Novel devices and functions in isolated and sequence of ring resonators

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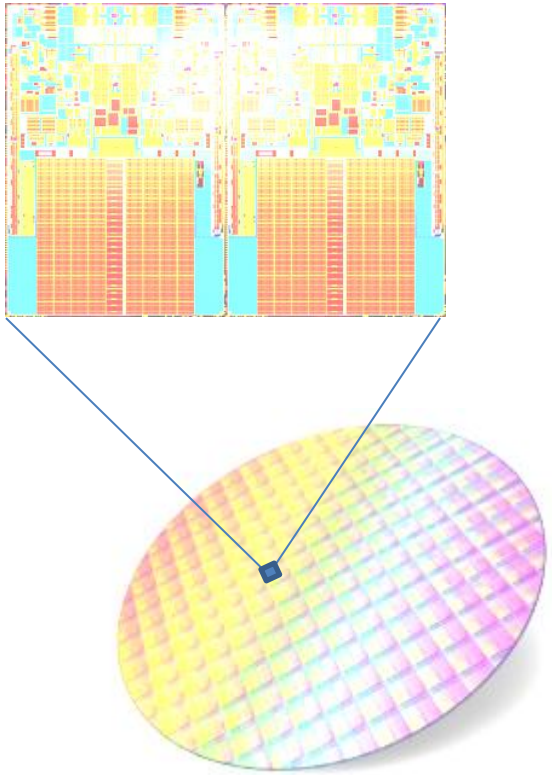
outline

- Introduction: silicon photonics
- Nanophotonics: ultra high Q microdisk
- Nanophotonics: coupled resonator induced transparency
- Nanophotonics: interferometric switching
- Conclusions

Silicon photonics

Material of choice for microelectronics:

- **Advanced fabrication capabilities**
- **Mass production**
- **Cheap**



Courtesy of Intel.

Solarpowerninja.com

http://www.galleries.com/Rock_crystal

- Semiconductor
- Band-gap: 1.12 eV
- Refractive index: 3.4
- Transparent in IR

- Insulator
- Band-gap: 8.9 eV
- Refractive index: 1.46
- Transparent in visible and IR

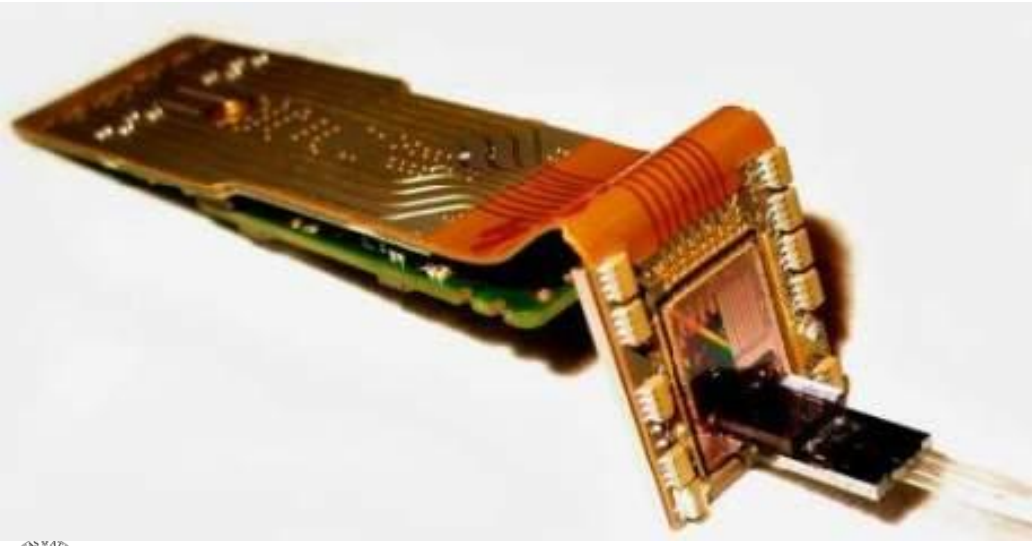
Silicon photonics

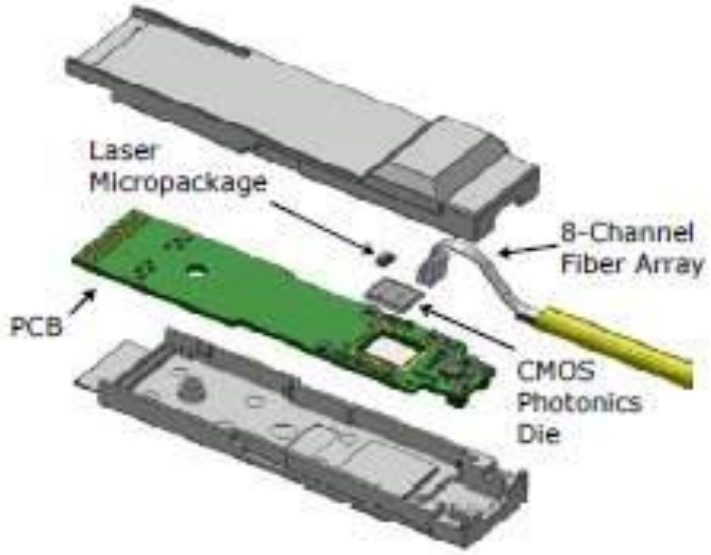
Integrated "On-chip" optical elements

CMOS compatibility

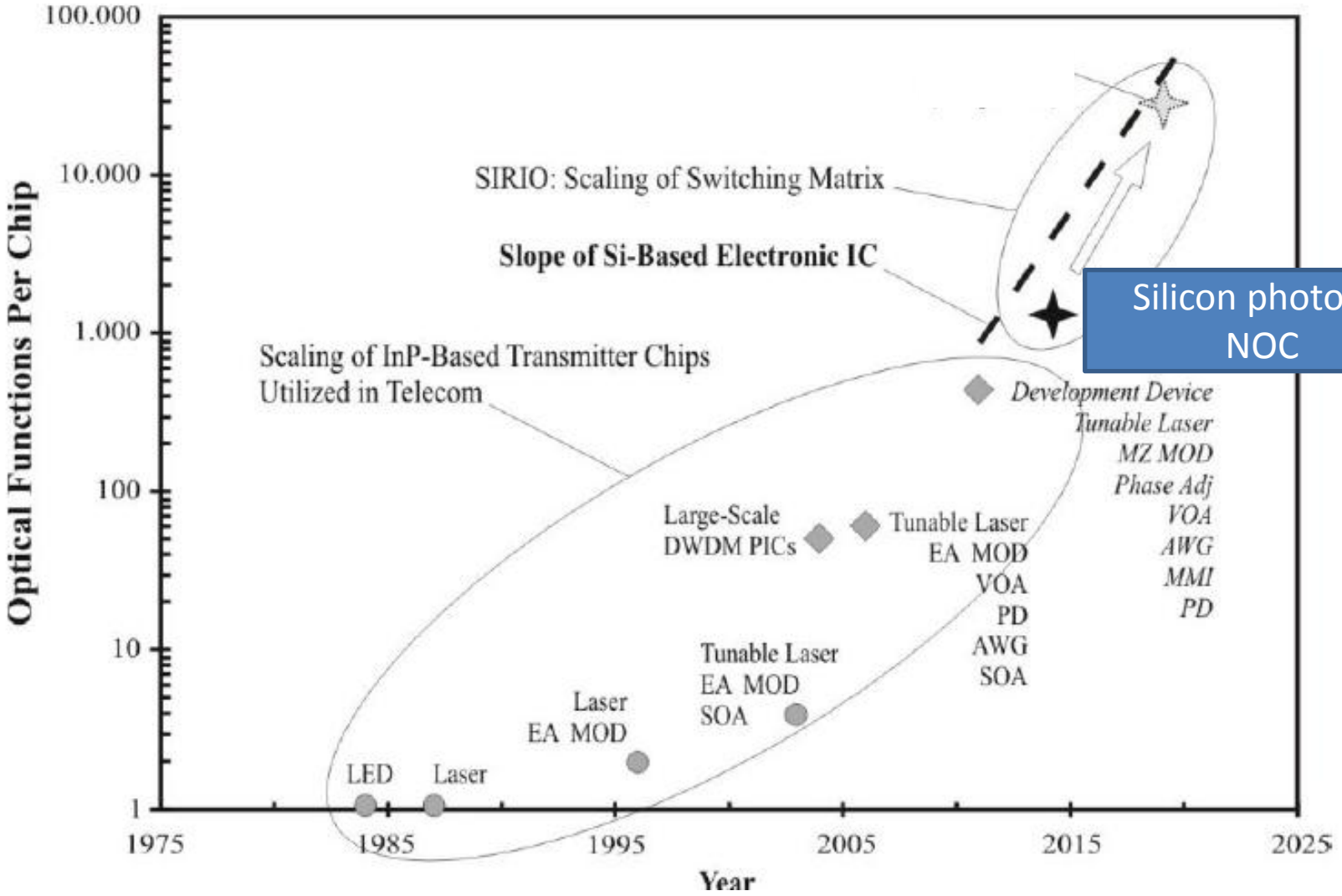
Luxtera single-chip 100-Gbps transceiver targets multiple applications

