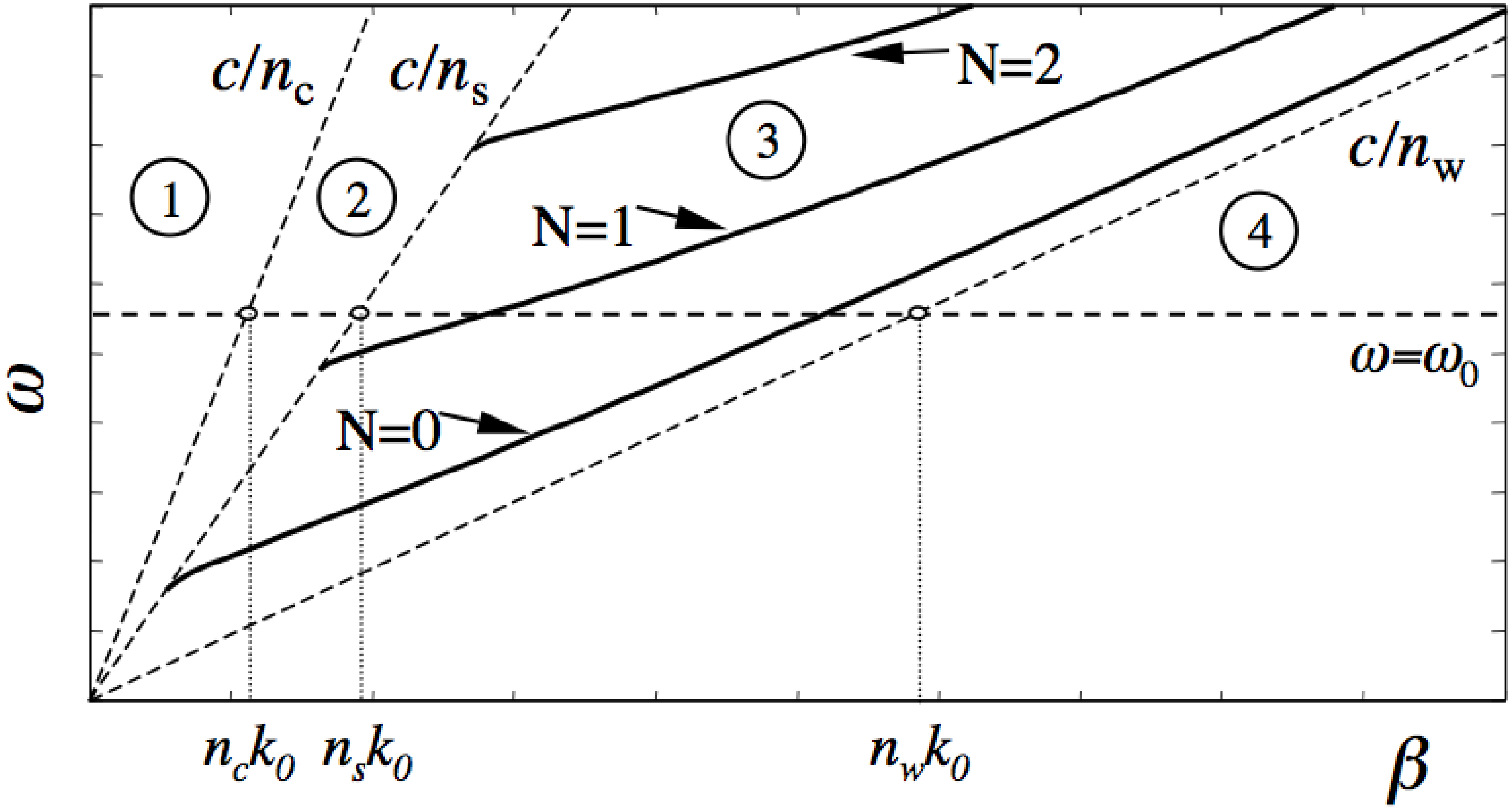
Mode shape



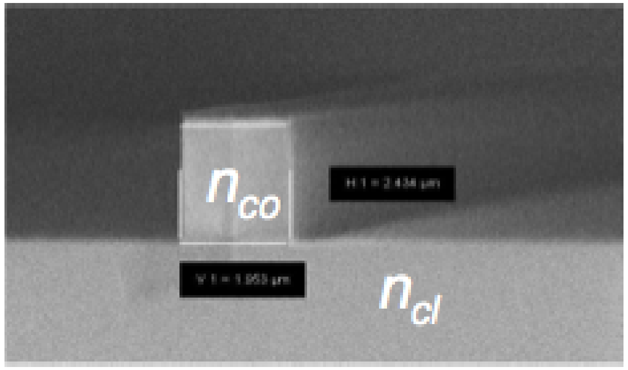
Phase constant $\beta = \frac{2\pi}{\lambda} n_{eff}$ Effective index

Group index $n_g(\omega) = \frac{c}{v_g(\omega)} = n_{eff}(\omega) + \omega \frac{dn_{eff}}{d\omega}$

Dispersion diagram



The index contrast Δn is the most important parameter of a dielectric waveguide

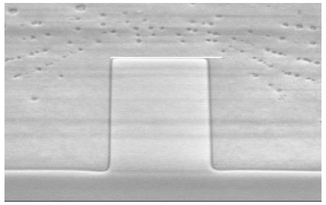


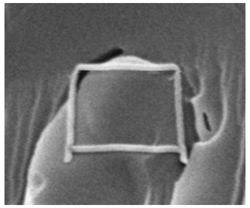
$$\Delta n = \frac{n_{co} - n_{cl}}{n_{co}}$$

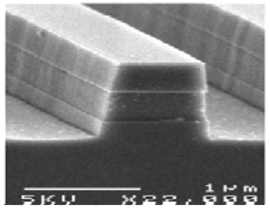
- Waveguide dimensions
- Fiber to waveguide coupling
- Bending radius
- Losses
- Directional couplers gap
- Birefringence, PDL

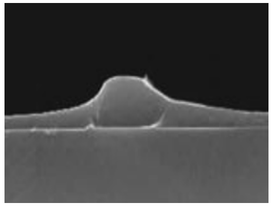
- Technological processes
- Material
- Tolerances

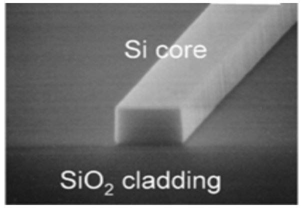
Technologies and Waveguides



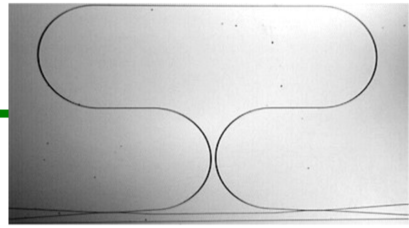






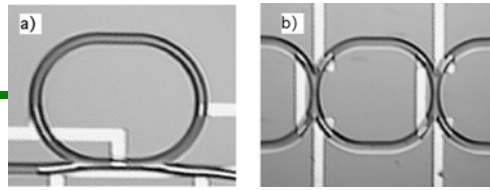


Ge:SiO_2	SiON	Si_3N_4	InP	As_2S_3	SOI	Δn
0.5…3 %	2…8 %	38 %	3 / 70 %	60…100 %	140%	

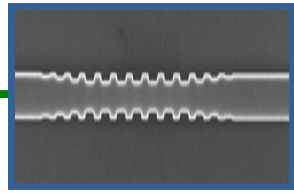


Mach-Zehnder

D. Couplers, Y, MMI, Star couplers

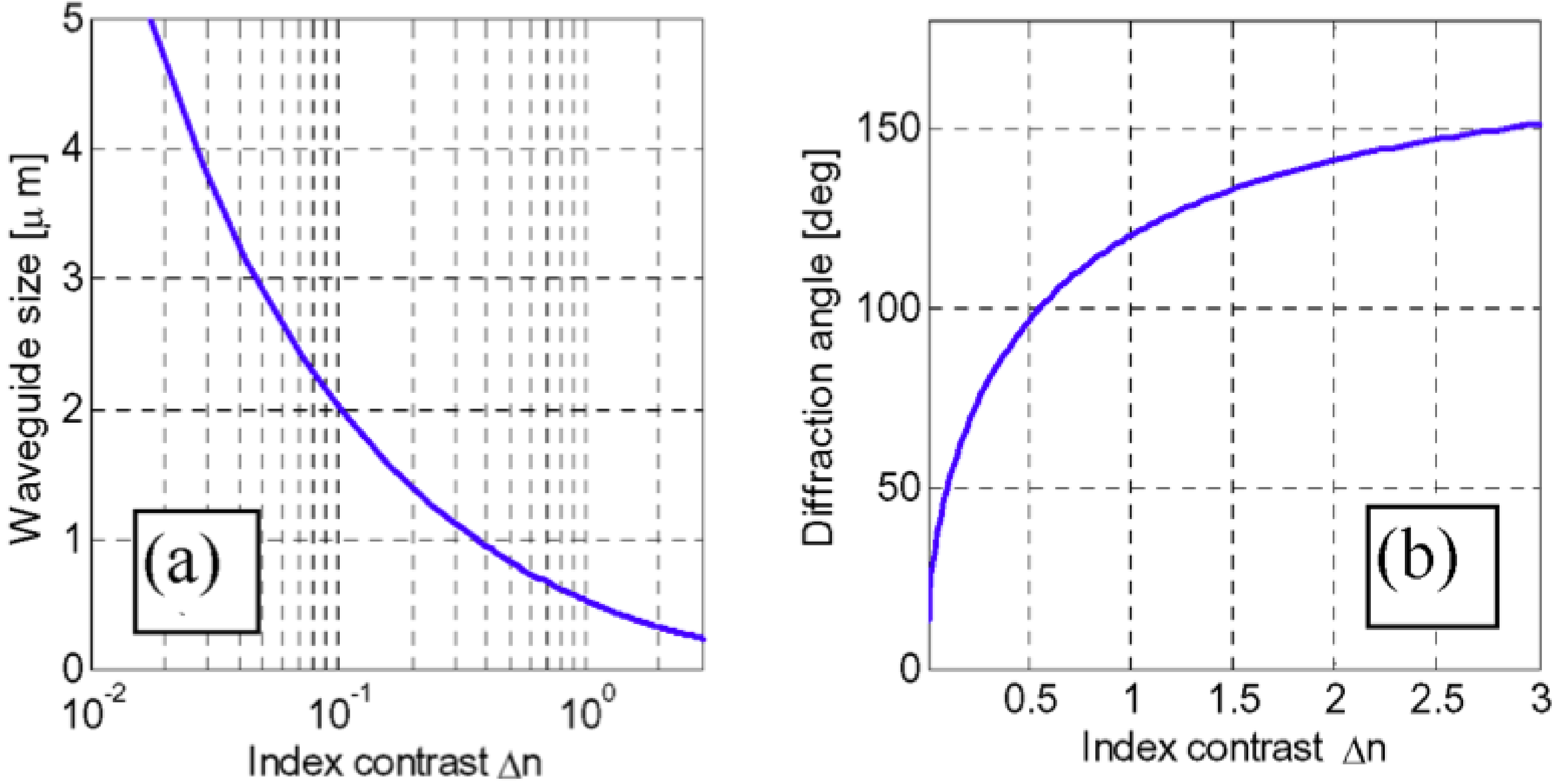


Ring Resonators



Gratings

Index contrast vs size and NA



High or low index contrast?

Low index contrast (0.69%) is an assessed technology but...

Few functions per chip
Interconnects leave large space unused
Restrictions on devices (ring resonators and Bragg gratings)
Large area waveguides, low nonlinearity

while high contrast....

Economics of wafer scale integration
Compact implementation of complex functions (system on a chip)
Allows certain functions not possible with low contrast
Multifunction chips
Compact nonlinear devices
Many chips per wafer = high yield

Low index contrast: classical integrated optics

Weakly Guiding “integrated” optics

SiO_2 doped Ge, B, P…, polymers

$\Delta n < 1\%$

Waveguide dimensions 5x5 μm

$R_{min} > 1$ cm

Low loss, < 0.1 dB/cm

Excellent fiber waveguide coupling (<0.1dB)

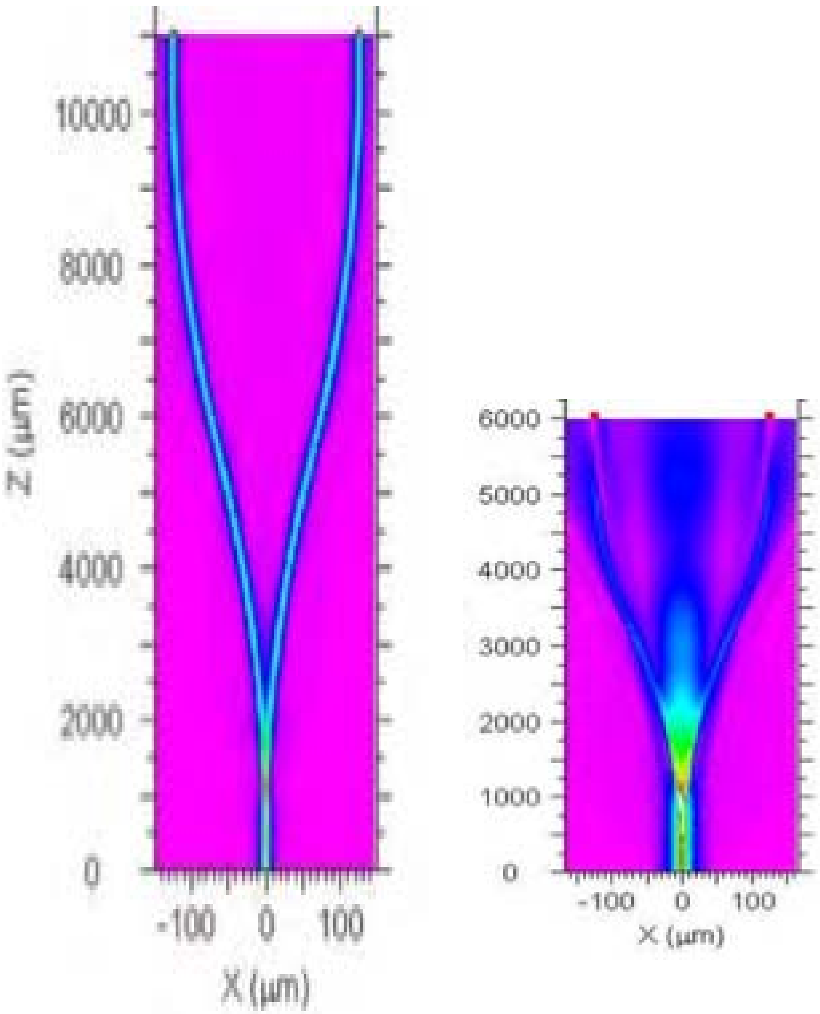
Low birefringence (10^{-5})

Foundries available on the market

Reliable and stable

Very low integration scale

Can be athermal



Integrated optics

SiON (eventually doped Ge), polymers

Δn < 3-5 % (1.5….20 %)

Waveguide dimensions 2x2 μm (4%)

1.2x1.2 μm (20%)

R_{min}: 1 mm (4%) …. 30 μm (20%)

Moderate loss, 0.15-0.5 dB/cm

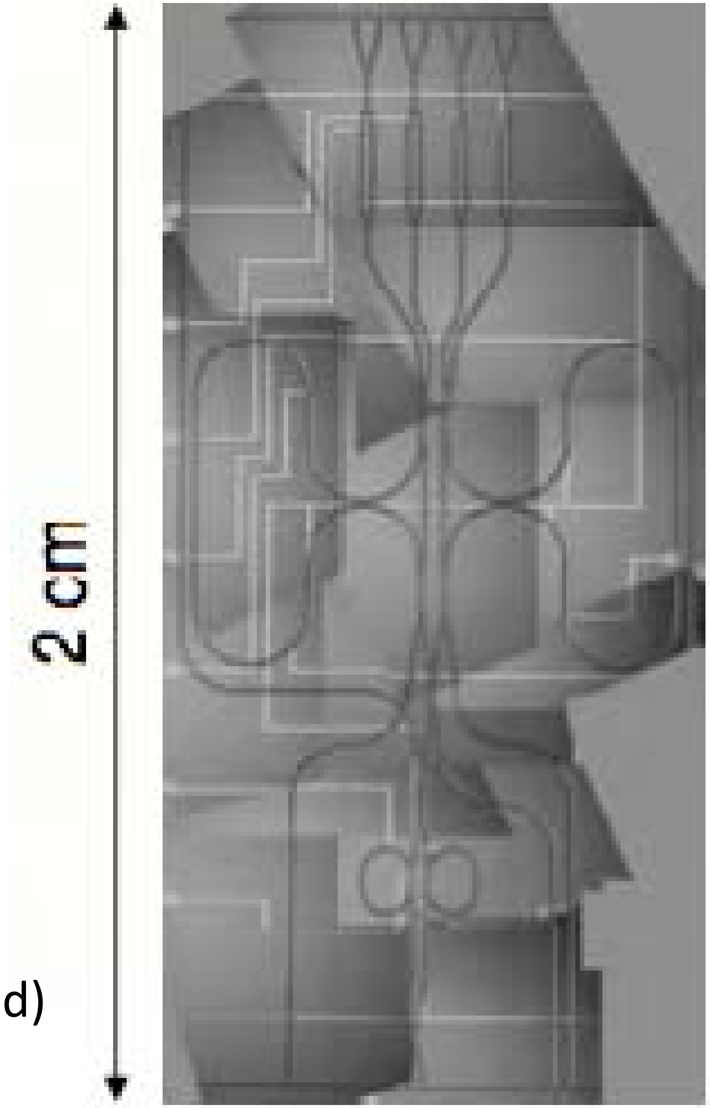
Fiber coupling need mode adapter (0.3 dB)

Low birefringence (10^{-5})

Foundries … a long story !

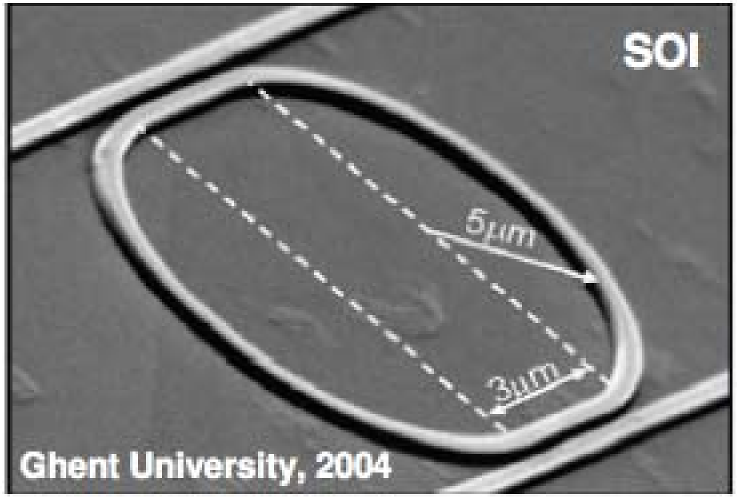
Non stoichiometric…., absorbs at 1510 (N-H bound)

Medium integration scale

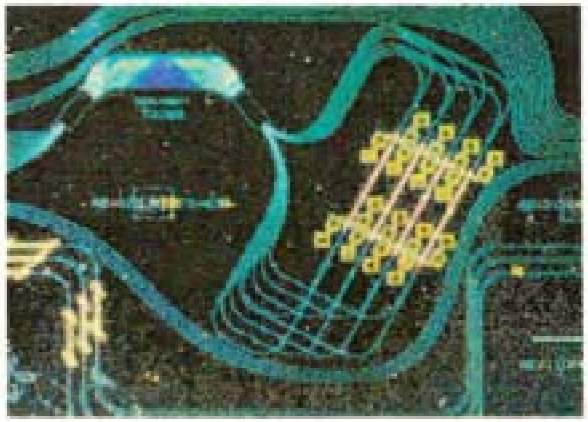


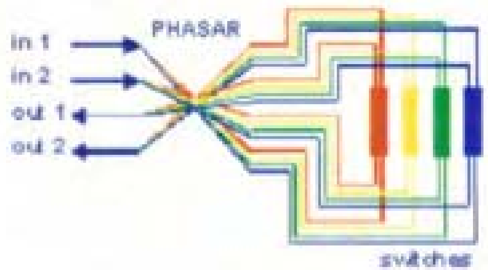
Semiconductors: very high index contrast

InP, GaAs, AlGaAs, Si
Δn ~ 30%
R min~5 μm
Waveguide dimensions <1x1 μm
Mode converters for fiber/waveguide coupling
Critical technology!
→ High loss (>1 dB/cm)

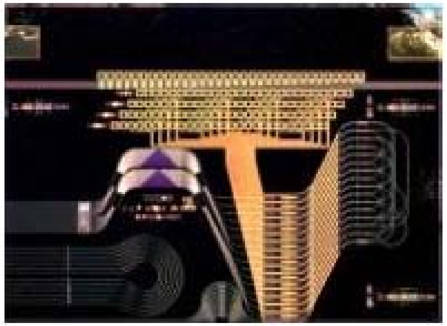


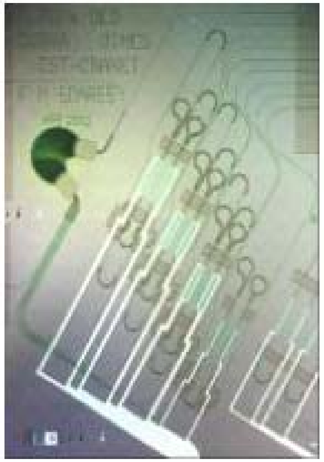
Modulo integrato per OXC in InP

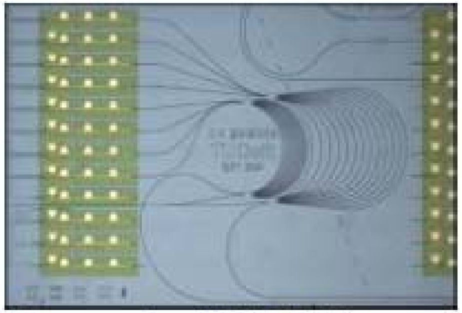


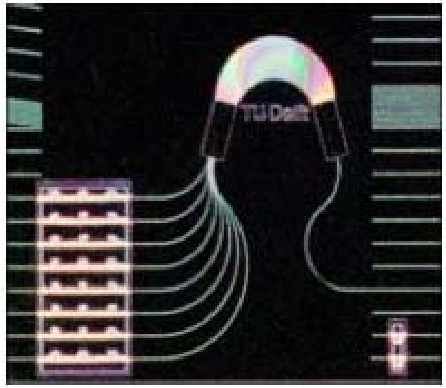


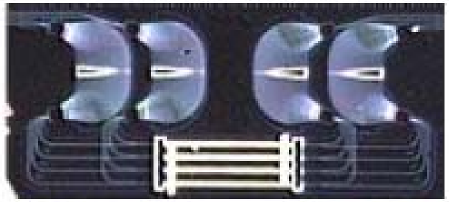
Photonics Integration


optical crossconnect

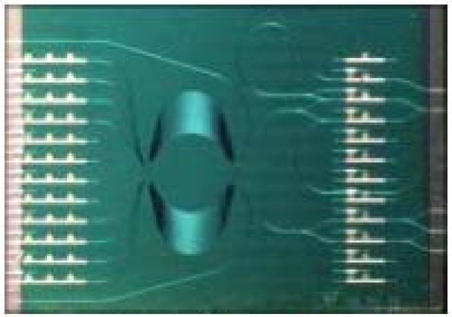

WDM-TTD switch

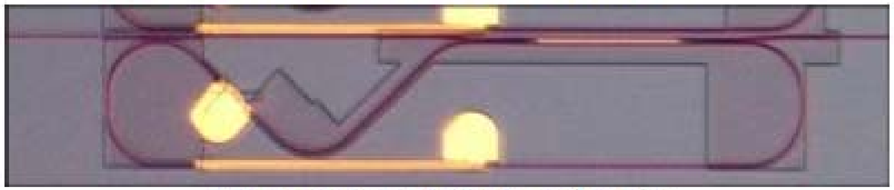

Cascaded WDM laser

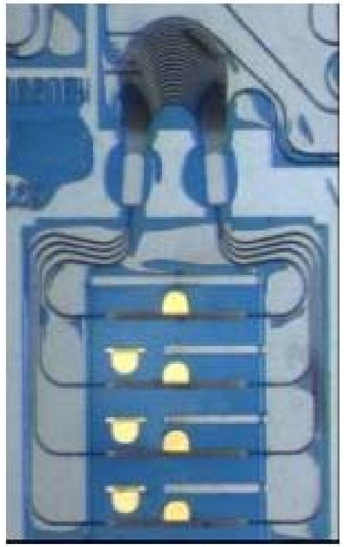

multiwavelength laser


optical crossconnect

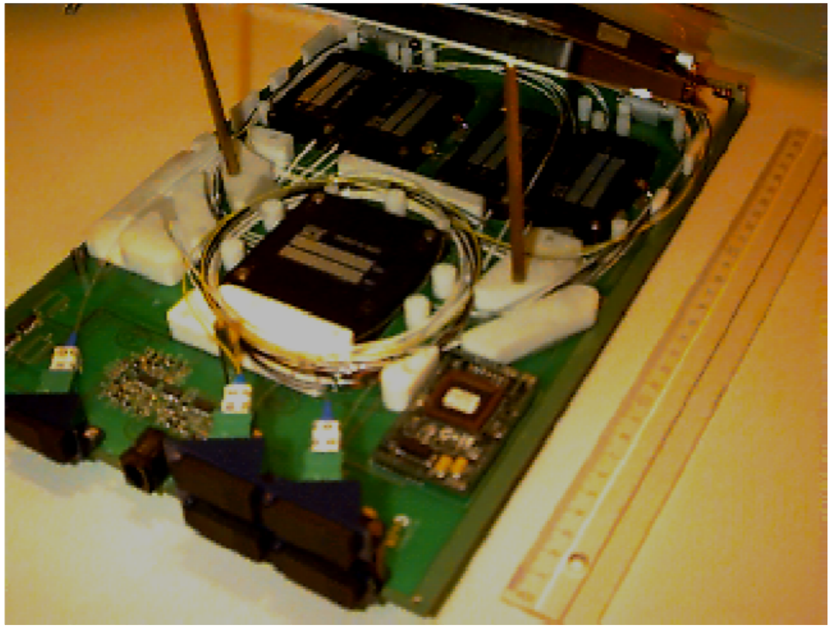

tunable multiwavelength laser


wavelength converter

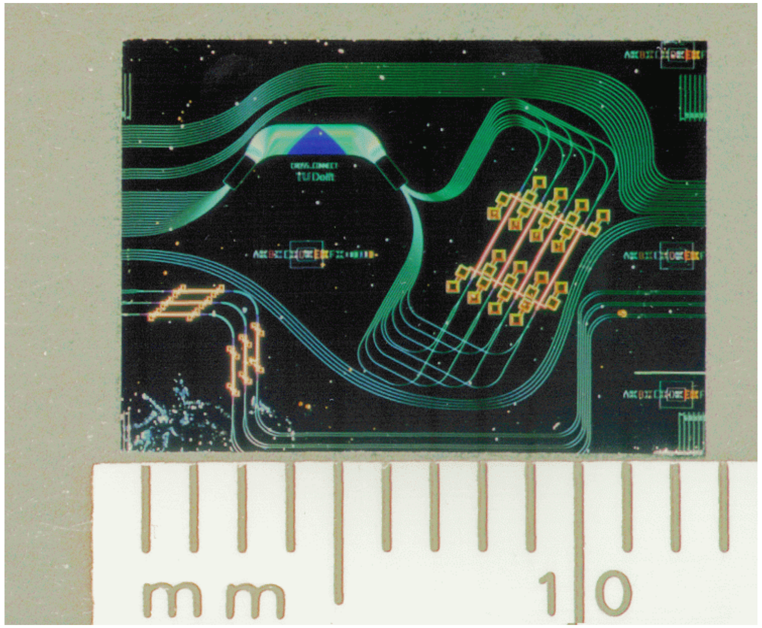

picosecond pulse laser


WDM ring laser

Courtesy of TU/e



Compact fibre-based cross-connect module 1997
4-channel 2x2 OXC



Photonic Integrated cross-connect chip 1998
4-channel 2x2 OXC

Courtesy of Tu/e – Eindhoven University

Towards 1 Tbit/s Tx&Rx system on chip…

Photonic Integration

Integrated Switching + WDM

Pervasive Digital Switching

infinera
what THE NETWORK will be

Why VLSI ?

