2572-2

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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POLITECNICO DI MILANO

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

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

(Waveguide theory and) photonic circuit design

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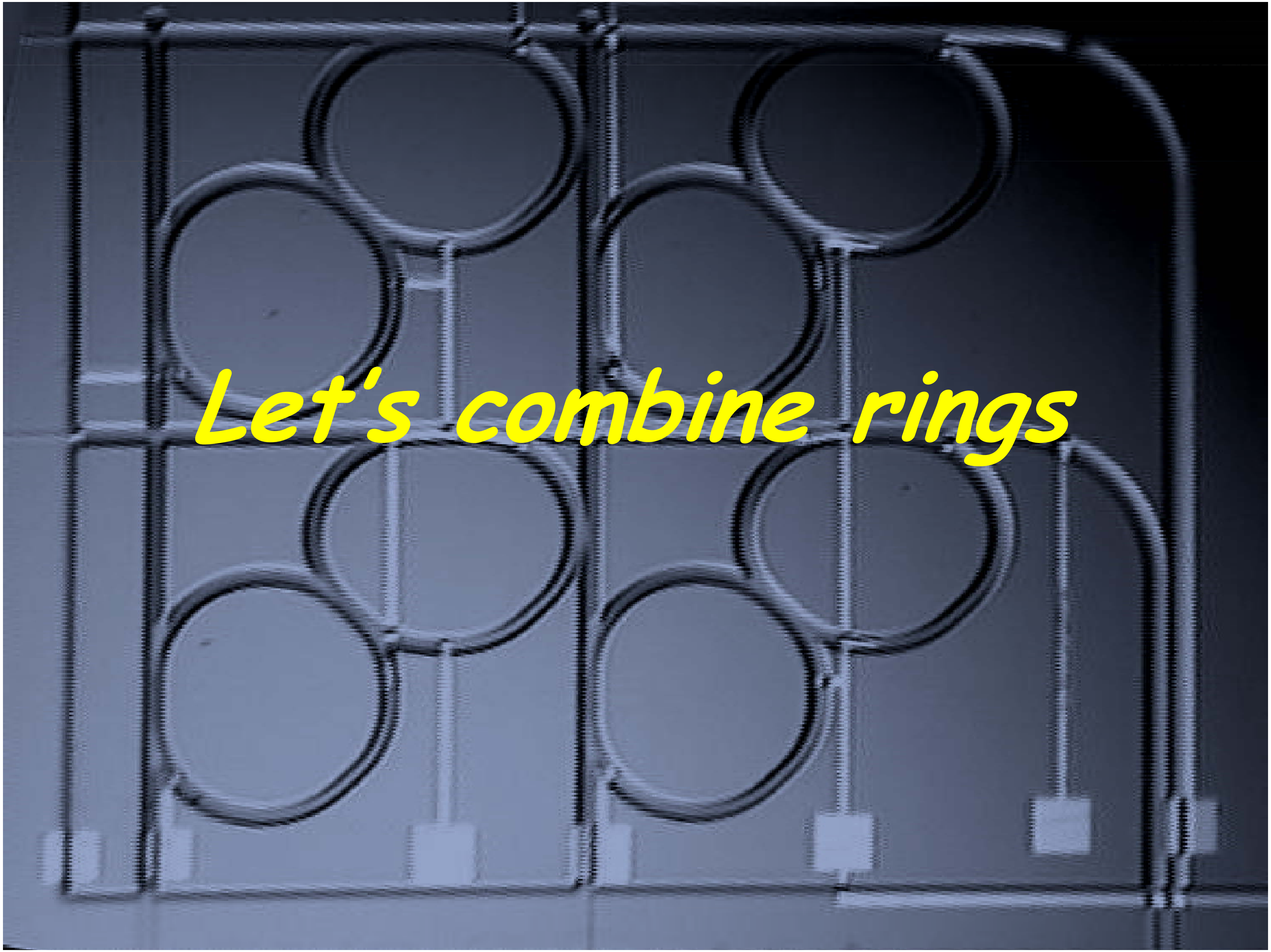
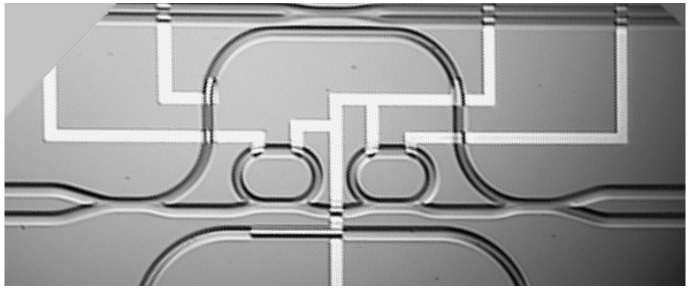
Waveguide theory and photonic circuit design

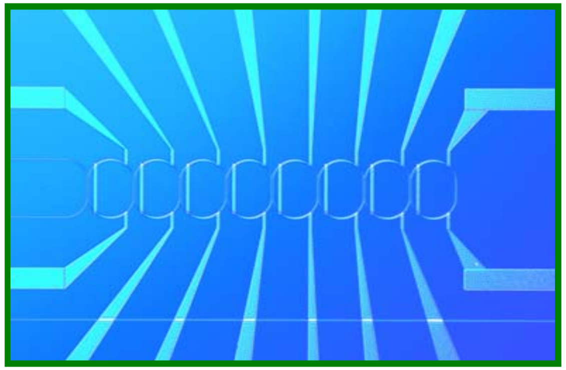
- Waveguides (no theory…)
- The role of index contrast in waveguides (survey of technologies, type of waveguides, index contrast…)
- Bends and advanced topics on bends (the matched bend,...)
- The dark side of integrated optical waveguides (backscatter, xtalk, losses, spurious modes, the (ng-neff) role….)
- 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

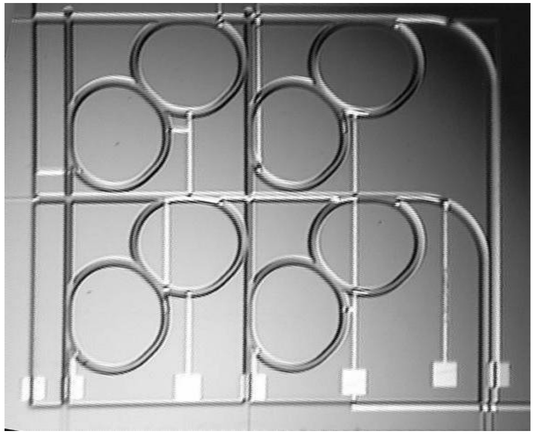
Let's combine rings



from Ring to Rings…



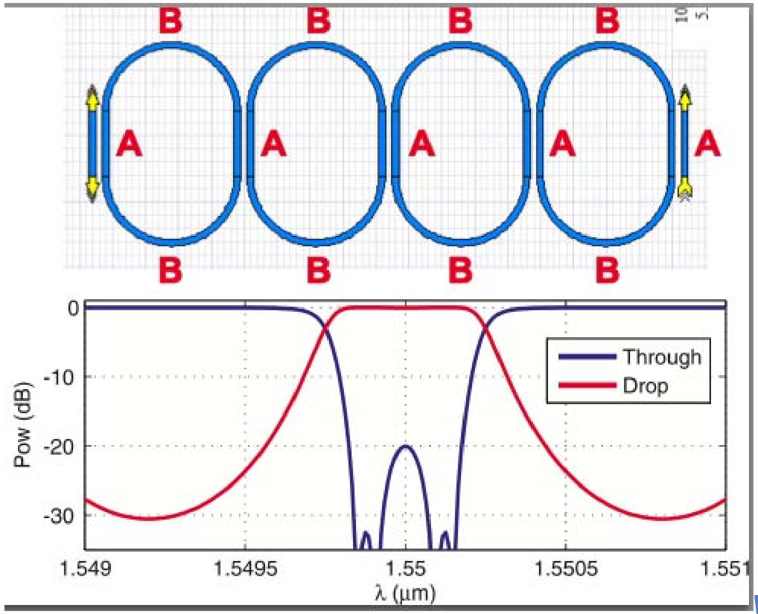


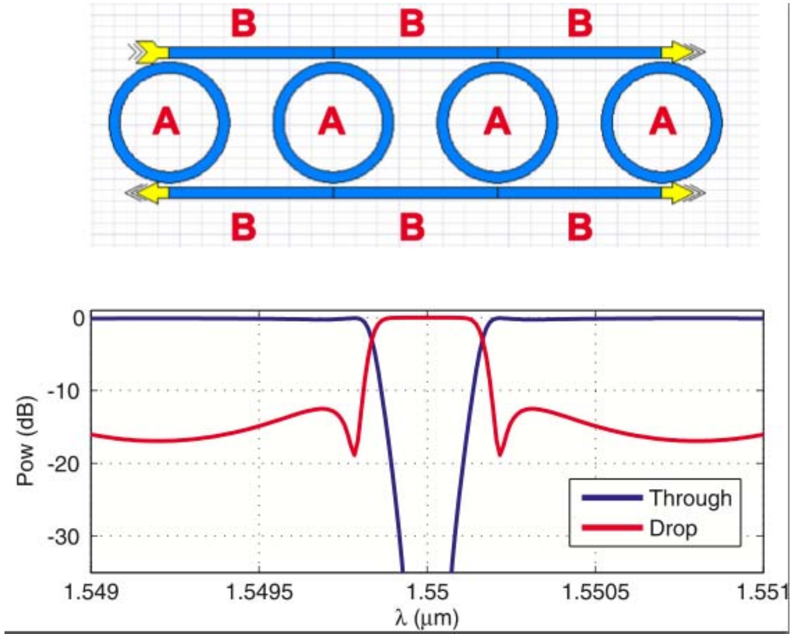


A. Yariv	Caltech	1999	Microwave
C. Madsen	Bell Labs	1999	DSP
R. Orta	Politecnico Torino	1999	DSP
A. Melloni	Politecnico Milano	2002	Microwave
V. Van	Maryland Univ.	2006	Electronic/Microwave

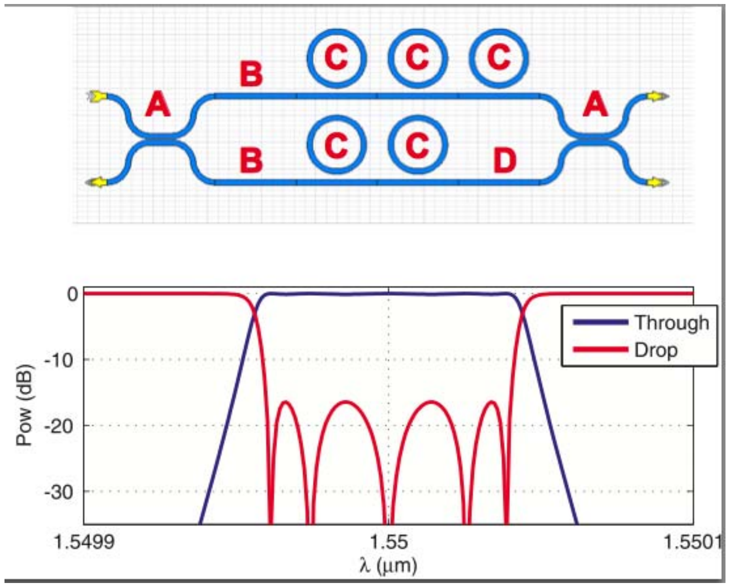
Books from I. Chremmos, O. Schwelb, D.G. Rabus, J. Hebneer, ….

from Ring to Rings…





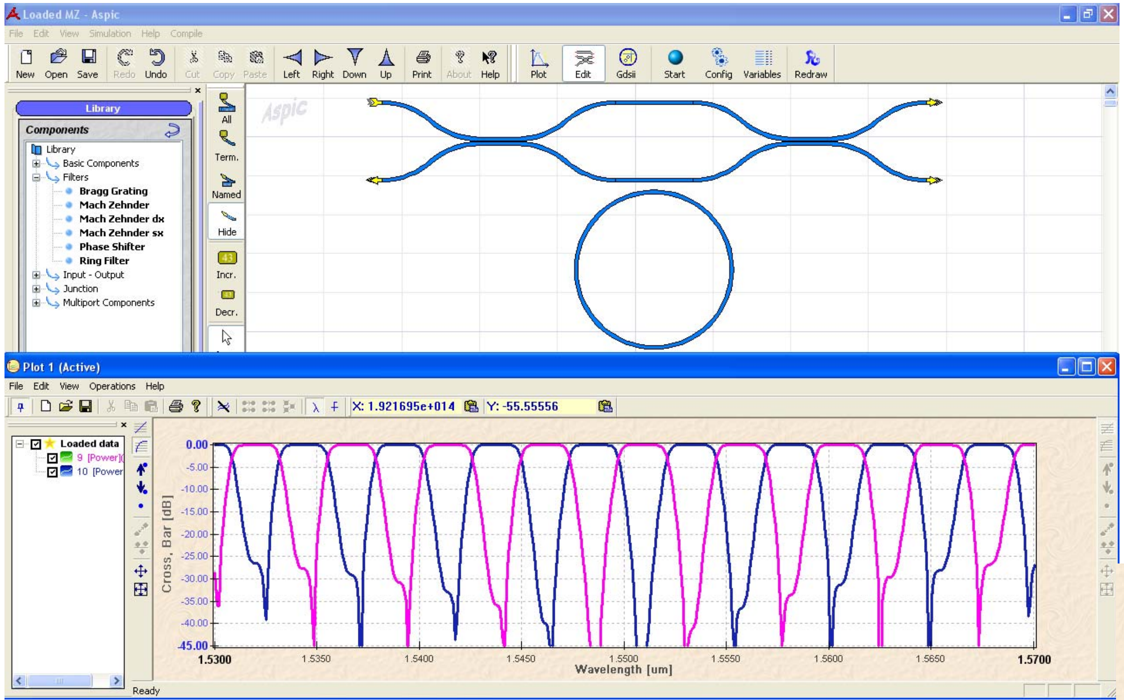
Parallel coupled bandstop filter



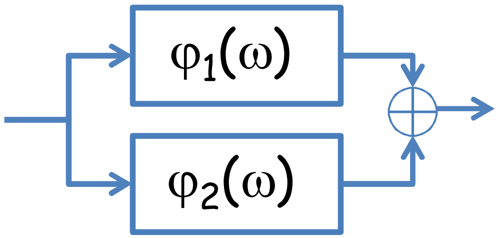
Directly coupled bandpass filter (CROW)