- The new transceiver chip, which measures 5x6 mm, offers 4x28-Gbps transmission over single mode fiber.
- The device features waveguide, waveguide structures, modulators, couplers, and photodetectors integrated at the wafer level. The photodetectors are germanium, but applied to the wafer using the same CMOS processes as the other devices. A single CW laser powers all four channels; it attaches to the CMOS wafer via a hybrid integration process.





Projected integration density



Silicon photonic NOC

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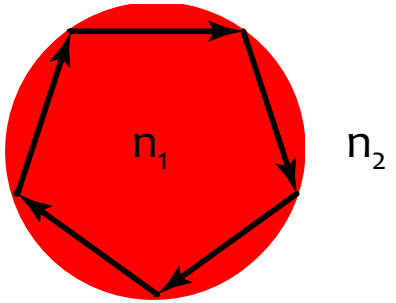
Introduction

Whispering gallery mode (WGM) resonator



- Circular geometry cavity
- Light is confined near the surface by total internal reflection

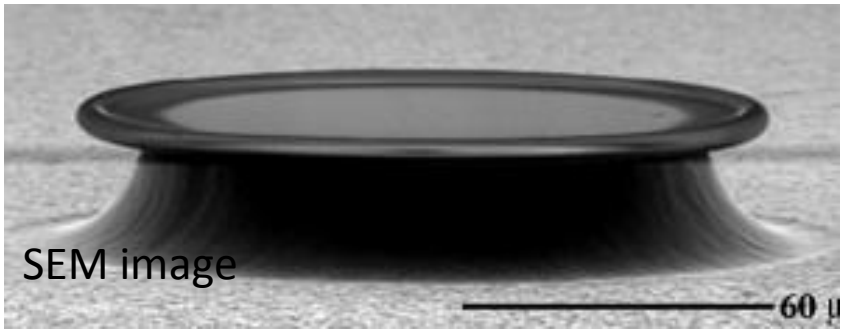
Quality factor (Q)

- Quantifies the stored energy and the light-matter interaction in the cavity
- Inverse value of the resonator loss (1/Q)

Ultra high Q resonator

microsphere

microtoroid



- **Quality factor** $Q \approx 8 \cdot 10^9$ $Q \approx 10^8$
- **Very low scattering losses – smooth surface**
- **Fabrication process** by melting silica microrods by reflowing silica microdisks

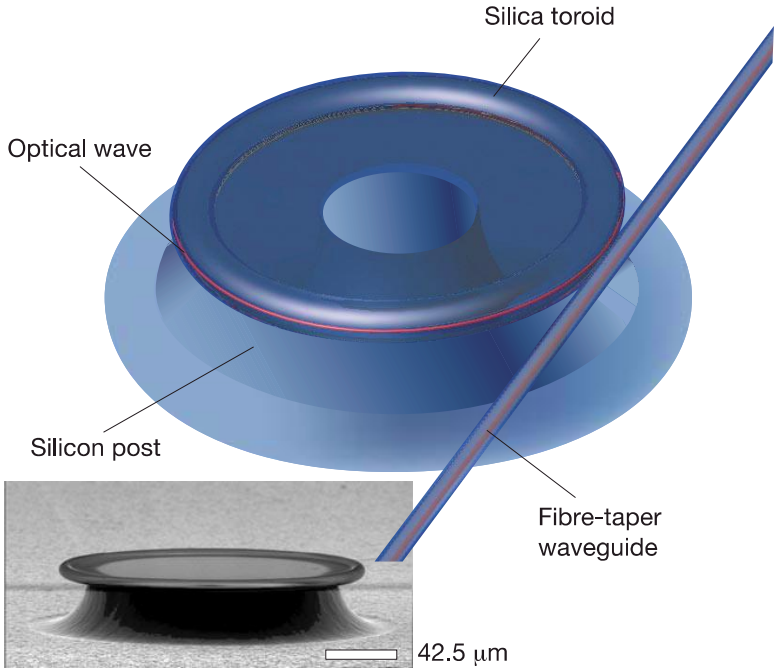
Unsuitable for photonic circuit integration and mass production

K. Vahala, Nature 424, 839 (2003)

Coupling to UHQ resonator

Coupling principle: by evanescent field

It requires nanometric gaps between the resonator and the fiber

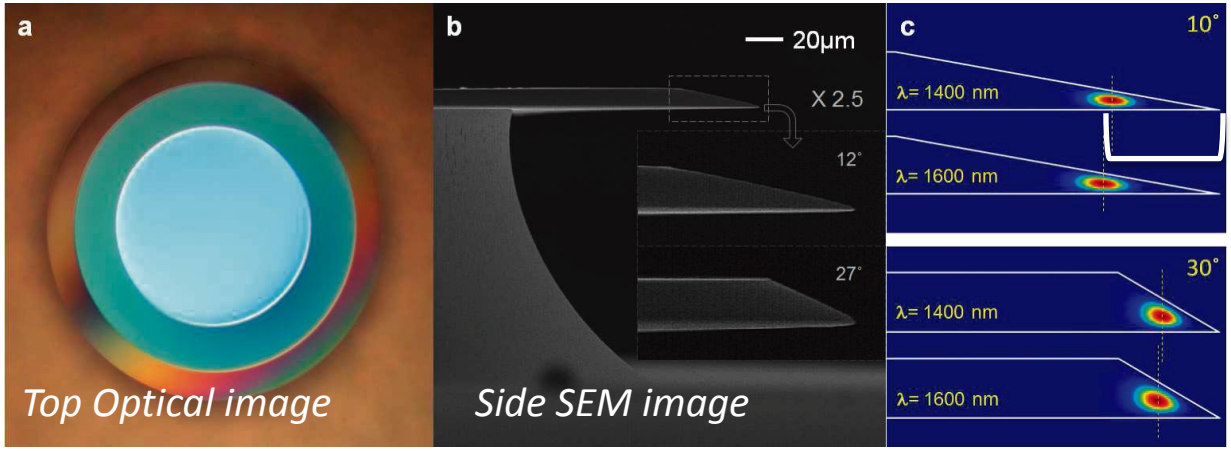


Difficult and complex experimental optical setup

Wedge WGM resonator

Alternative UHQ WGM resonator CMOS compatible

Microdisk with wedge-shaped edge



modes are far from the periphery

Mode intensity profiles

Very low loses Modes are isolated from the surface roughness

New Q factor benchmark on a chip $Q \approx 9 \cdot 10^8$ using very large resonators >5 mm [millimeter]*