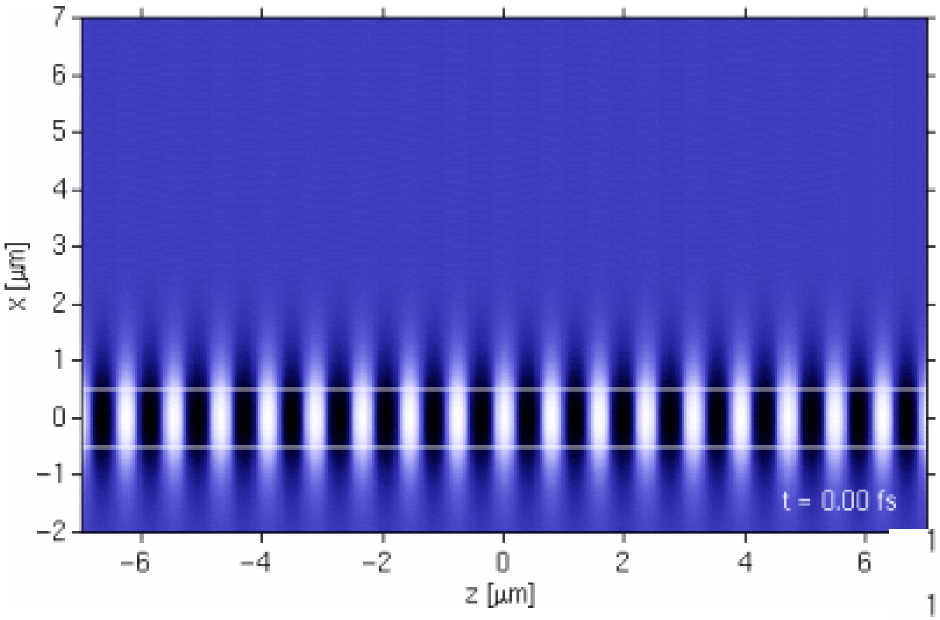
$$Yield \propto 1/(Chip\ Area * \#\ defects\ per\ cm^2)$$

$$\text{“Cost”} \propto Chip\ Cost\ /\ \#\ functions\ /\ Yield$$

70 % of the cost is in the package…

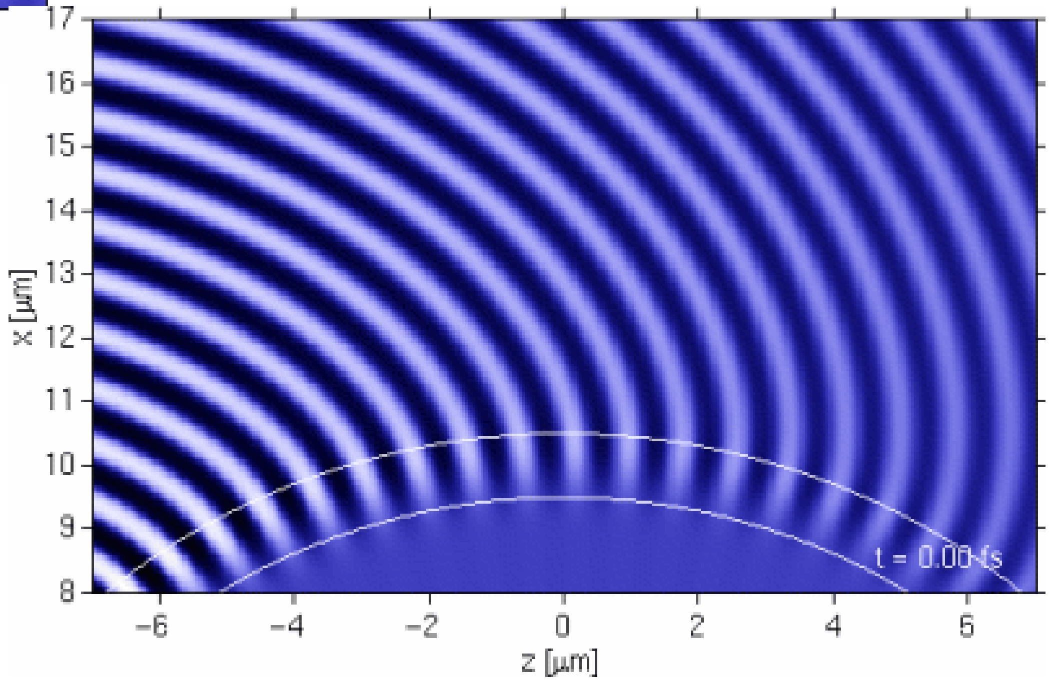
90% of the time goes in testing and validation…

Let's bend the waveguide !

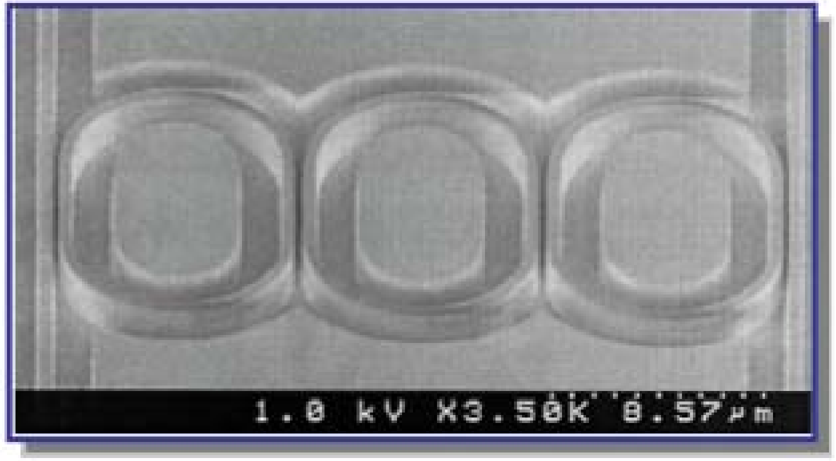


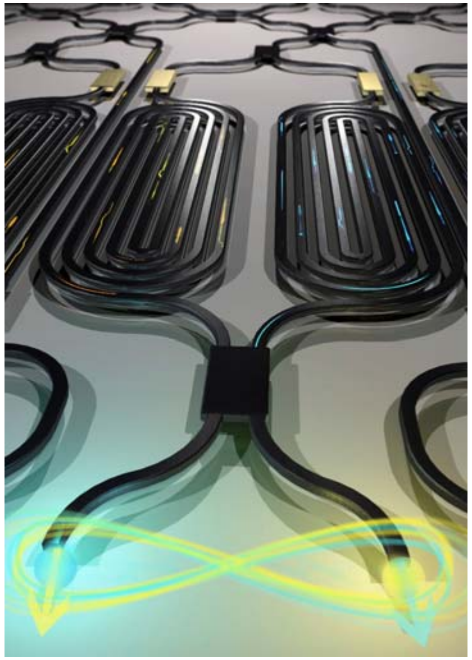
A straight waveguide….

… and a bent waveguide

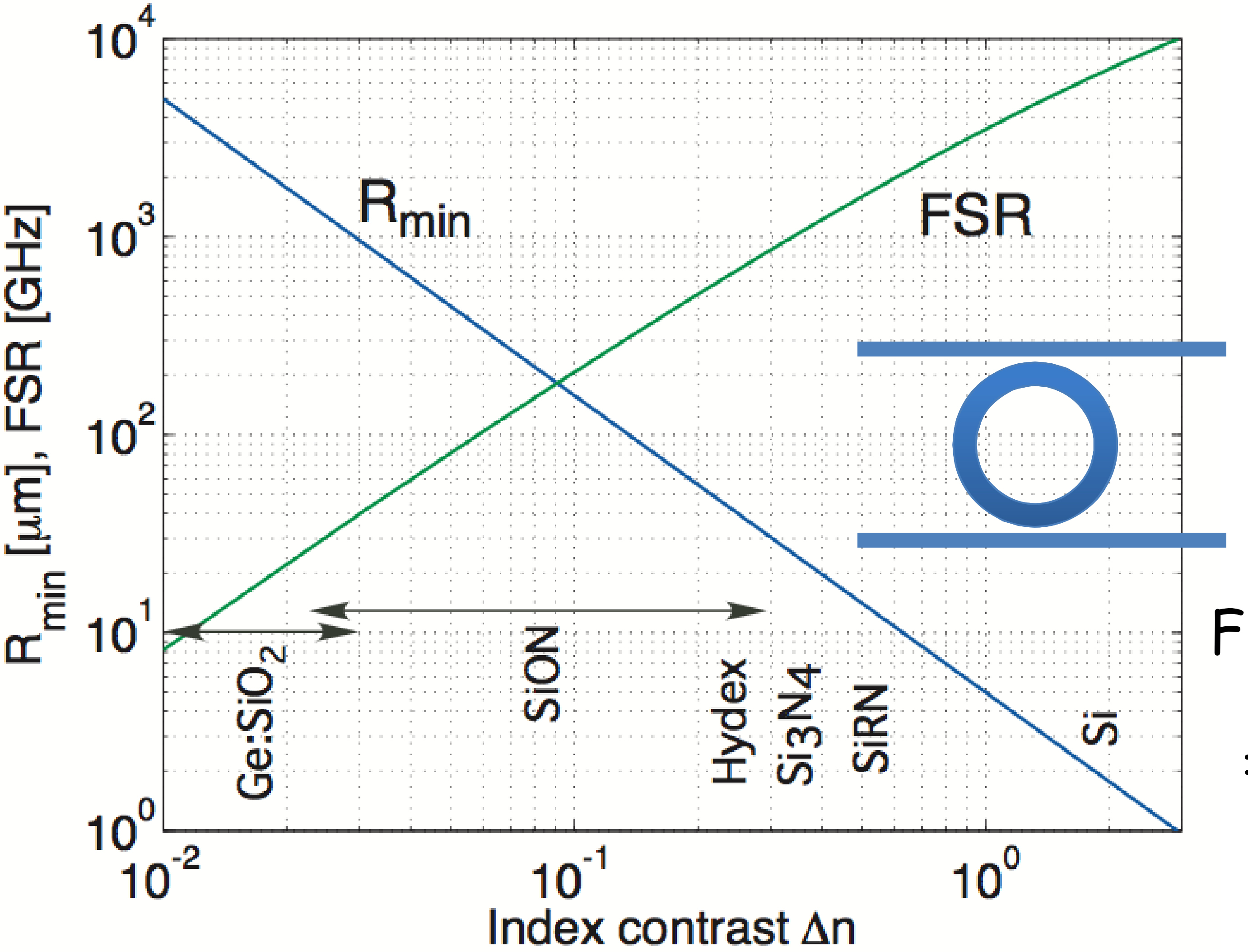


Bends




Bending radius and FSR



Losses Δn^4

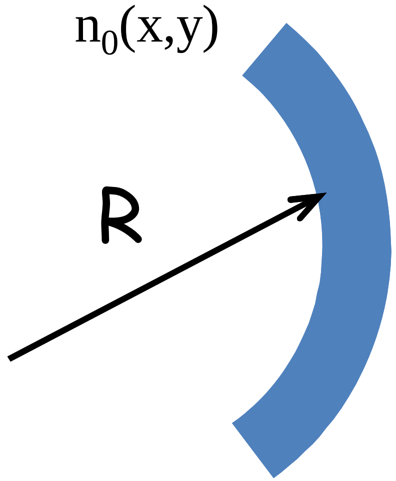
$R_{min} \approx 5 \cdot \Delta n^{-1.5}$ μm

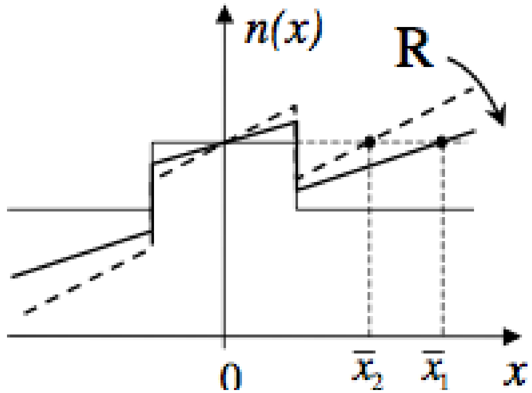
(0.1 dB/rad)

FSR= $c/(2\pi R n_g)$=

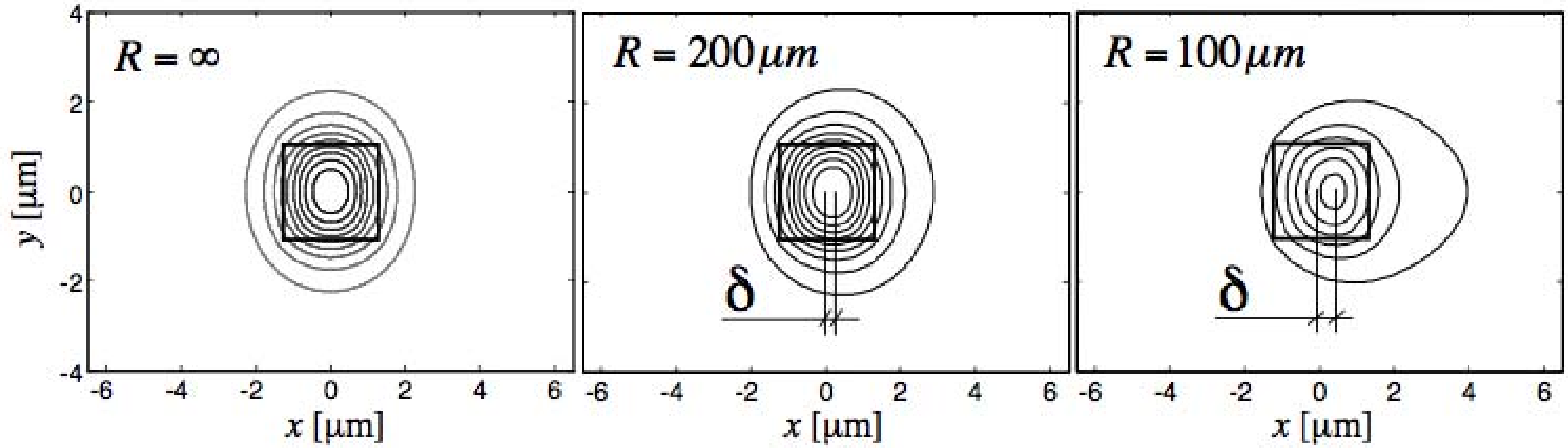
=$29 \cdot \Delta n^{-1.5}$ [nm]

Bent waveguide



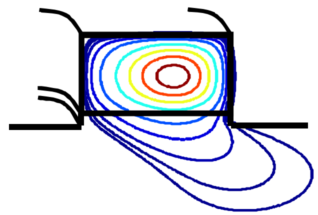


$$n(x,y) = n_0(x,y)e^{x/R} \simeq n_0(x,y)\left(1 + \frac{2x}{R}\right)$$



Bent waveguide

$$e^{R\theta}\, e^{-CR} \qquad n_{eff} = n_{eff0} + \frac{B}{R^2} \qquad \propto R$$



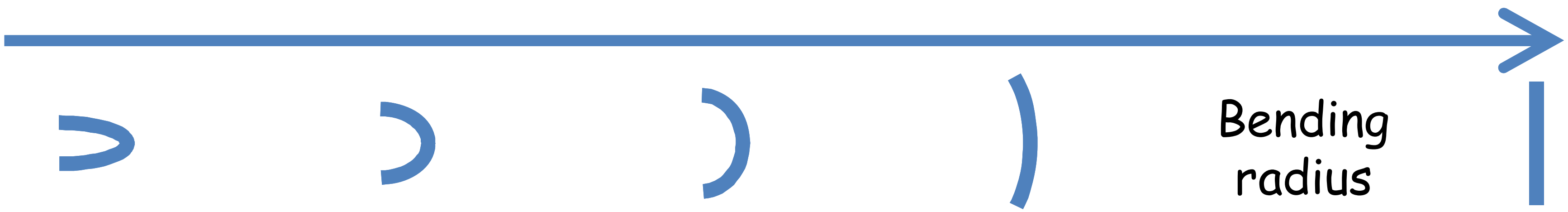
Disaster !

Radiative losses

Effective index perturbation

High order mode excitation

Mode distortion

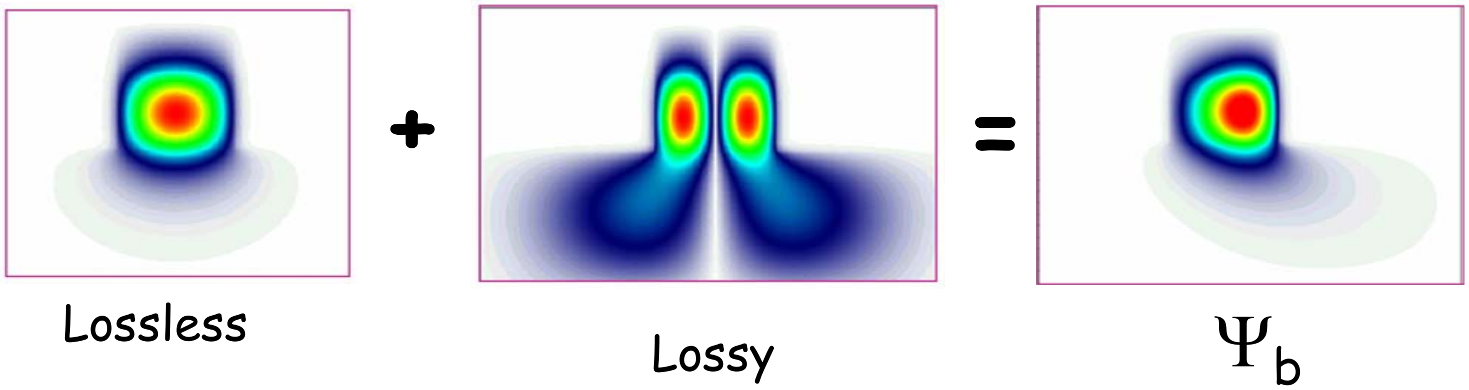


Bend and straight modes

Bend mode=linear combination of straight modes
Straight mode=linear combination of bend modes

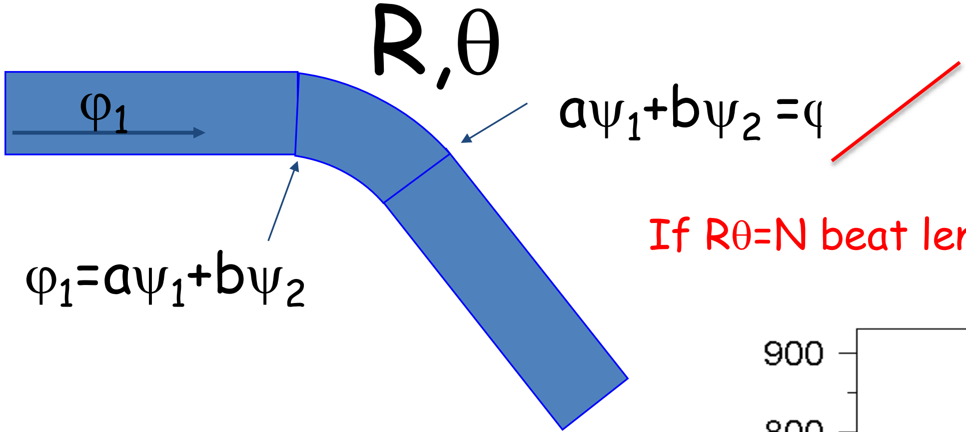
For monomode waveguide only 2 modes are sufficient

$$\Psi_b = a_1\varphi_1 + a_2\varphi_2$$



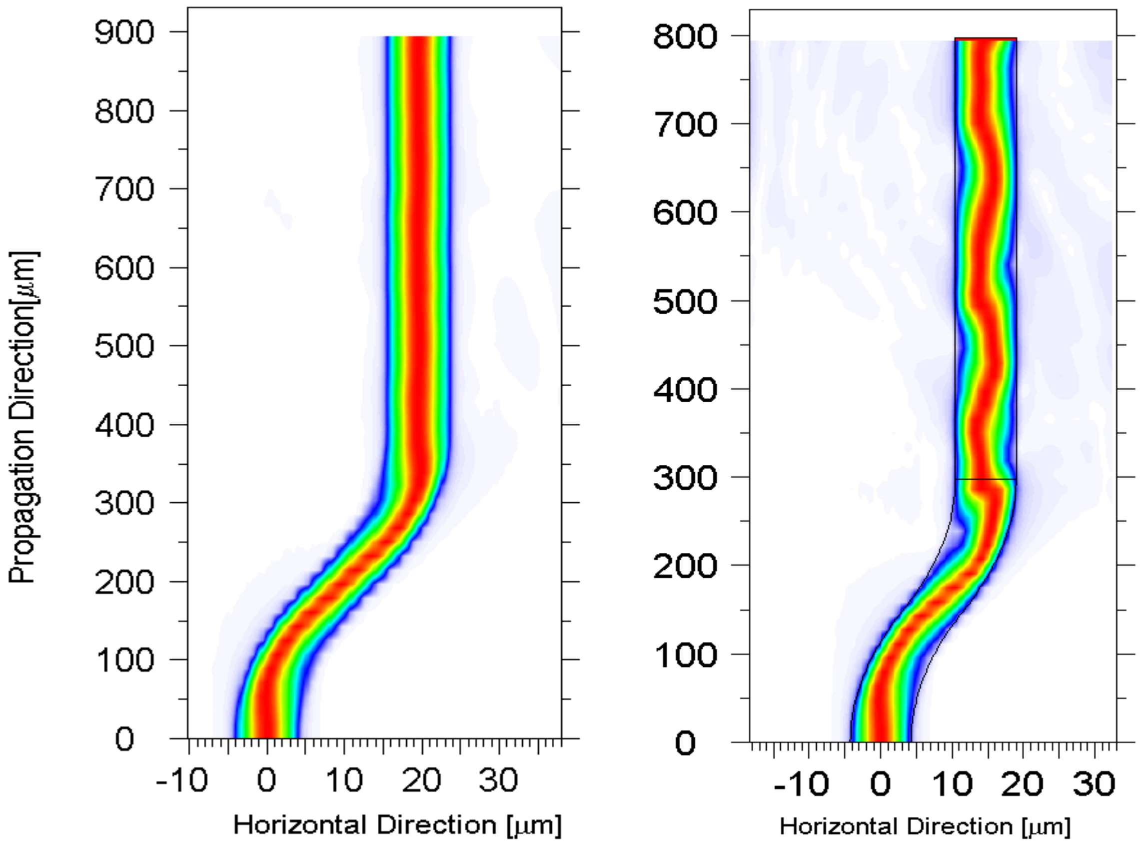
Loss and distortion !

The matched bend



If Rθ=N beat lengths

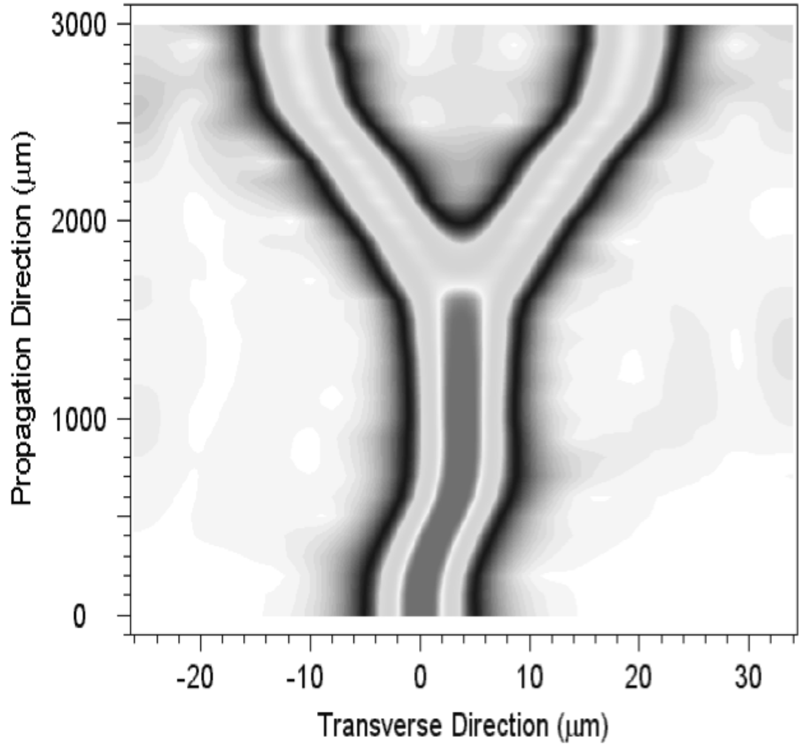
$$R_{mb} = \frac{\sqrt{\left(\frac{2m\pi}{\theta}\right)^2 - 4\beta_1\beta_2 c_{12}^2}}{\beta_1 - \beta_2}$$



The matched bend

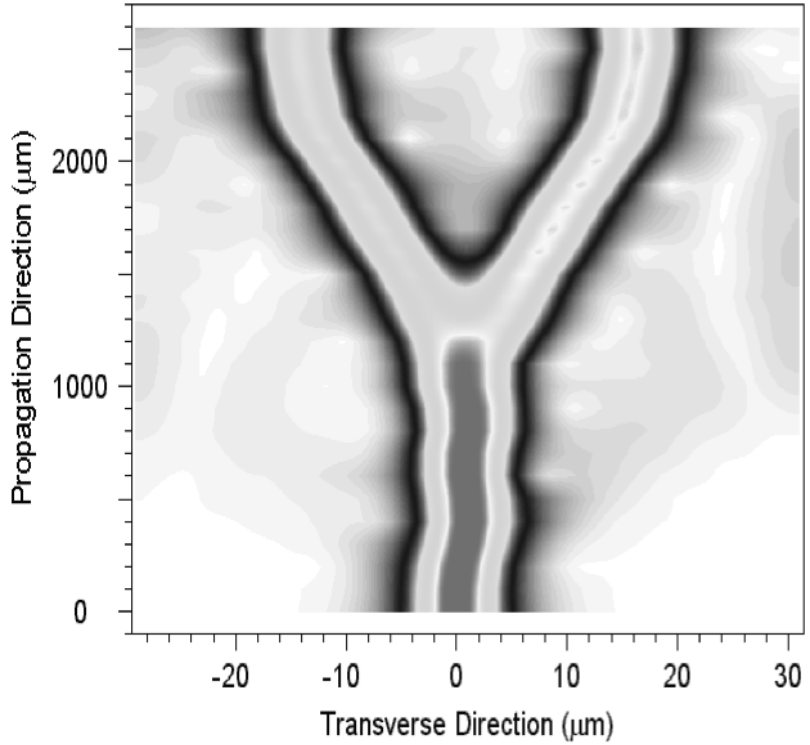
Matched bend

50.0%   49.7%



Unmatched bend

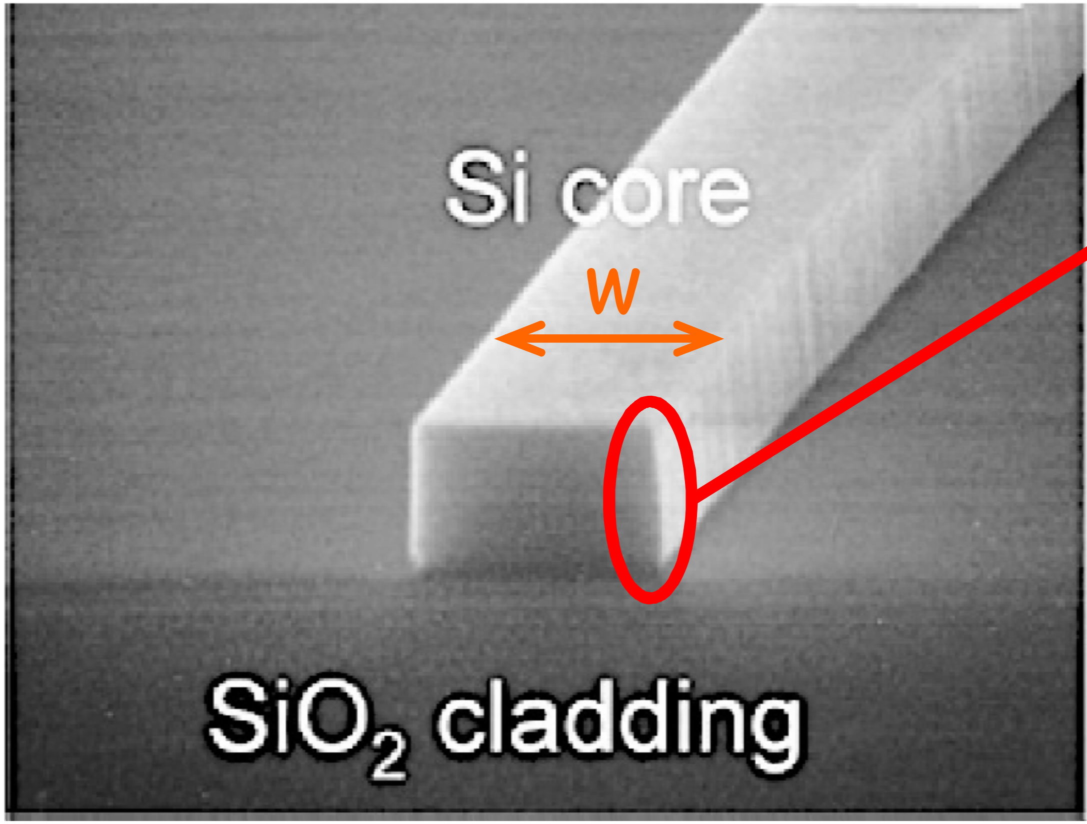
42.7%   56.6%



Lithium Niobate waveguide, R=5 cm $\theta=0.5°$

(Roughness induced) **Backscatter**

Waveguide surface…



Cross section shape

Stress and strain

Sidewall Roughness

Surface states

Doping (10^{15})

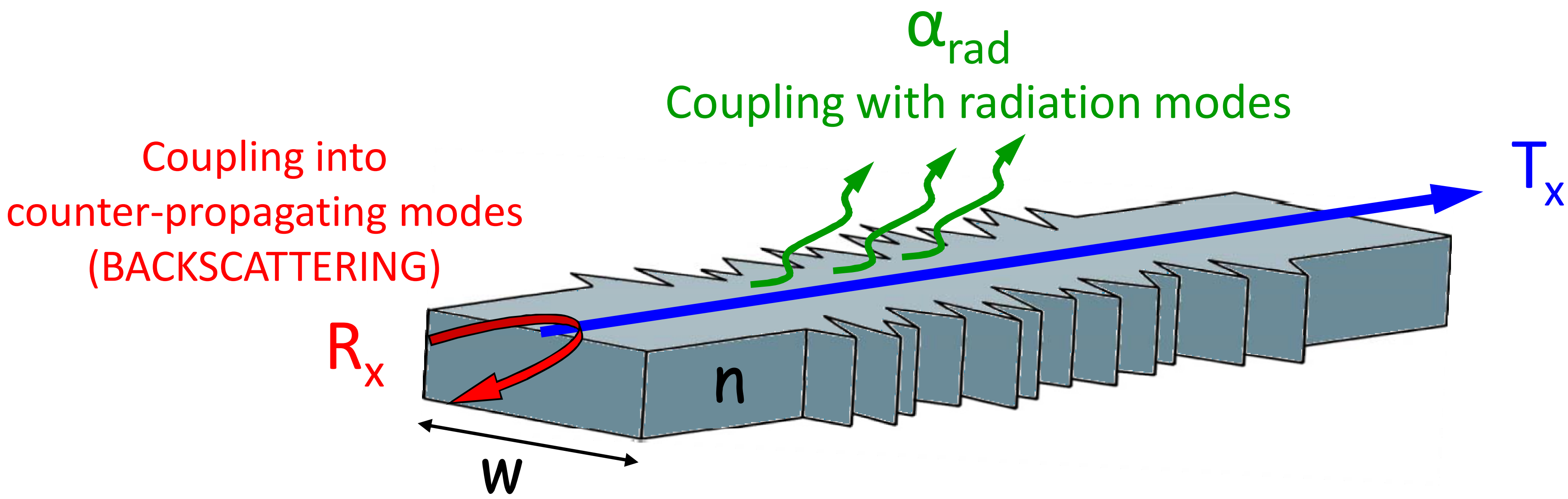
…….