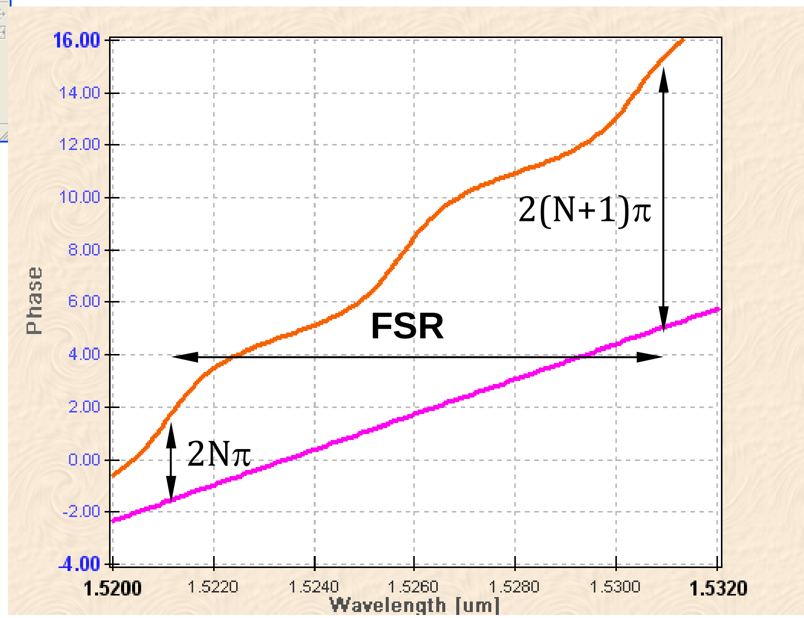
Ring-loaded Mach-Zehnder filter

Ring loaded Mach-Zehnder



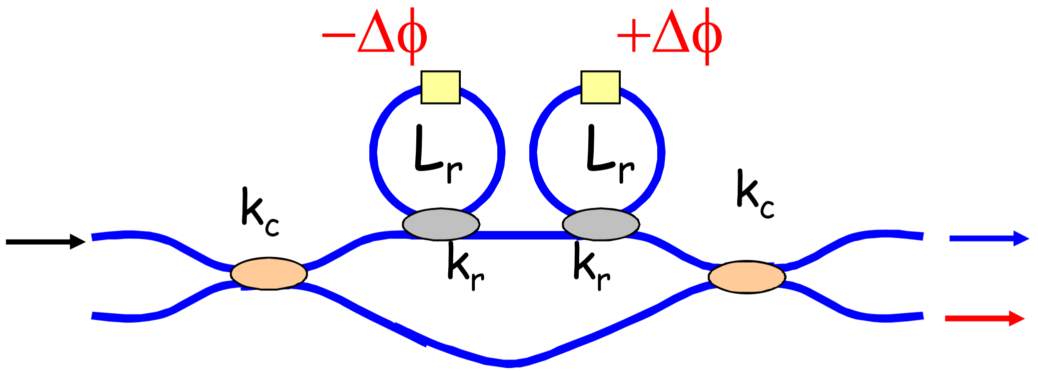
APF allows to shape the phase response

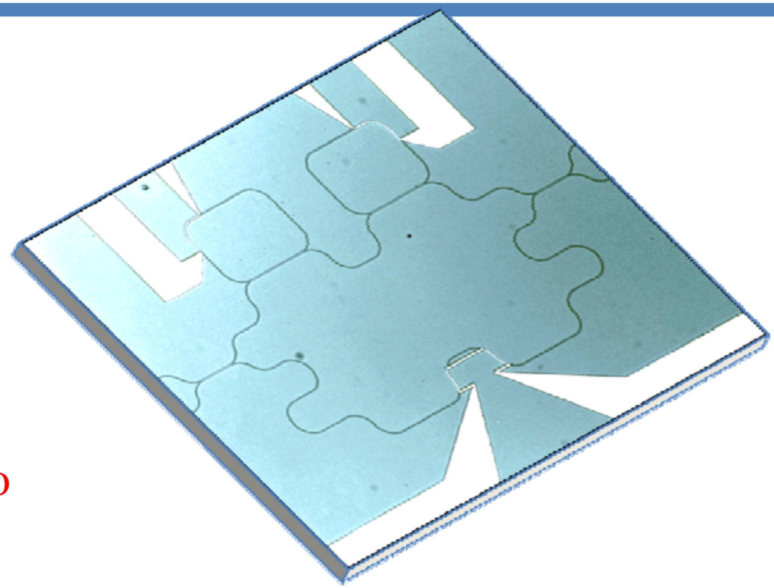




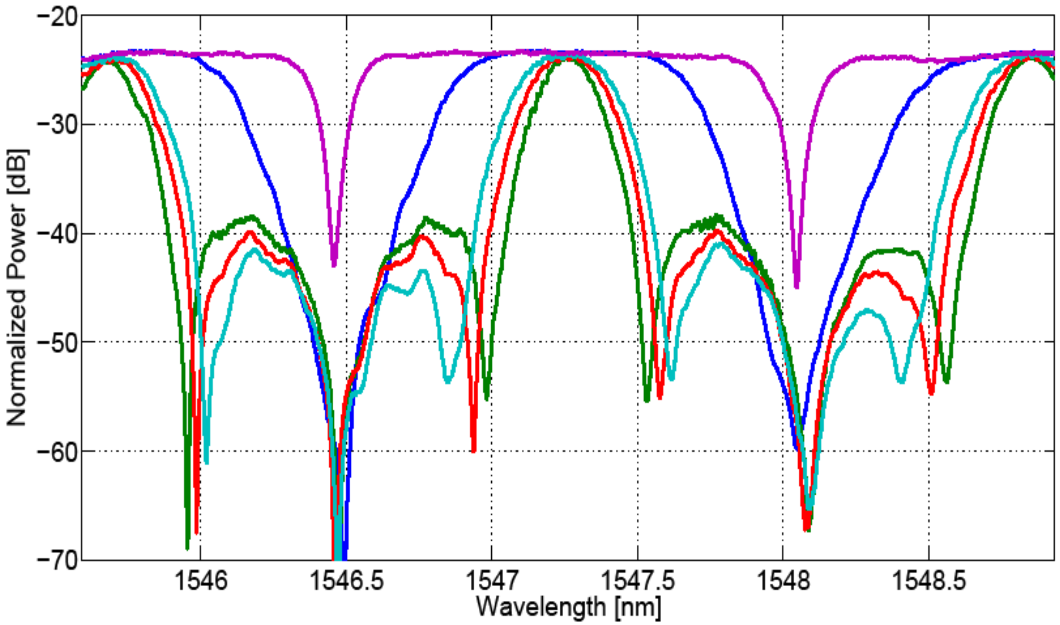
Advanced Simulator for Photonic Integrated Circuits

Tunable bandwidth filter





Bandwidth tunability is obtained by varying Δφ



FSR = 200 GHz

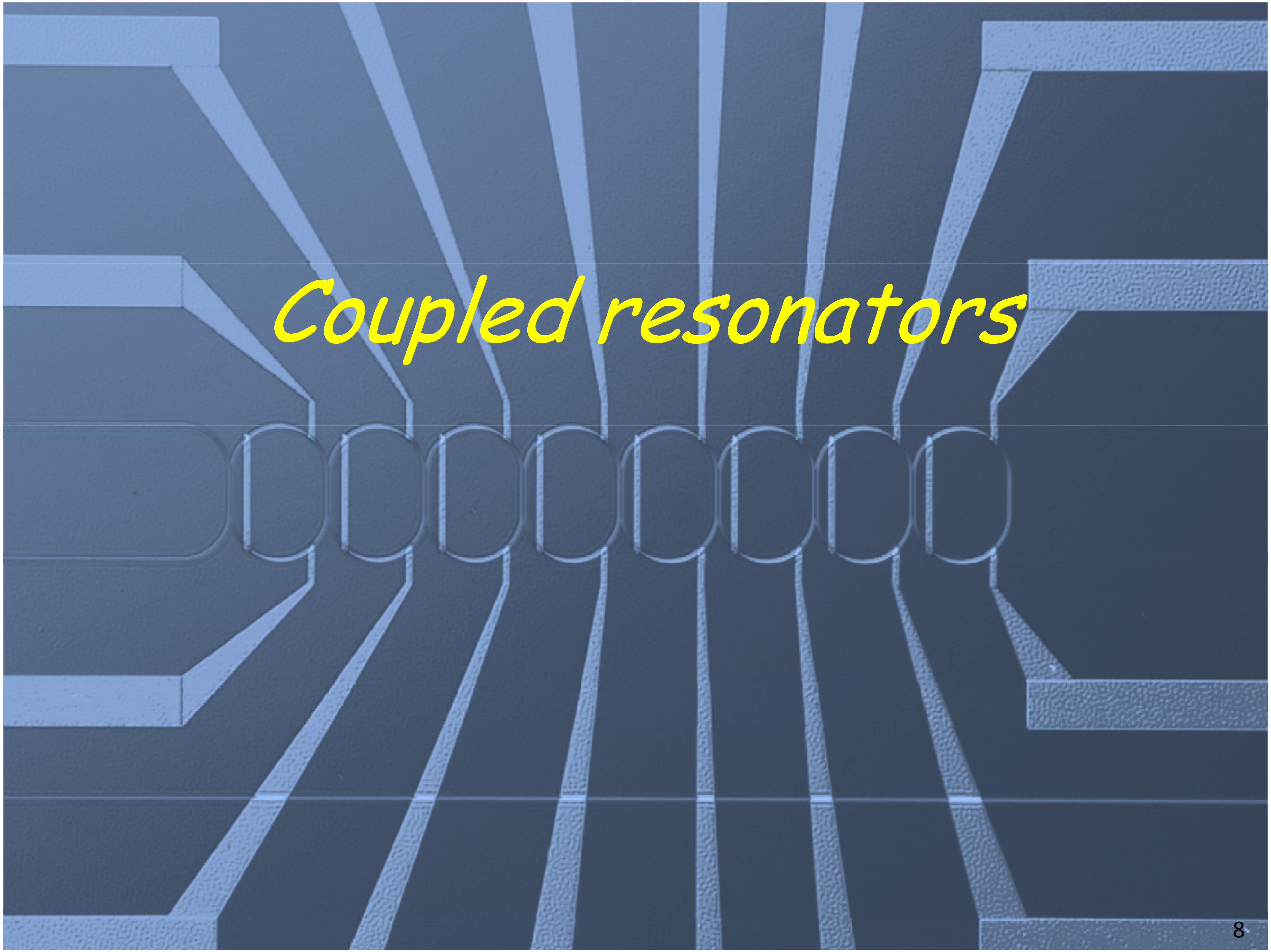
B = 23 GHz … 175 GHz

IL < 0.6 dB

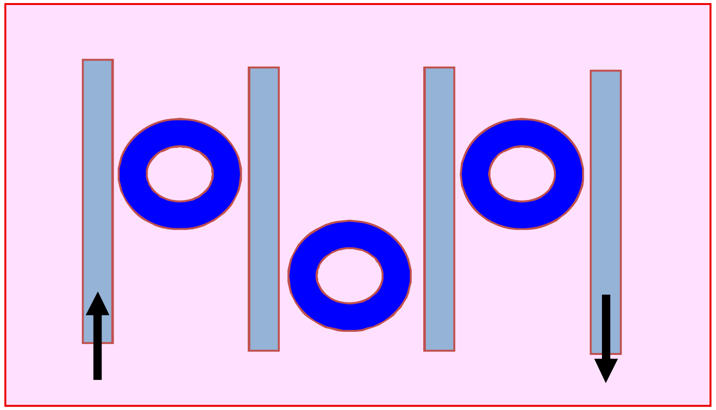
ER > -18 dB

University of Glasgow

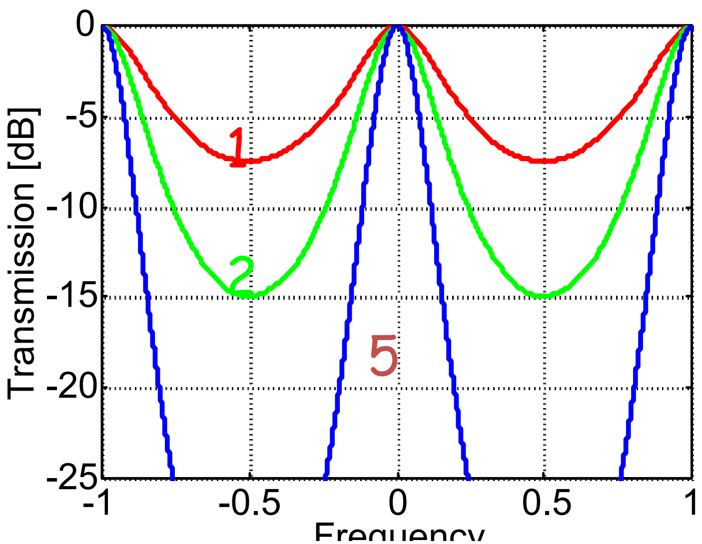
Coupled resonators

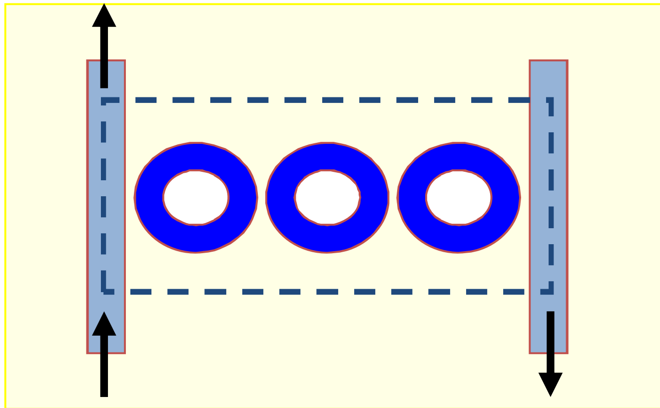


Direct coupled cavities vs cascaded cavities

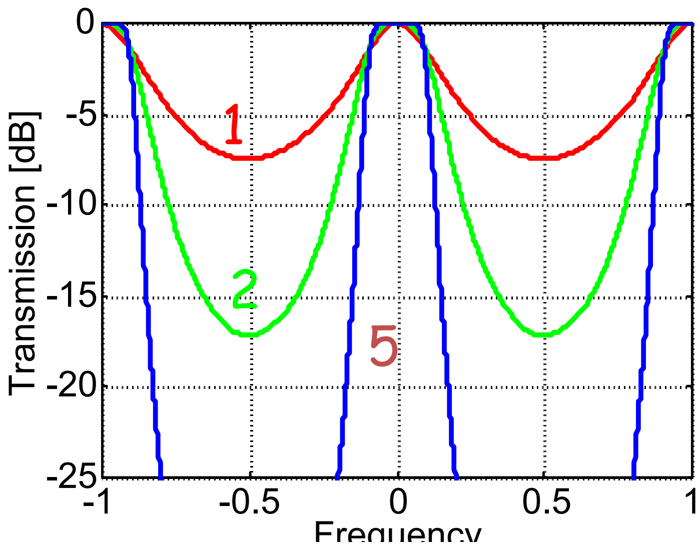


Cascaded cavities
(SCISSOR)

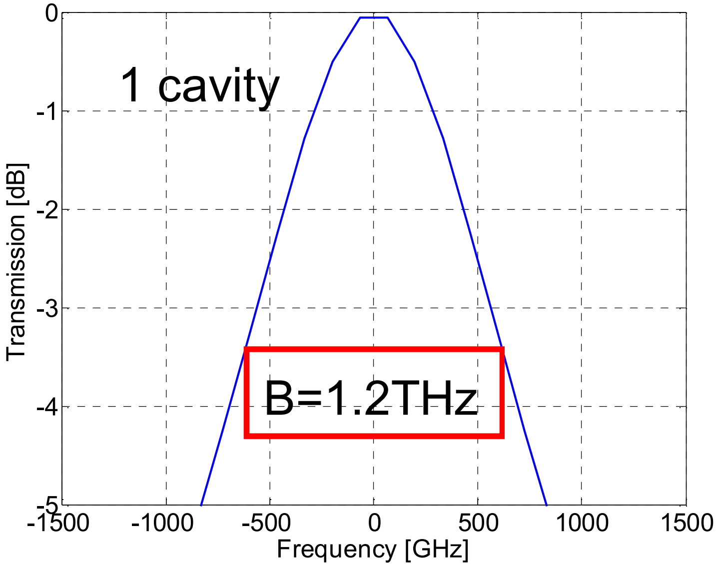




Direct coupled cavities
(CROW)



Identical cavities ?