Difficult to access to microtoroids

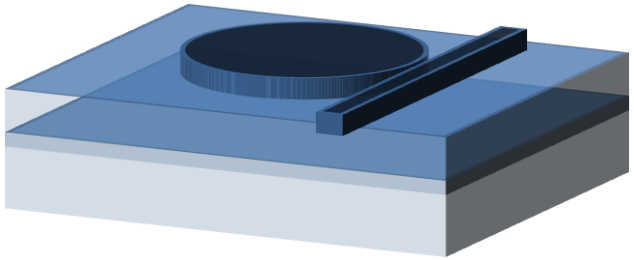
Fabrication process By Surface oxidation and wet etch

How can we couple with ?

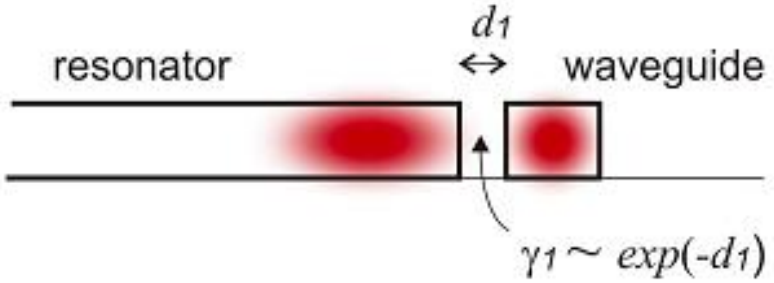
(*)H. Lee et al, nature photonics (2012)

Conventional lateral coupling

Sketch of horizontal coupling scheme



Mode profile sketch

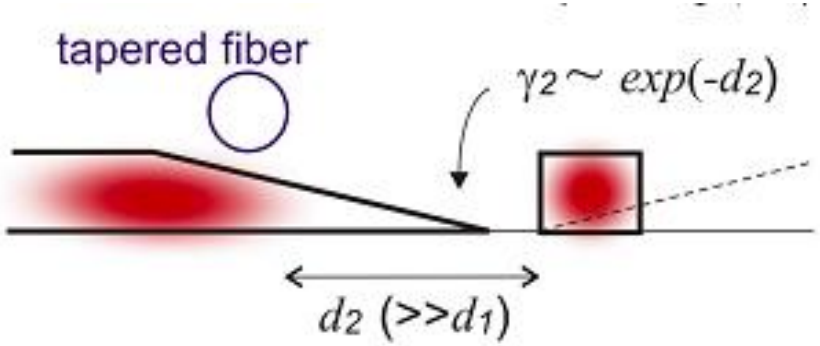


- The coupling principle is by evanescent field

- The coupling rate decays exponentially with the gap

- For an accurate gap control a single mask is used

Conventional lateral coupling



- **Coupling becomes inefficient as the wedge mode is retracted**

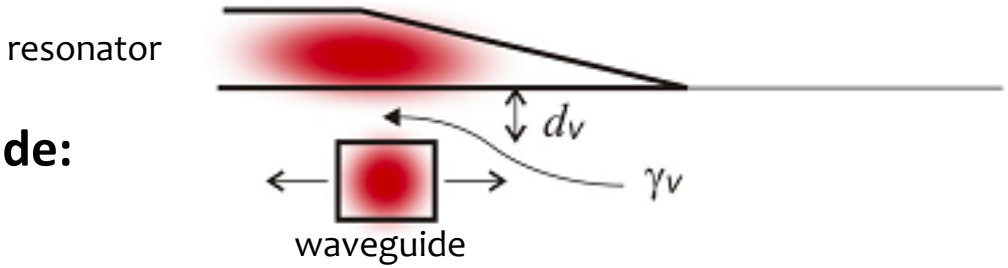
- **In a realistic fabrication, the waveguide retracts forming a wedge shape (quenching the coupling)**

Finally an off-chip technique is used (with tapered fiber)

The same difficult and complex experimental optical setup

Our proposal: Vertical coupling scheme

Mode profile sketch



The cavity and the waveguide:

- Lay in different planes
- Could be separated by low refractive index solid materials or air
- Are fabricated independently with different masks

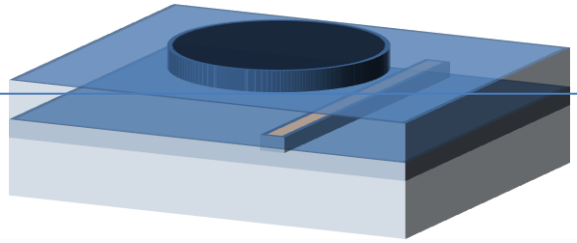
- This process permits to realize the shallow-angle wedge while the waveguide remains intact
- Allows to adjust the coupling distance in the horizontal and vertical direction