$\Delta n_{eff} / \Delta w = 2 \cdot 10^{-3}$

$\Delta w = 1\text{nm} \rightarrow \Delta\lambda = 1\text{nm}$

$\sigma = 1\text{nm} \rightarrow \alpha = 1\ \text{dB/cm}$

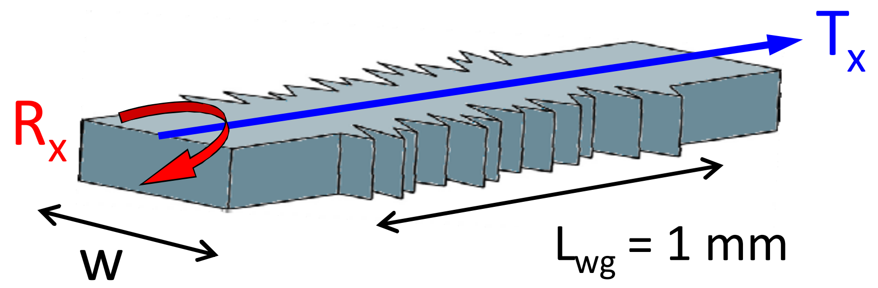
Sidewall roughness δw → Scattering processes



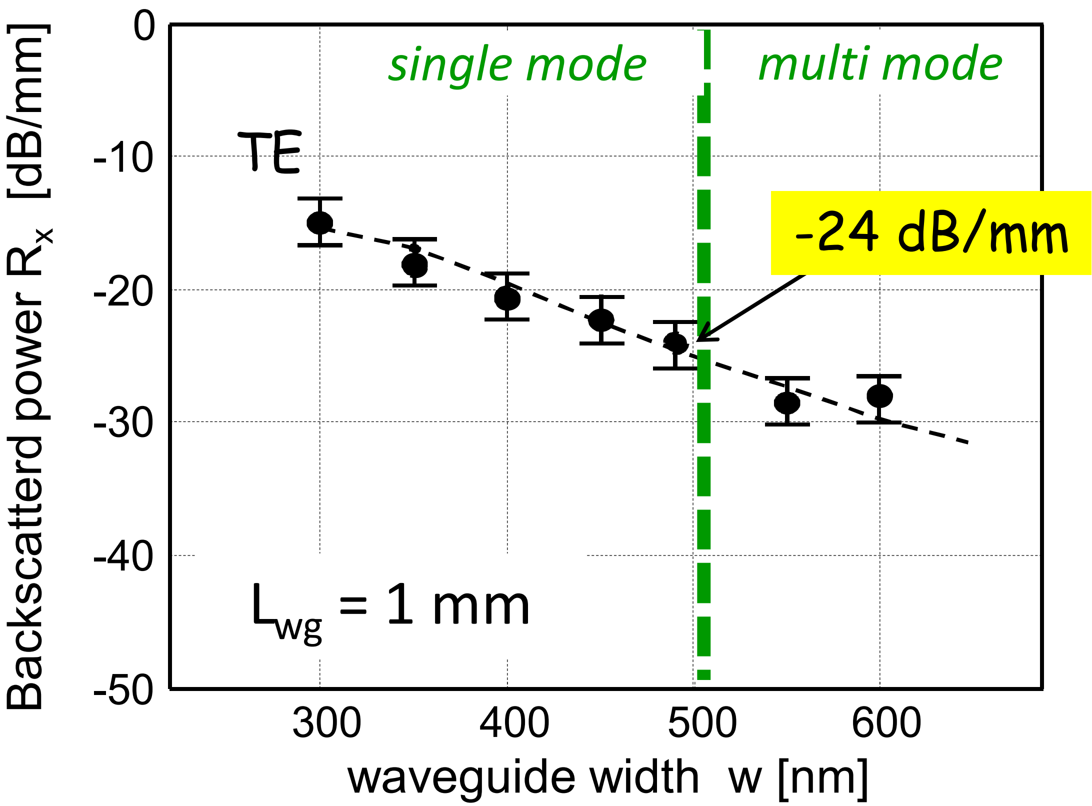
Scattering $\propto$ δw^2, Δn^2

Silicon wires: $\delta w \approx 5$ nm → $\alpha_{tot} = 10$ dB/cm

Backscattering in silicon wires



Roughness rms $\delta w < 2$ nm

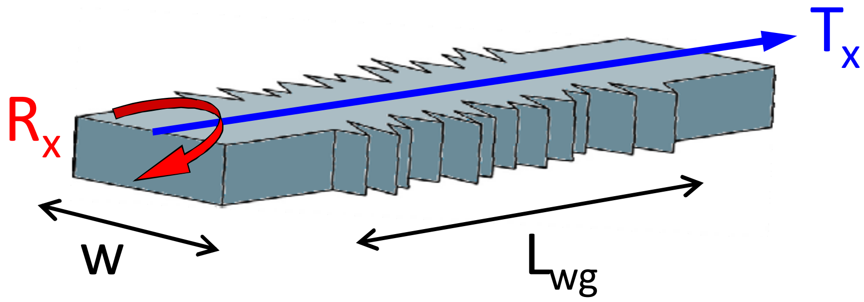


Backscattering gives a small contribution to propagation loss

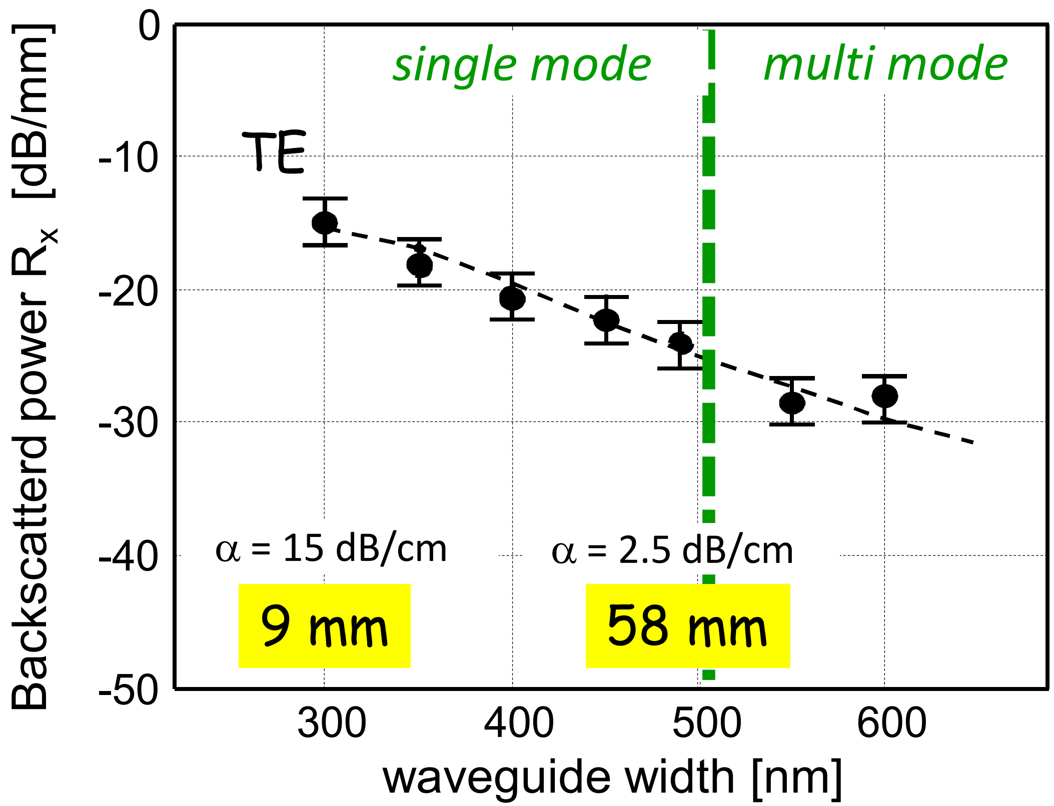
$R_x \approx 10\% \, \alpha$

However…

Backscattering in silicon wires



Roughness rms $\delta w < 2$ nm



T_x reduces with L_{wg}

R_x increase with L_{wg}

$T_x = R_x$

Reflection equals transmission after a wg length L_{wg} of only…

High vs low index contrast

Silicon (Δn = 140%)

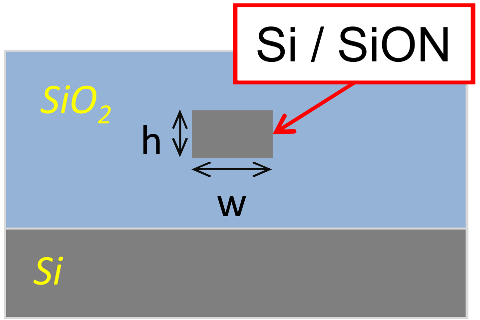
h = 220 nm

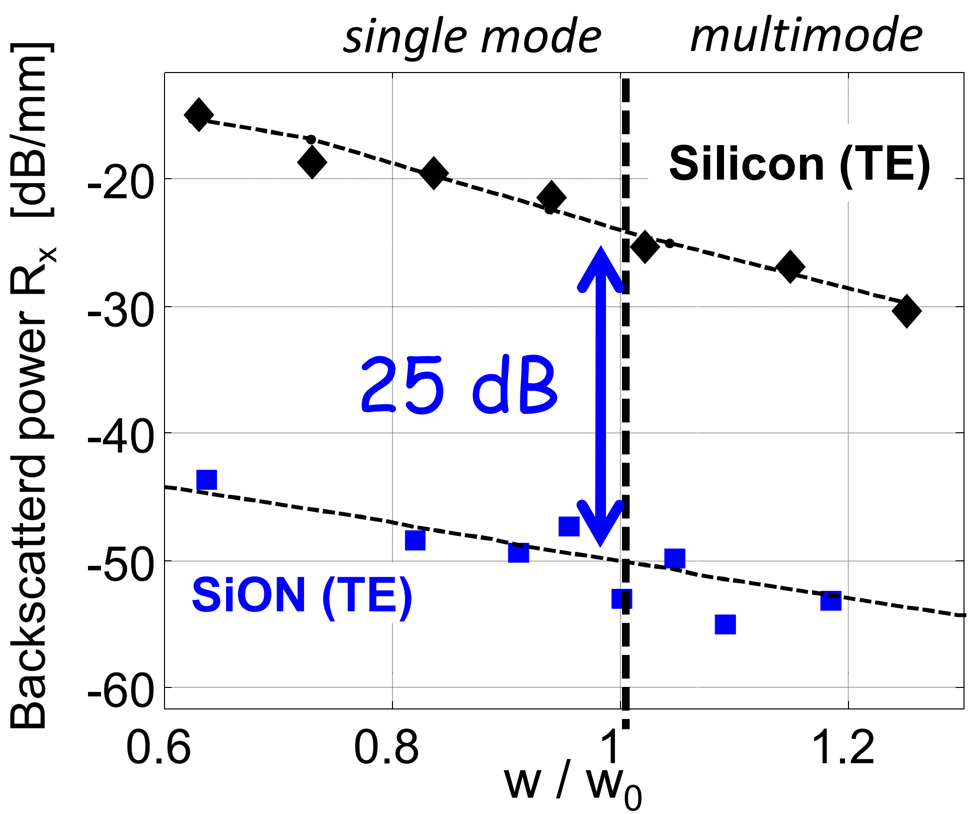
w_0 = 490 nm

SiON (Δn = 4.5%)

h = 2.2 μm

w_0 = 2.2 μm





<u>> 2 order of magnitude</u>

higher than in

low Δn waveguides

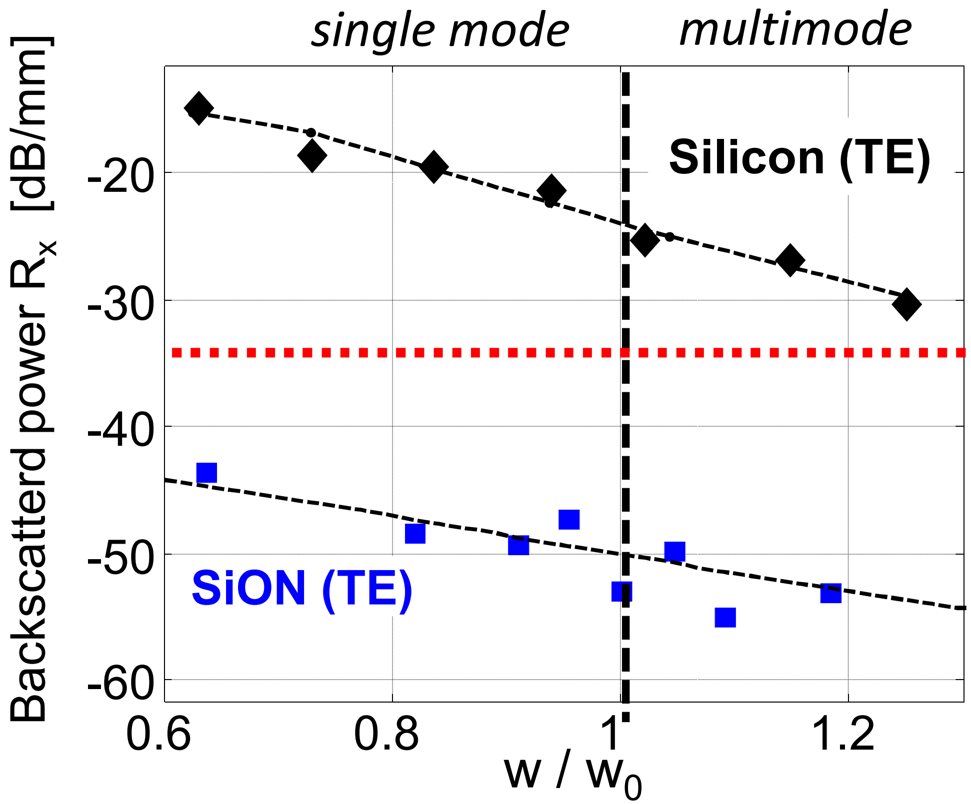
High vs low index contrast

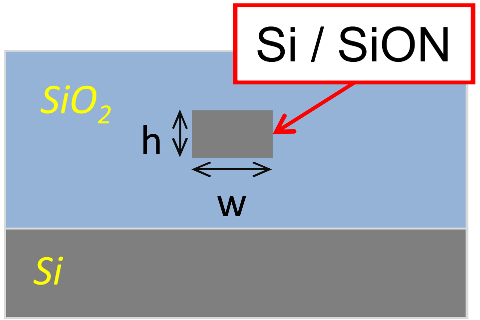
Silicon (Δn = 140%)

h = 220 nm
w_0 = 490 nm

SiON (Δn = 4.5%)

h = 2.2 μm
w_0 = 2.2 μm





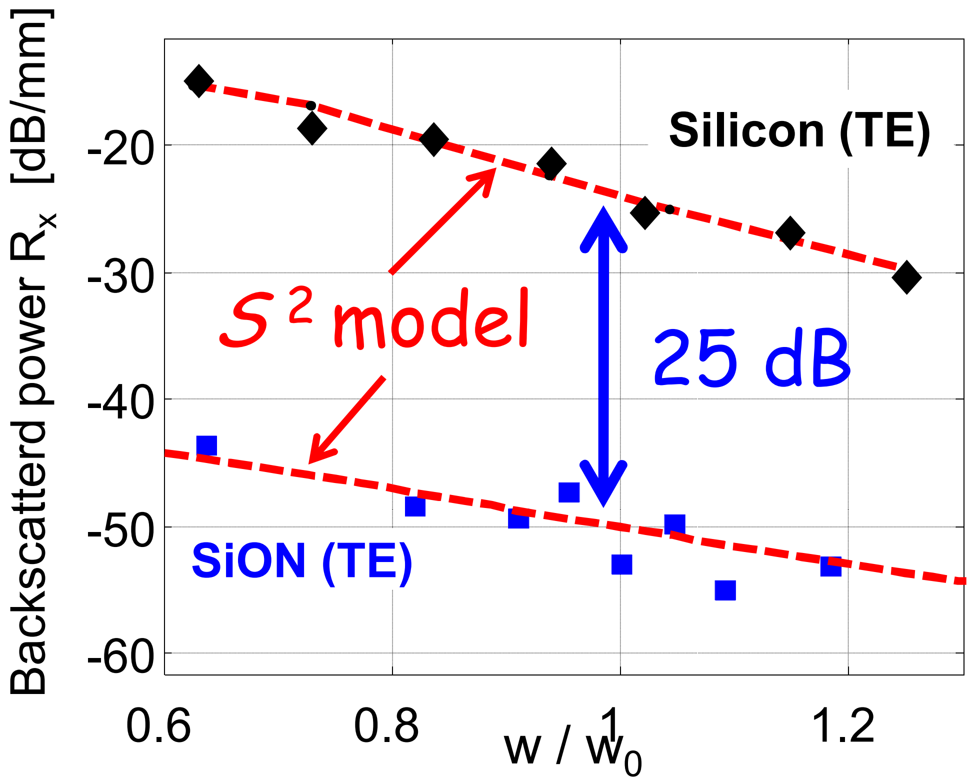
Maximum waveguide -32 dB length for a given backscattering level ?

SOI WG (Δn ≈ 140 %)	SiON WG (Δn ≈ 4.5 %)	SiO_2:Ge WG (Δn < 1 %)	Optical fiber (Rayleigh)
L = 200 μm	L = 7 cm	L = 1 m	L = ∞

What backscattering depends on?

Let's find a golden rule

Given a certain roughness δw, backscattered power depends only on the square sensitivity S^2



$$S = \frac{\partial n_{eff}}{\partial w}\left(= \frac{\partial n_{eff}}{\partial \lambda} \right) = n_g - n_{eff}$$

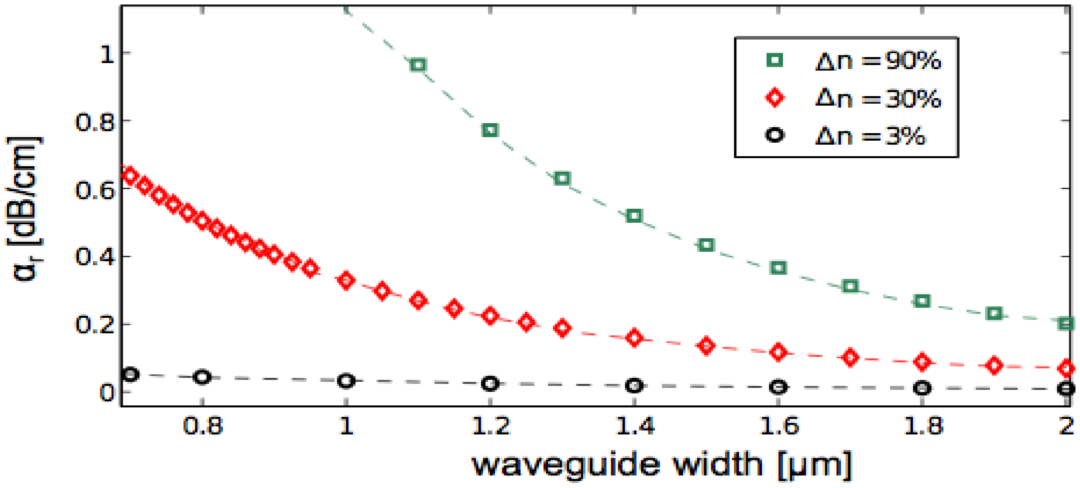
The S^2 relation holds independently of size, shape, material and index contrast (Δn)

F. Morichetti *et al.*, PRL 104, 033902 (2010)

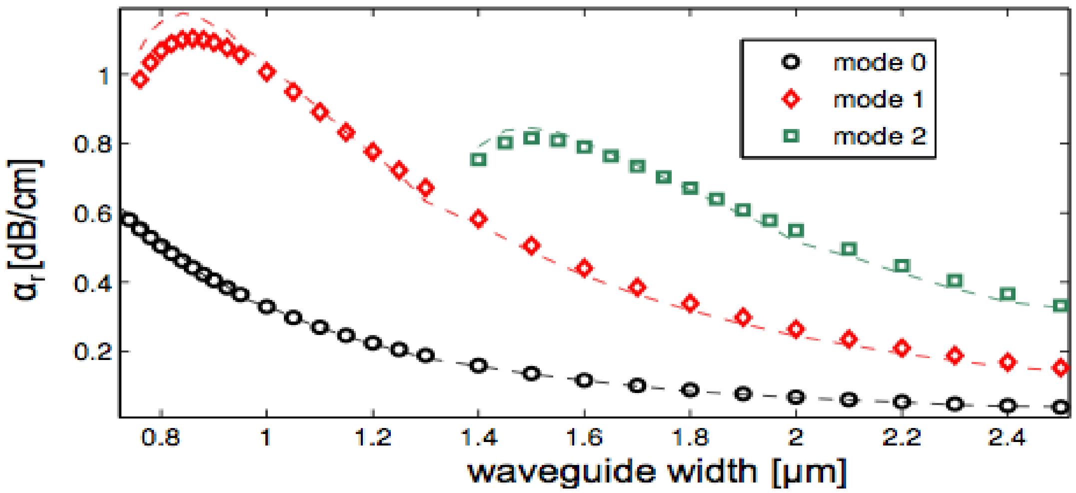
Also attenuation goes as n_g-n_{eff}

$$\alpha_r = A\frac{\partial n_{eff}}{\partial w}$$

$$(n_g - n_{eff}) = \frac{2c}{P}\int_{-\infty}^{+\infty} dxdy[\mathbf{E}_z \cdot \mathbf{E}_z^* + \mathbf{H}_z \cdot \mathbf{H}_z^*]$$



(a)

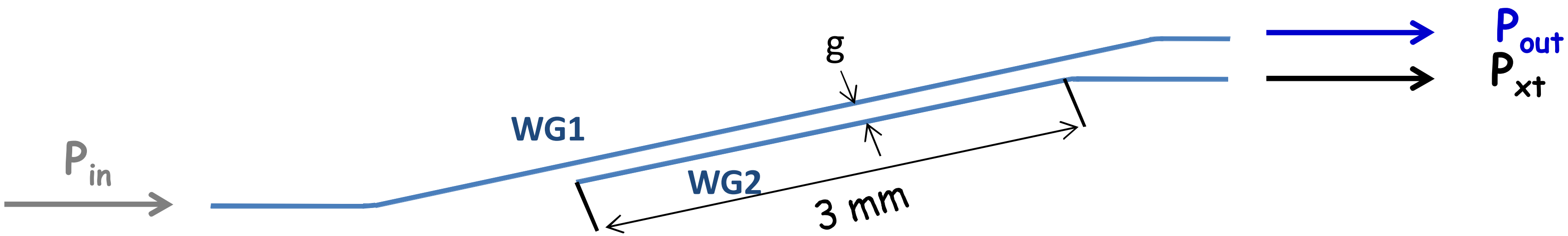


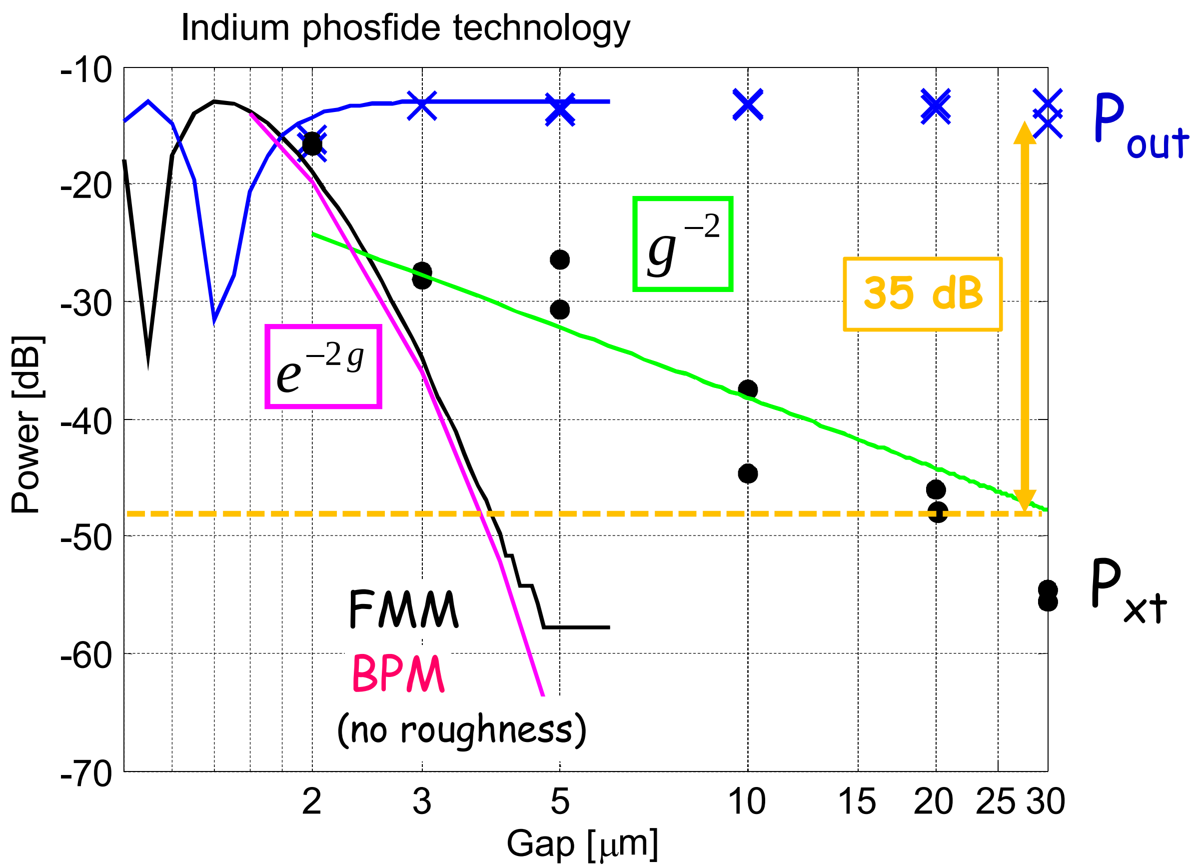
(b)

Attenuation and backscatter vs technology

Technology	$\Delta n\%$	loss [dB/cm]	r_b [dB/mm]	L@-30dB
SOI	140	2.5	-25	0.3 mm
Si_3N_4	37	$0.1 \div 2$	$-30 \div -40$	$1 \div 10$ mm
SiON	4.5	0.2	-50	10 cm
InP/InGaAsP	$3.0 \div 5.0$	$1.0 \div 2.0$	<-40	30 cm
SiO_2:Ge	< 1	0.1	<-60	> 1 m
Fibre [61]	0.2	$2 \cdot 10^{-6}$	-102 (Rayleigh)	∞

Radiation mode Xtalk





$g < 2.5\ \mu m$

Power transfer due to **evanescent** mode coupling

$$\propto \exp(-2g)$$

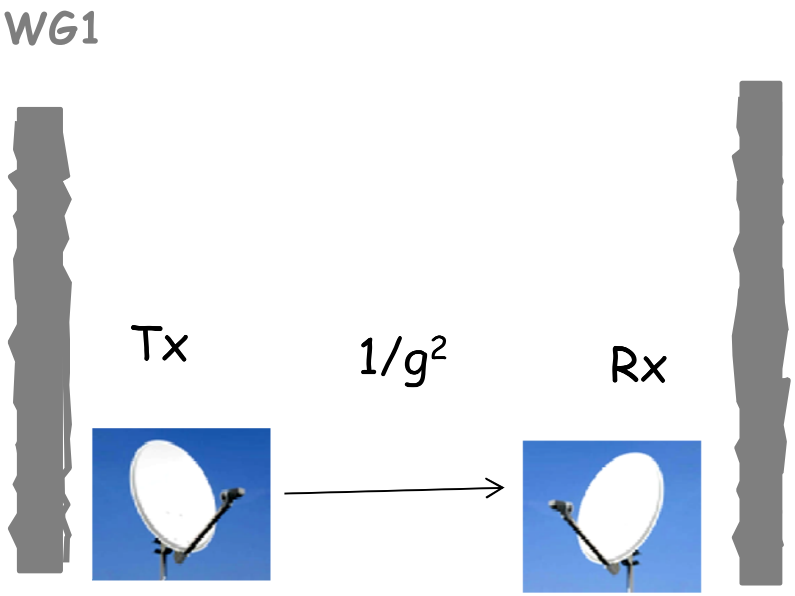
$2.5\ \mu m\ g < 30\ \mu m$

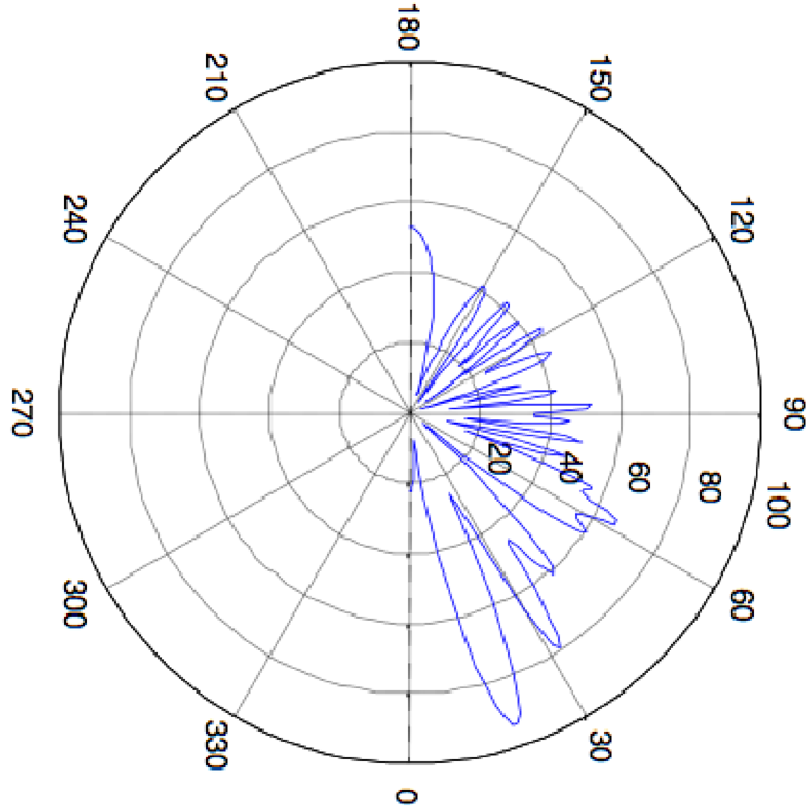
Xtalk due to **radiation** mode coupling

$$\propto g^{-2}$$

WG2

An intuitive view of xtalk





Minimize S to minimize backscatter

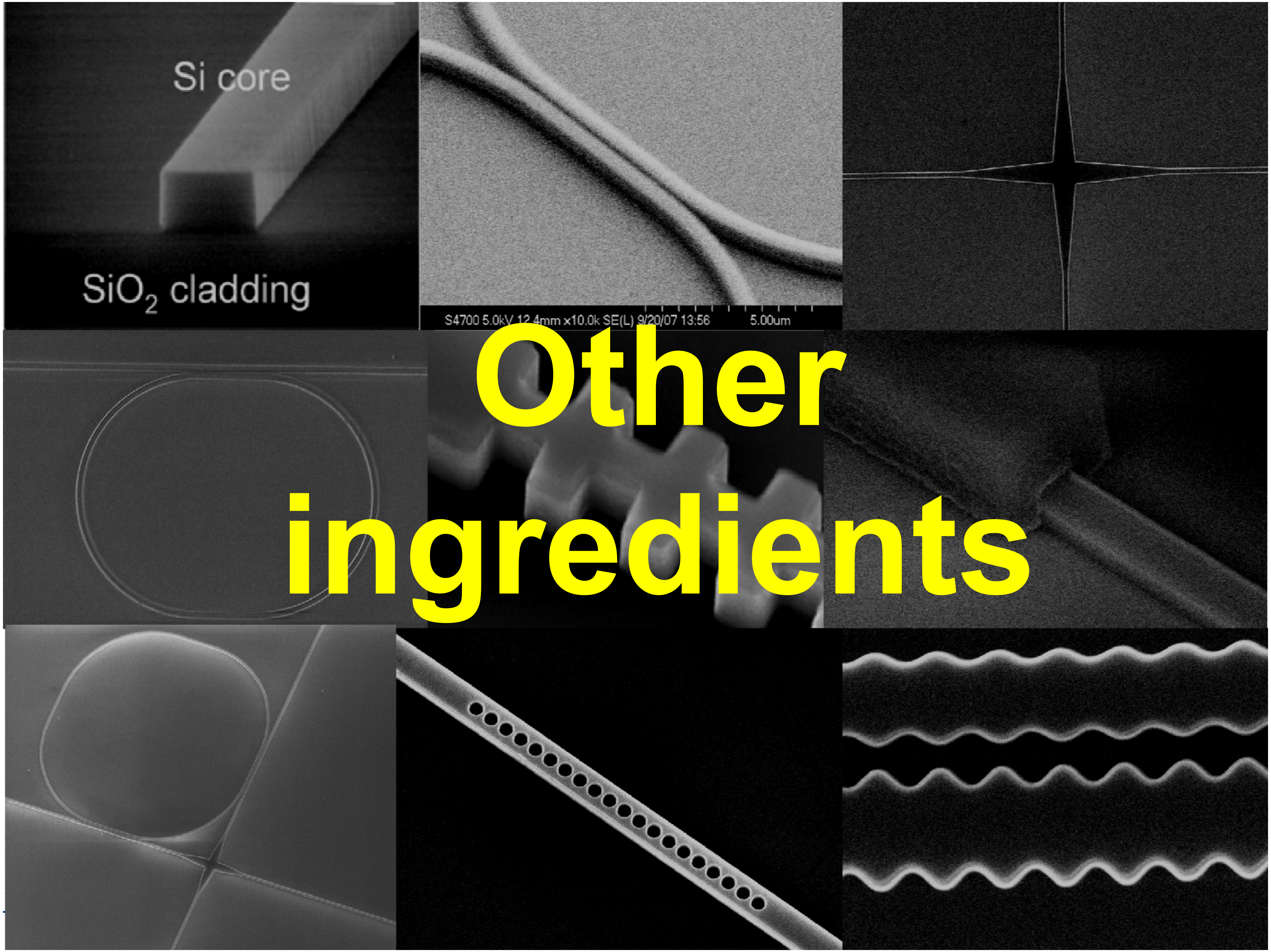
- Reduce the index contrast: S_{SOI}=1.6e-3; S_{SiON}=1e-5