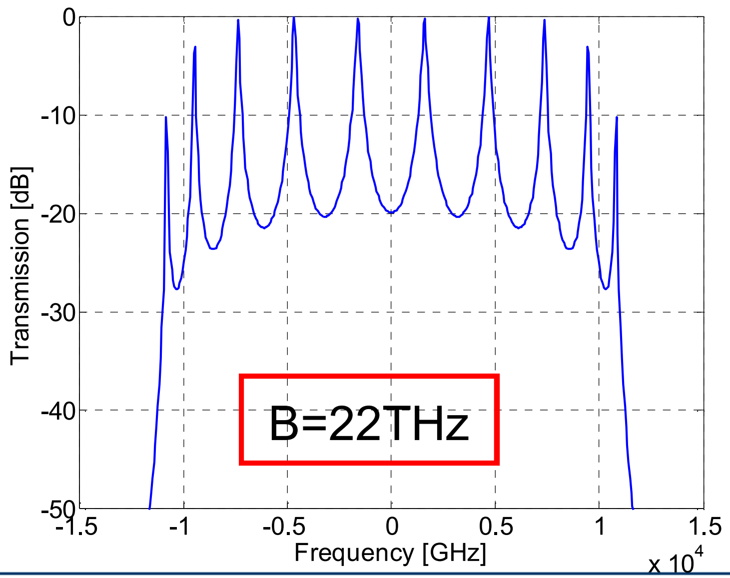
K=0.01

1st order cavity d=$\lambda/2$

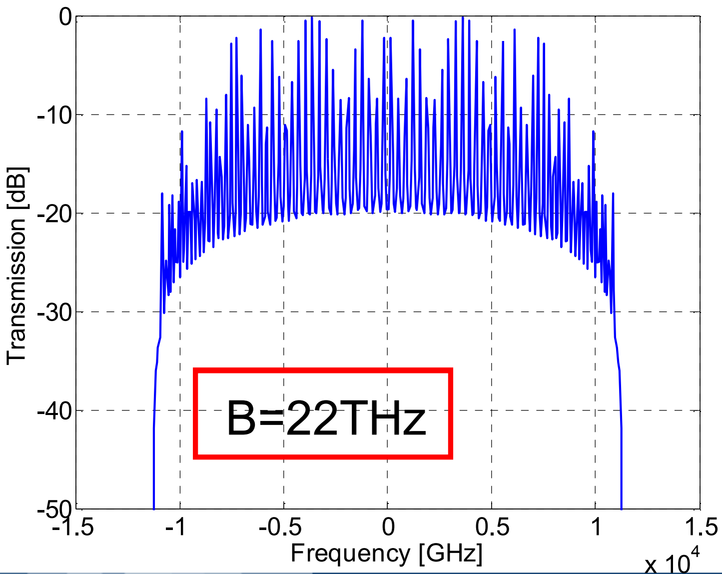
$B_{1\ cavity}$=1.2 THz

B_{CROW}=22.5 THz

10 cavities

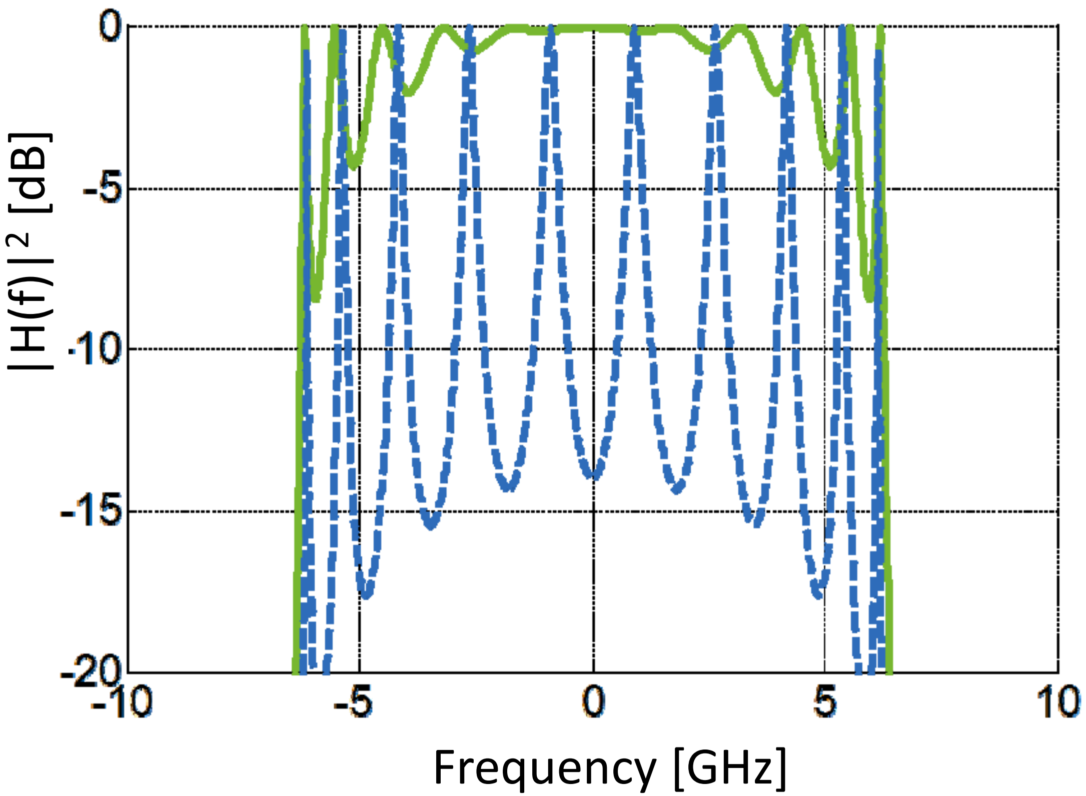


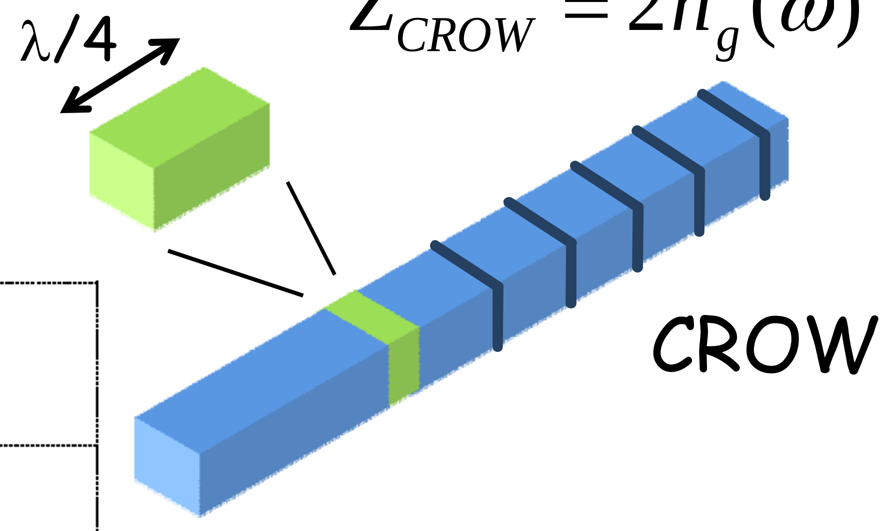
100 cavities



CROW impedance matching

-14 dB → 0 dB





$$Z_{CROW} = 2n_g(\omega)$$

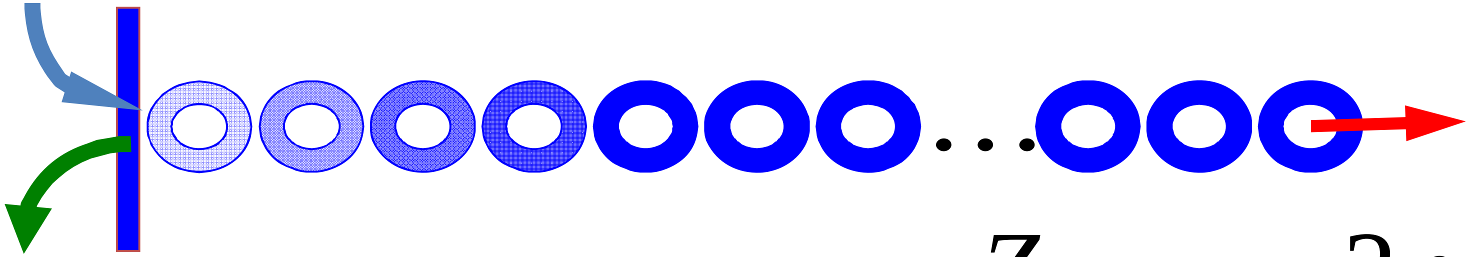
$$Z_W = n_{eff}$$

Quarter-wave matching

$$n_{eff}^{(\lambda/4)} = n_{eff}\sqrt{2n_g}$$

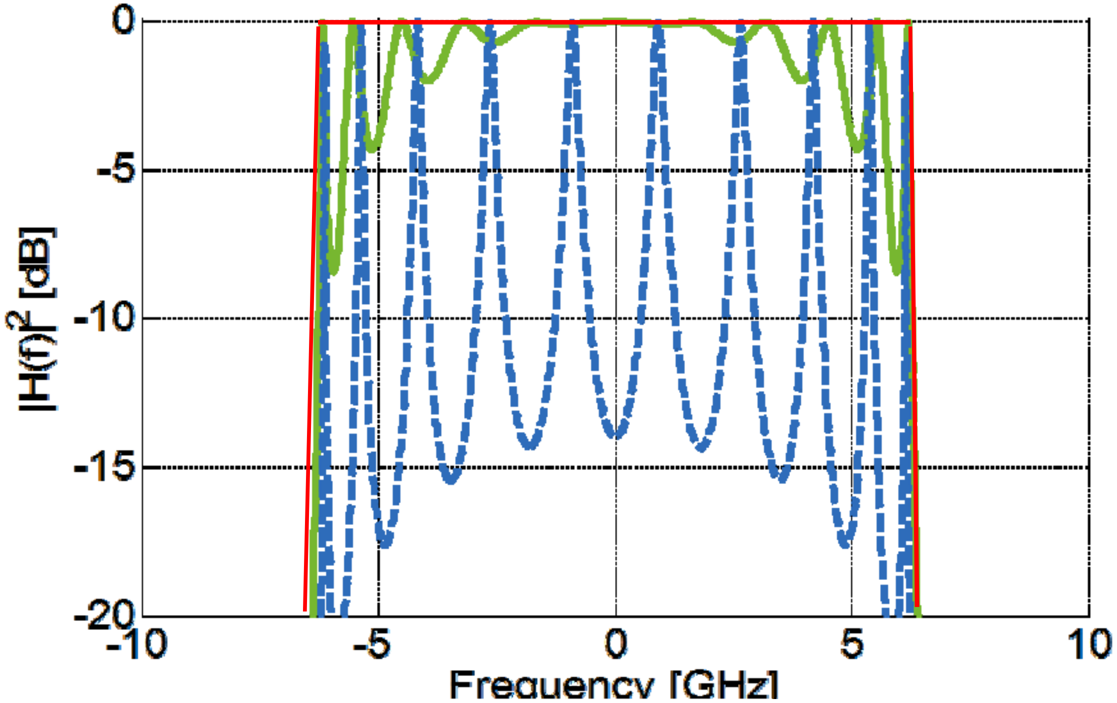
No impedance matching

Impedance Matching (Apodization)



$$Z_W = n_{eff}$$

$$Z_{CROW} = 2n_g(\omega)$$

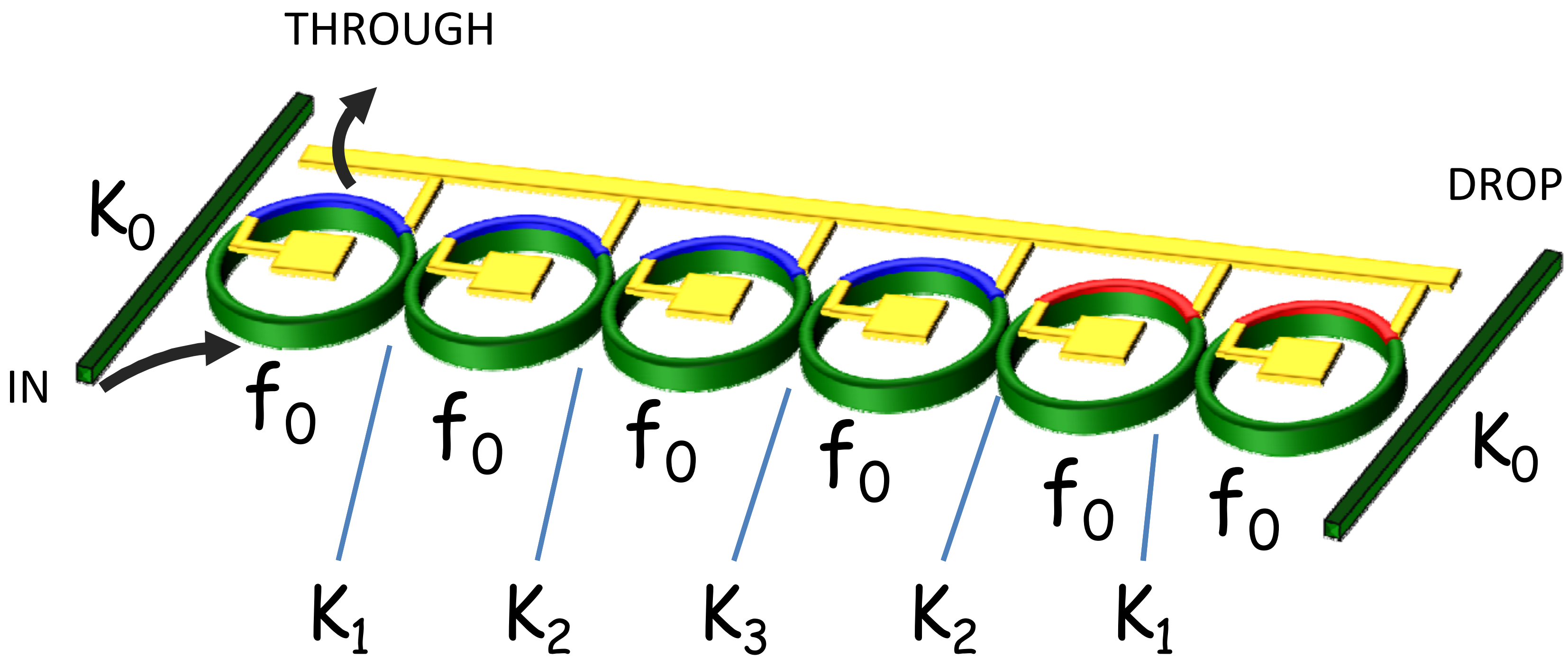


Quarter-wave matching

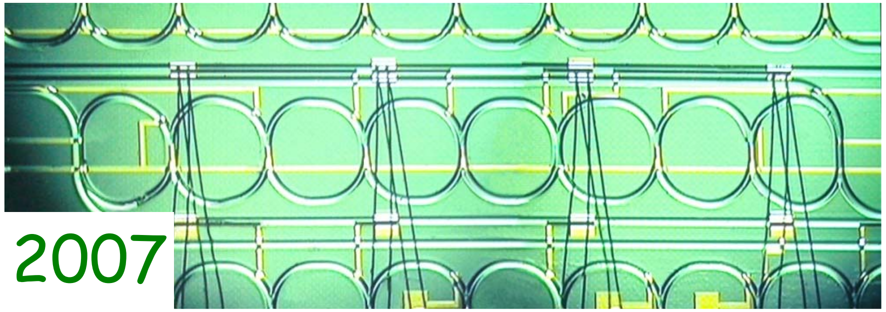
$$n_{eff}^{(\lambda/4)} = n_{eff}\sqrt{2n_g}$$