An efficient coupling condition for wedge resonators could be reached

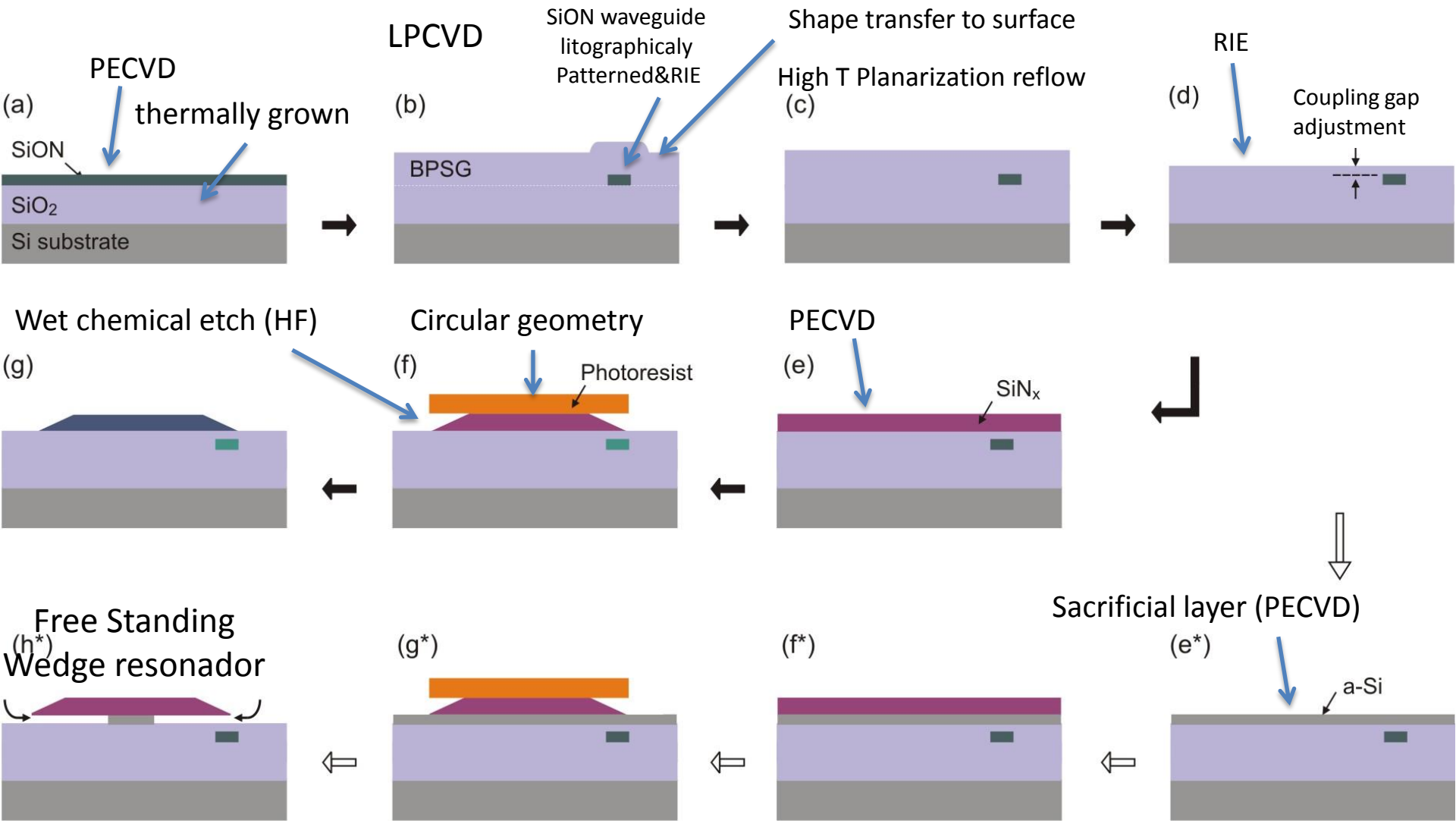
Our proposal: Vertical coupling scheme

Additional advantages

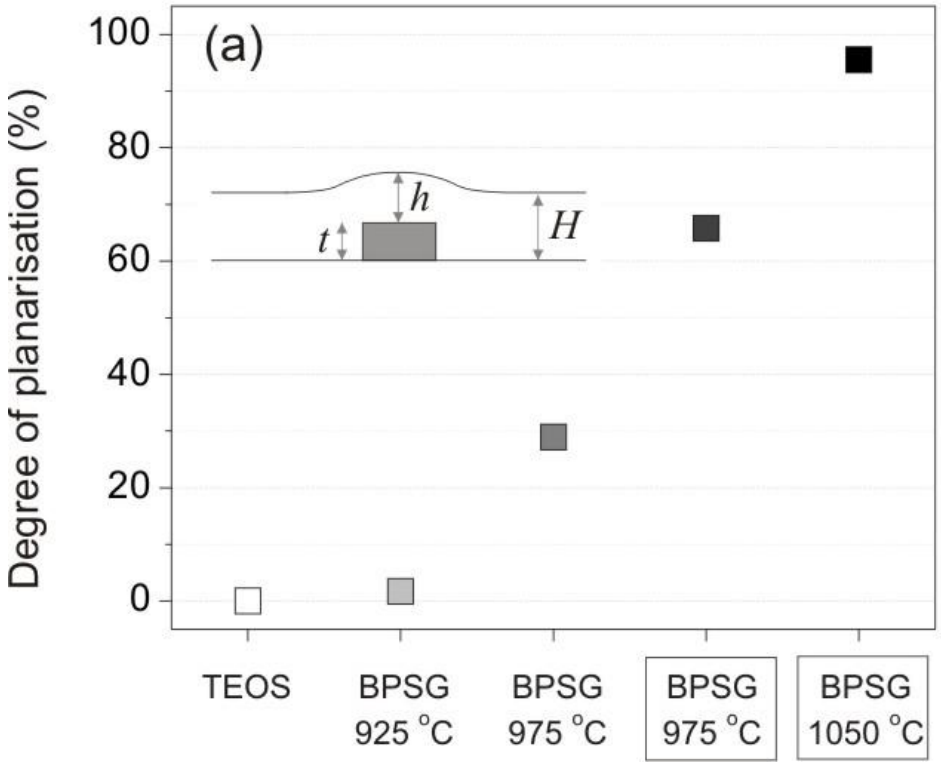
Vertical coupling	vs.	Horizontal coupling
• The 2-mask process allows to use different materials for the waveguide and the resonator		• A 1-mask process imposes the same material for both the waveguide and the resonator
• The coupling gap is defined and controlled through deposition, by means of conventional optical Lithography		• The coupling gap is defined through E-beam or deep-UV Lithography