- Use TM mode: in SOI S_{TE}=1.7e-3; S_{TM}=7e-4 (> 15 dB)

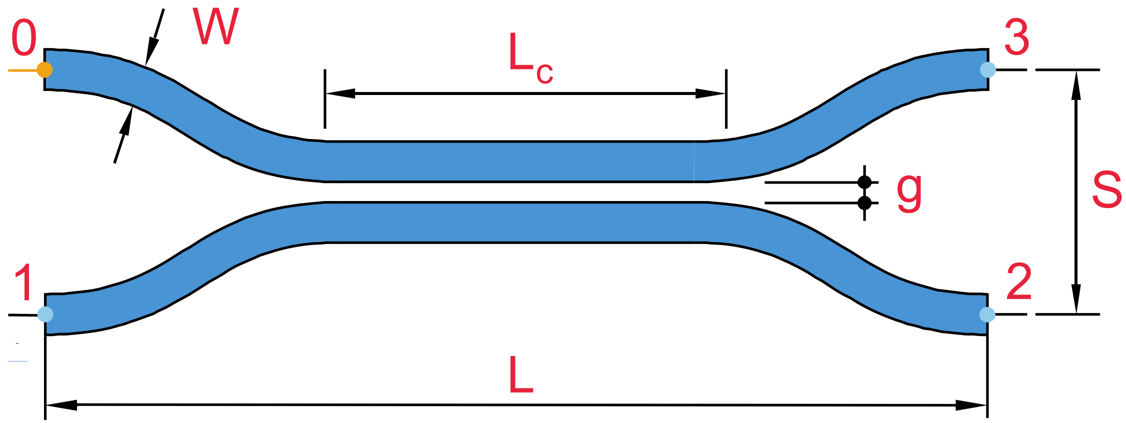
- Use a suitable upper cladding: backscatter of SOI wg with
  Air -18dB/mm; SiO_2 -21dB/mm; SU8 -23dBmm

- Engineer the waveguide cross section shape:
  silicon wire -21dB/mm; rib -39 dB/mm

Other ingredients



Directional coupler

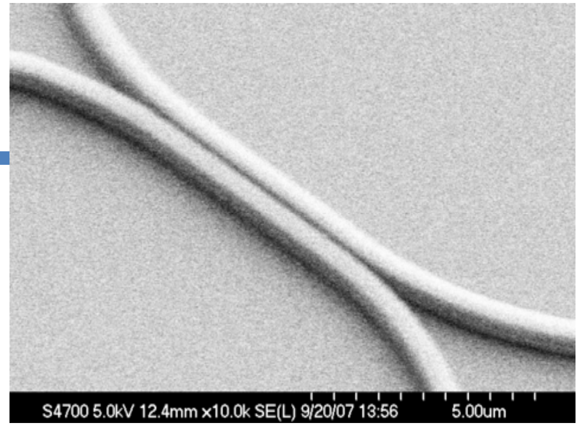


The transmission matrix of the coupler is

$$T_C = \sqrt{I_L} e^{-j\frac{2\pi}{\lambda}L_o} \begin{bmatrix} \cos\delta L_{ct} + jR\sin\delta L_{ct} & -jS\sin\delta L_{ct} \\ -jS\sin\delta L_{ct} & \cos\delta L_{ct} - jR\sin\delta L_{ct} \end{bmatrix} \quad (7)$$

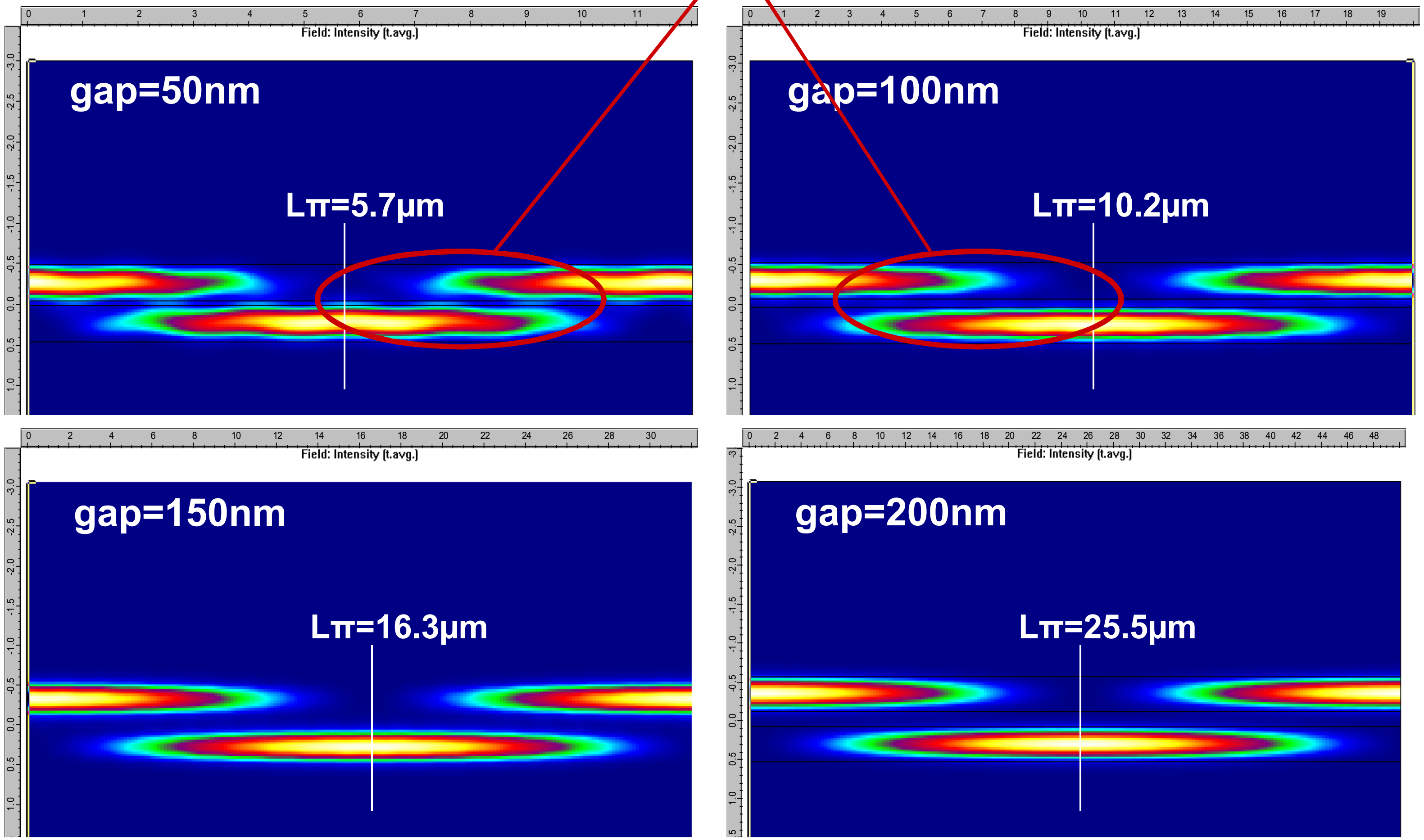
where $R = \Delta\beta/2\delta$ and $S = \kappa/\delta$ measure the degree of asymmetry of the structure, and $\delta = \sqrt{\Delta\beta^2/4 + \kappa^2}$. Clearly $K = S^2 \sin^2 \delta L_{ct}$. The coupling length is $L_{ct} = L_c + L_t$, being $L_t = \sqrt{\pi R_t/\gamma}$ the contribution of the transition regions.

Directional coupler

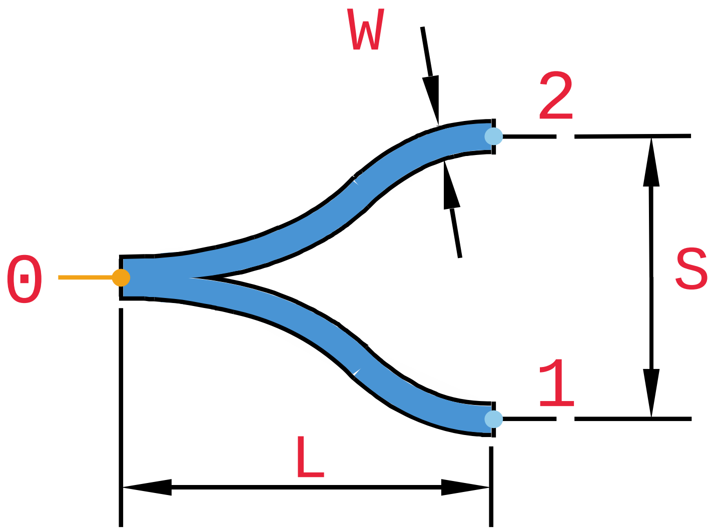


Typical Insertion Loss < 0.1 dB (0.03-0.06 dB)

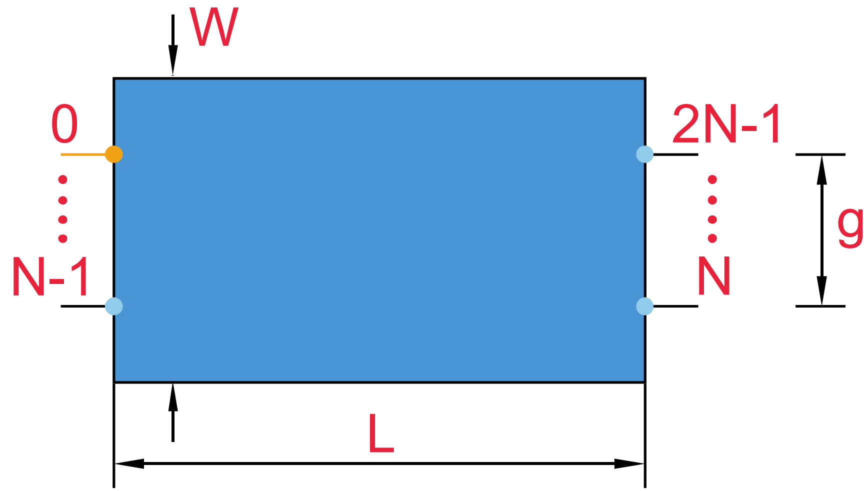
Small gaps excite higher order modes



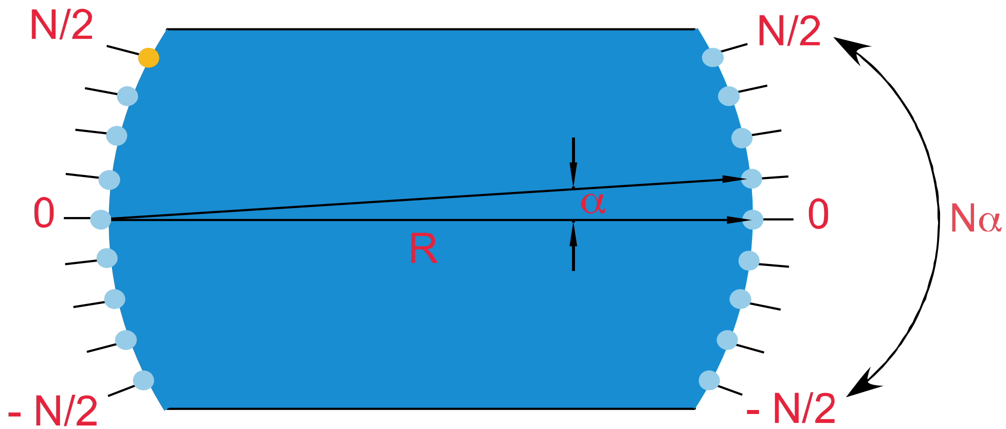
Other splitter/combiners



Y-Branch

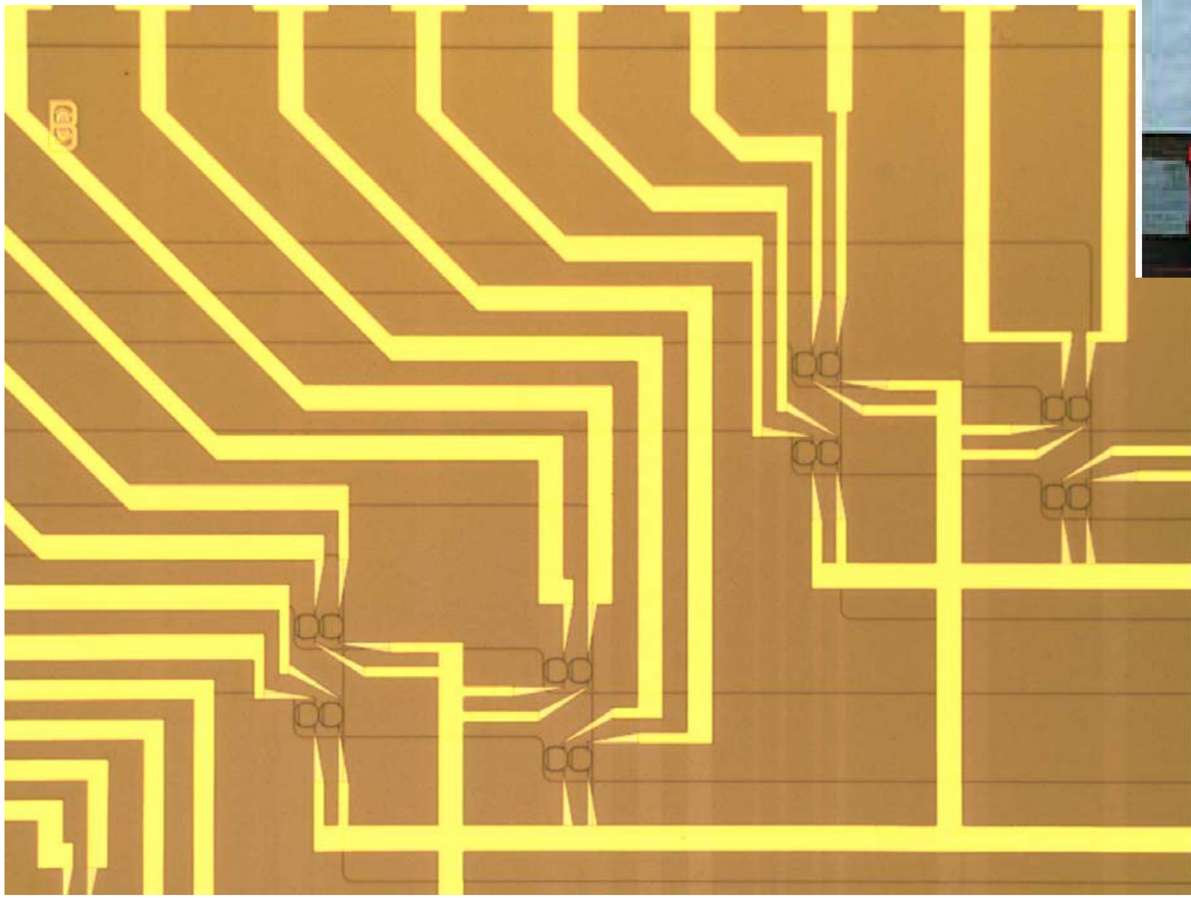


MMI – Multimode Intertference Coupler

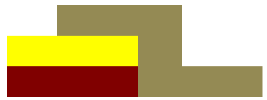


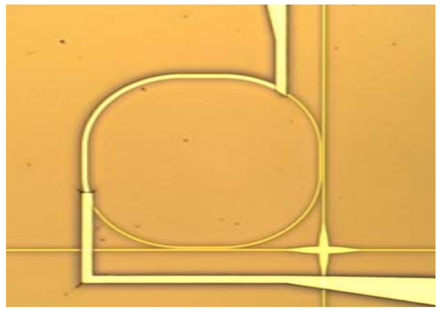
Star Coupler

Power is nothing without control…

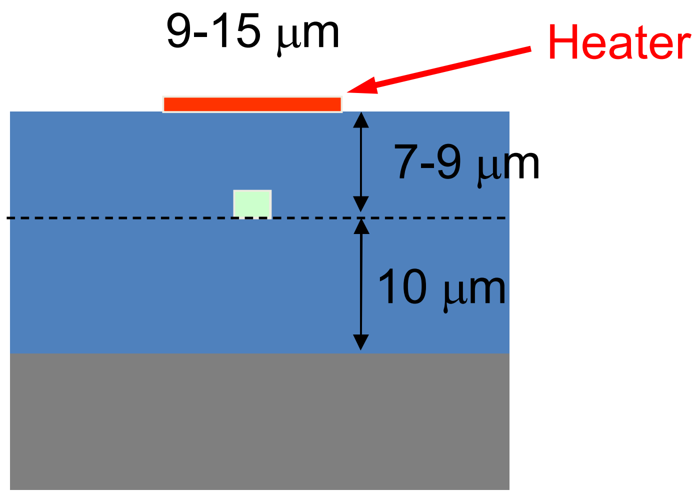


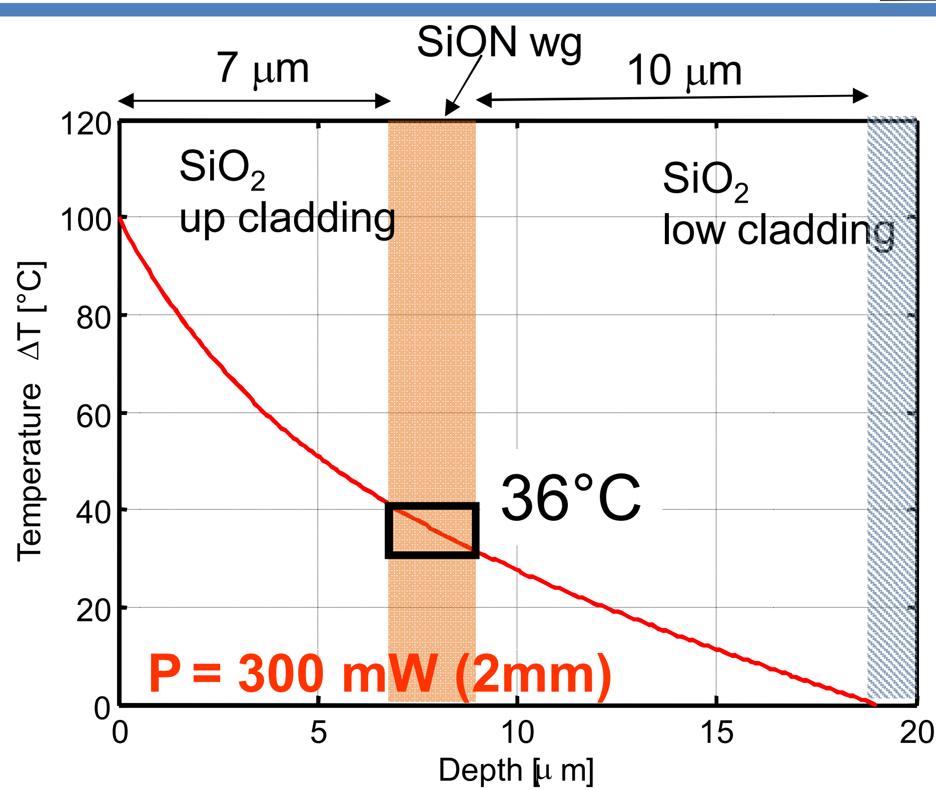
Au+NiCr+Ti





Thermal Control in SiON





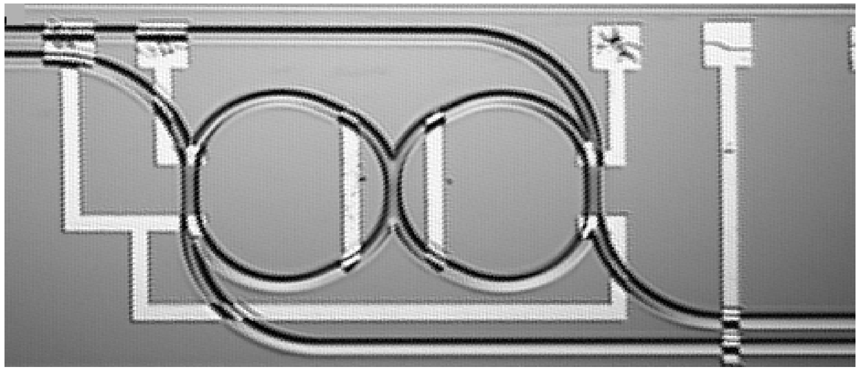
Typical length 1-3 mm

π shift =300mW (100°C)

$\Delta n_{eff} / \Delta T = 1.1 \cdot 10^{-5}\ °C^{-1}$

Response time: ~100μs

$\Delta B < 2 \cdot 10^{-5}$ /100°C

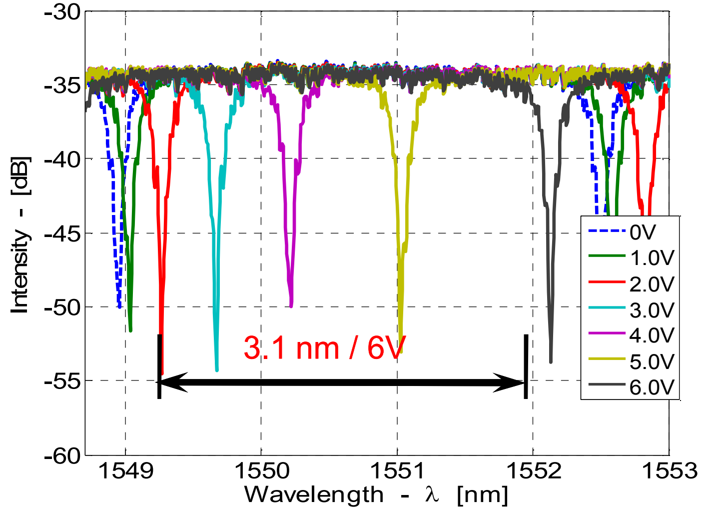


Thermal Control in SOI

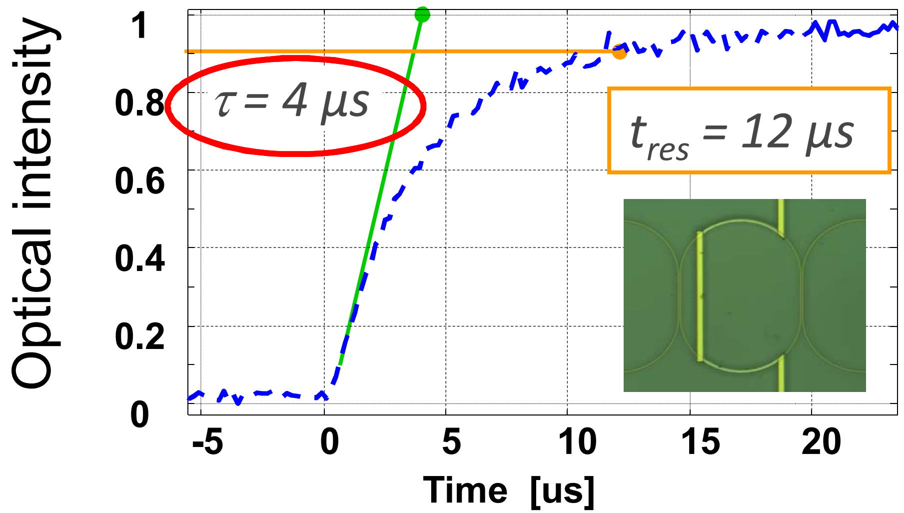
Thermo-optic efficiency

Power consumption: 52 µW/GHz
12.5 mW/GHz in SiON

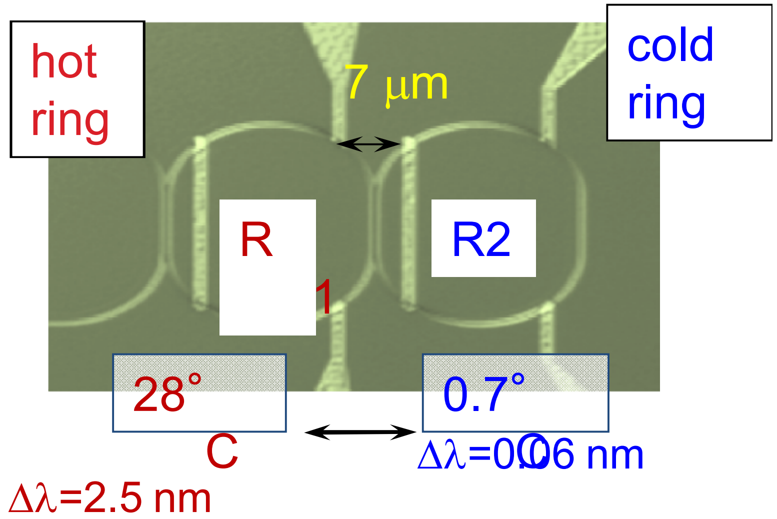
Δf=2B=200 GHz = 10 mW/ring



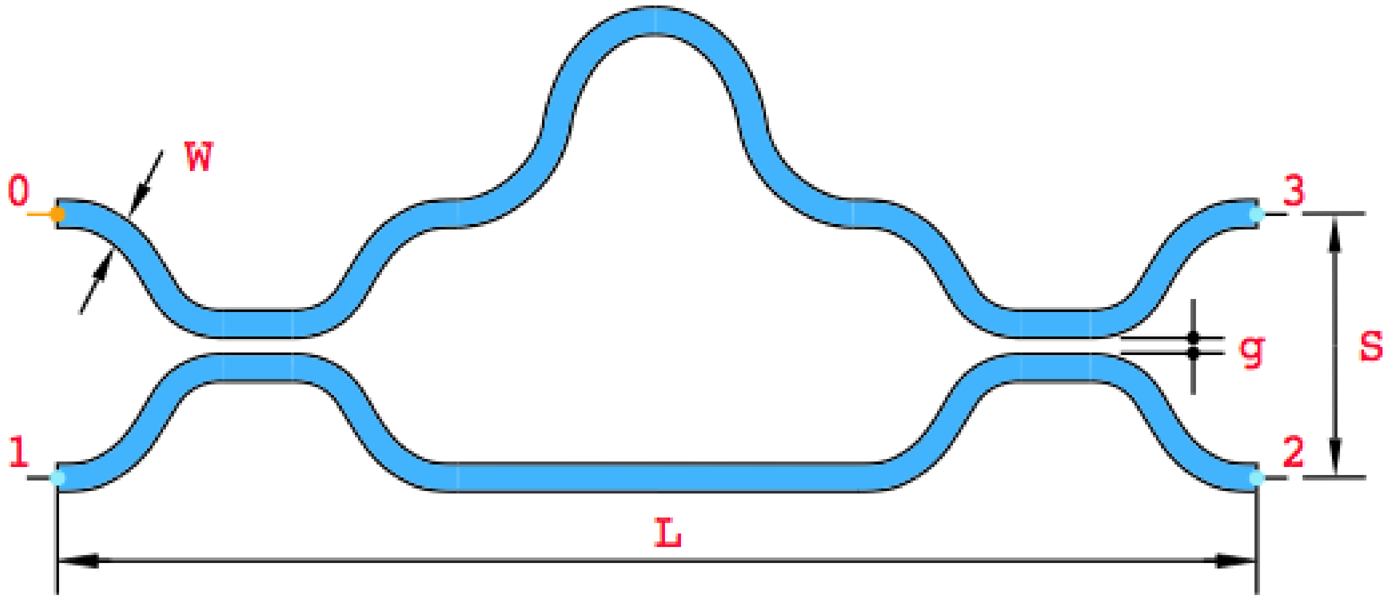
Time response



Thermal crosstalk



Mach-Zehnder interferometer (Filter)