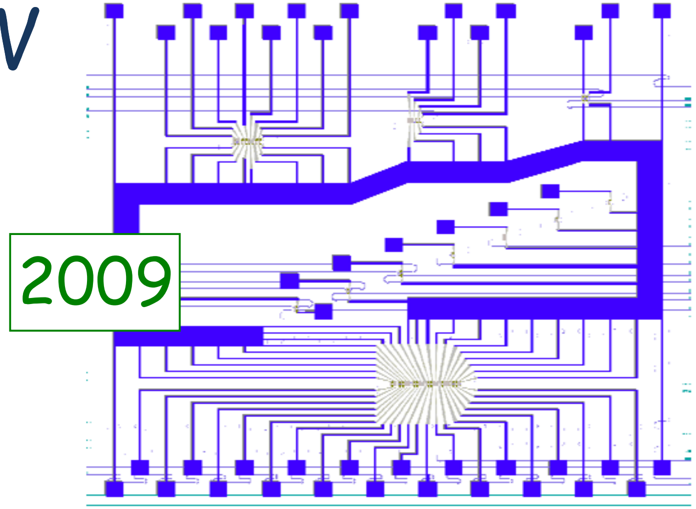
No impedance matching

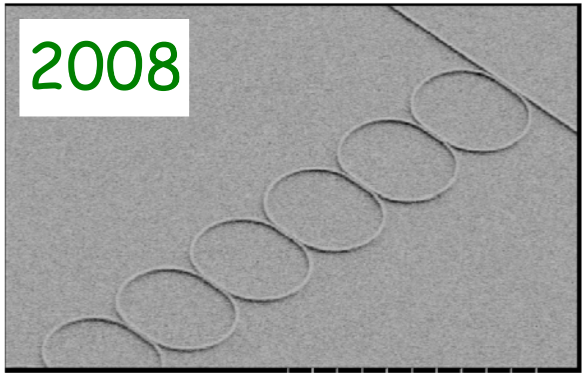
Coupled ring resonators

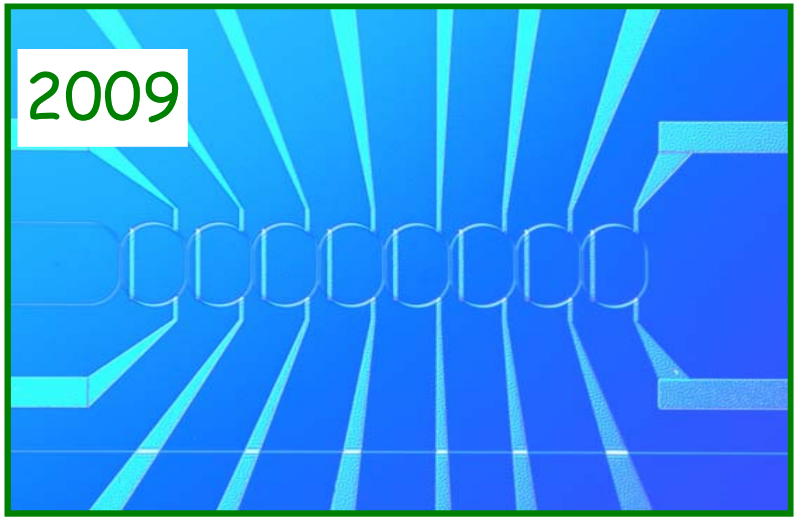


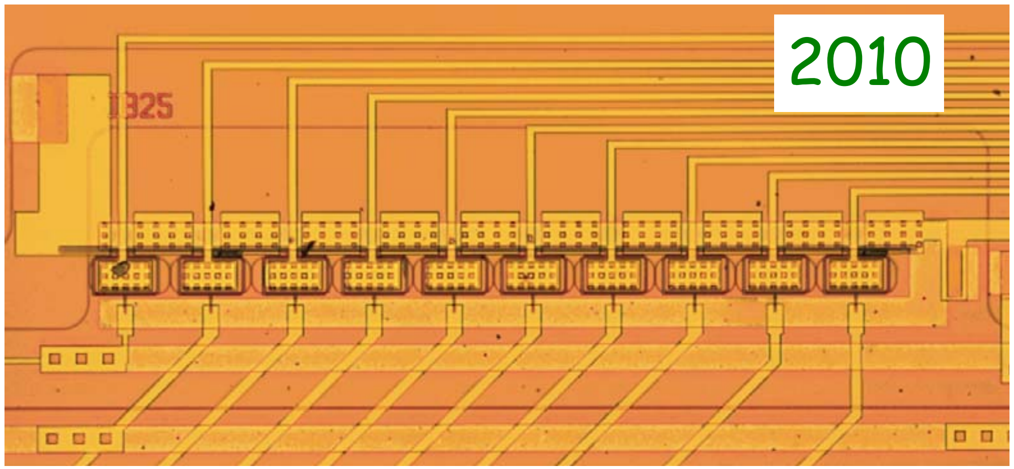
Progress in tuneable ring-CROW

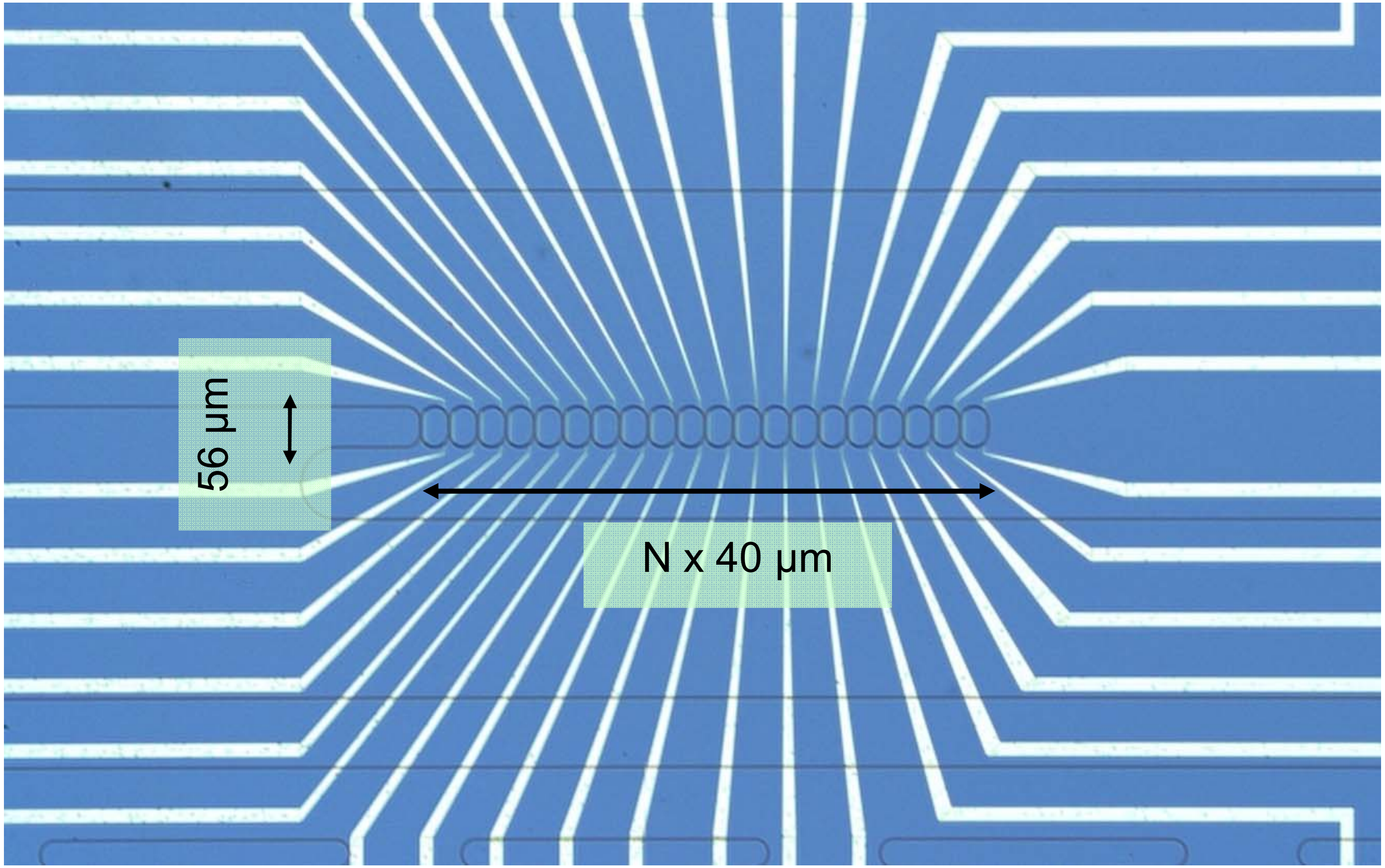








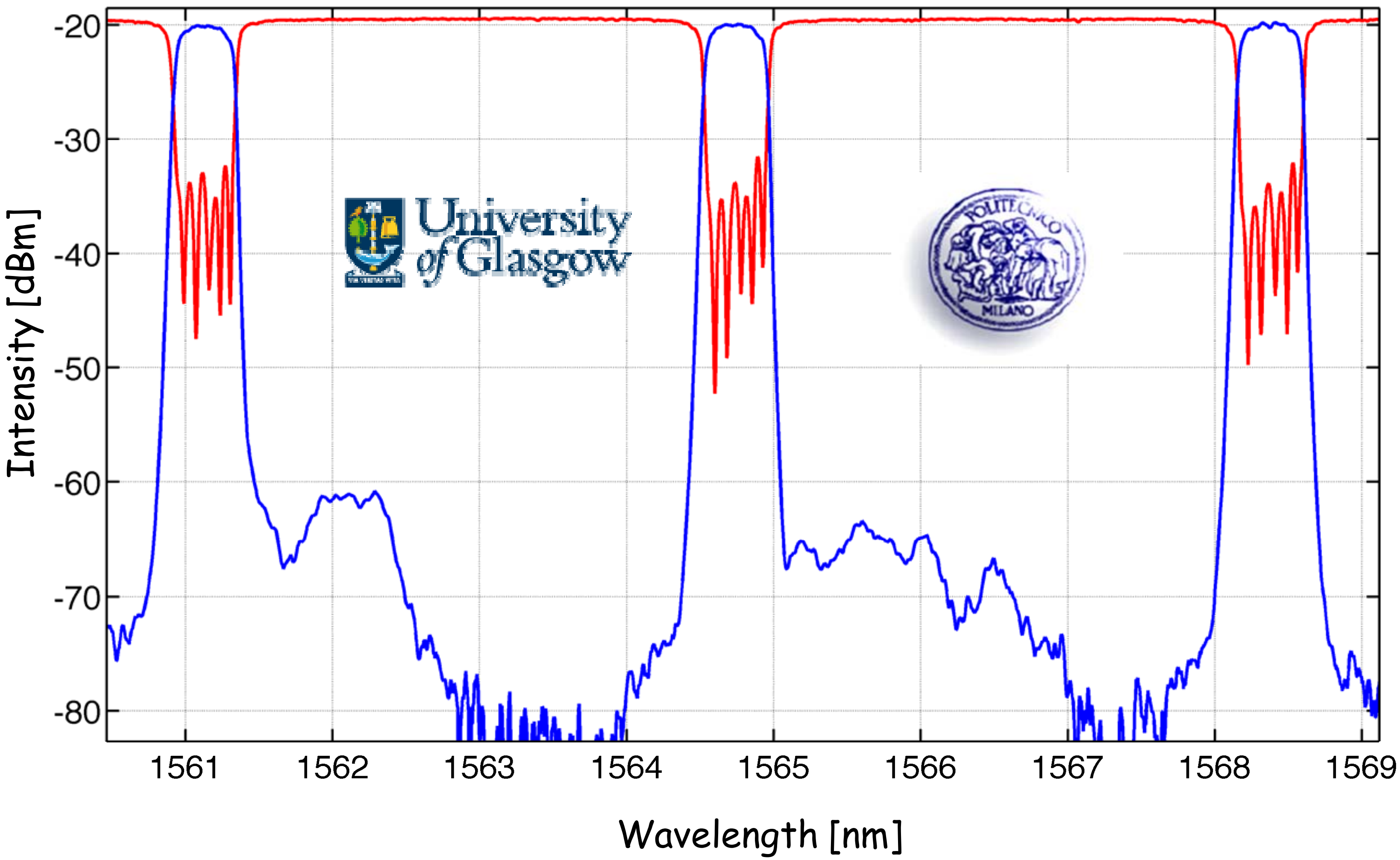




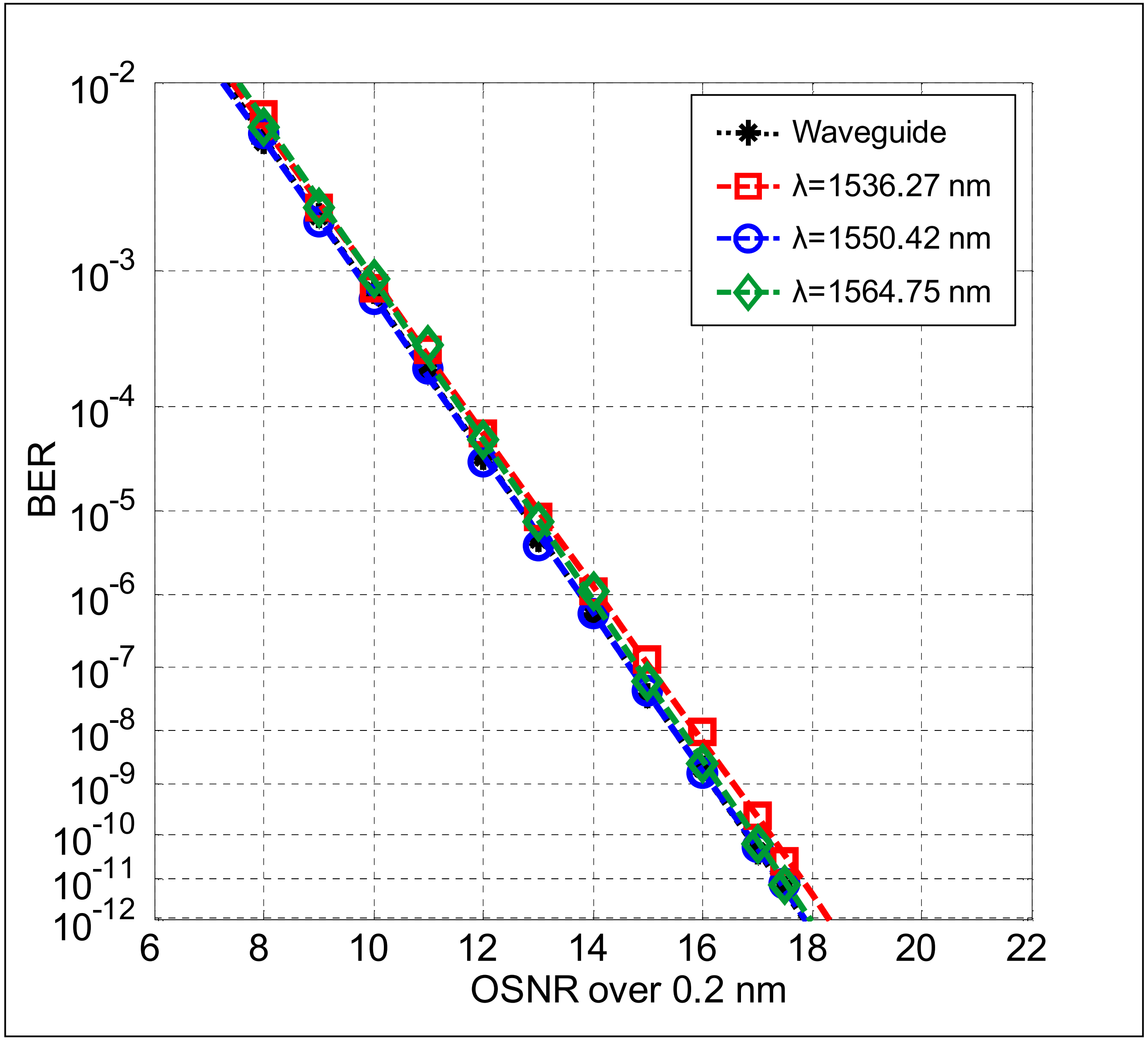
F. Morichetti et al., *The first decade of coupled resonator optical waveguides: bringing slow light to applications*.
Laser & Photonics Reviews, 6: 74–96 (2012)

8-rings Bandpass filters in SOI

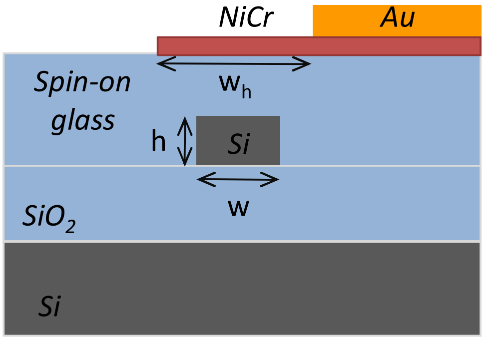
Return loss: -15 dB; IL 0.5 dB; In-band ripple <0.2 dB; Off-band rejection >50 dB