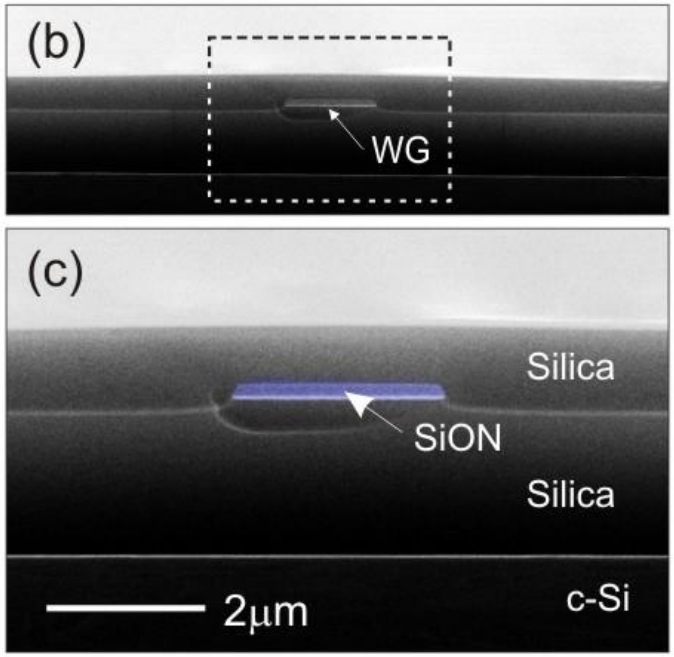


Fabrication process

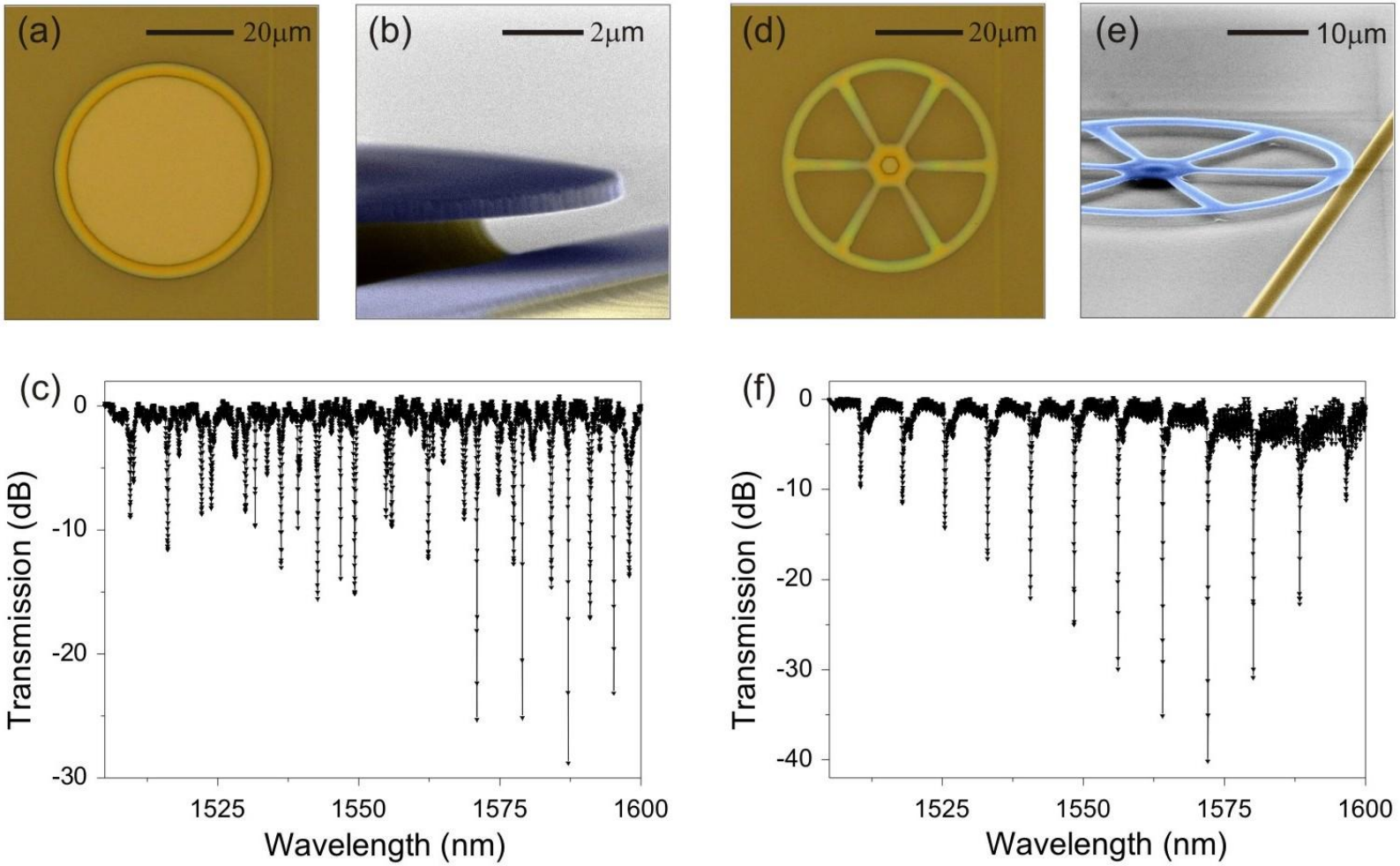


Planarization by reflow



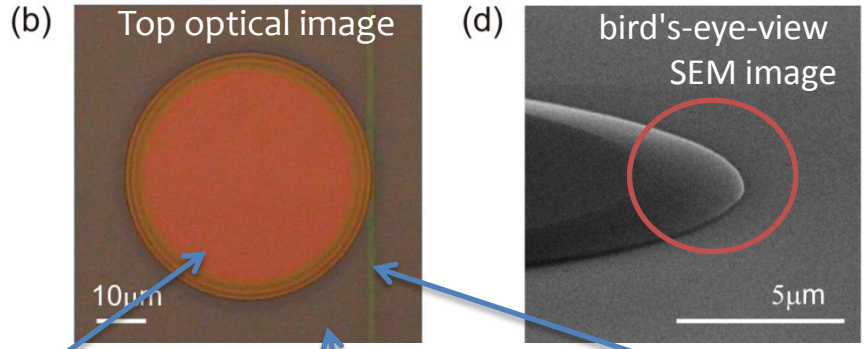


Free standing structures

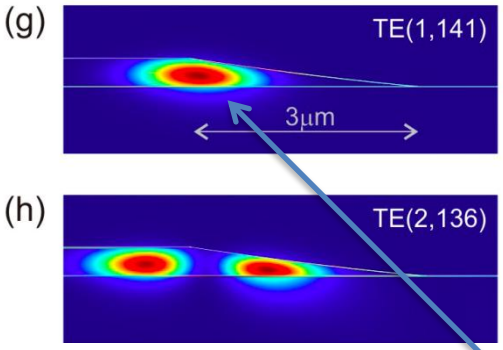


On-chip wedge WGM resonator

Vertically waveguide coupled Wedge resonator



Calculated Mode intensity profiles



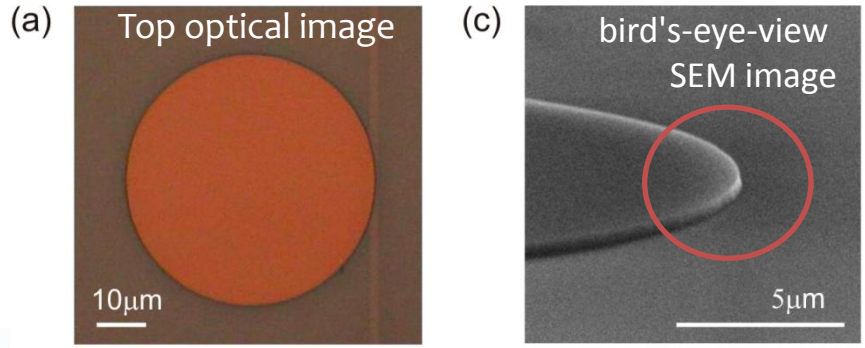
1st radial family

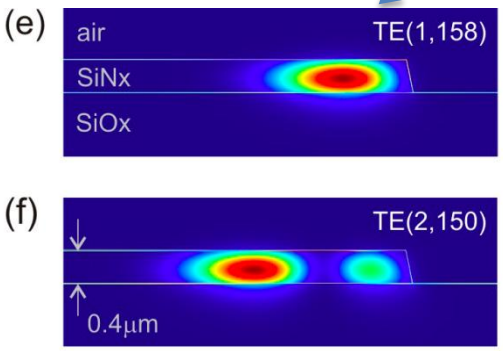
2nd radial family

Different shape of the borders

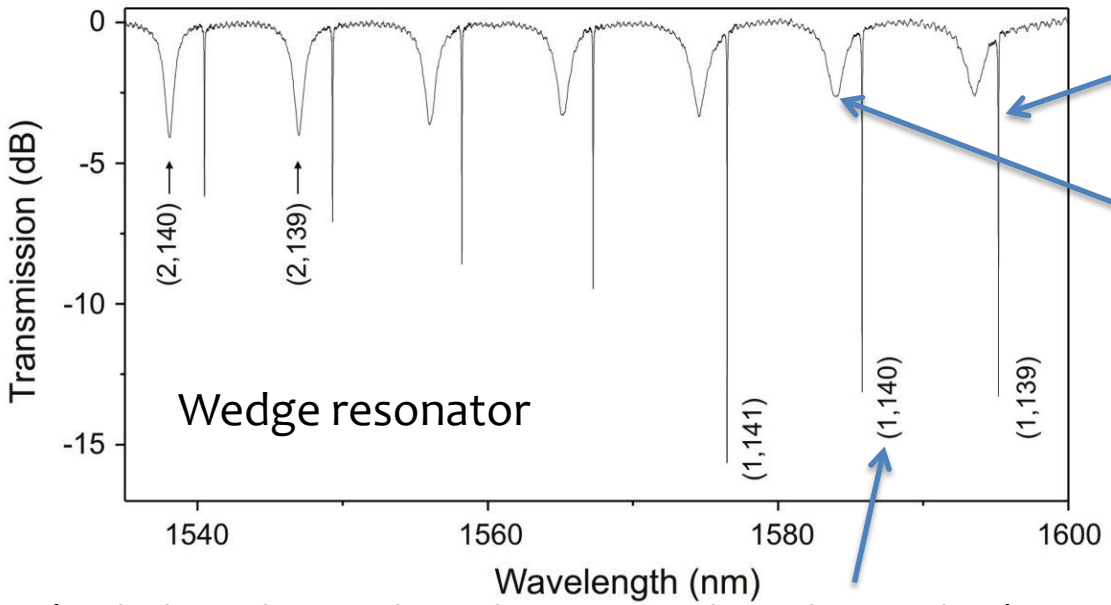
Different position of the mode profiles

Comparison with conventional disk resonators





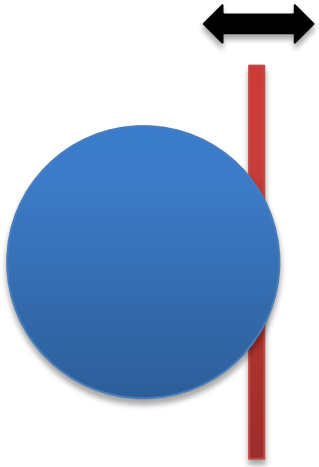
Transmission spectrum



Narrow dips
1st radial mode family

Broad dips
2nd radial mode family

(radial mode number, the azimutal mode number)



It possible to select the radial mode family