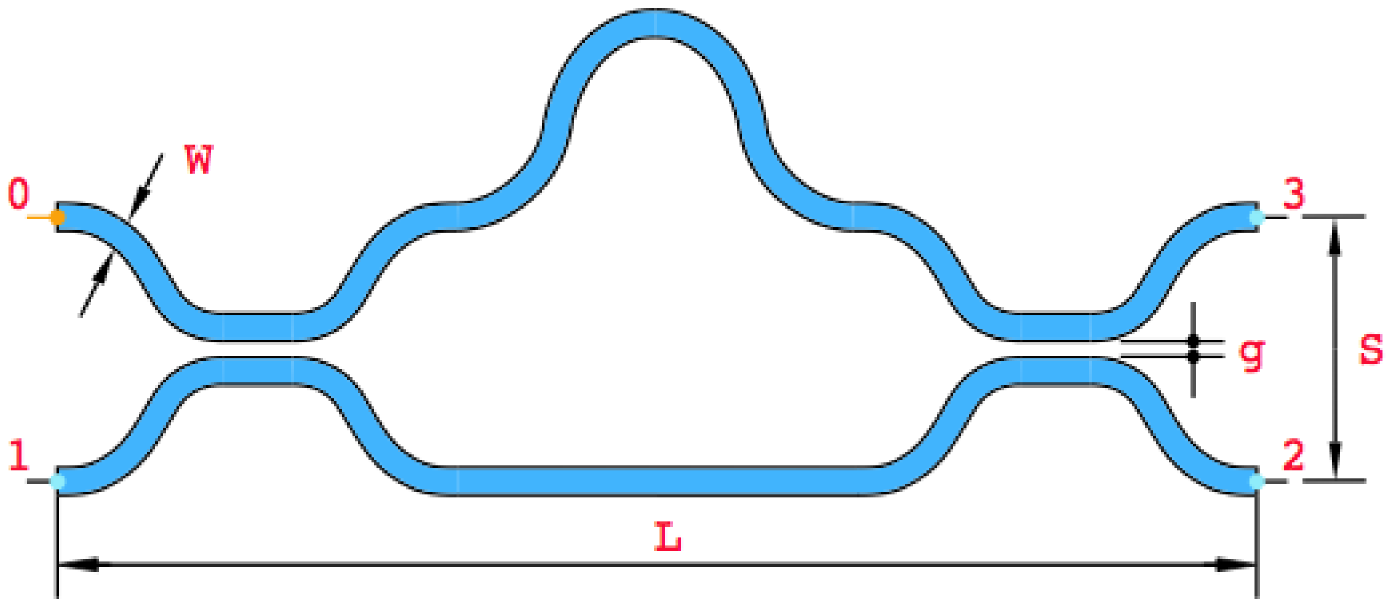
It is a Finite Impulse Response filter, FIR

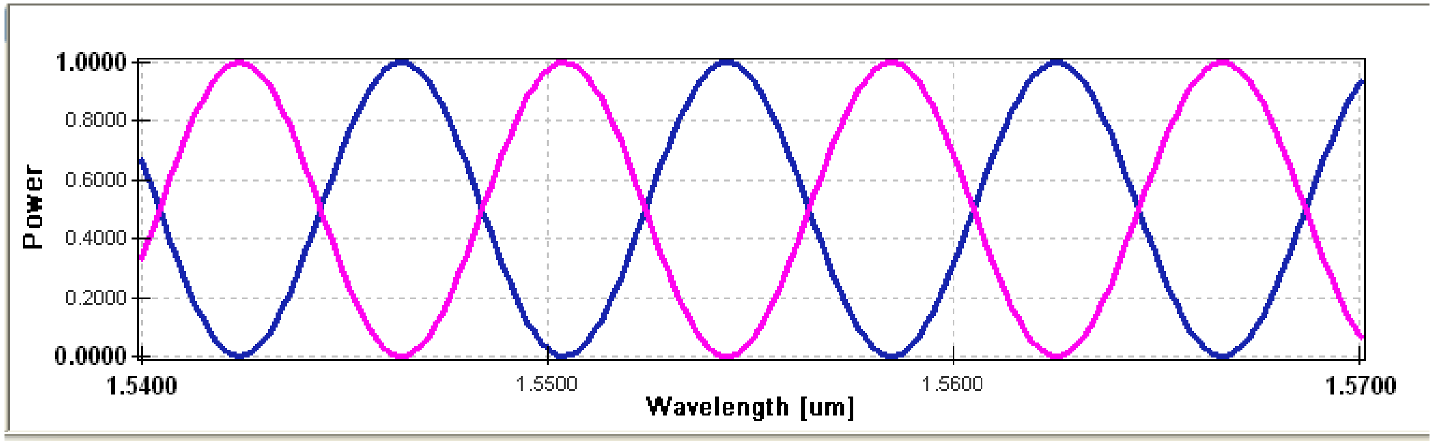
DROP port: 1 zero

THROUGH port: 1 zero

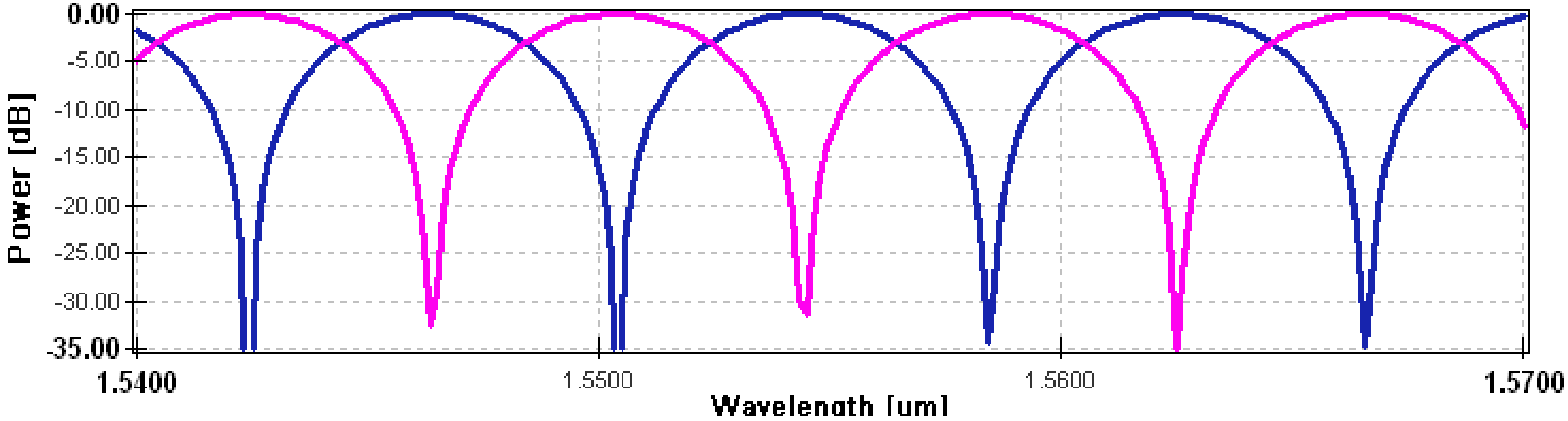
(2 zeroes in the origin)

Mach-Zehnder interferometer (Filter)



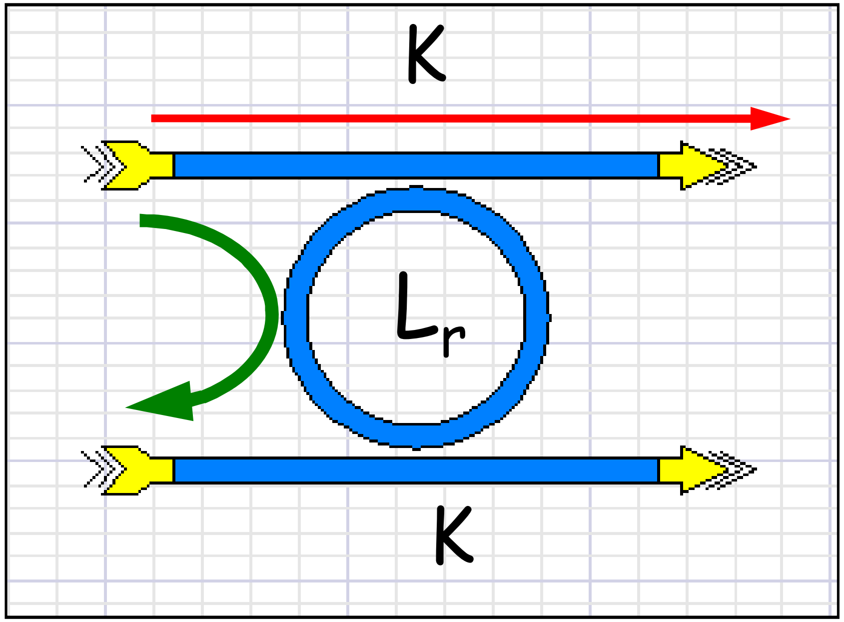


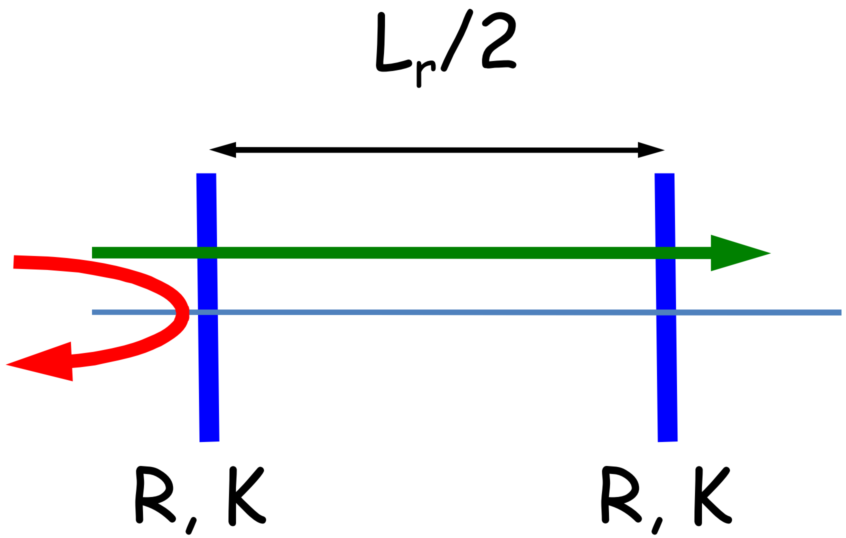
Mach-Zehnder interferometer (Filter)



$$FSR = \frac{c}{n_g \Delta L} \qquad \frac{2\pi}{\lambda} n_{eff} \Delta L = 2M\pi$$

Ring resonators = Fabry-Perot



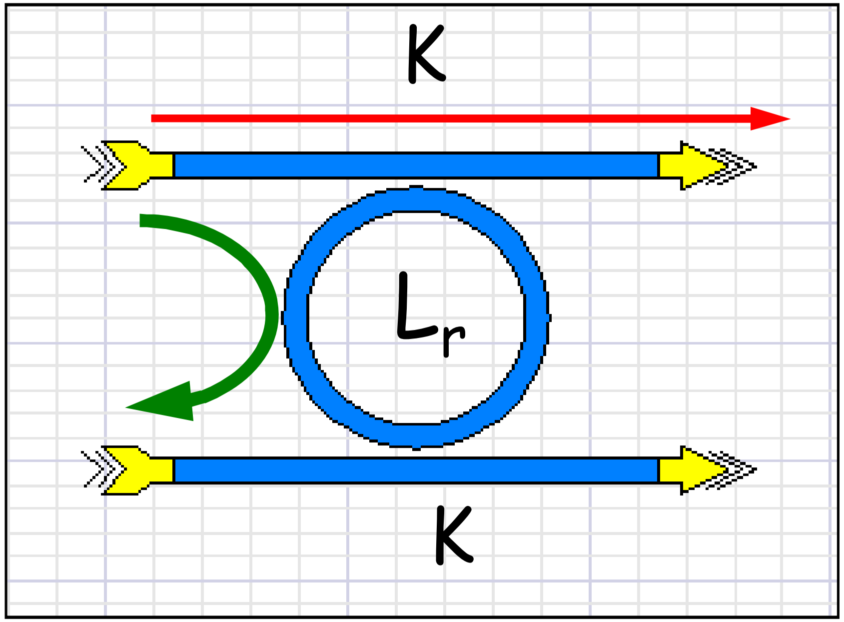


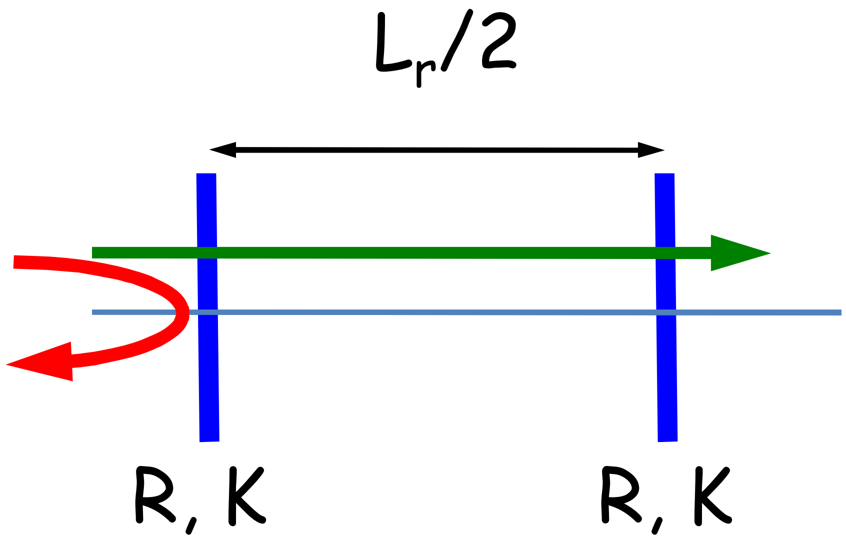
It is an Infinite Impulse Response filter, IIR

DROP port: 1 pole

THROUGH port: 1 pole, 1 zero

Ring resonators = Fabry-Perot





$$\lambda_0 = N n_{eff} L_r$$

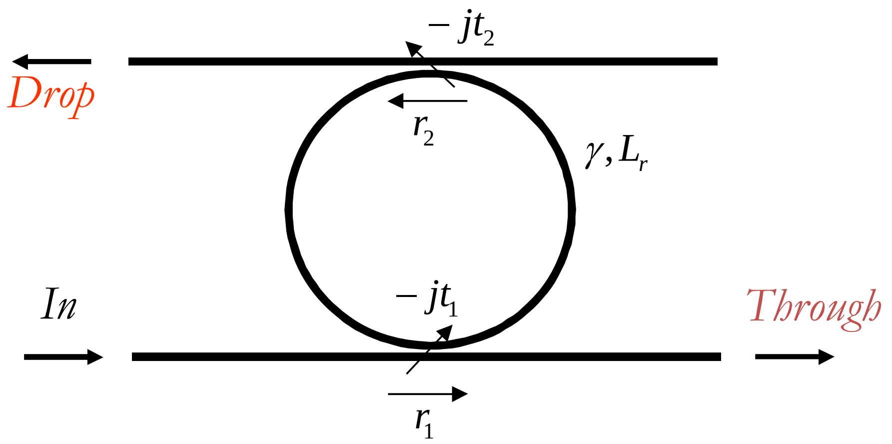
$$\mathcal{F} = \frac{\pi\sqrt{1-\kappa}}{\kappa} = \frac{\mathrm{FSR}}{B}$$

$$\mathrm{FSR} = \frac{c}{n_g L_r}$$

$$Q = \frac{f_0}{B}$$

$$\kappa = \sqrt{K}$$

Ring Resonator Filter



$$H_{through}(z) = \frac{r_1 - \gamma r_2 z^{-1}}{1 - \gamma r_1 r_2 z^{-1}}$$

$$H_{drop}(z) = -\frac{t_1 t_2 \sqrt{\gamma z^{-1}}}{1 - \gamma r_1 r_2 z^{-1}}$$

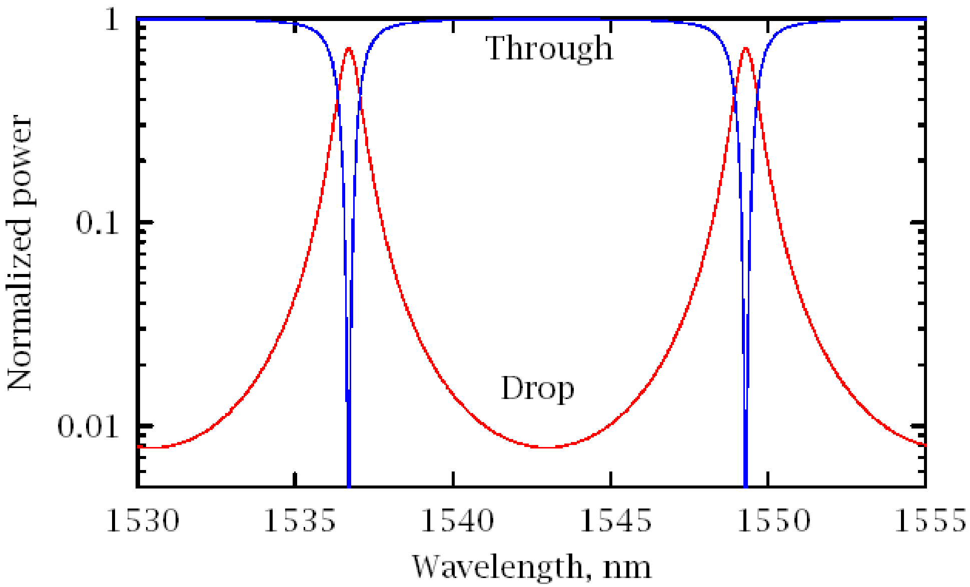
$$z = e^{-j\beta L_r}$$

Resonance condition:

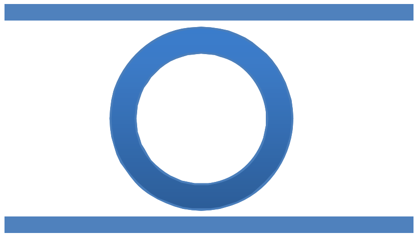
$$\beta L_r = 2m\pi, \quad m = 0,1,2,...$$

Free Spectral Range:

$$FSR = \frac{c}{n_g L_r}$$

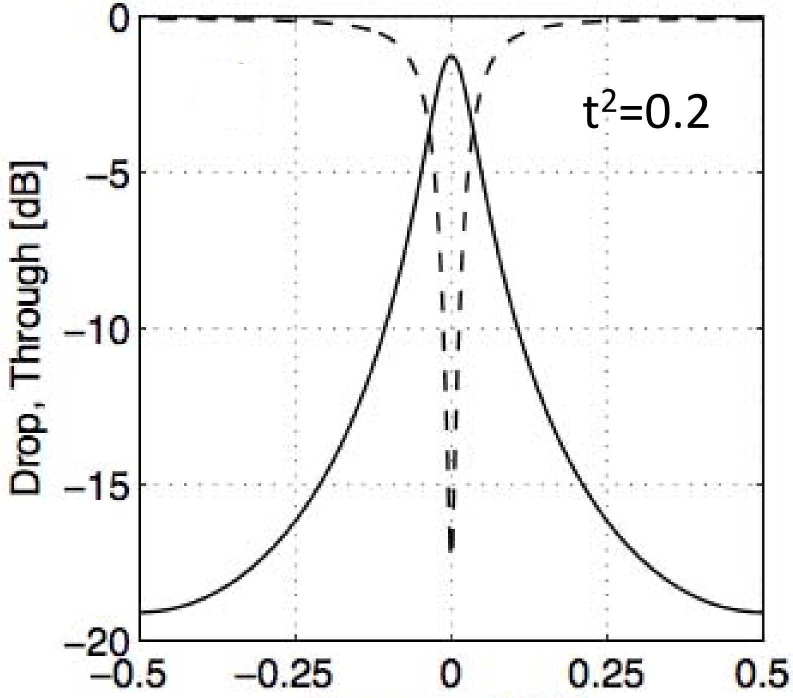


Ring Resonator Filter

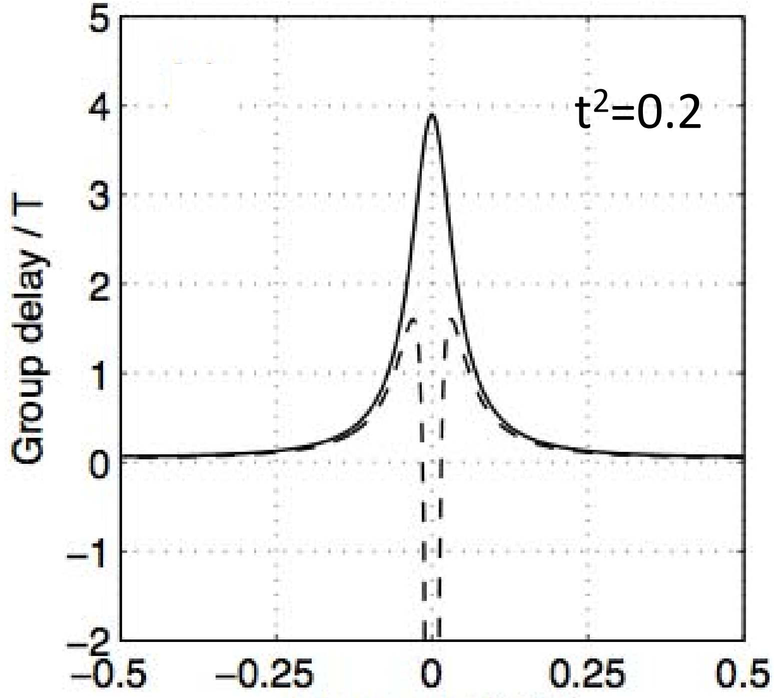


Transmission

Group Delay

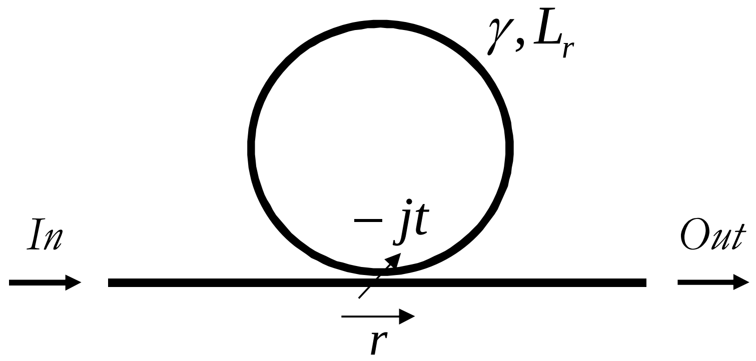


Frequency/FSR

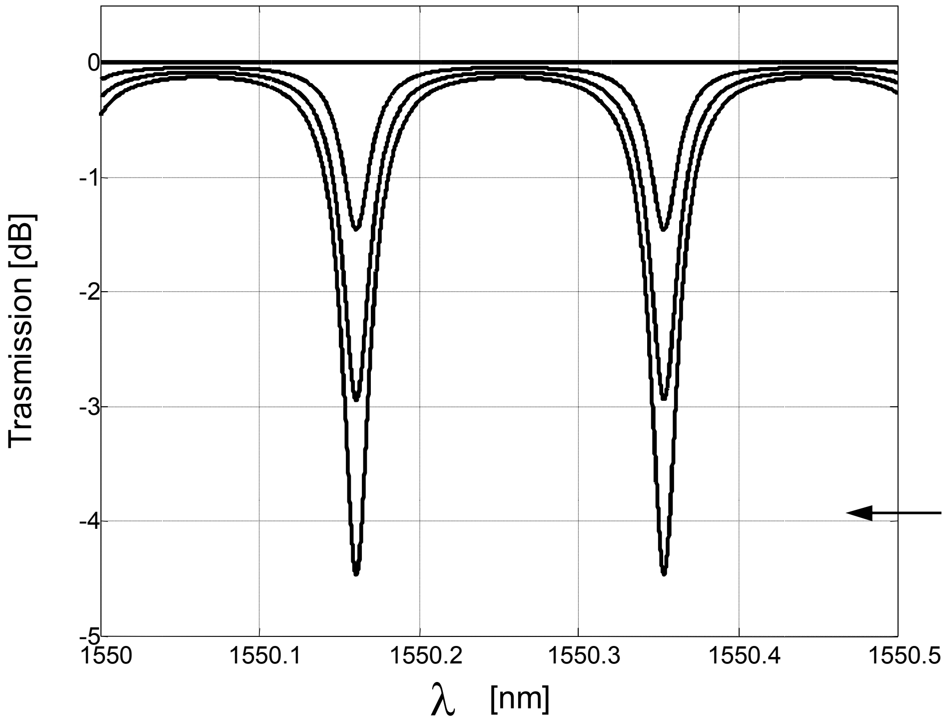


Frequency/FSR

Phase shifter (all pass filter)



$$T(\omega) = \frac{r - \gamma e^{-j\beta L_r}}{1 - \gamma r e^{-j\beta L_r}}$$



Resonance condition:

$$\beta L_r = 2m\pi, \quad m = 0,1,2,...$$

Free Spectral Range:

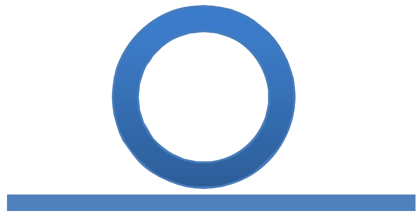
$$FSR = \frac{c}{n_g L_r}$$

$t^2 = 0.5$, $\gamma = 0 \ldots 0.75$ dB

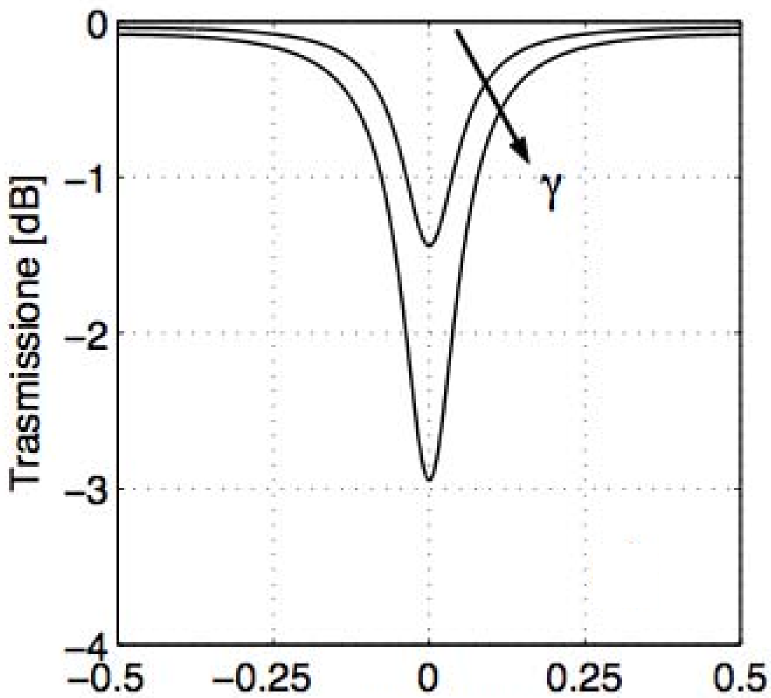
critical coupling $\gamma = r$

(γ=1 lossless)

Phase shifter (all pass filter)

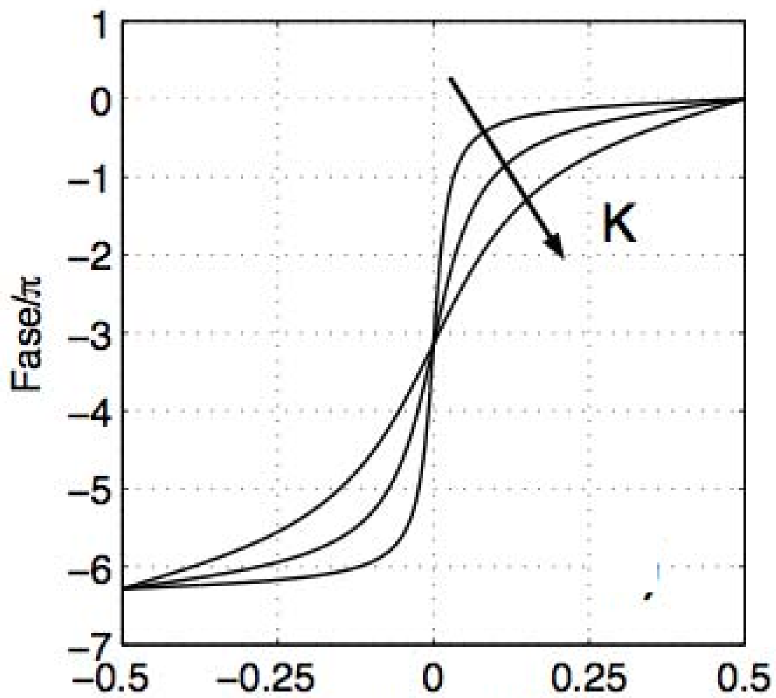


Transmission



Frequency/FSR

Phase



Frequency/FSR

Effect of a refractive index perturbation

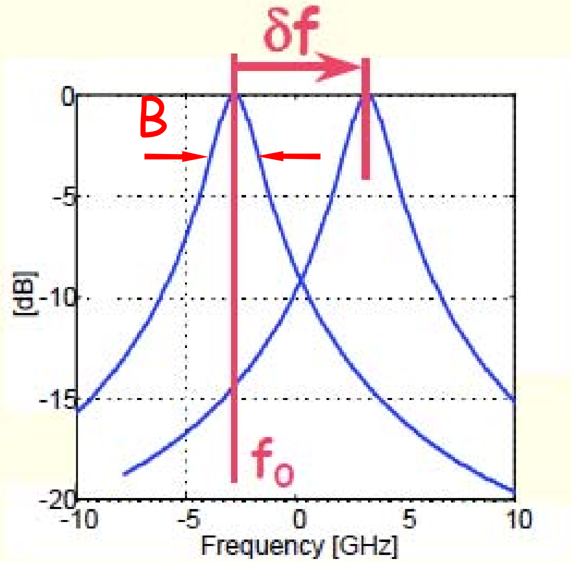
δn due to Tolerances, Temperature, Birefringence, aging…

A refractive index variation δn produces a frequency shift δf

$$\frac{\delta f}{f_0} = -\frac{\delta n}{n_{eff}}$$

δn must be controlled to guarantee $\delta f < B$

$$B > \delta n \, \mathrm{FSR} \frac{L_r}{\lambda_0}$$



$$\delta n L_r = \frac{\lambda}{\mathcal{F}}$$

a lot of formulae….

$$Q = \omega \times \frac{\text{field energy stored by the resonator}}{\text{power dissipated by the resonator}}$$

$$\gamma = e^{-\alpha L_r}$$

lossless: $\gamma = 1$

$$Q = \frac{f_0}{B} = \frac{\pi n_{eff}}{\lambda_0} \frac{L_r \sqrt{\gamma t}}{1 - \gamma t}$$

$$B = \frac{\text{FSR}}{\pi} \left(\frac{1}{r\sqrt{\gamma}} - r\sqrt{\gamma} \right)$$