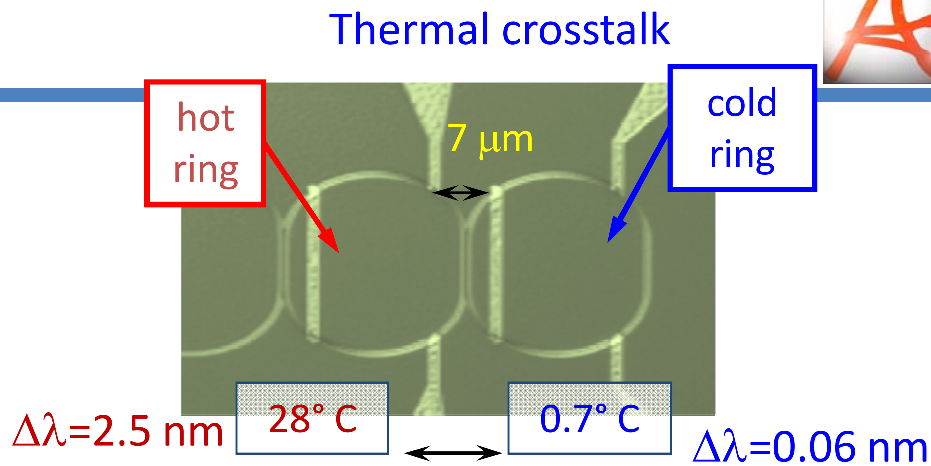


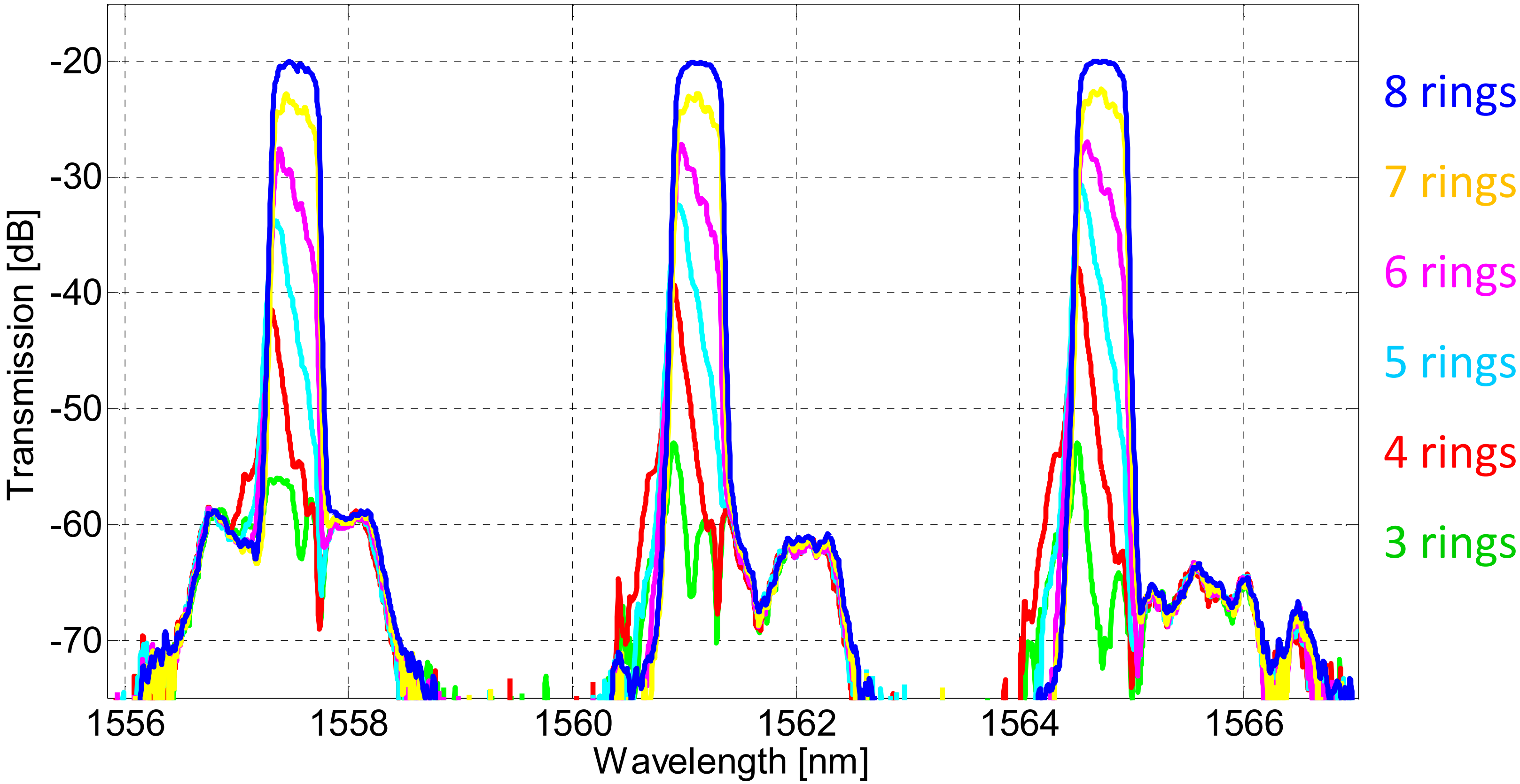
8-rings Bandpass filters in SOI



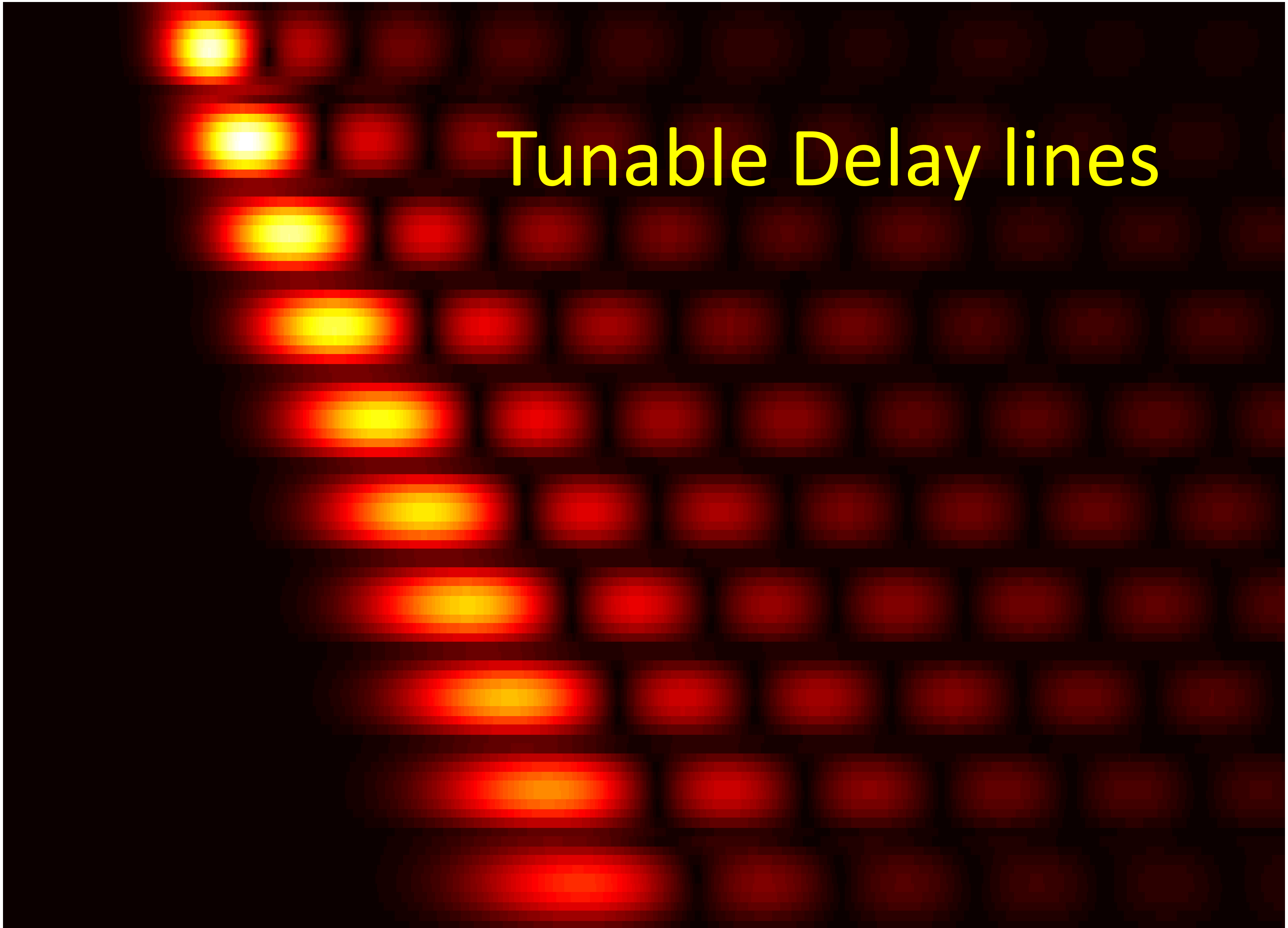
Thermal tuning





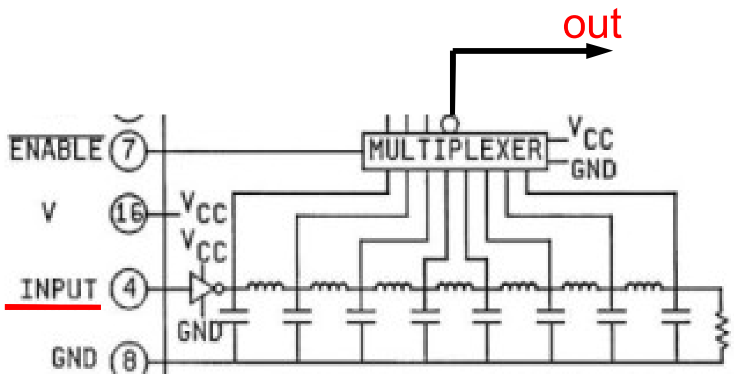


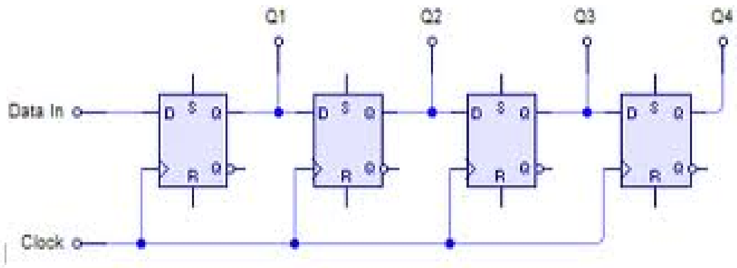
Tunable Delay lines



On-Chip Tunable delay… not an easy task !!!

Electronic





Microwave

Photonics

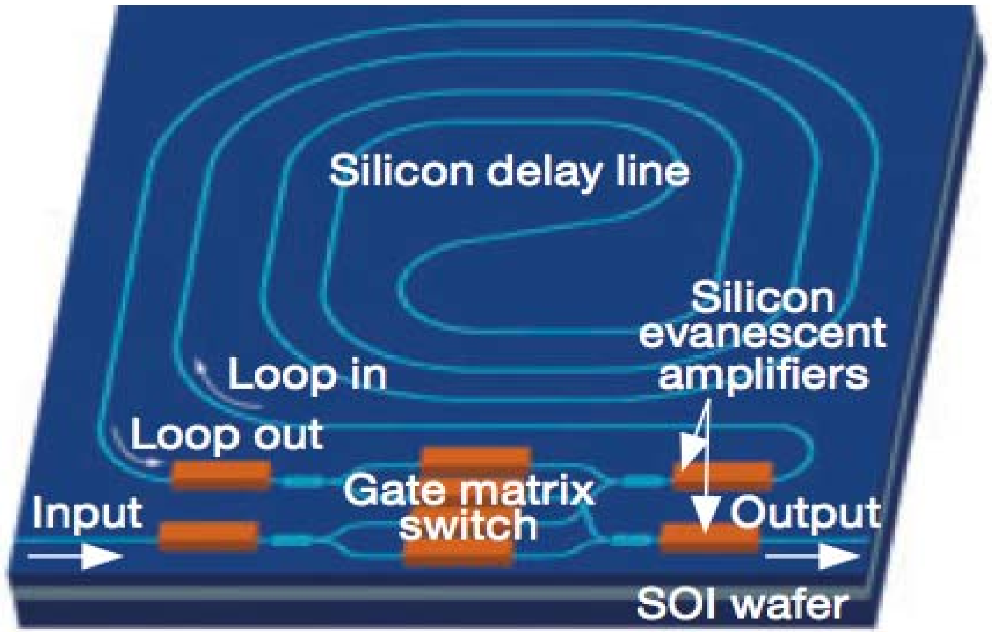
- let photons run around (coil of fiber)
- slow down photons

Recirculating buffer

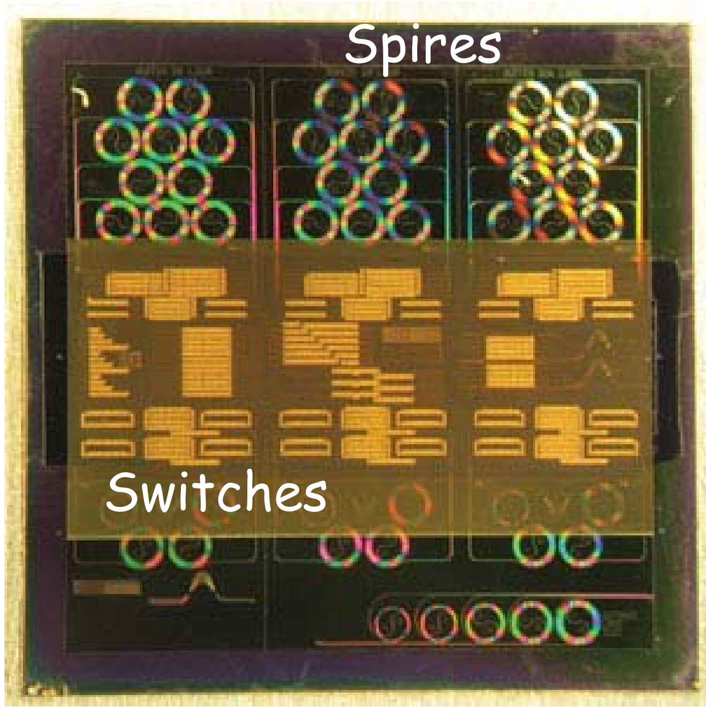
Discrete delay line, Packet(s) delay and Buffer

Technologies: 2007 Glass for the spire + InP for the switch
2010 All Silicon (15 dB/ns)

Trade off between waveguide attenuation and switch ER (limit)



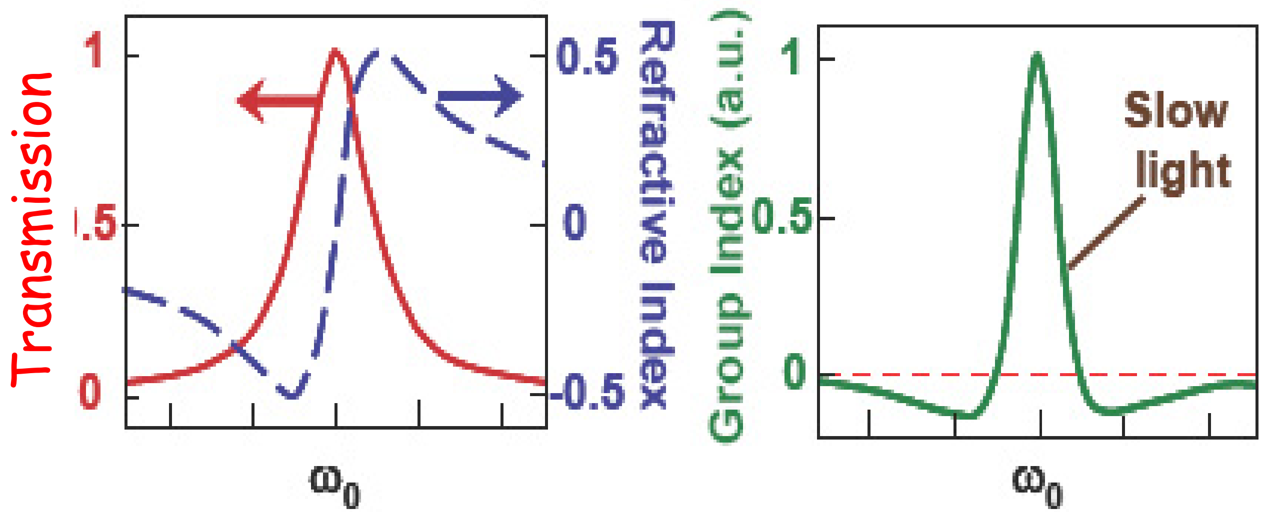
Courtesy of John Bowers, University of California, Santa Barbara



INTEL 2010

Slow down photons

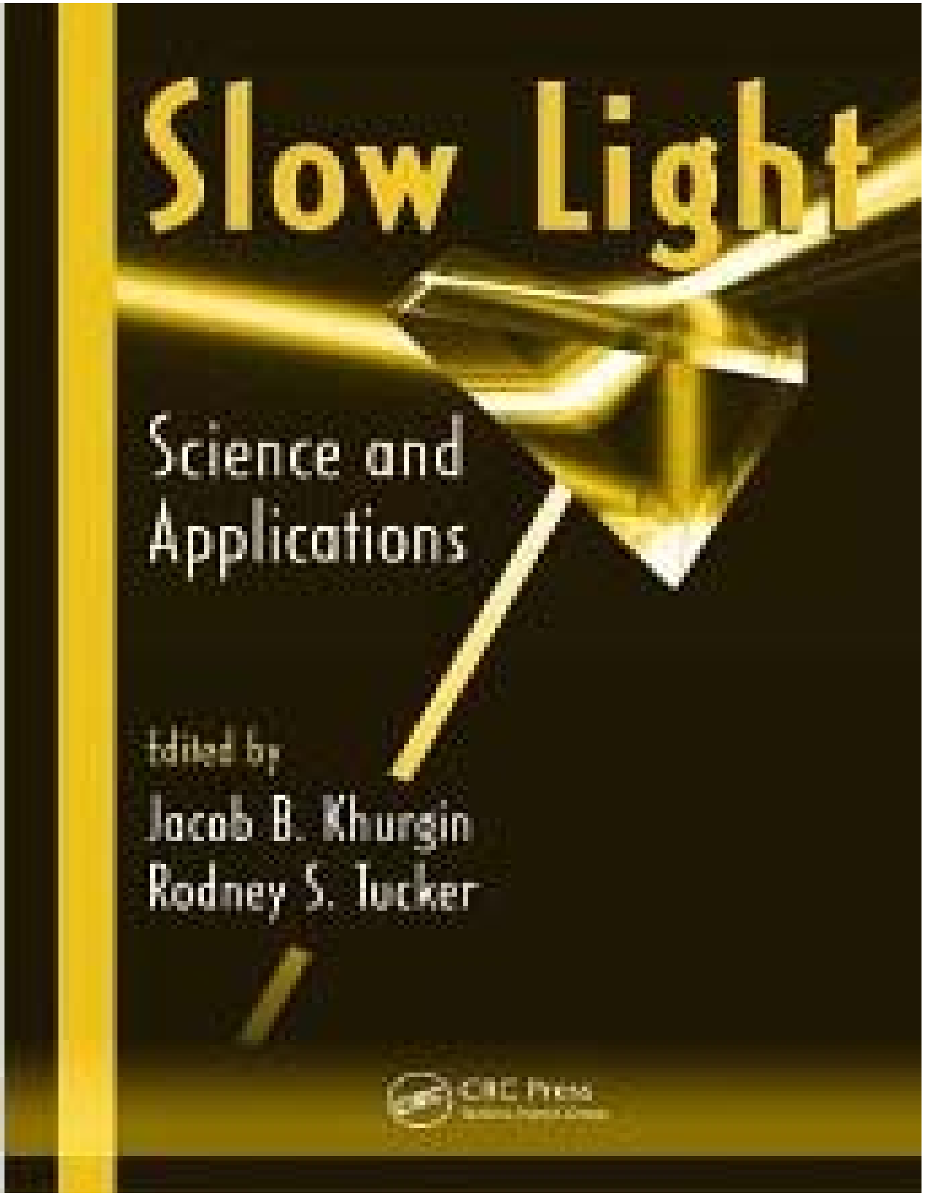
$$velocity = \frac{c}{group\ refractive\ index}$$



n_g of the material: Atomic resonances, band edge, EIT, CPO,…

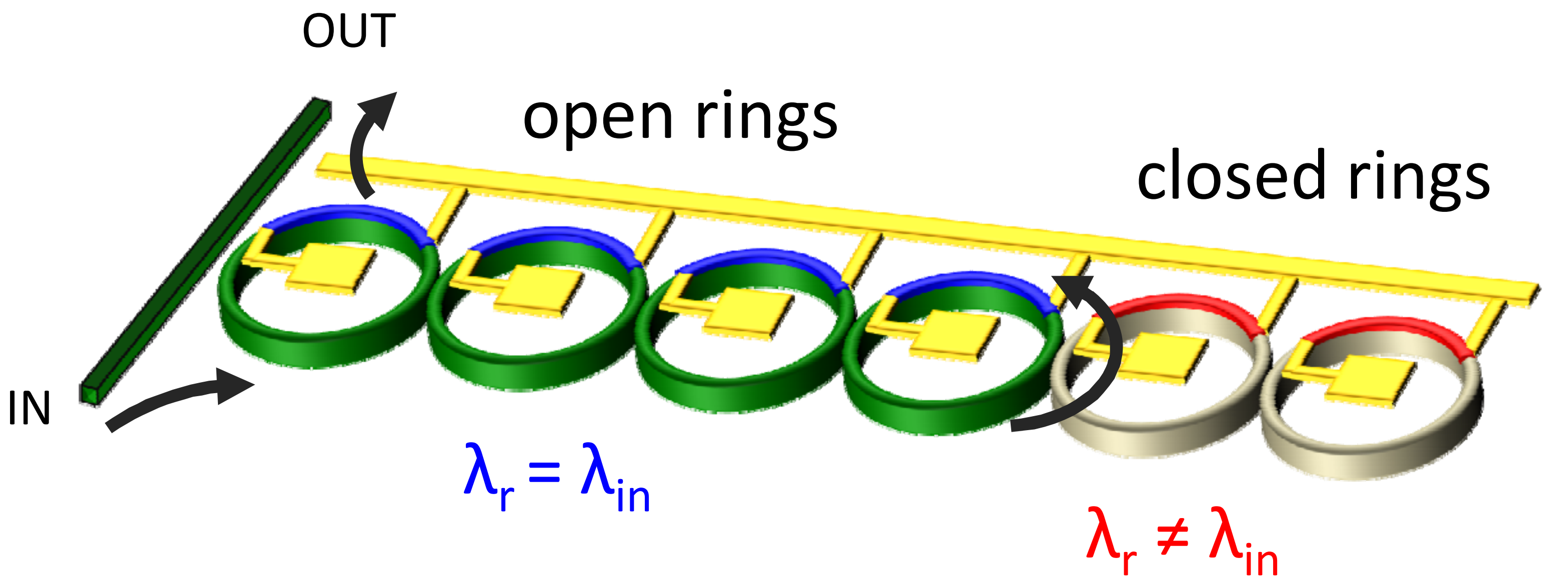
n_g of the circuit: Resonators, Bragg Gratings, Photonic Crystals, Brillouin and Raman,…