by means of changing the horizontal position of the waveguide.

The first mode family shows less transmission – it's coupled more efficiently

We have selected the 1st radial mode family because it shows higher Q's

Q factor analysis

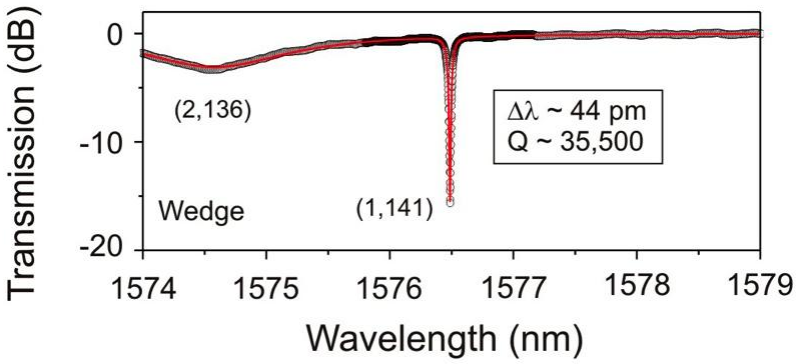
Q-factor could be extracted from the lorentzian fit of the transmission spectrum dips

$$Q \approx \frac{l(n,m)}{FWHM}$$

3rd telecom window

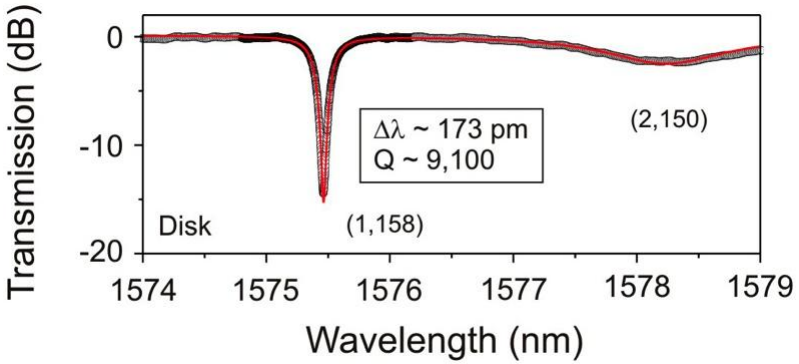
Wedge resonator

Q≈35,500



Disk resonator

Q≈9,100

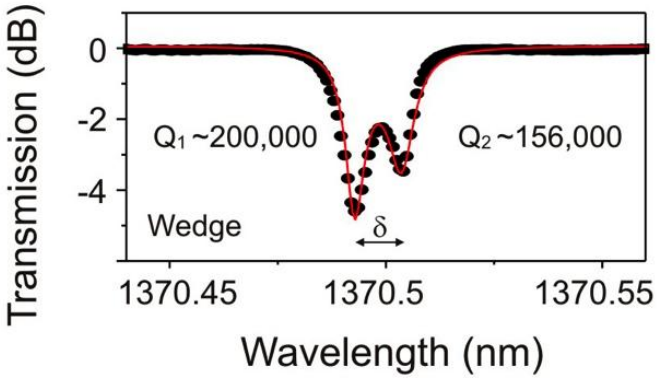


the wedge resonator shows 3 to 4 times larger Q

Q factor analysis

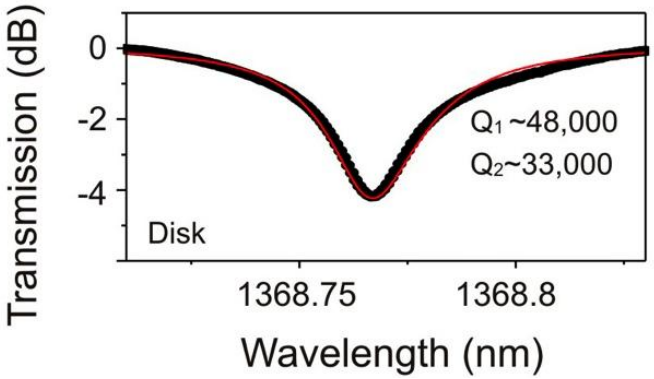
Q-factor could be extracted from the lorentzian fit of the transmission spectrum dips

$$Q \approx \frac{l(n,m)}{FWHM}$$



FOR THE WEDGE RESONATOR

- The mode is split into a doublet because of the scattering-induced coupling between clockwise and counter-clockwise modes