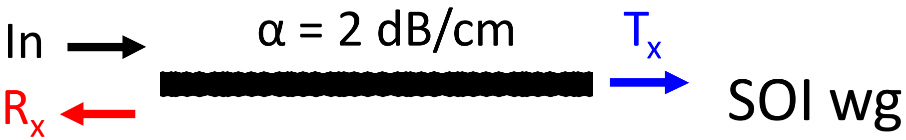
$$\mathcal{F} = \frac{FSR}{B} = \frac{\pi \sqrt{\gamma t}}{1 - \gamma t}$$

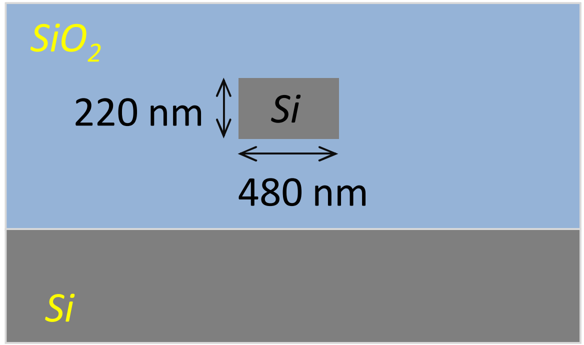
$$\tau_g = T \left(\frac{\gamma}{\gamma - r} - \frac{\gamma r}{1 - \gamma r} \right) \xrightarrow{\gamma = 1} T \frac{1 + r}{1 - r}$$

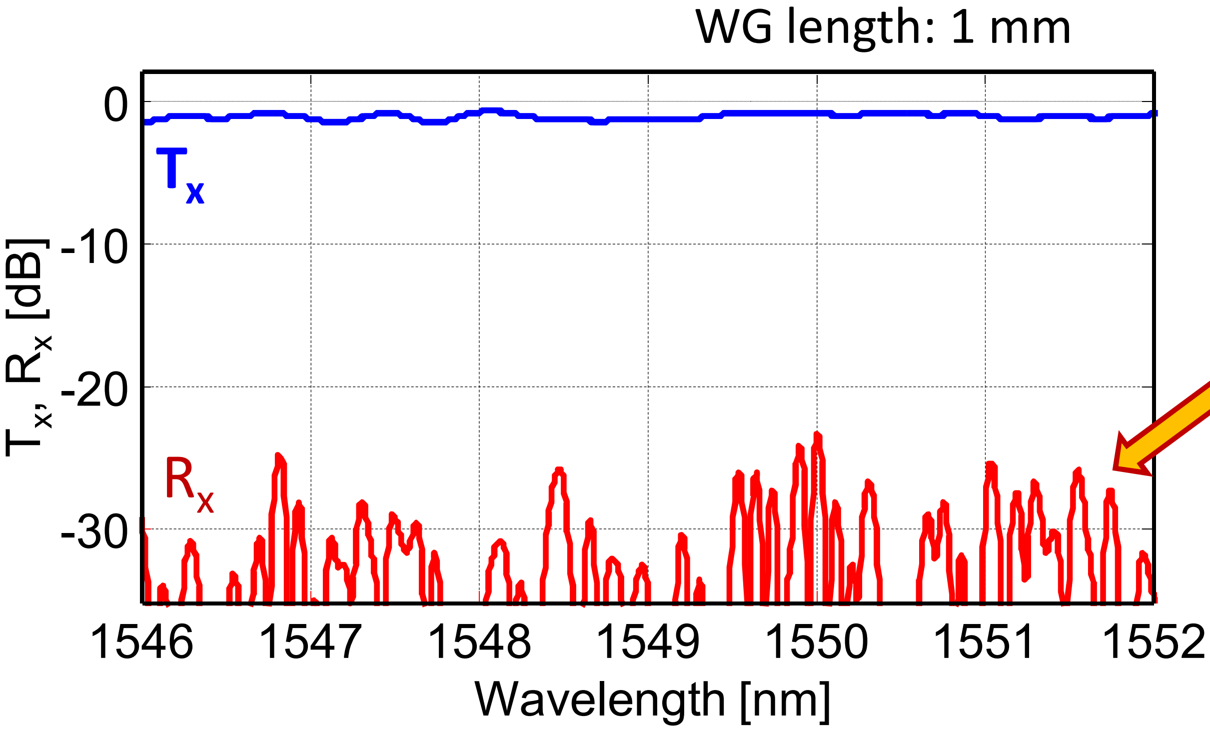
$$\text{ER} = \frac{(K-2)^2}{K^2}$$

$$\text{Intensity enhancement} = \frac{2\text{FSR}}{\pi B}$$

Spectrum of backscattering

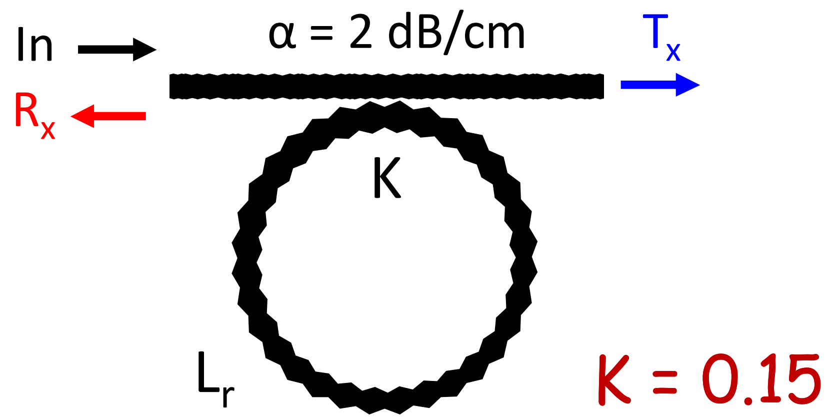




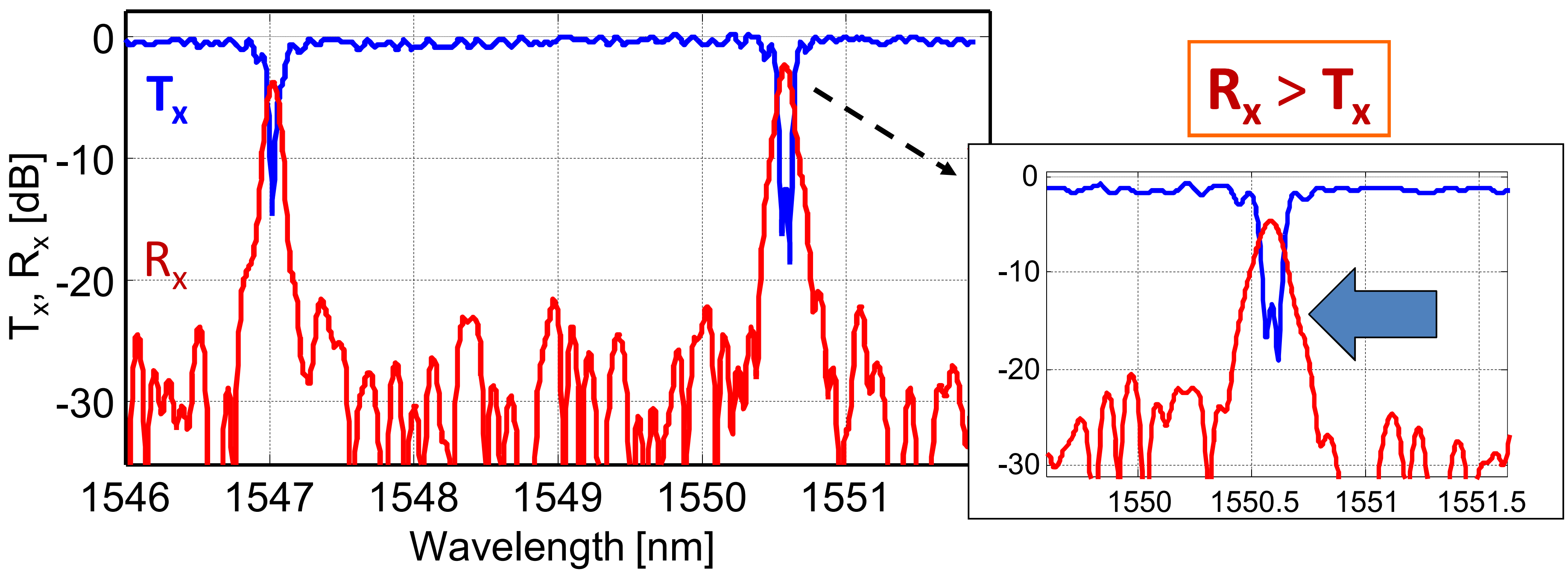


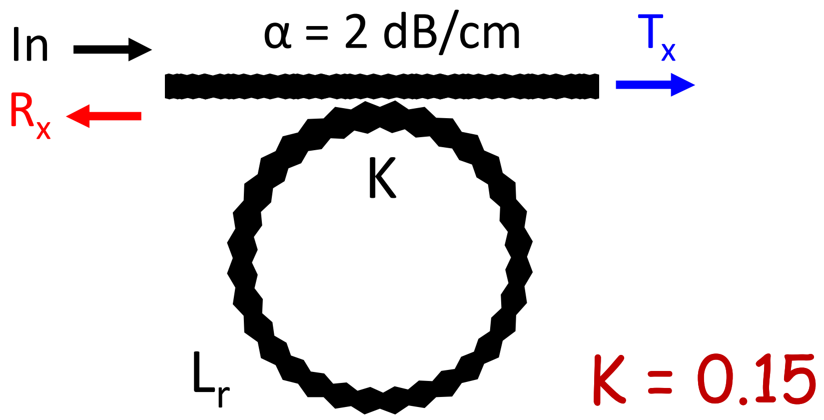
Backscatter is a **random white noise** in wavelength-domain

Backscattering in ring resonators



- Reflection can even exceed transmission
- Spectral response distortions (notch splitting)

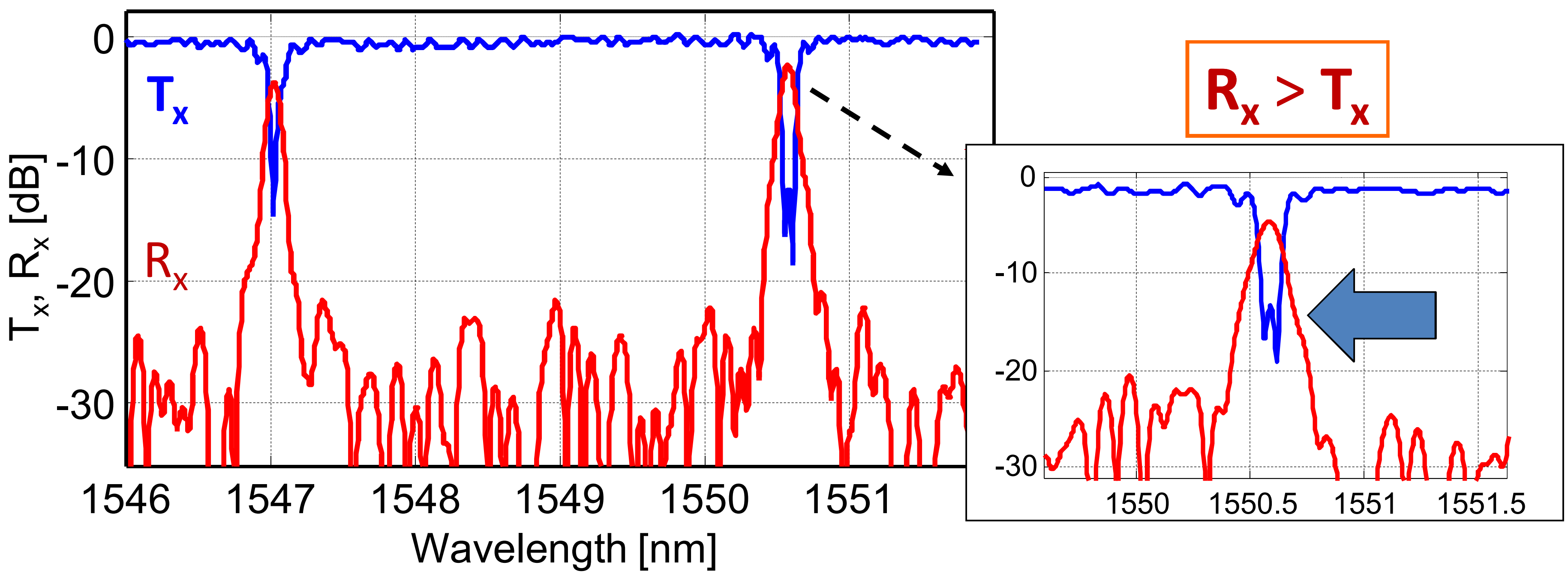




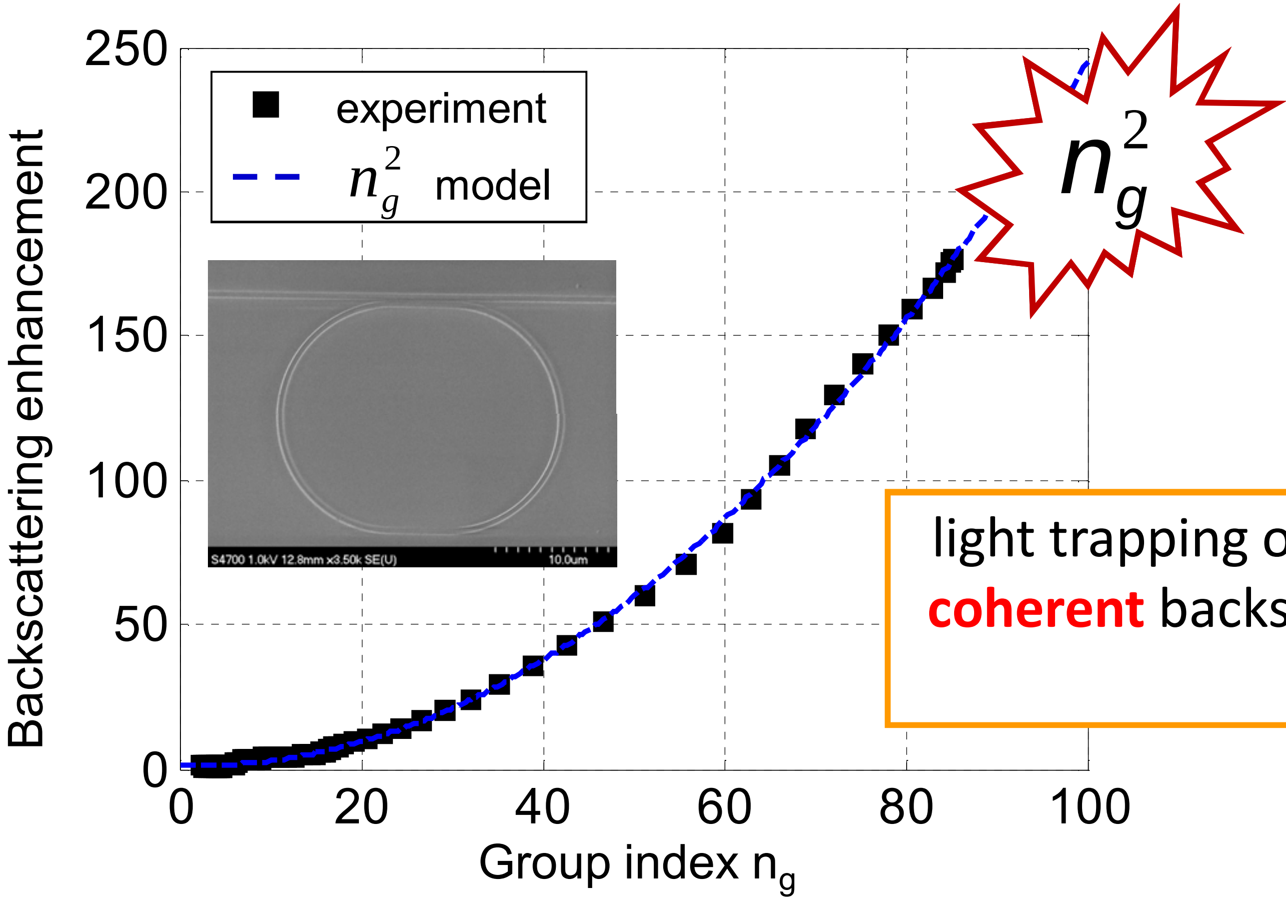
Where is the light ?

Ring with Finesse ≈40
Waveguide attenuation 2.0 dB/cm
(roundtrip losses=0.025dB)

Finesse * roundtrip loss = 1 dB



Backscattering in ring resonators



light trapping originates **coherent** backscattering

(Q factor, finesse…)

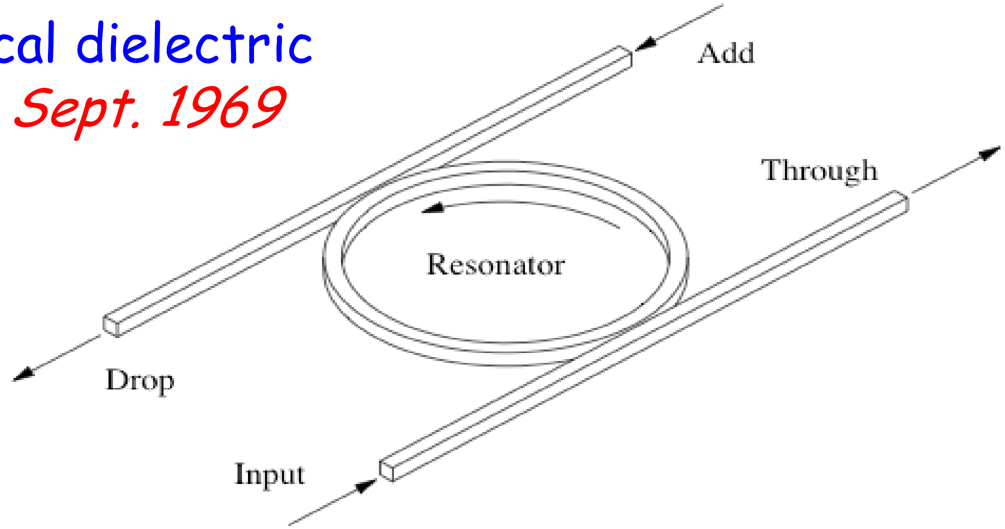
F. Morichetti et al., APL 96, 081112 (2010)

An excursus on ring-resonators

history, properties and applications

Ring resonator: the origin

E. A. J. Marcatili, "Bends in optical dielectric guides," *Bell Syst. Tech. J. 48, Sept. 1969*



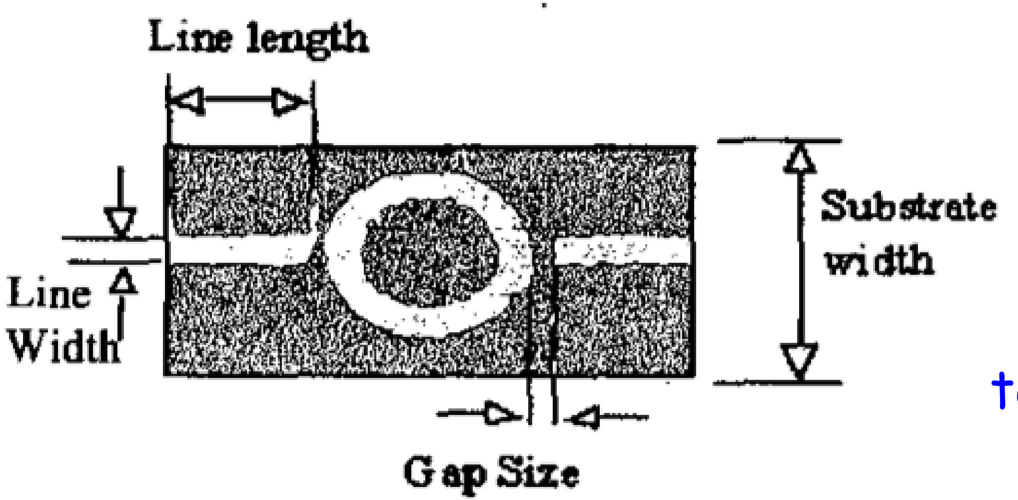
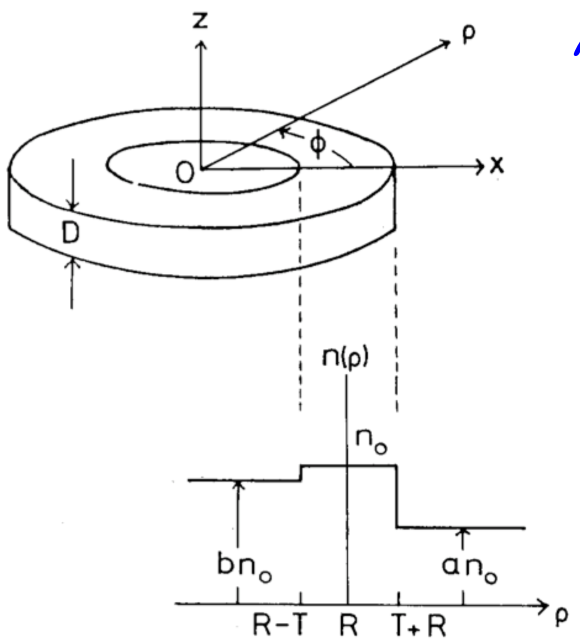


Fig.1a Ring resonator;

P. Troughton, "Measurement techniques in microstrips", Elect. Letters, January 1969

Ring resonators: the origin



M. Miyagi, "Design theory of high-Q optical ring resonator with asymmetric three-layered dielectrics", Optical and Quantum Electronics, October 1978 (McGill University, Canada)

R. G. Walker and C.D.W. Wilkinson "Integrated optical ring resonators made by silver ion-exchange in glass", Applied Optics, April 1983

GLASGOW UNIVERSITY

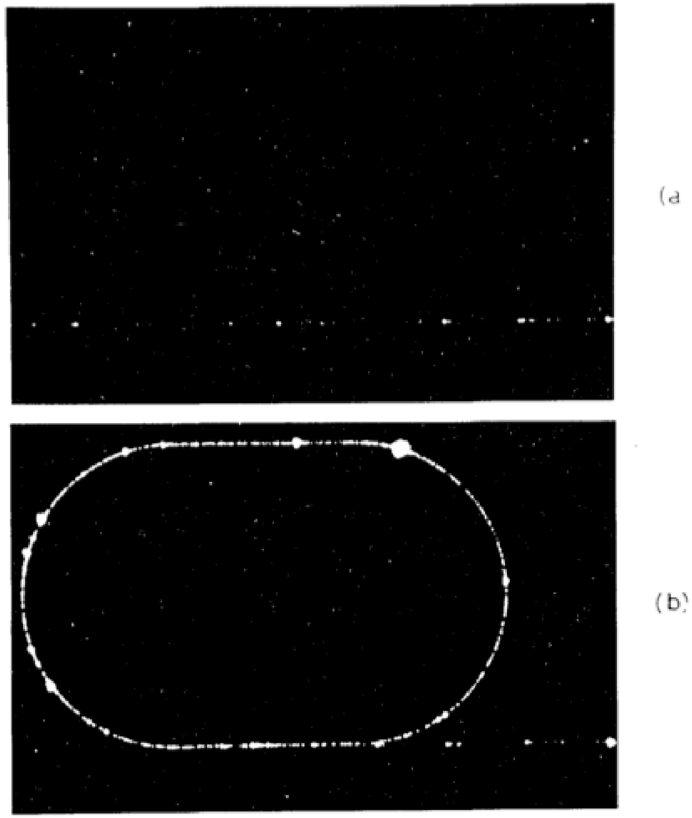


Fig. 6. Photomicrographs of surface scatter from racetrack resonator 1D (no postbake): (a) at resonance; (b) at antiresonance. Finesse = 18.8; η = 76%.

Ring resonators: the origin

Fig. 6. Photomicrographs of surface scatter from racetrack resonator 1D (no postbake): (a) at resonance; (b) at antiresonance. Finesse = 18.8; η = 76%.

on
made
plied

GLASGOW UNIVERSITY

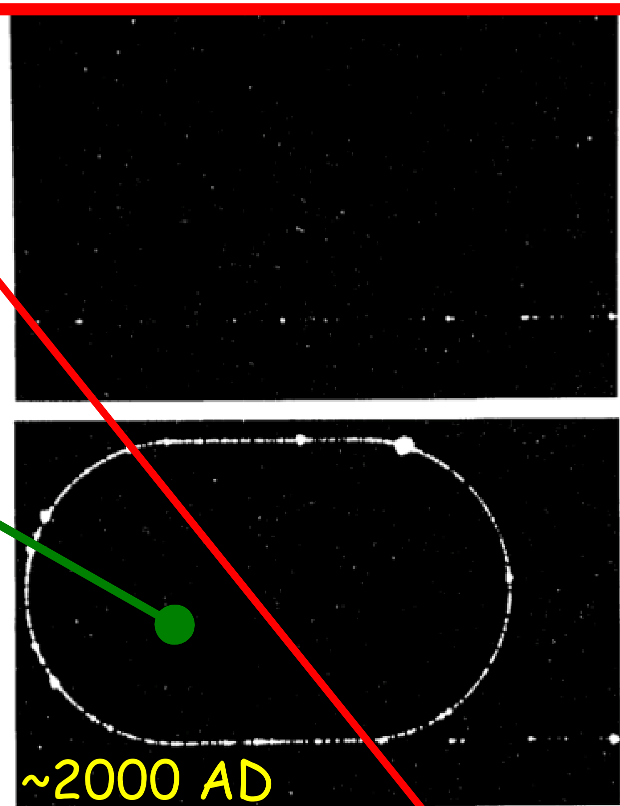


Fig. 6. Photomicrographs of surface scatter from racetrack resonator 1D (no postbake): (a) at resonance; (b) at antiresonance. Finesse = 18.8; η = 76%.

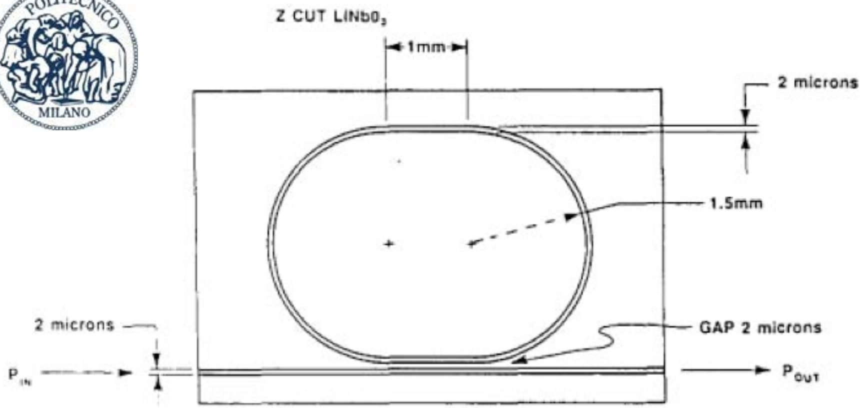
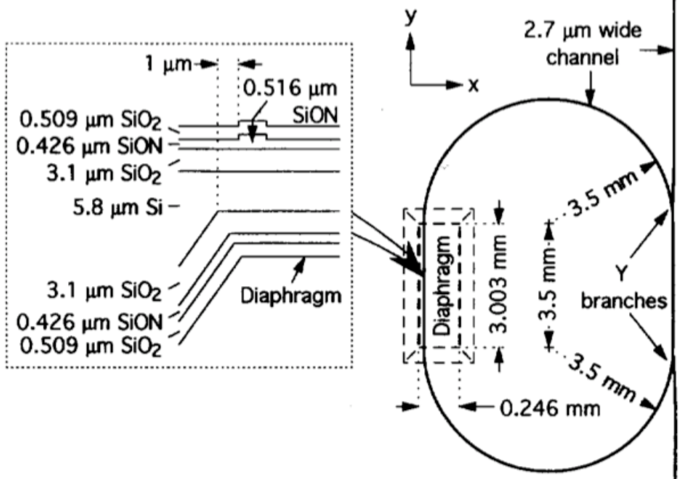


Fig. 1. Schematic of resonator.