Slow down photons



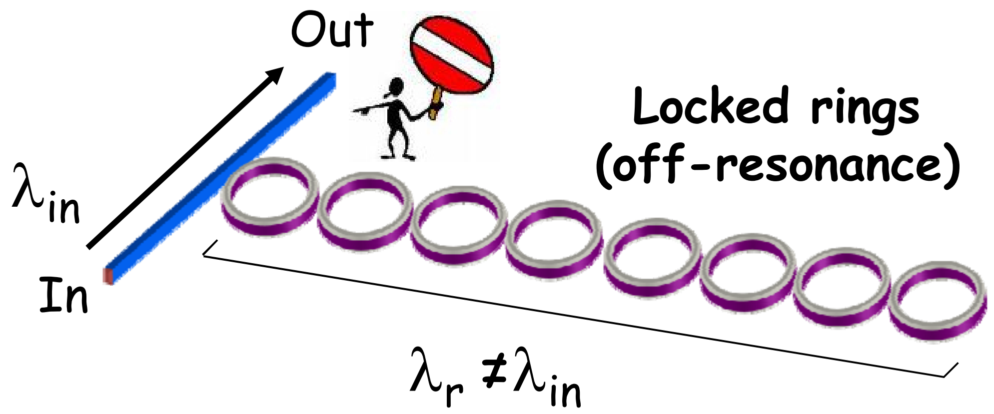
Tunable Delay lines

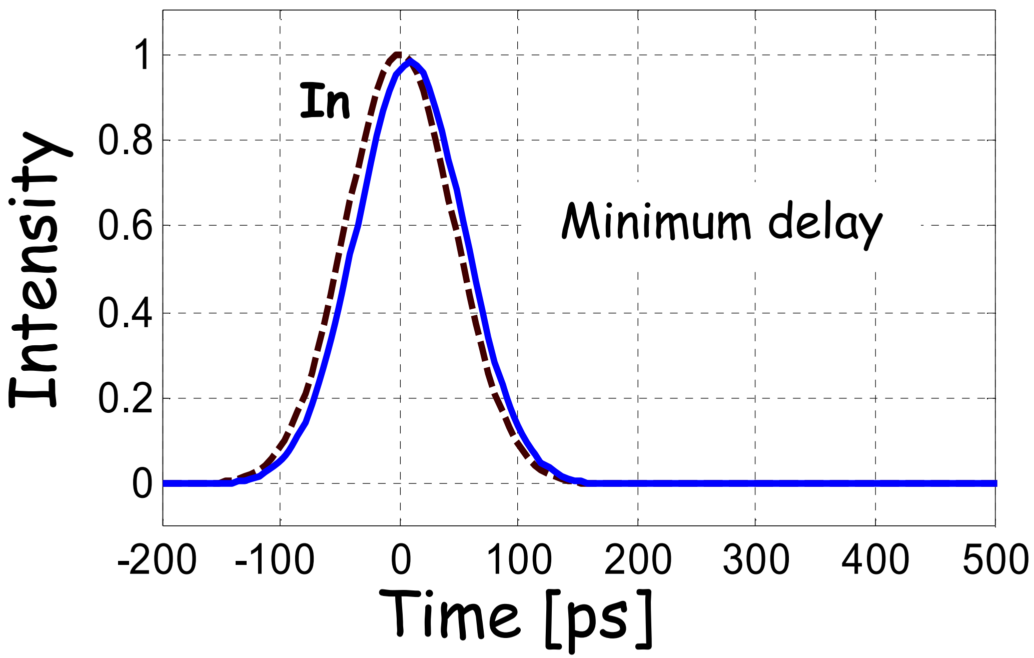
1 byte continuously tuneable delay at 10 and 100 Gbit/s demonstrated

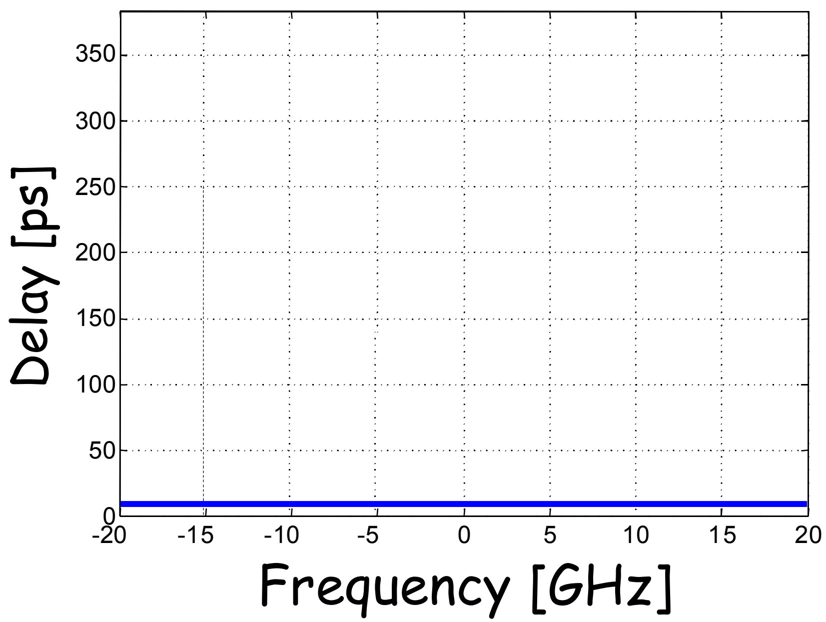


F. Morichetti et al., Optics Express, Vol. 15, 25, December 2007
A. Canciamilla et al., Journal of Optics, IOP, 2010
A. Melloni et al., IEEE Photonics Journal, vol. 1, no. 4, 2010

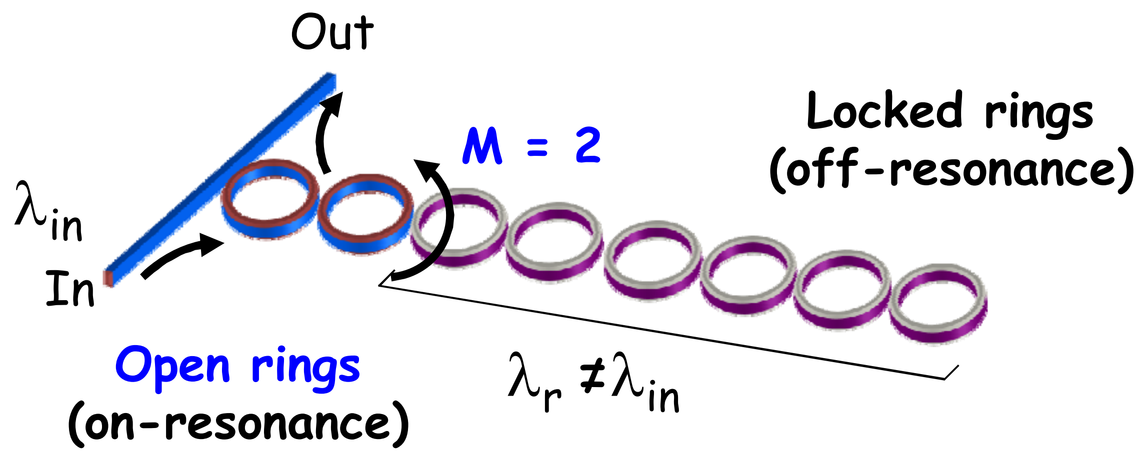
The CROW in reflection

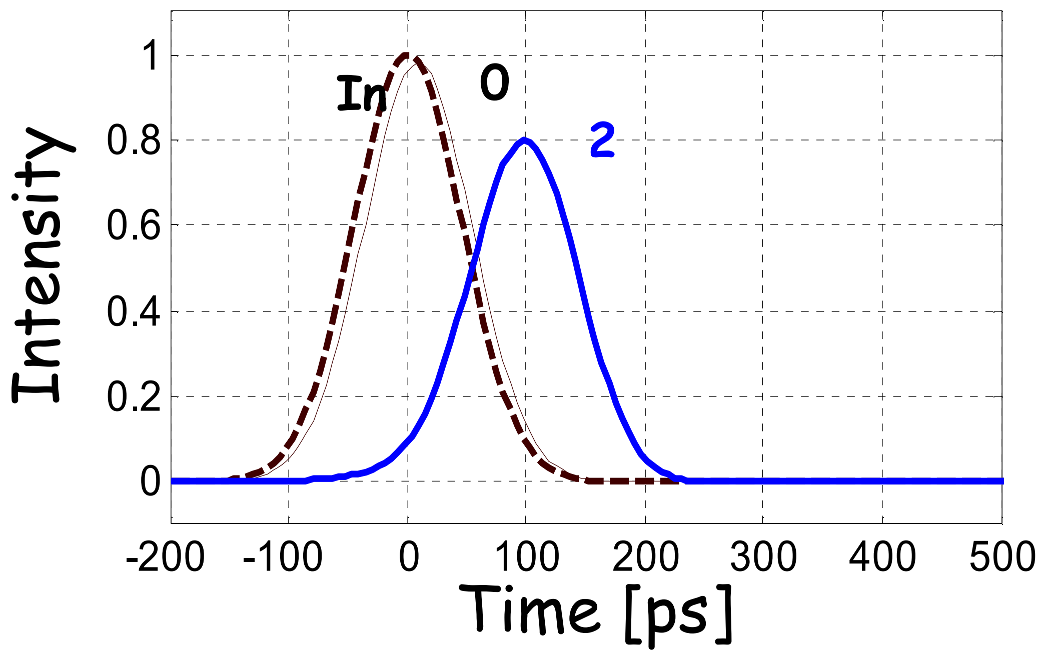


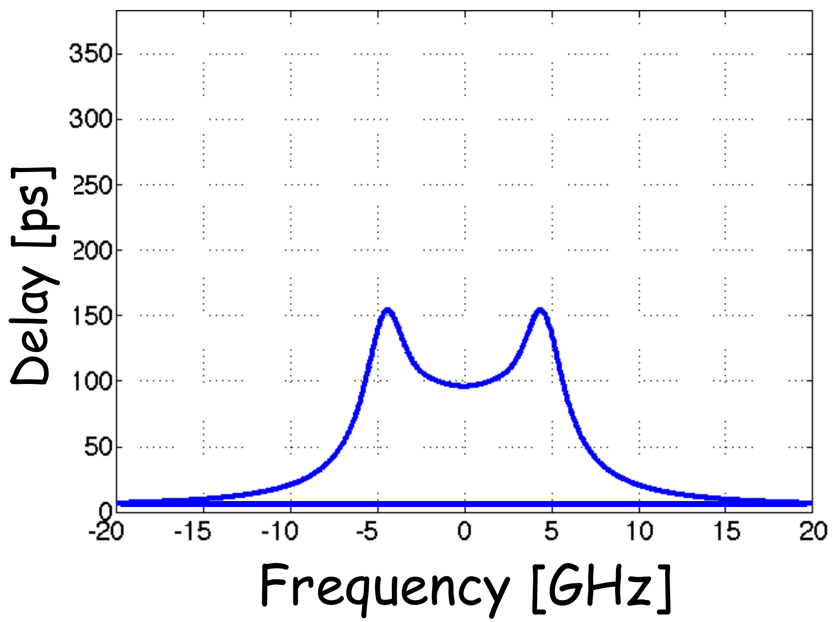




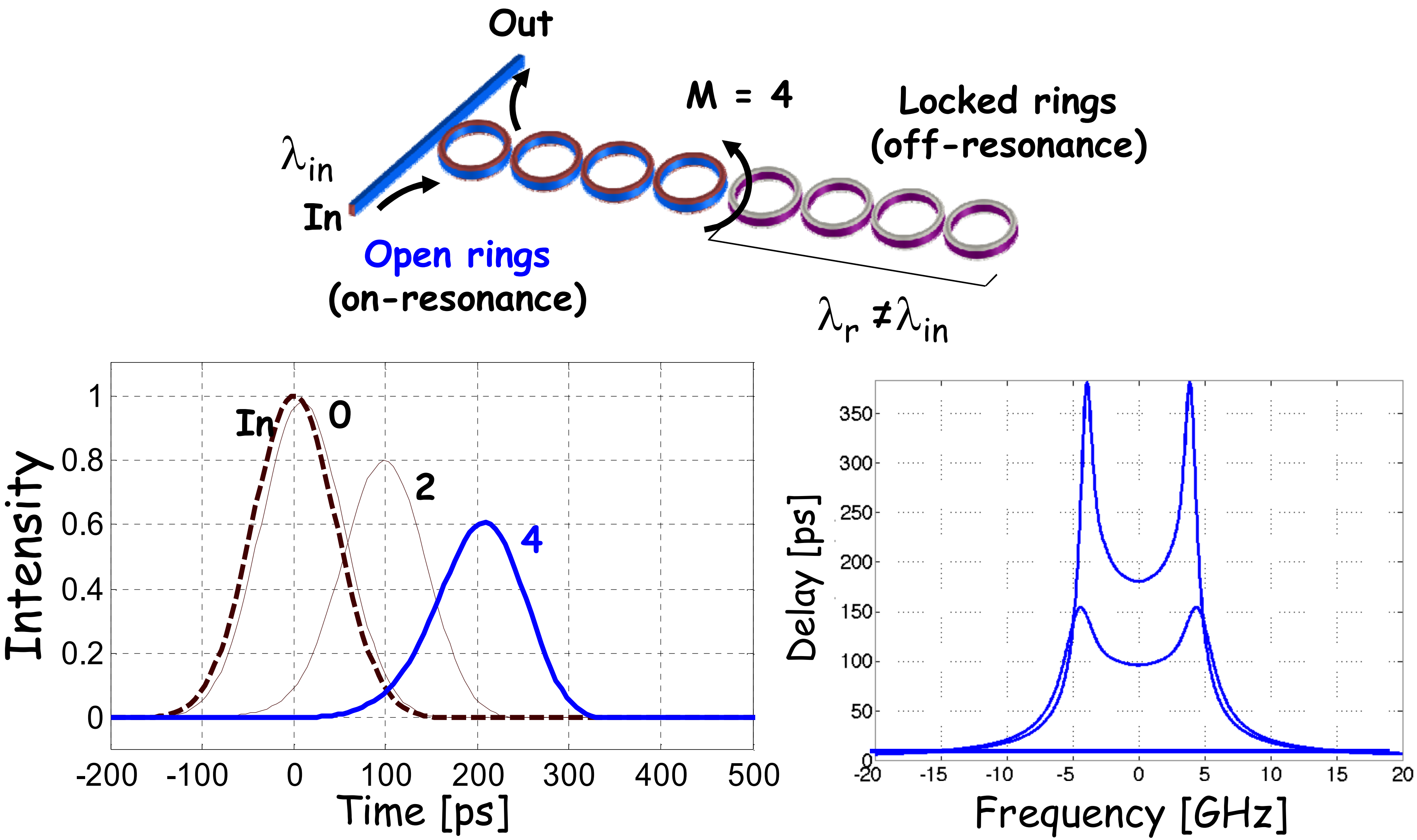
The CROW in reflection





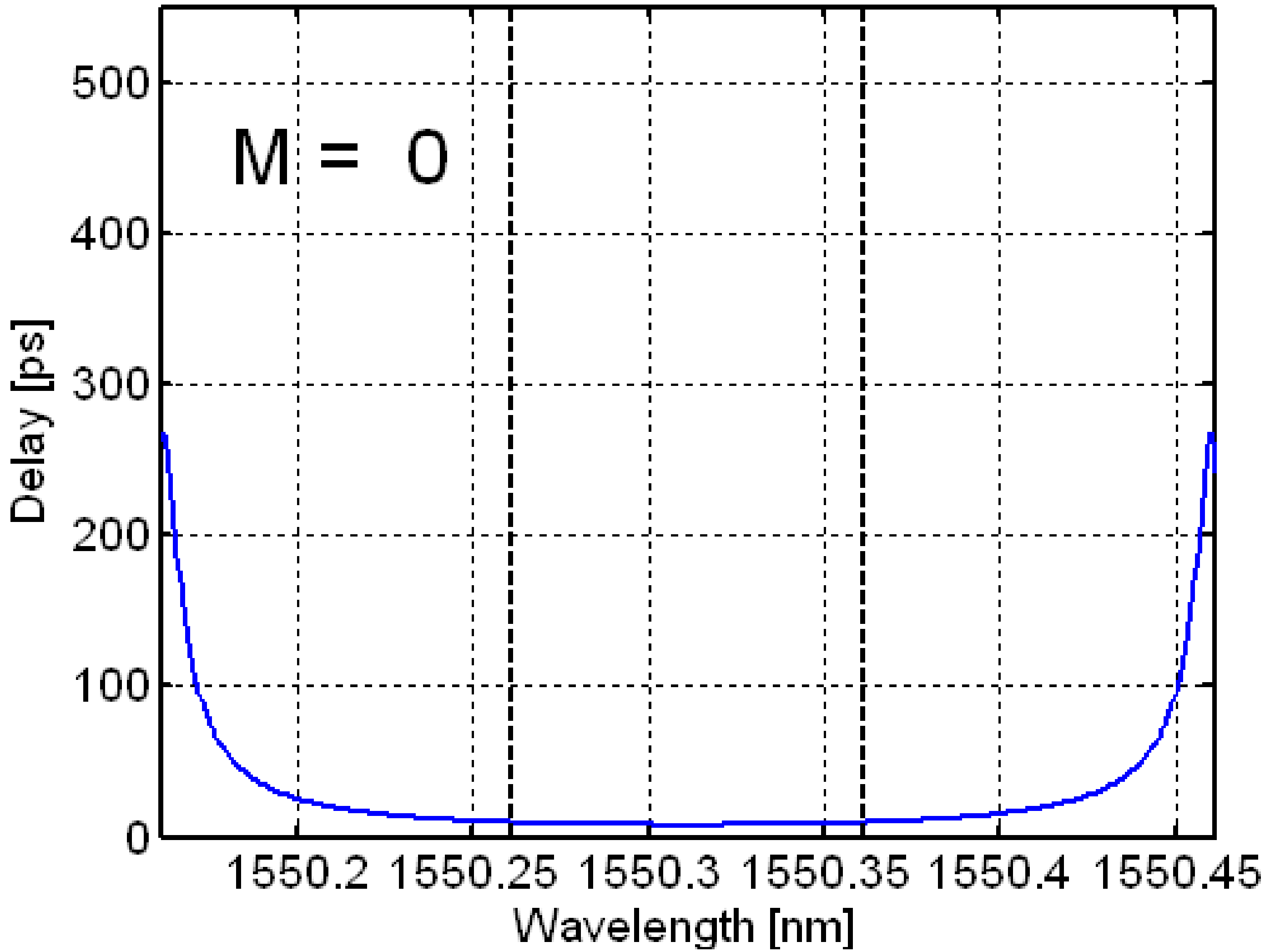


R-CROW: a reconfigurable delay line



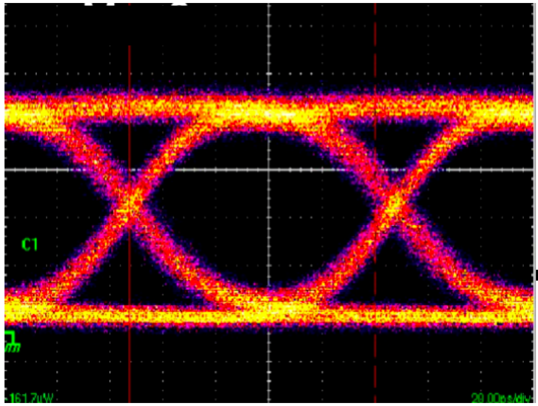
F. Morichetti et al., Optics Express, no. 25, Dec. 2007