FOR THE DISK RESONATOR

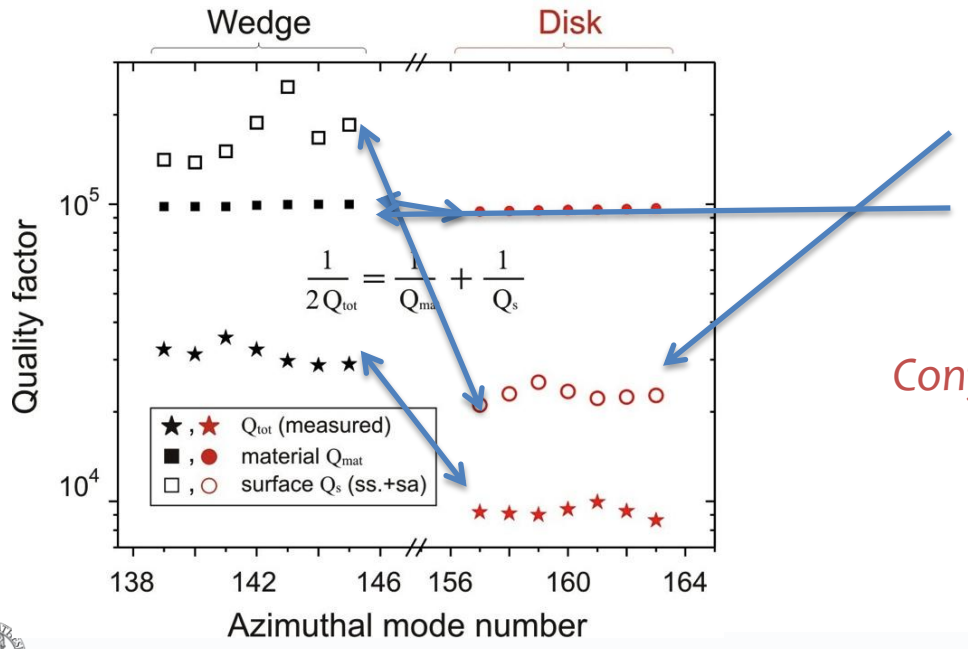
- The coherent sum of lorenzians hides the splitting of the modes

wedge resonator shows 5 times larger Q-value due to the reduced scattering losses

Quality factor contributions for Wedge and Disk resonators

- **Coupling losses $1/Q_c$** equal - critical coupling regime
- **Radiation losses (calculated) $1/Q_r$** $1/Q_r=1/10^{16}$ for 50um disk -- negligible
- **Material losses (calculated) $1/Q_{mat}$** Almost the same
- **Total losses (measured) $1/Q_{tot}$** 3-4 times less for the wedge resonator
- **Surface losses (scattering + absorption) $1/Q_s$** extrapolated from the addition of all losses

3rd telecom window



Main limiting contribution

Dry etch resonator → Surface loss

Wedge resonator → Material loss

Confirmation of the surface loss reduction by using the wedge resonator

applications

PRL 104, 103901 (2010) PHYSICAL REVIEW LETTERS week ending 12 MARCH 2010

Probing the Spontaneous Emission Dynamics in Si-Nanocrystals-Based Microdisk Resonators

A. Pitanti,[1,*] M. Ghulinyan,[2] D. Navarro-Urrios,[3] G. Pucker,[2] and L. Pavesi[1]
[1]*Nanoscience Lab., Department of Physics, University of Trento, via Sommarive 14, Povo (TN), Italy*
[2]*Advanced Photonics & Photovoltaics, Fondazione Bruno Kessler, via Sommarive 18, Povo (TN), Italy*
[3]*MIND-IN2UB, Departament d'Electrònica, Universitat de Barcelona, Carrer Martì i Franquès 1, 08028 Barcelona, Spain*
(Received 7 July 2009; revised manuscript received 9 February 2010; published 9 March 2010)

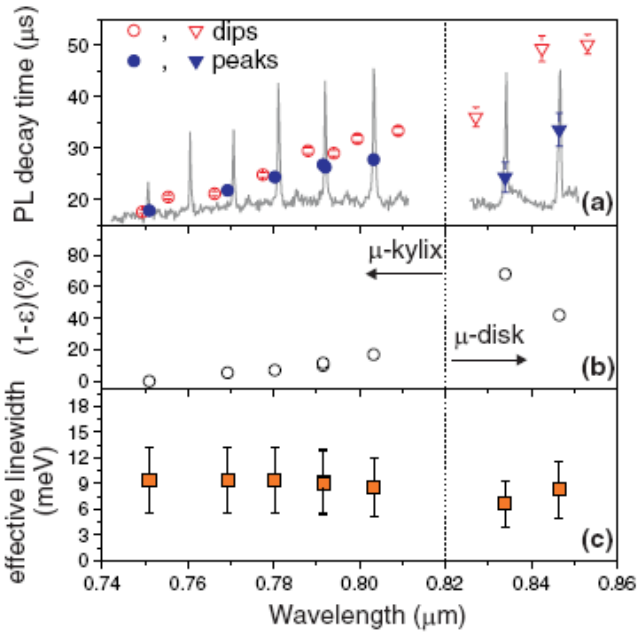
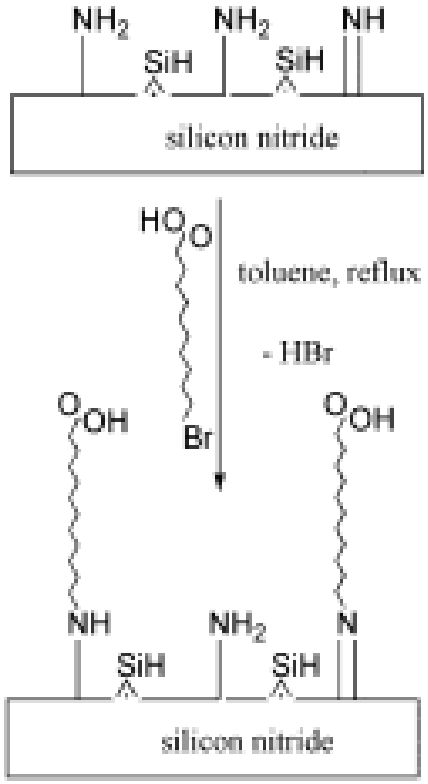
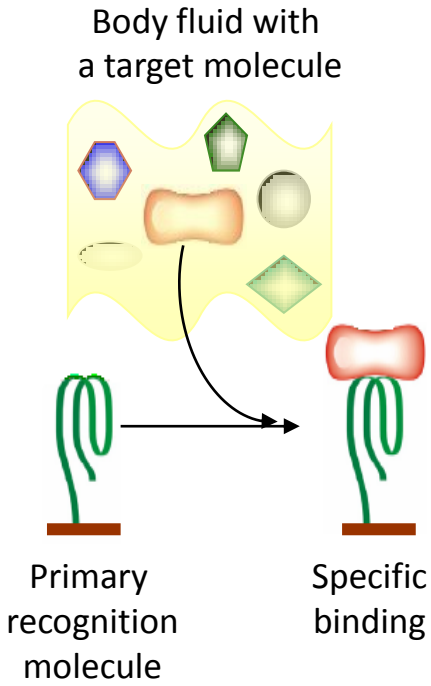