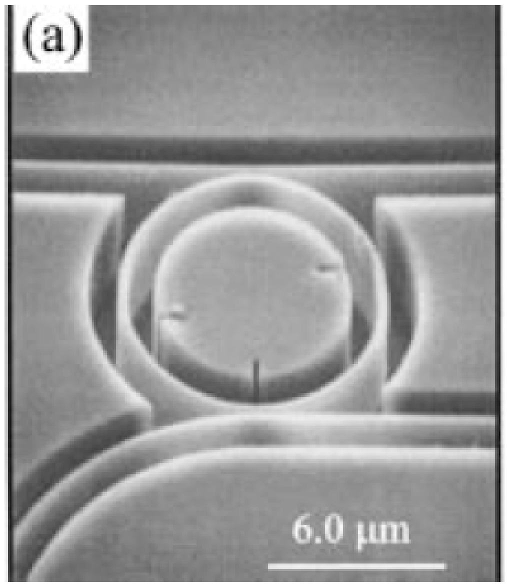
Z-cut LiNbO3

A. Mahapatra, Applied Optics, August 1985



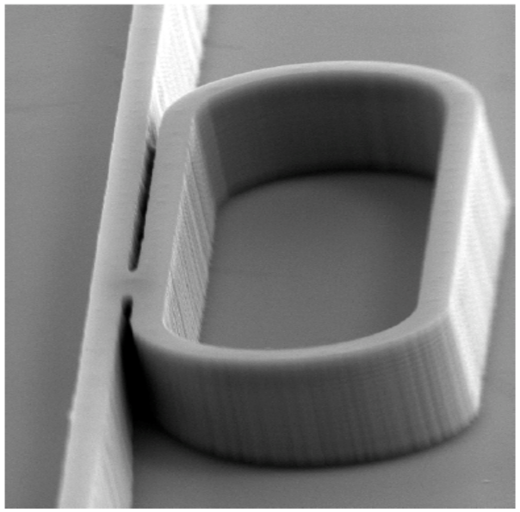
Silicon Oxynitride

De Brabander, PTL, May 1994

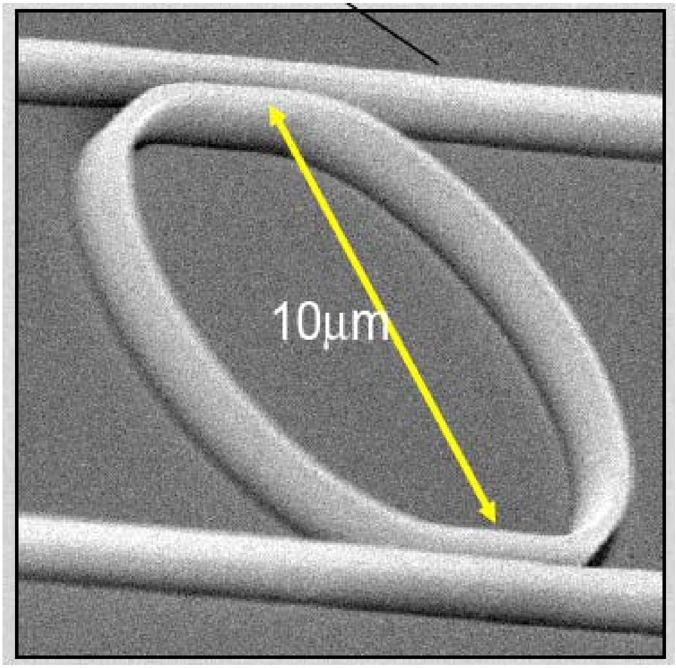


AlGaAs/GaAs
D. Rafizadeh, JLT 1998

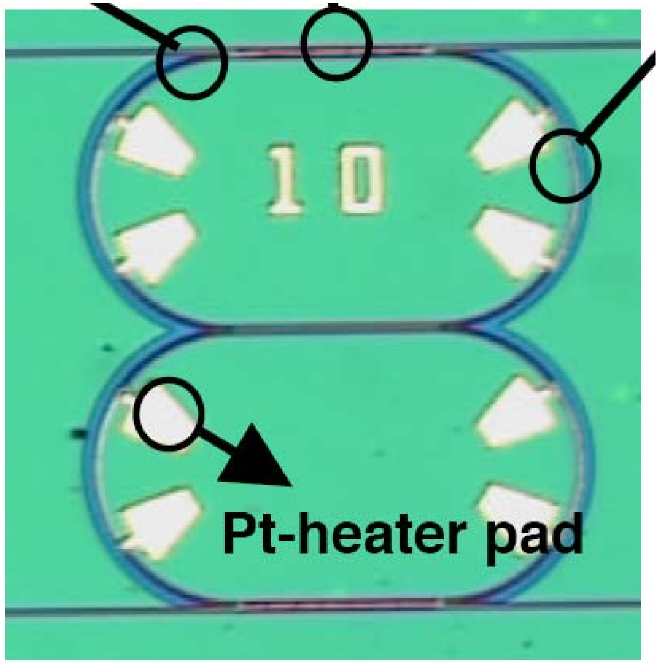
The smallest ring, R=2.2 μm



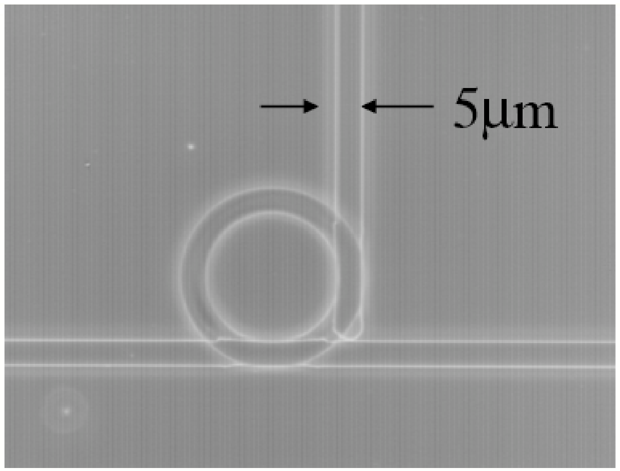
InP, P. Absil, Univ. Maryland, 2001



Silicon on Insulator
Ghent University
2003



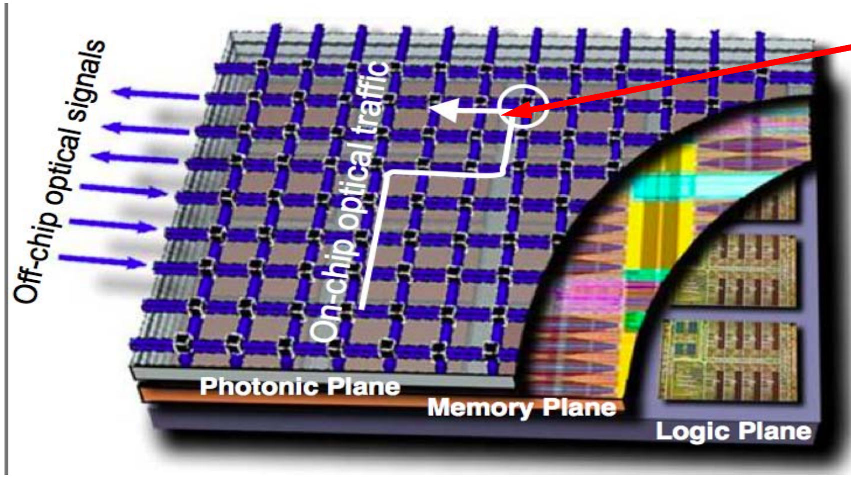
Indium Phosphide
Fraunhofer Institute
2003



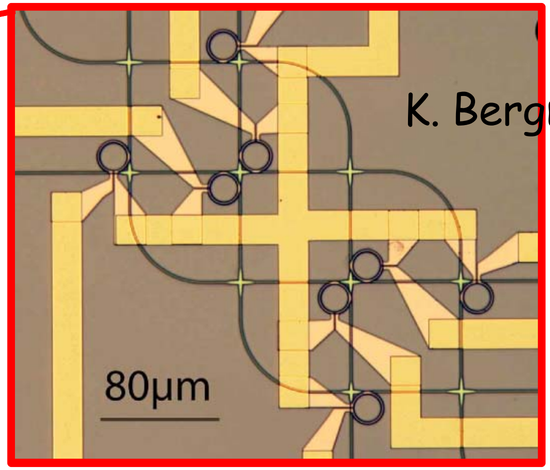
Polimer, A. Rabiei, ETH, 2003

Ring resonators: a key building block

Optical Interconnects

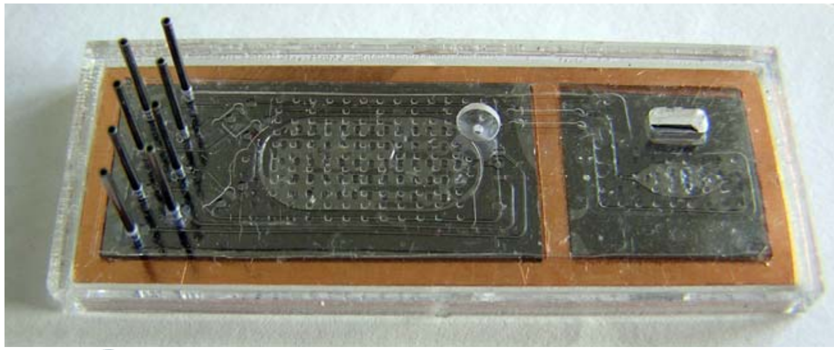


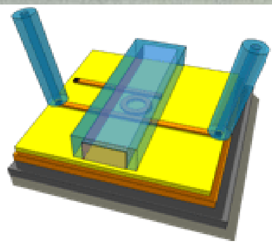
IBM

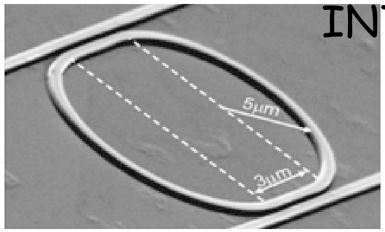


K. Bergman

Optical (bio)sensors

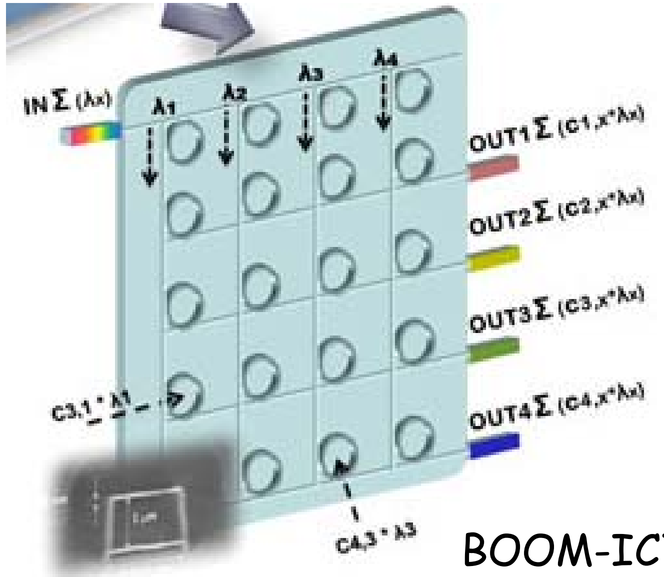






INTOPSENS

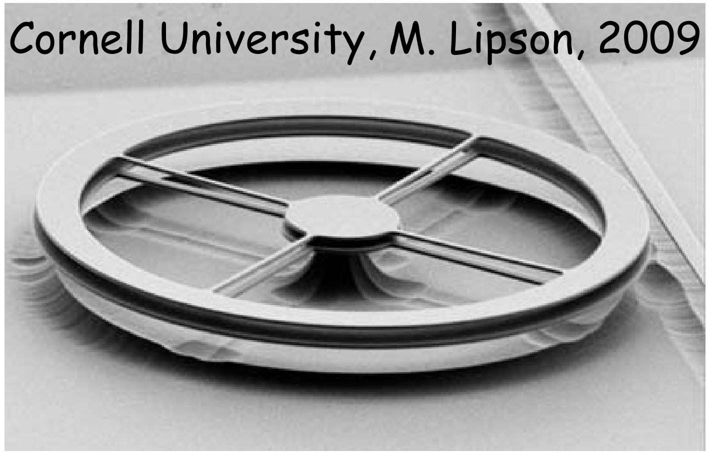
Telecommunications

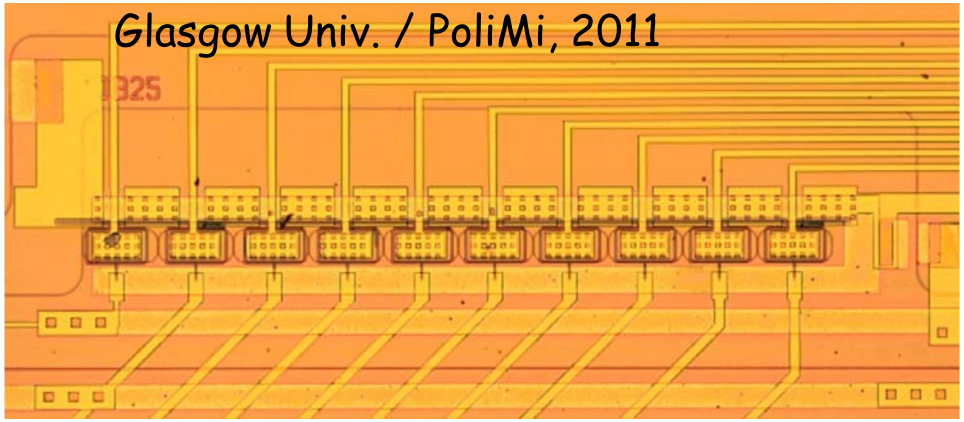


BOOM-ICT

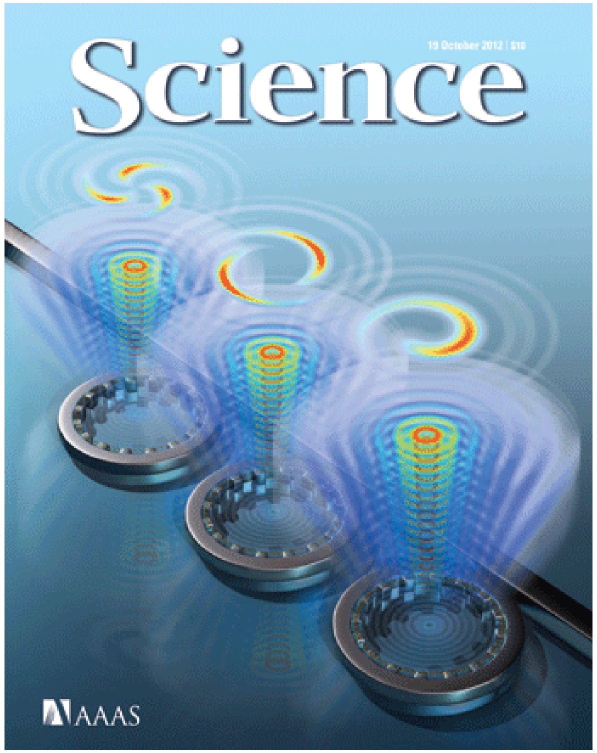
fully-reconfigurable wavelength routing cross connects

Ring resonators: a key building block

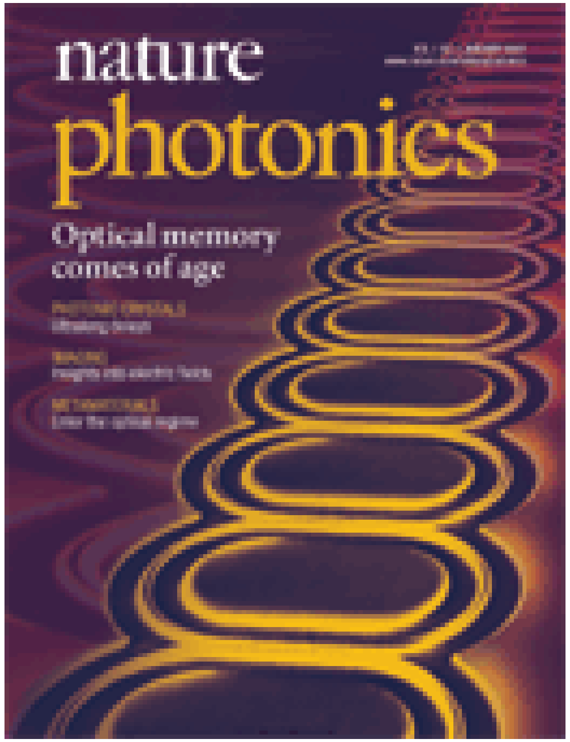




2012



2007



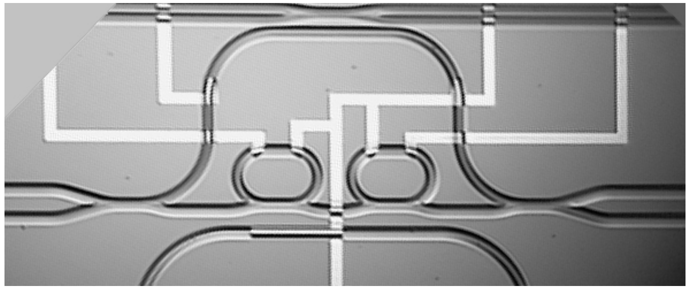
To be continued….

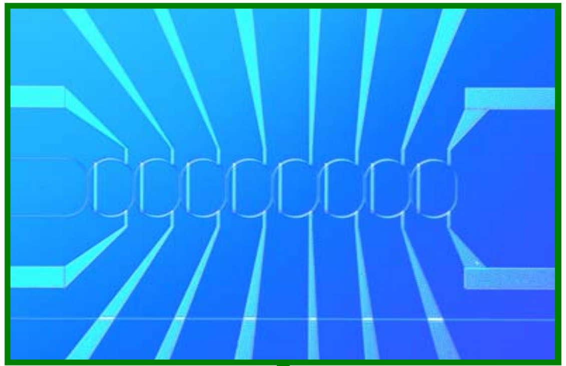
Tomorrow, more rings more fun…!

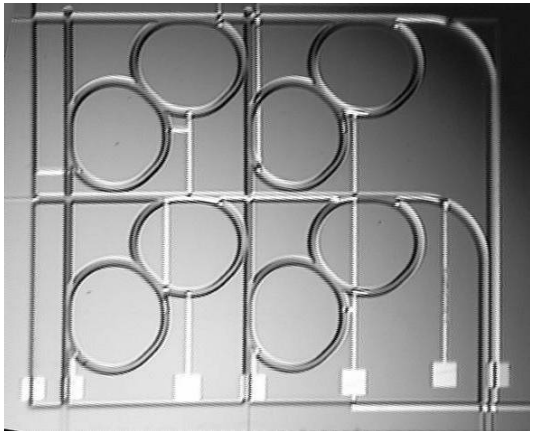
Winter College on Optics: Fundamentals of Photonics
Theory, Devices and Applications

The Abdus Salam
International Centre
for Theoretical Physics
50th Anniversary 1964 - 2014

from Ring to Rings…



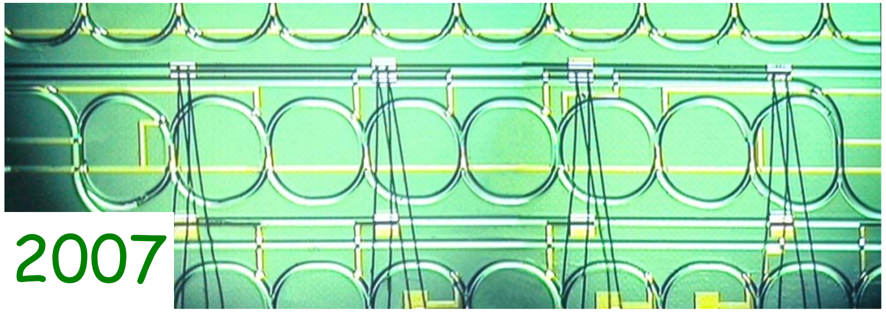


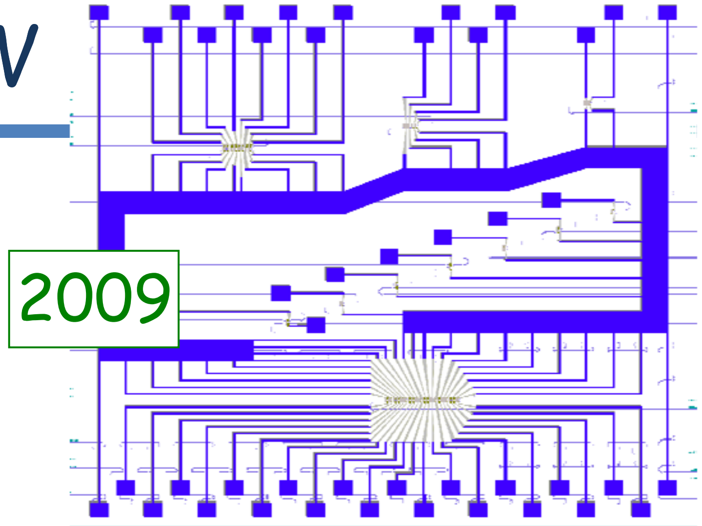


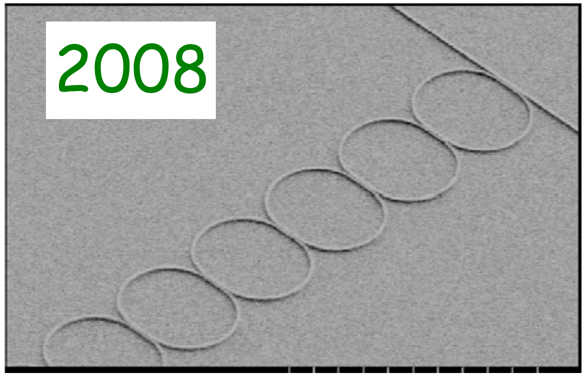
CROW – Coupled Resonator Optical Waveguide

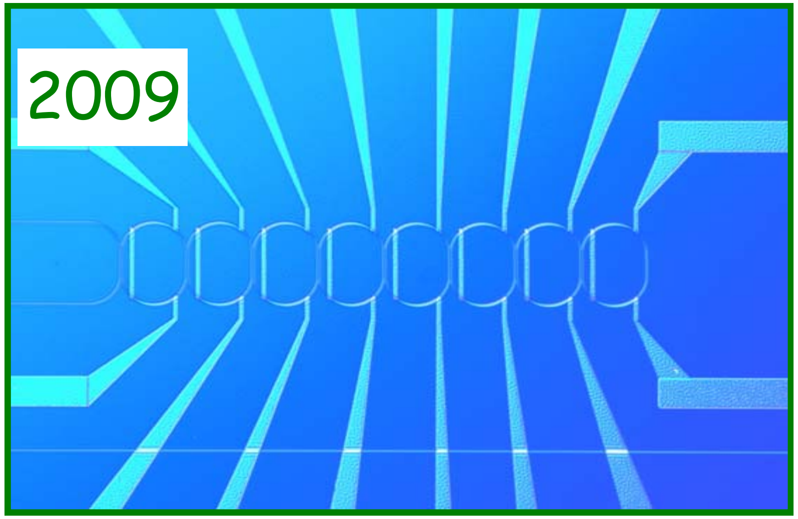
A. Yariv	Caltech	1999	Microwave
C. Madsen	Bell Labs	1999	DSP
R. Orta	Politecnico Torino	1999	DSP
A. Melloni	Politecnico Milano	2002	Microwave
V. Van	Maryland Univ.	2006	Electronic/Microwave

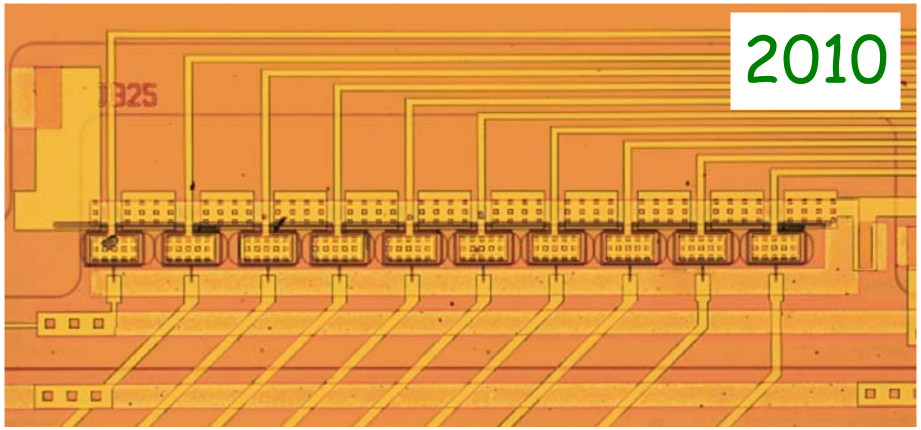
Progress in tuneable ring-CROW



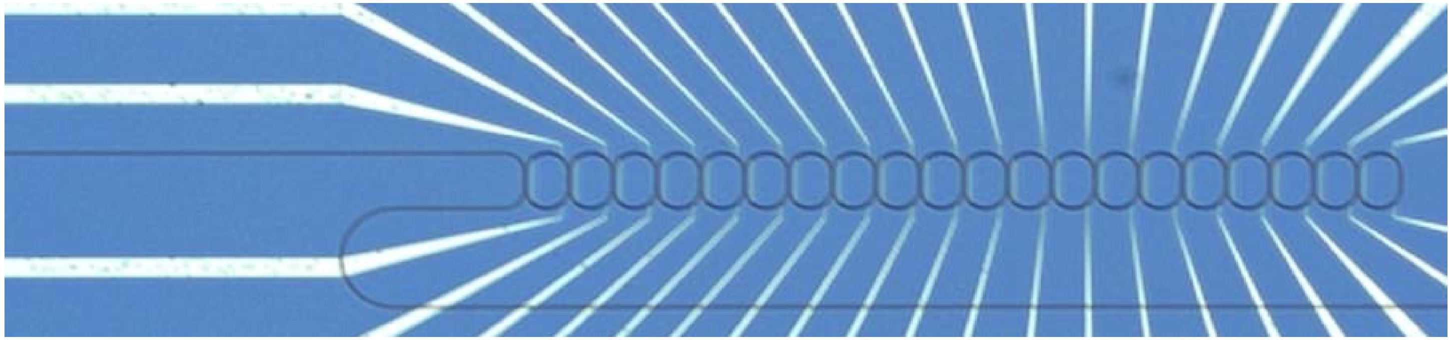


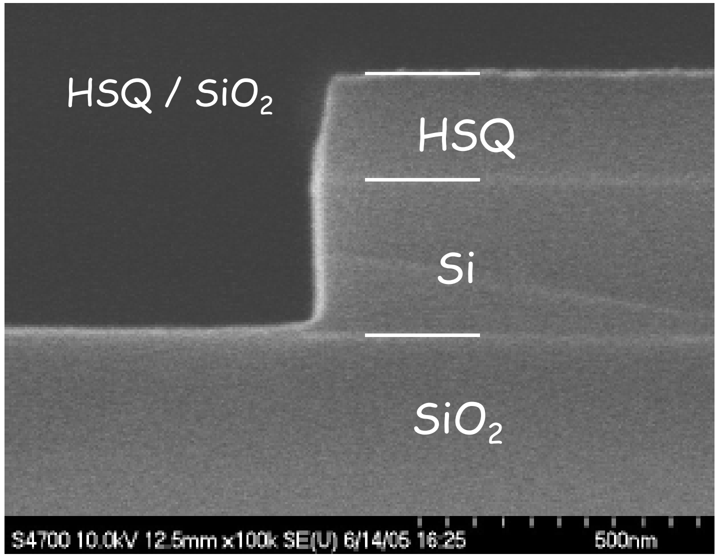






A reconfigurable CROW





waveguide section: 480 nm x 220 nm

Propagation loss: 0.9 – 1.5 dB/cm

buried in SiO_2 1 μm thick

NiCr heaters

Each cavity can be addressed

Negligible thermal cross-talk (Si)

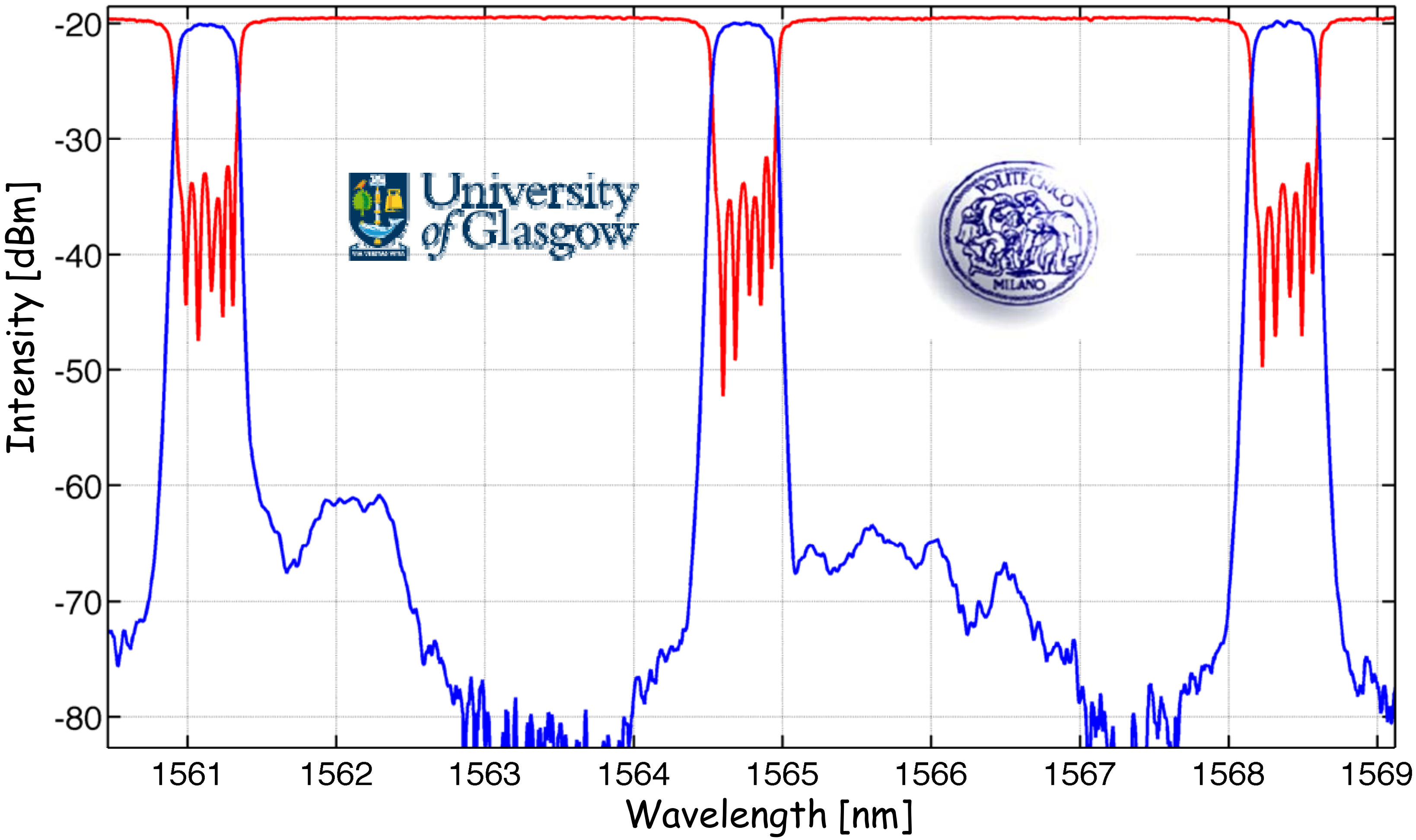
Response time: 4 μs

Power consuption: 52 μW/GHz

(10 mW @ 100Gb/s)

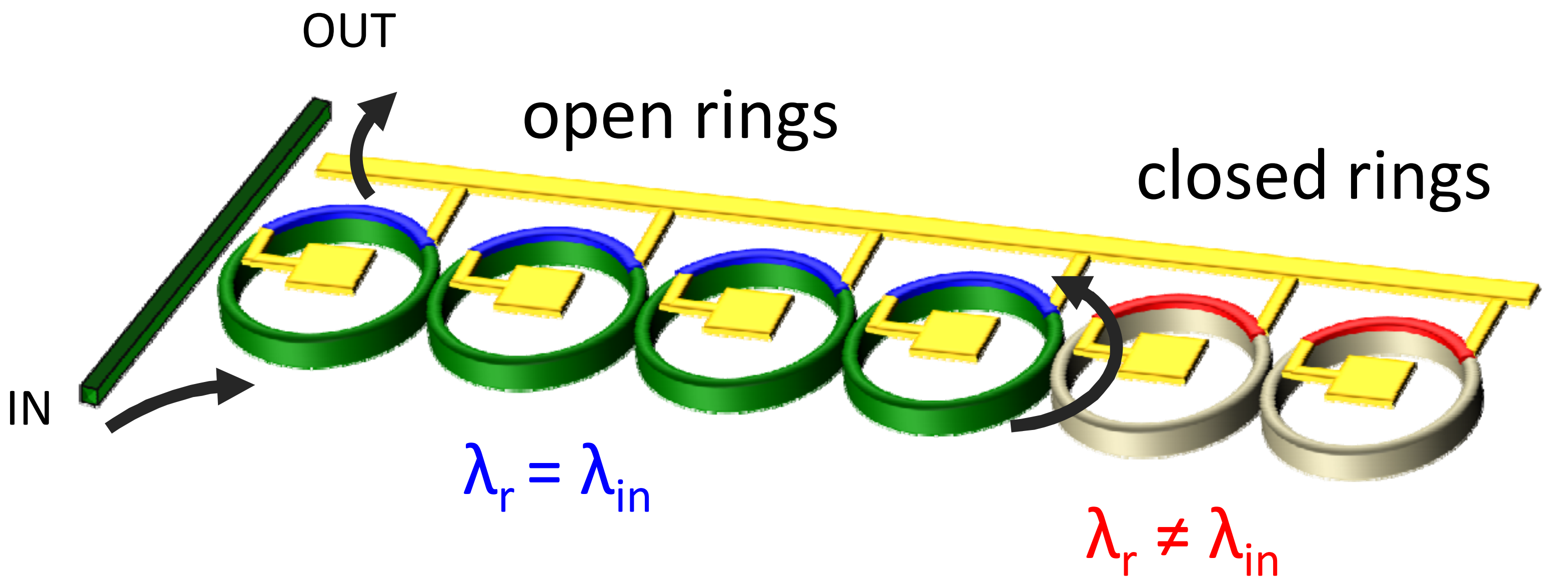
8-rings Bandpass filters in SOI

Return loss: -15 dB; IL 0.5 dB; In-band ripple <0.2 dB; Off-band rejection >50 dB