R-CROW continuous tuning



Data transmission at 10 Gbit/s

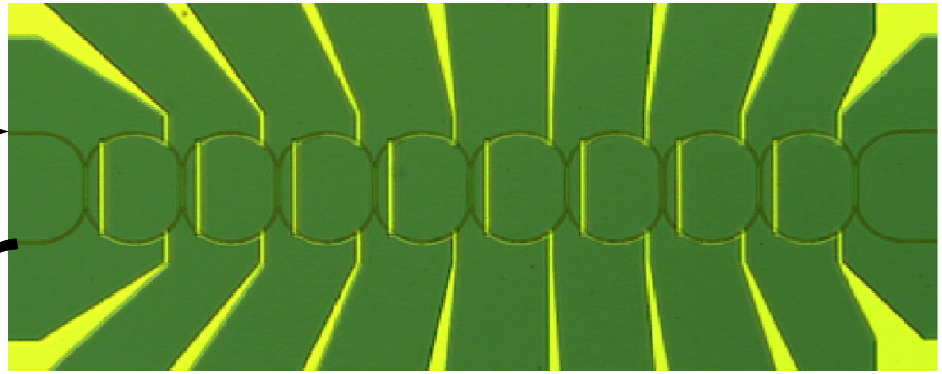
100 ps



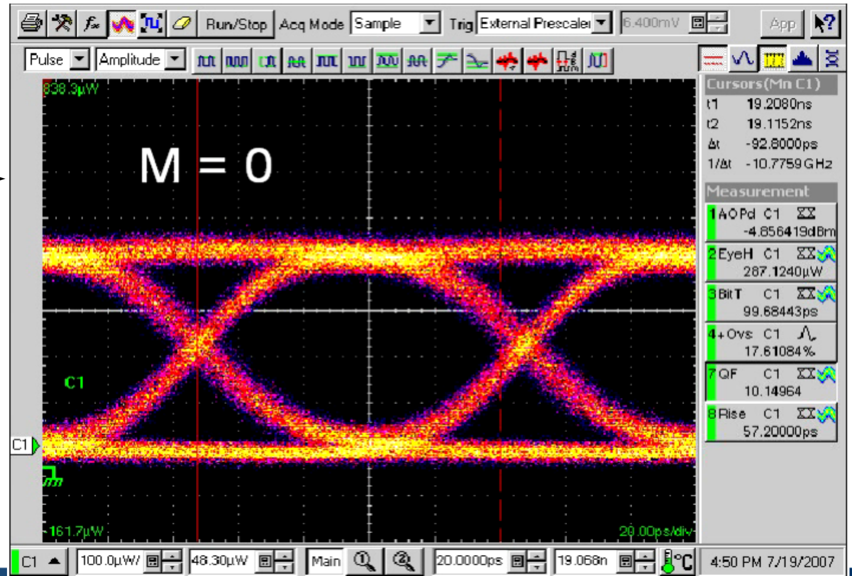
In

Intensity modulation

OOK NRZ @ 10 Gbit/s



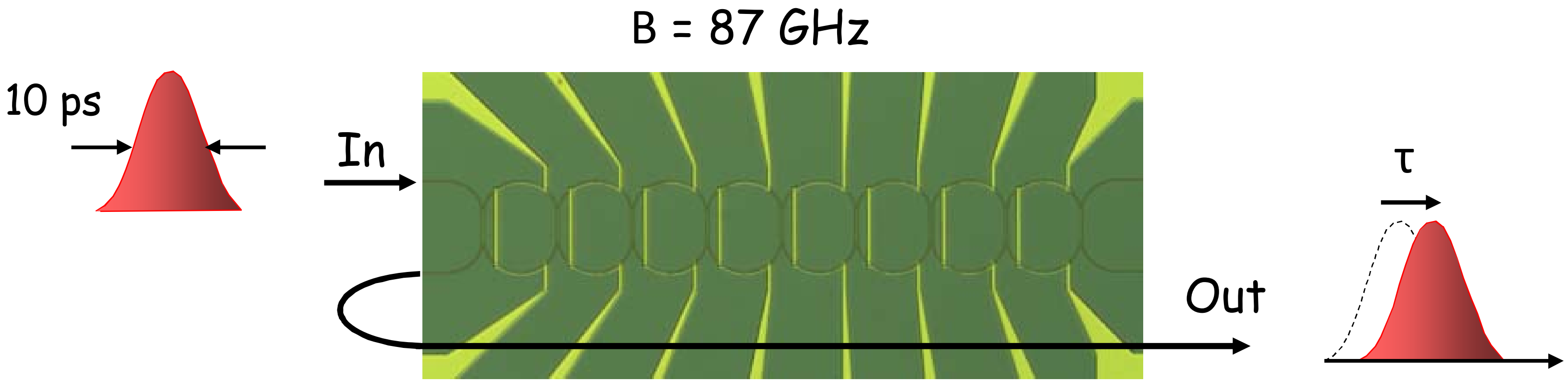
Out



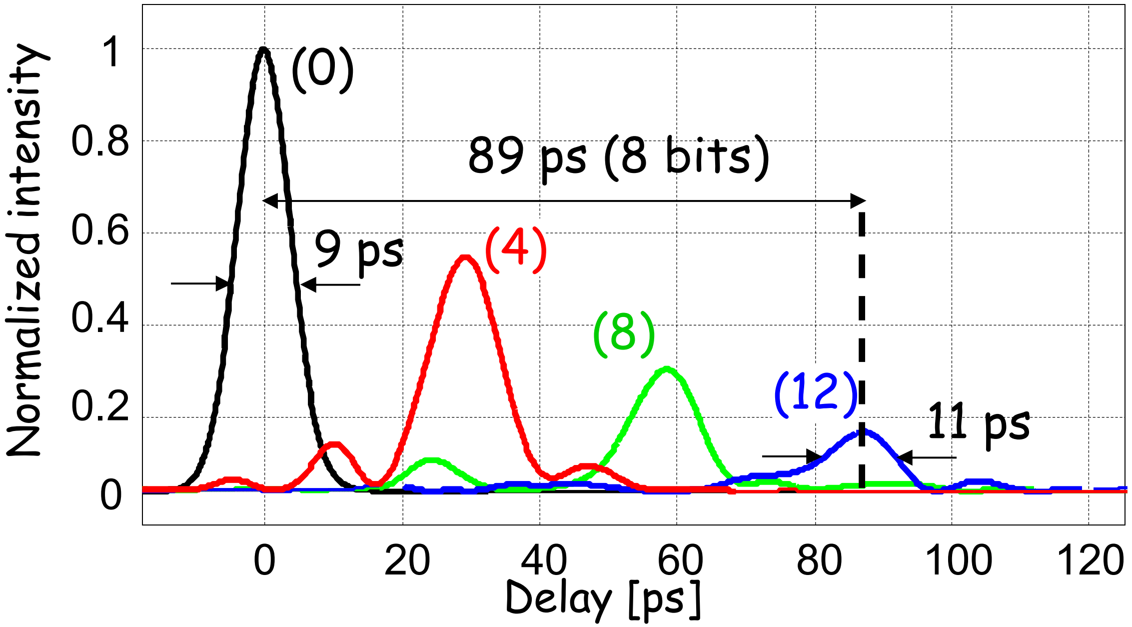
Reconfiguration

- hitless
- time 100 μs
- power 5 mW

Tuneable pulse delay @100Gbit/s



Fractional delay = 7.5 ps/RR



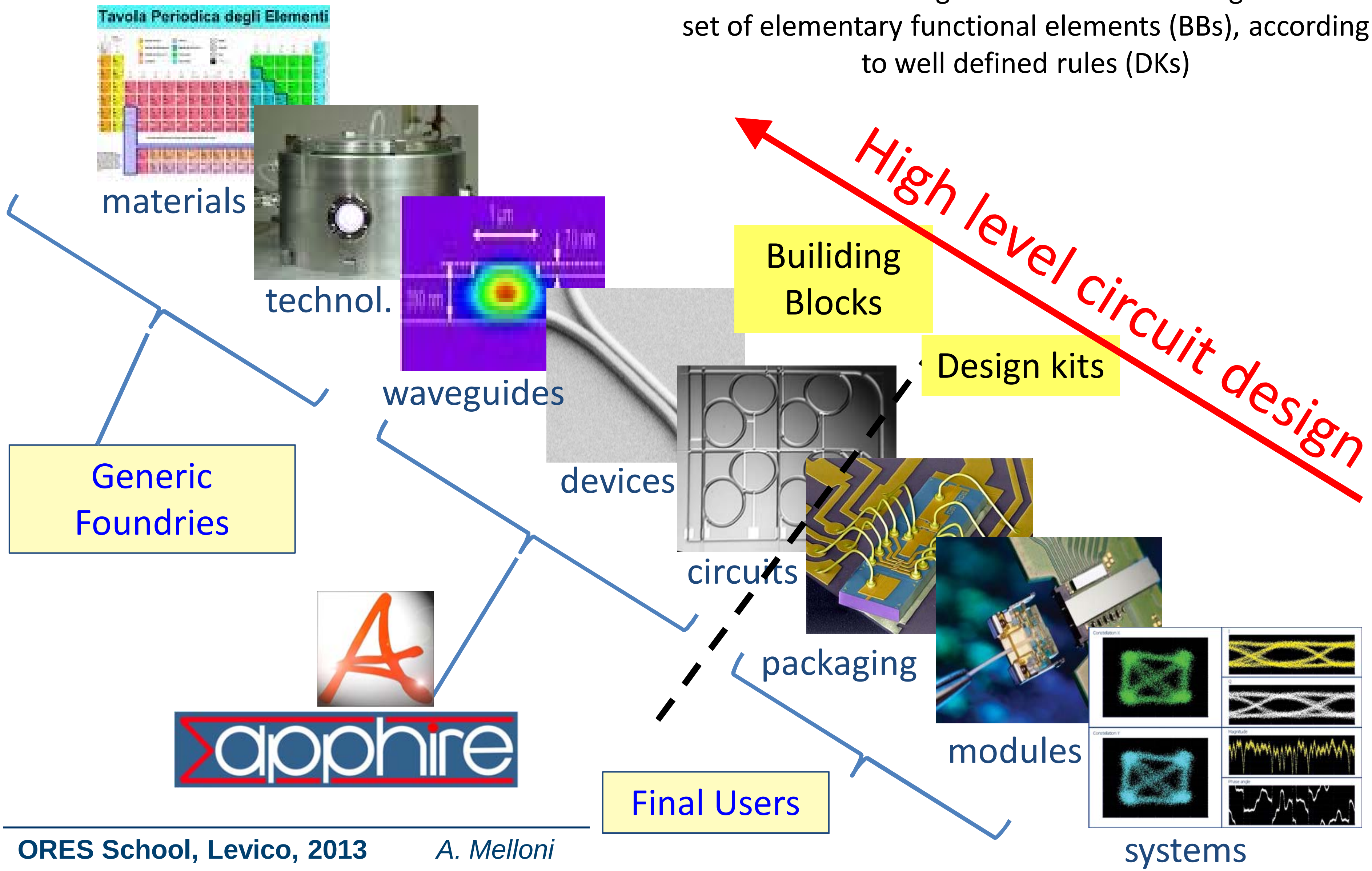
Storage efficiency
0.66 bit/RR

Fractional loss
≈ 1.1 dB/bit

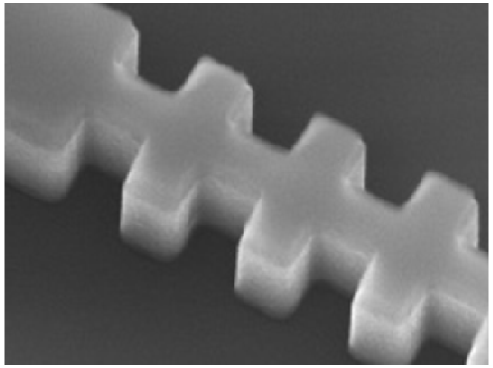
Pulse Broadening (1 byte)
≈ 20%

High level circuit design

Final User: PICs design at a circuit level using a selected set of elementary functional elements (BBs), according to well defined rules (DKs)



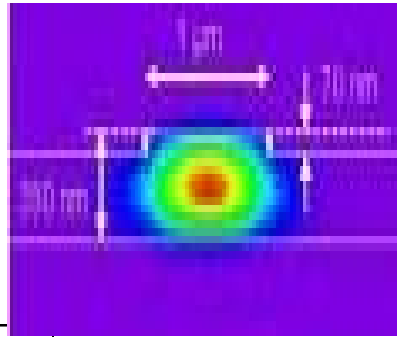
Modelling of photonic Building Blocks



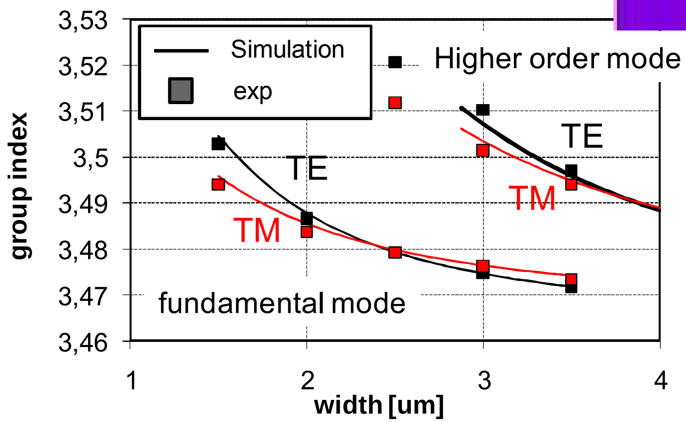
EM analysis

$$\nabla \times \mathbf{E} = -j\omega \mathbf{B}$$
$$\nabla \times \mathbf{H} = j\omega \mathbf{D} + \mathbf{J}$$
$$\mathbf{B} = \mu \mathbf{H}$$
$$\nabla \bullet \mathbf{D} = \rho$$

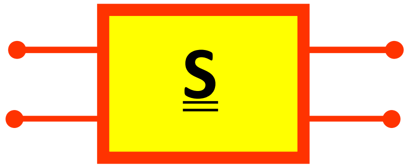
Numerical simulations



Characterization



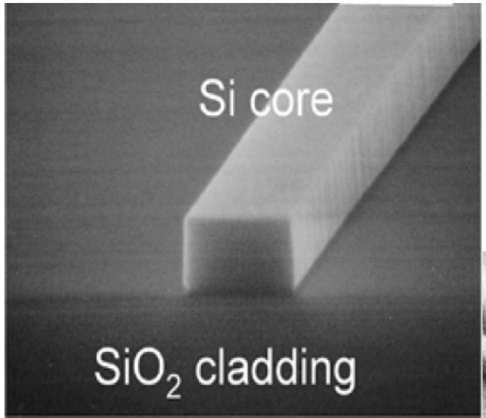
BB model



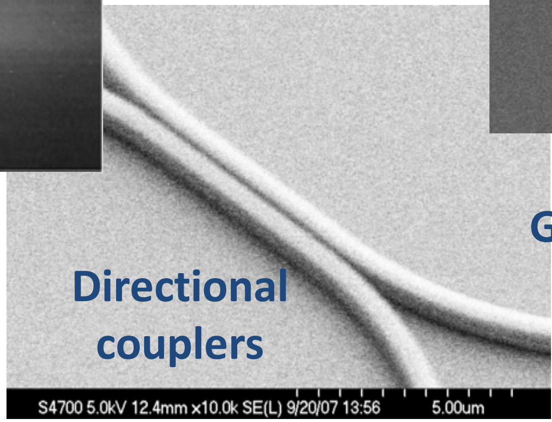
Circuit approach
(high abstraction level)