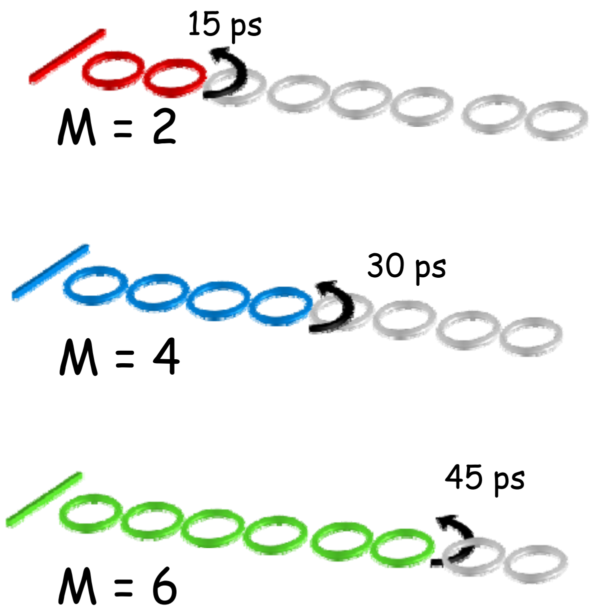
Tunable Delay lines

1 byte continuously tuneable delay at 10 and 100 Gbit/s demonstrated



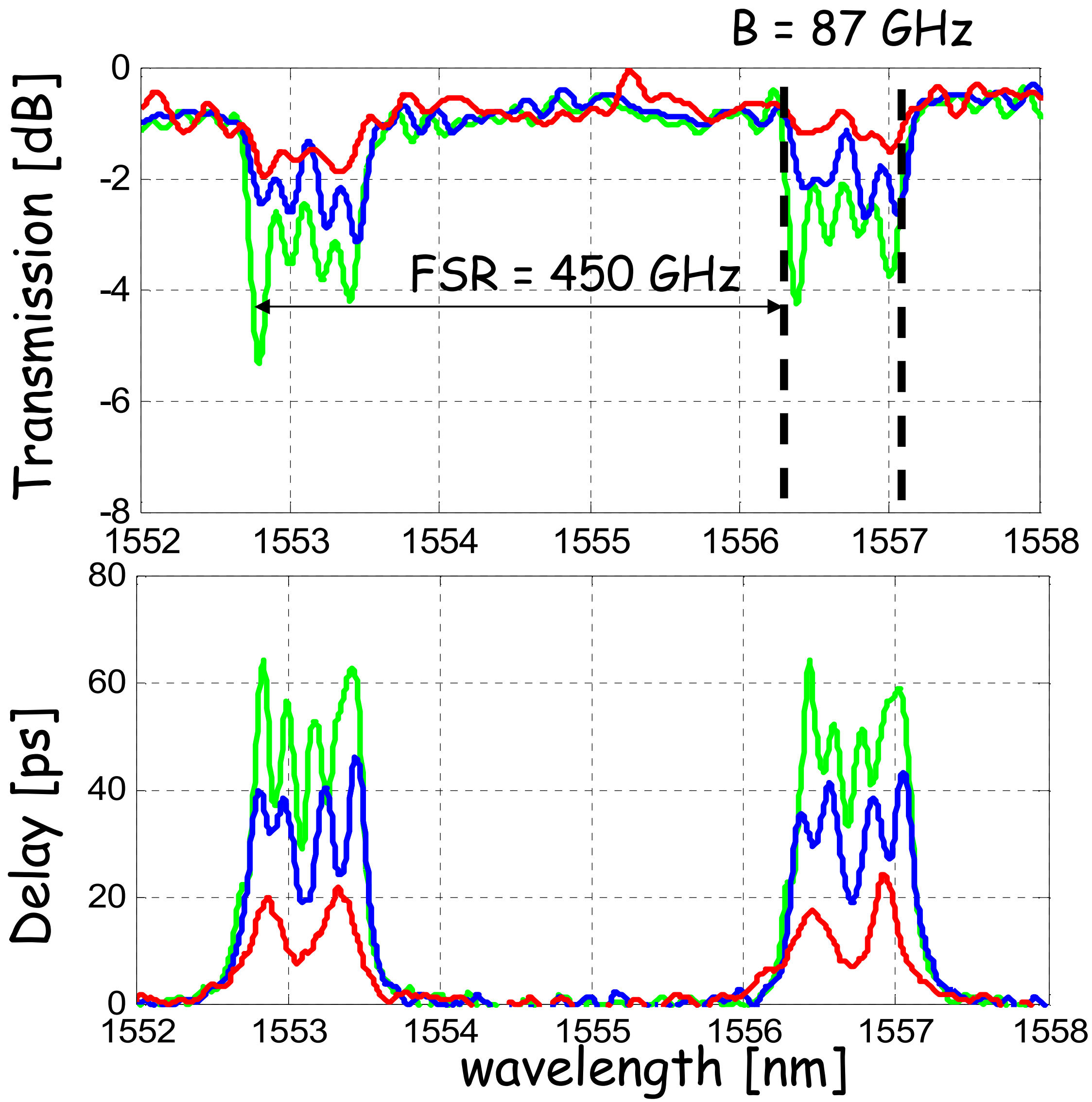
F. Morichetti et al., Optics Express, Vol. 15, 25, December 2007
A. Canciamilla et al., Journal of Optics, IOP, 2010
A. Melloni et al., IEEE Photonics Journal, vol. 1, no. 4, 2010

Tuneable ring-based CROW in SOI



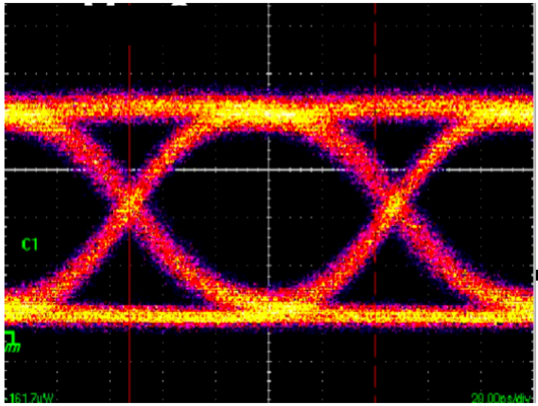
$$Delay = \frac{2}{\pi B} M$$

= 7.5 ps/ring



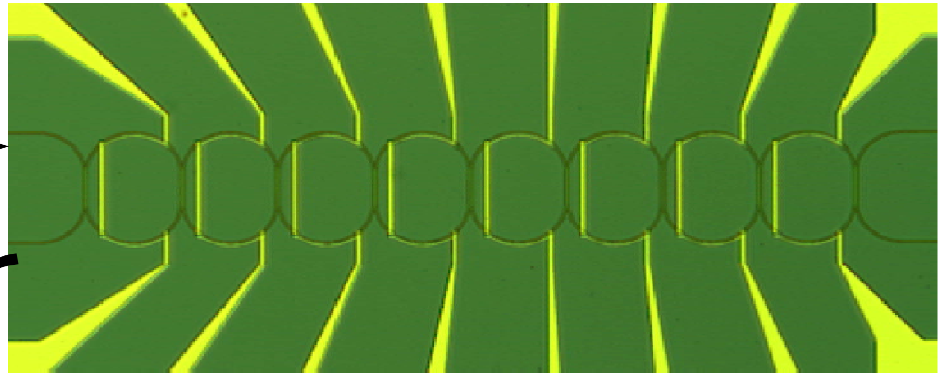
Data transmission at 10 Gbit/s

100 ps

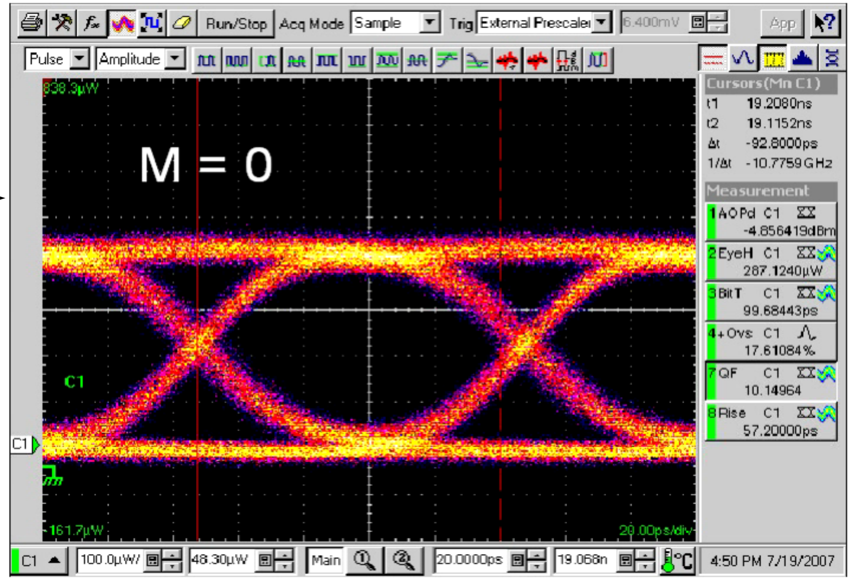


In

Intensity modulation
OOK NRZ @ 10 Gbit/s



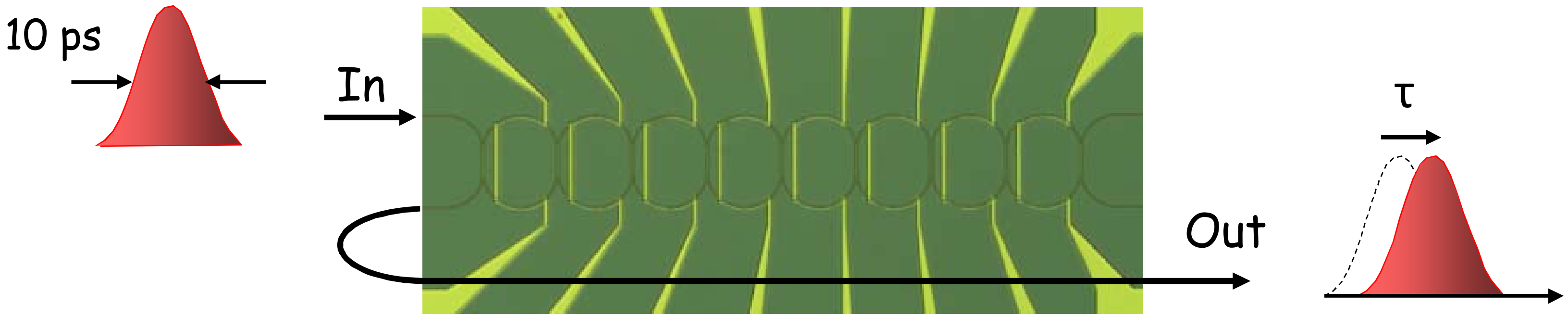
Out



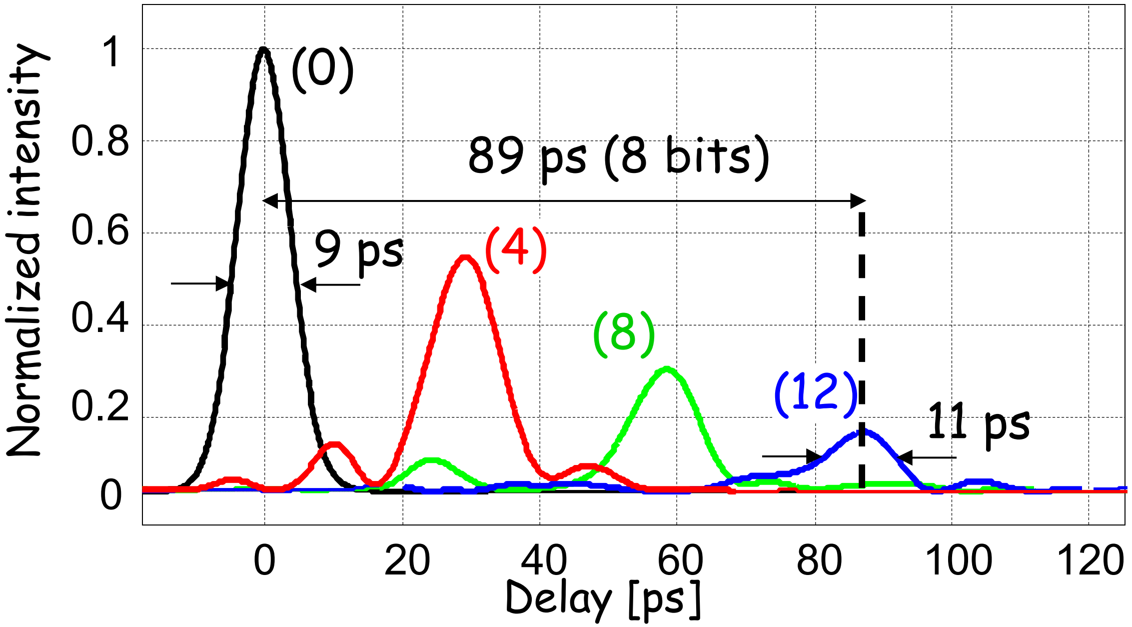
Reconfiguration
- hitless
- time 100 μs
- power 5 mW

Tuneable pulse delay @100Gbit/s

B = 87 GHz



Fractional delay = 7.5 ps/RR

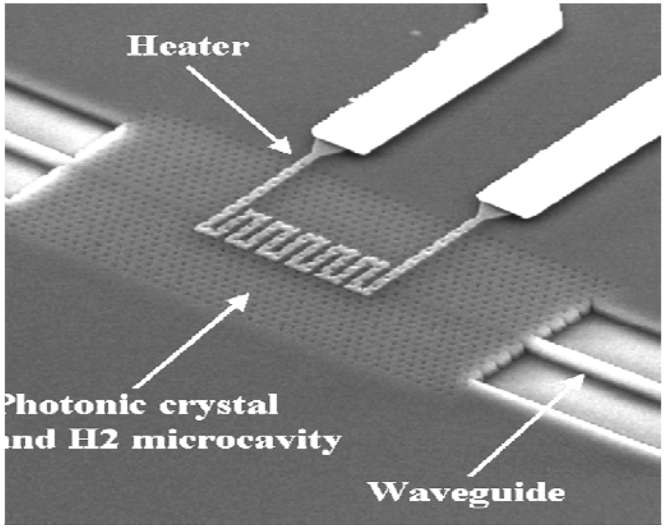


Storage efficiency
0.66 bit/RR

Fractional loss
≈ 1.1 dB/bit

Pulse Broadening (1 byte)
≈ 20%

Tuning / Reconfiguration



R. De La Rue, Opt. Express **12**, 2004

FLEXIBLE !!

Each cavity can be addressed

Negligible thermal cross-talk (Si)

Response time: 4 μs

Power consuption: 52 μW/GHz

(20 mW @ 100Gb/s)

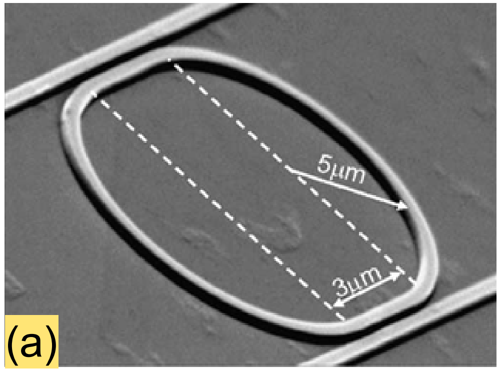
Power consuption: 30 mW/π

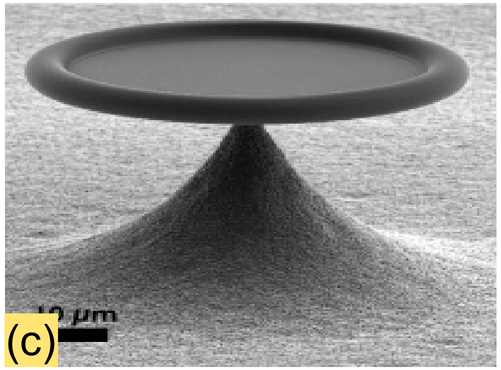
2 mW/nm

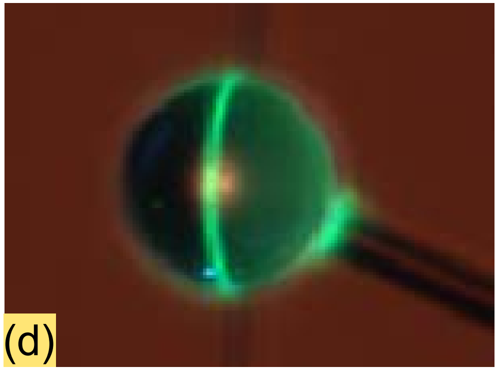
Pulse spatial extention $$N_{cp} = \pi \frac{B_p}{B_{crow}}$$

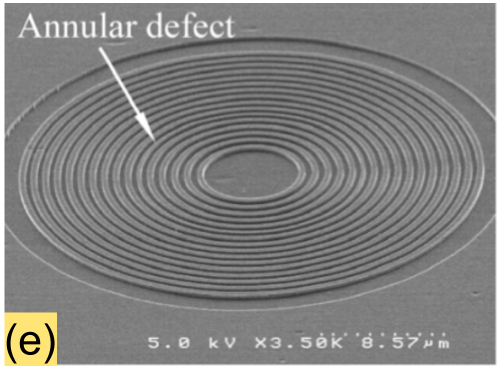
resonators 1

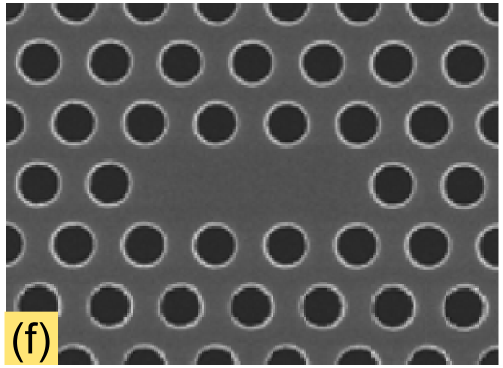
POLITECNICO DI MILANO

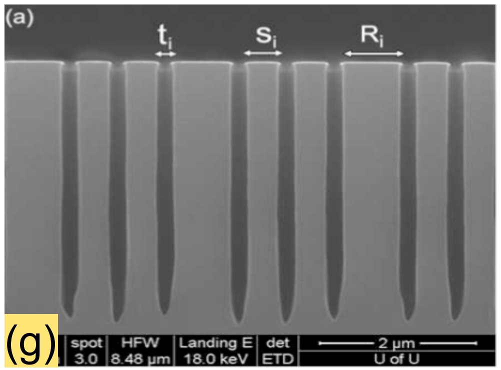


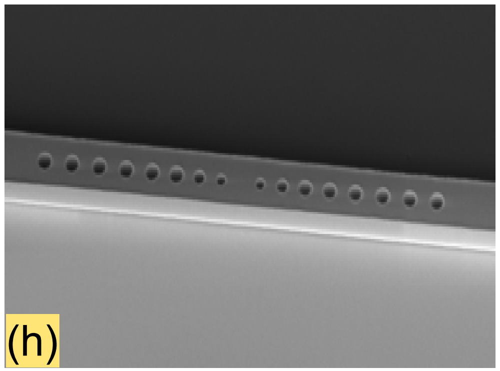












Other properties…

Tolerances

$$\frac{\delta\lambda}{\lambda} = \frac{\delta\beta}{\beta} = \left(\frac{\kappa_t}{\beta}\right)^2 \frac{\delta\kappa_t}{\kappa_t} = -\left(\frac{\kappa_t}{\beta}\right)^2 \frac{\delta d}{d}$$

δd=1 nm --> $\delta\lambda$=100 GHz

Polarization conversion

Induced by bending, sidewall angle, asymmetry and roughness

Proportional to 1/R and Hybridness (E_z/E_x)

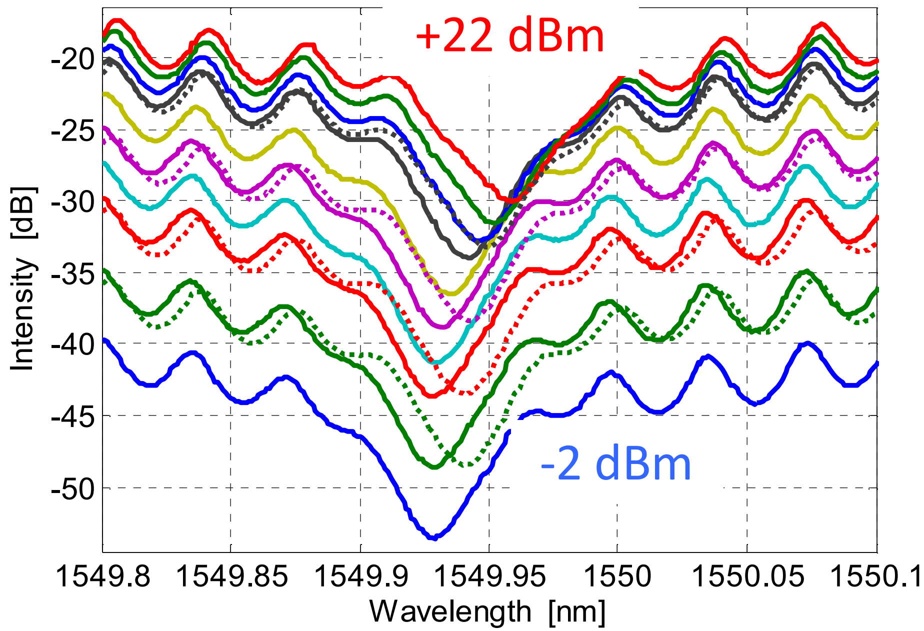
(stay away from low birefringence wg…)

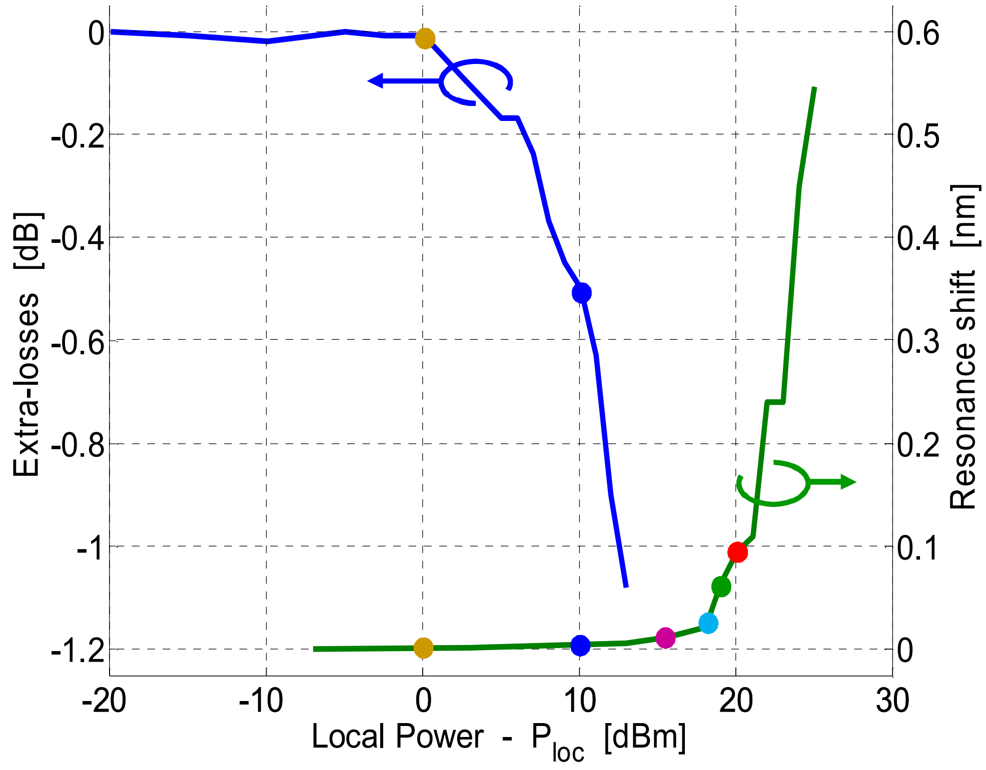
The ingredients

Just a taste of nonlinearity

Silicon (and InP) ring resonator

TPA → FCA → ΔT





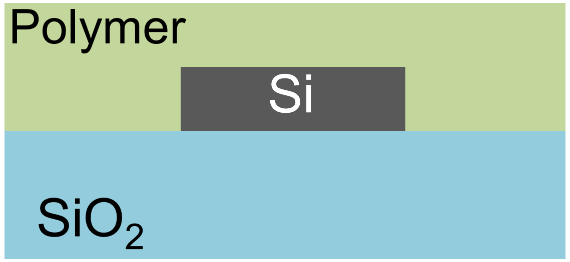
Insertion loss

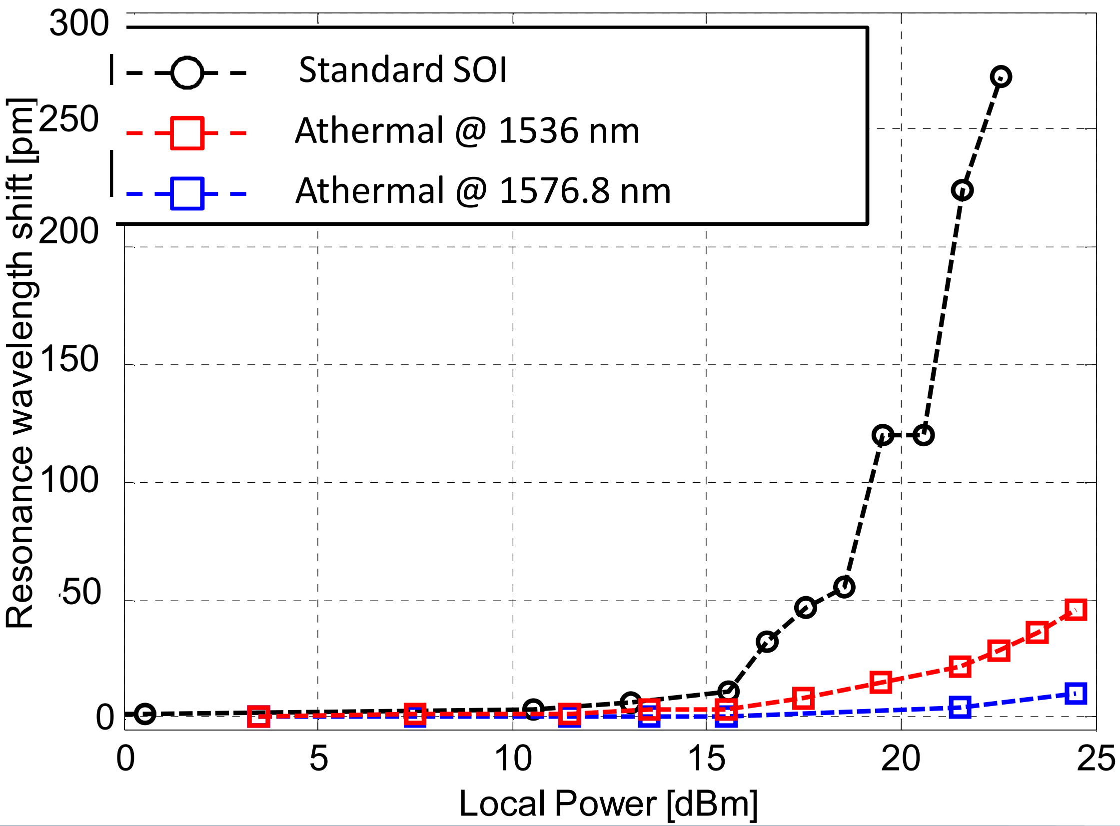
Frequency shift

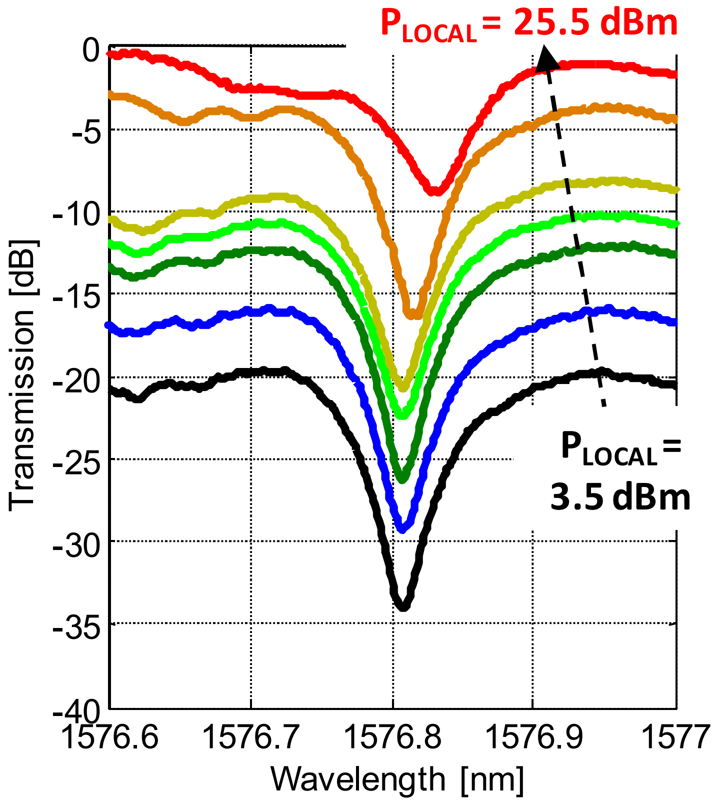
Spectral distortion

Towards power insensitive operation

Si ring resonator







Thermal compensation of TPA