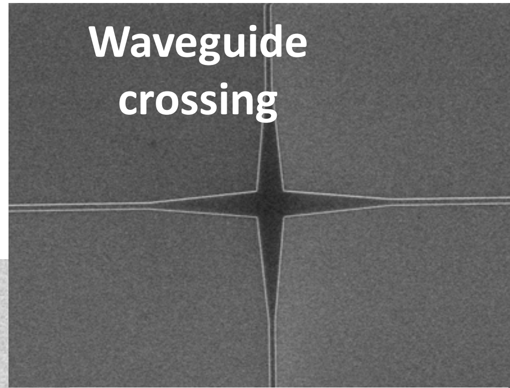
- realistic model
- no information on geometry & materials
- access only to input/output port waves
- very fast, suitable for large circuits

BBs of the SAPPHIRE platform

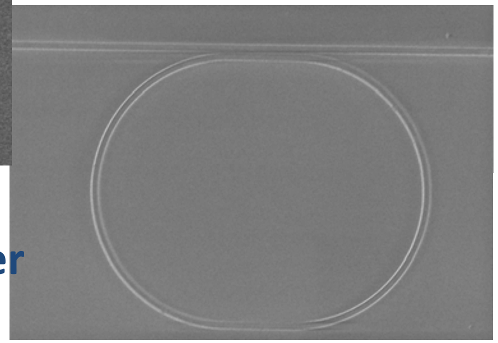


Straight & bent waveguides

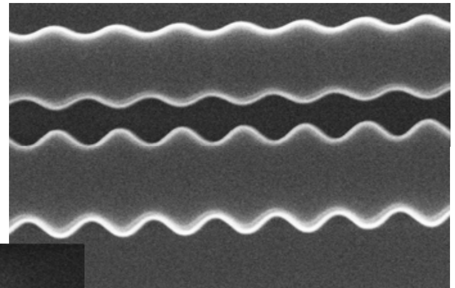


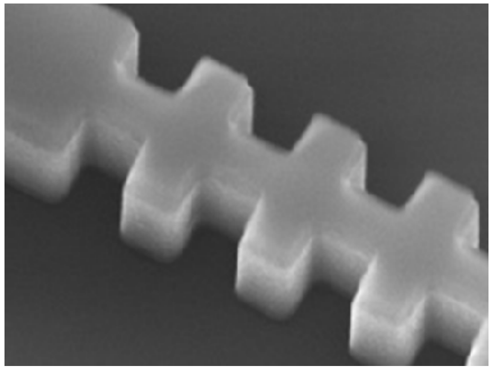


Ring resonators

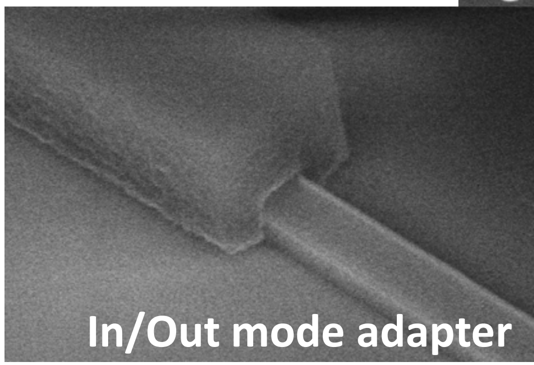


Grating assisted coupler (GAC)

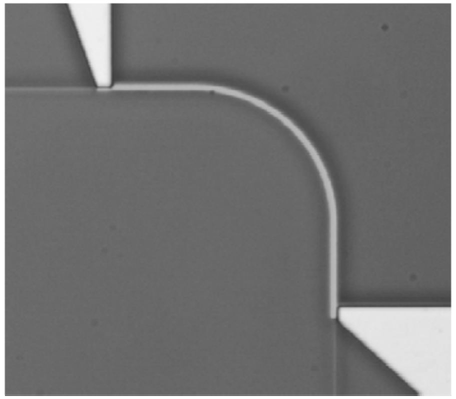




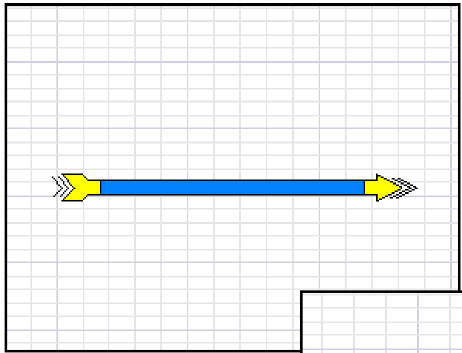
Bragg gratings



Heaters

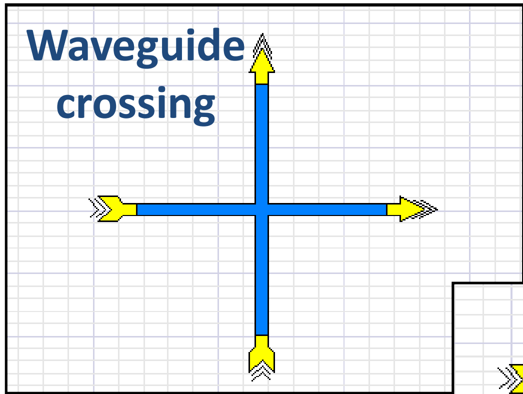


BBs of the SAPPHIRE platform

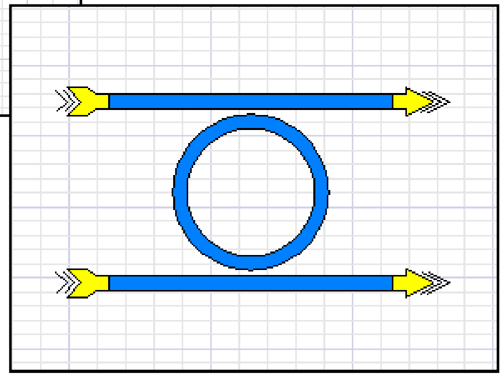


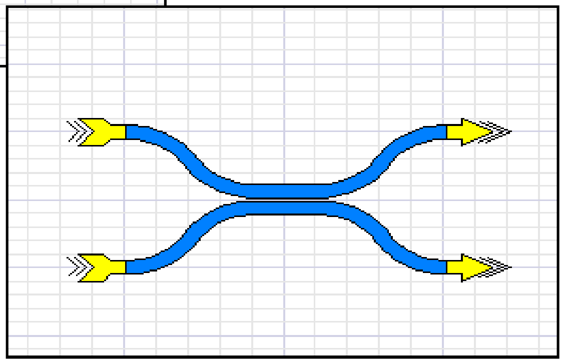
Straight & bent waveguides

Waveguide crossing



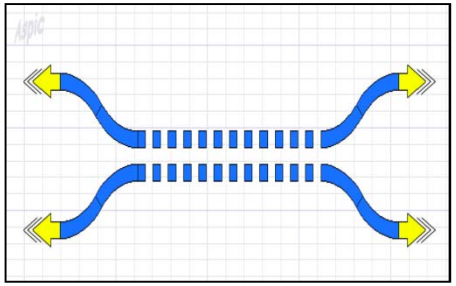
Ring resonators

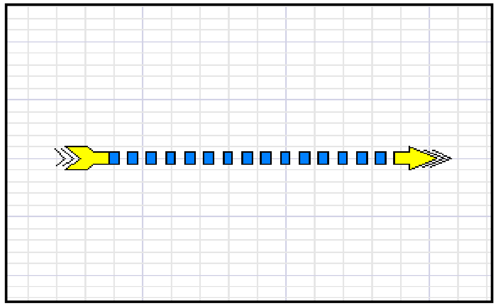




Directional couplers

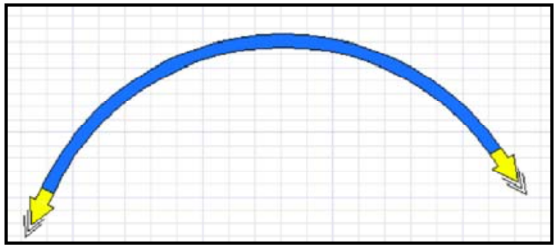
Grating assisted coupler (GAC)

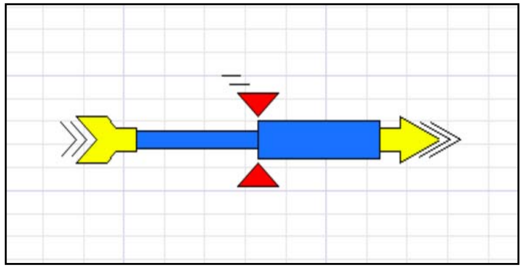




Bragg gratings

Heaters

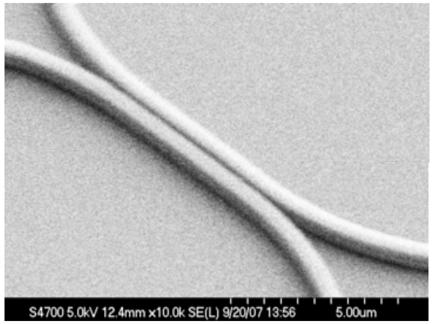




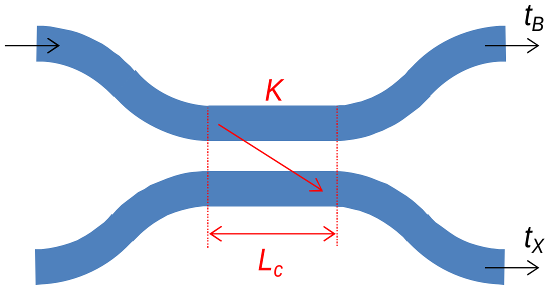
In/Out mode adapter

Design kits

BB



model



Design rules

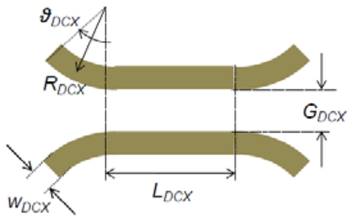
- BB connections
- validity range of the model
- layout constraints
- quality assessment
- ...

$$t_X = \sqrt{I_L}\, exp\left(-j\frac{2\pi}{\lambda}L_{opt}\right)(-jsin(\kappa L_c + \varphi_0),$$

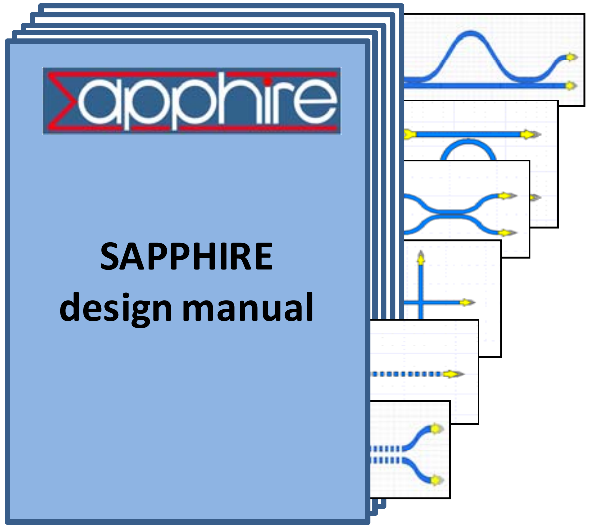
Analytical model (S matrix)

Parameter	Symbol	Value		
		Typical	min	max
Effective index	n_{eff}	See platform circuit parameters (Sec. 2.1.3.5		
Group index	n_g			
Propagation loss [dB/cm]	α_{dB}			
Coupling coefficient [μm^{-1}] (*)	κ	0.018	0.017	0.019
Transition coupling [rad] (*)	φ_0	0.051	-	-
Coupling loss [dB]	α_c	0.06	0.05	0.1
Transition length [um]		20.944	-	

Circuit parameters & variables

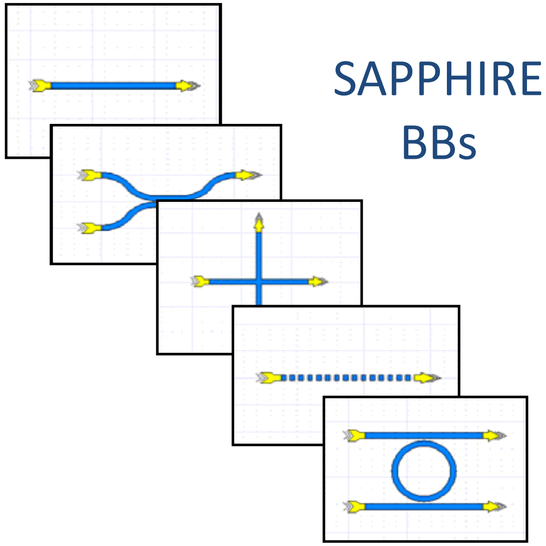


Mask layout

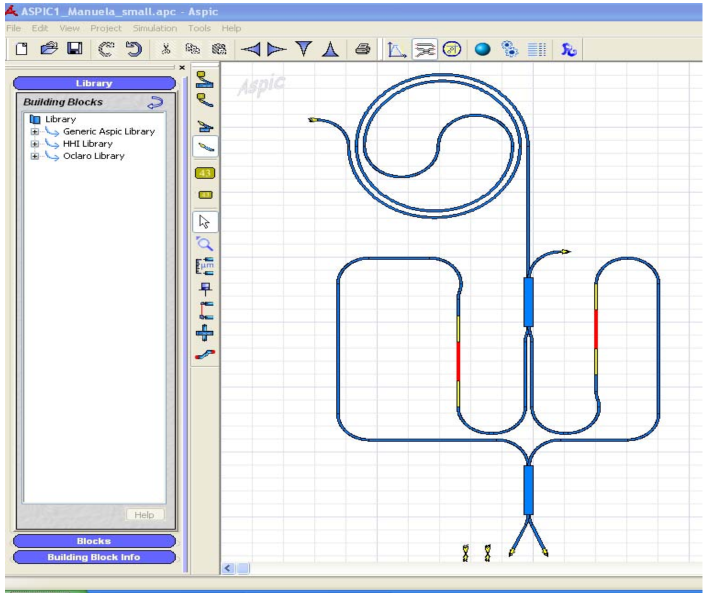


Release 1 (July 2012)

Libraries for ASPIC™ simulator



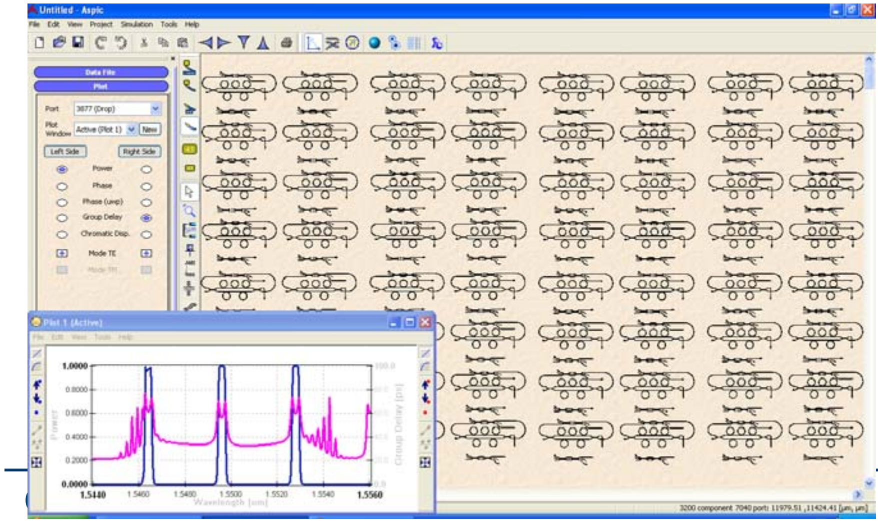
SAPPHIRE
BBs



www.aspicdesign.com

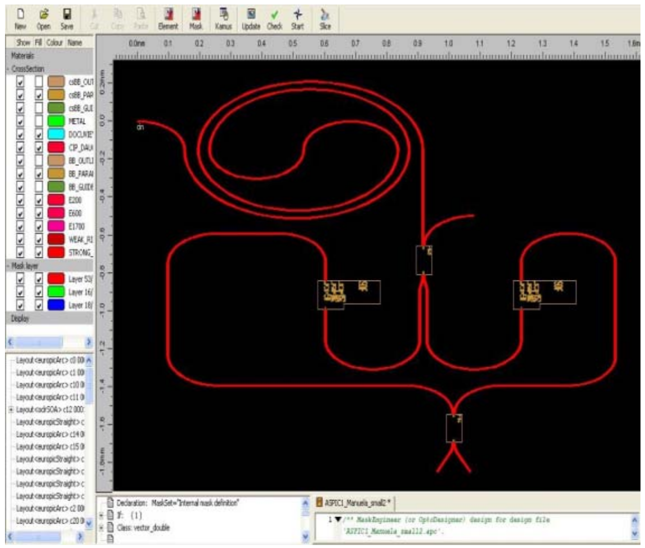
Play with
realistic BB

1600 BBs; 100 lambda points → 1 min



Phoenix

Direct
exportation of
the mask layout



CITCUIT SIMULATOR

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