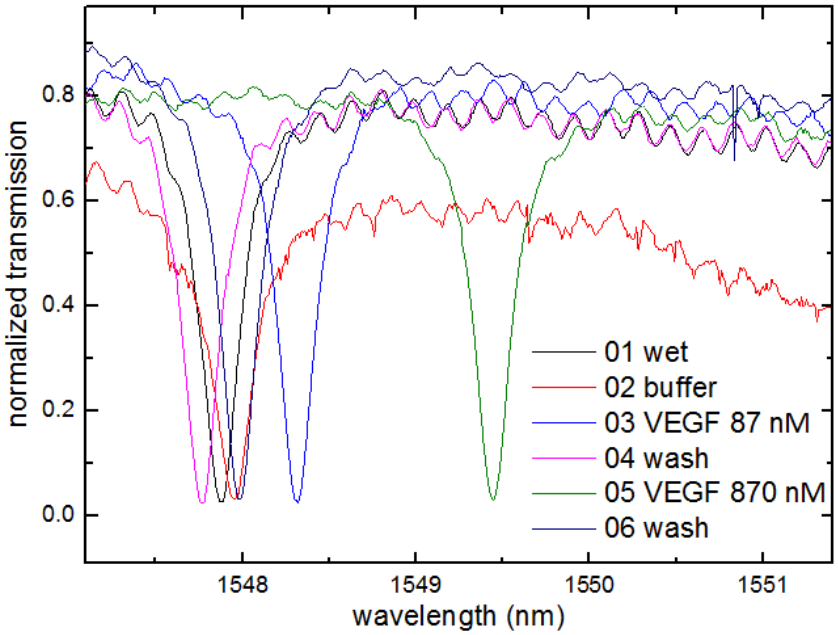
FIG. 4 (color online). (a) Measured PL lifetimes for the peaks (●, ▼) and dips (○, ▽) of the WGM spectrum. (b) Calculated lifetime shortening $\epsilon = \frac{\tau_{dip}}{\tau_{peak}}$ and (c) the estimated Si-NC effective linewidth at room temperature.

applications



wet chemical functionalization of flat PECVD SiN to obtain –COOH groups projecting from the surface via **thermal grafting on amino groups** (insertion of a bond on N–H by 12-Br-dodecanoic acid resulting in N–C bond formation)





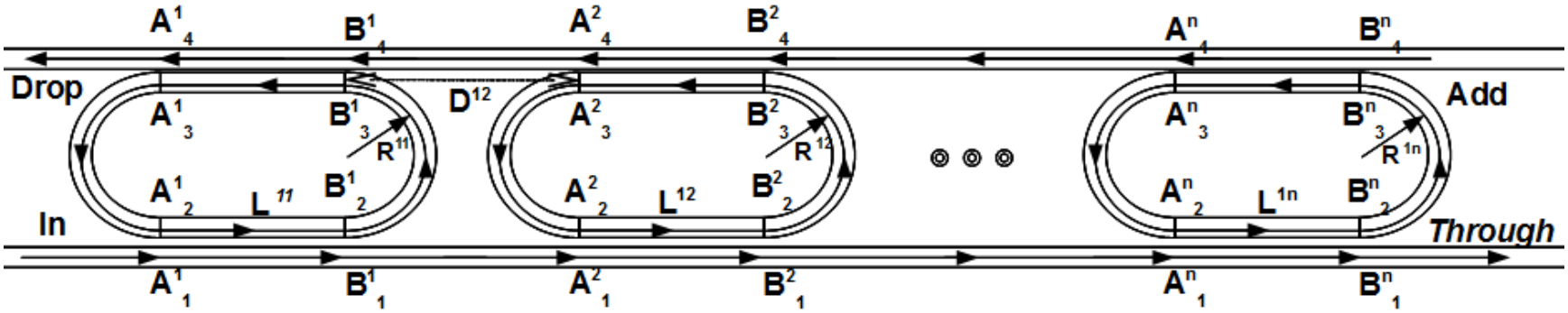
VEGF: vascular endothelial growth factor - stimulates the growth of new blood vessels. **Central role in pathologies such as tumors, cronical ischemia, retinopathy**

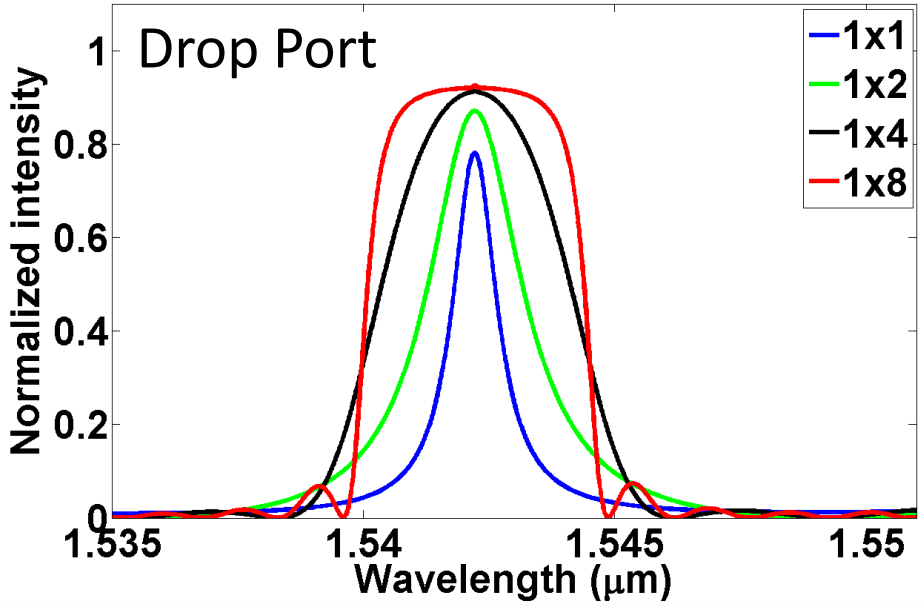
outline

- Introduction
- Nanophotonics: vertical coupled microcavities
- Nanophotonics: coupled resonator induced transparency
- Nanophotonics: interferometric switching
- conclusions

SCISSOR: theoretical

Side-Coupled Integrated Spaced Sequence of Resonators

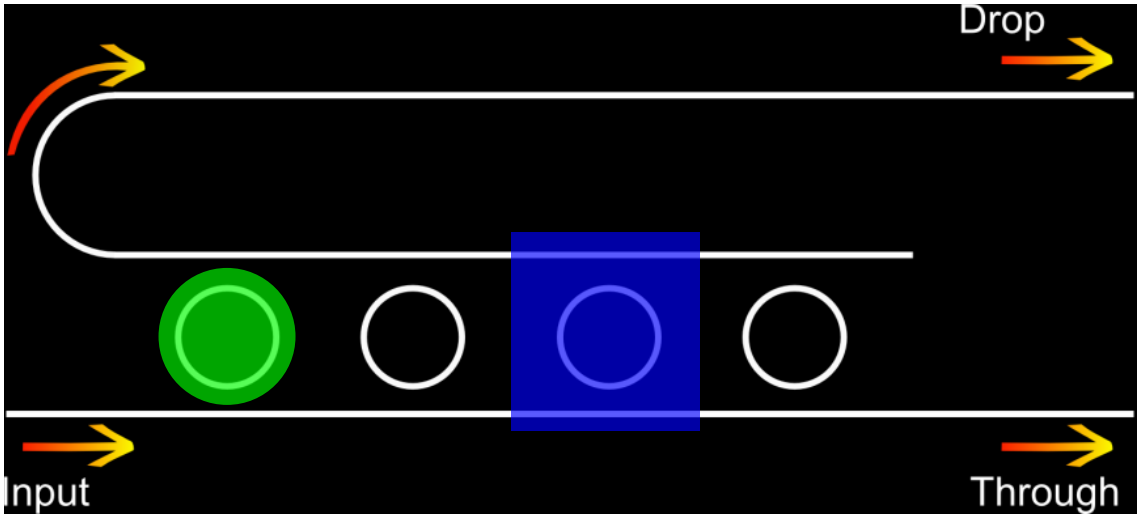




- Box-like response suitable for coarse WDM and band routing
- Large extinction

Two resonance mechanisms

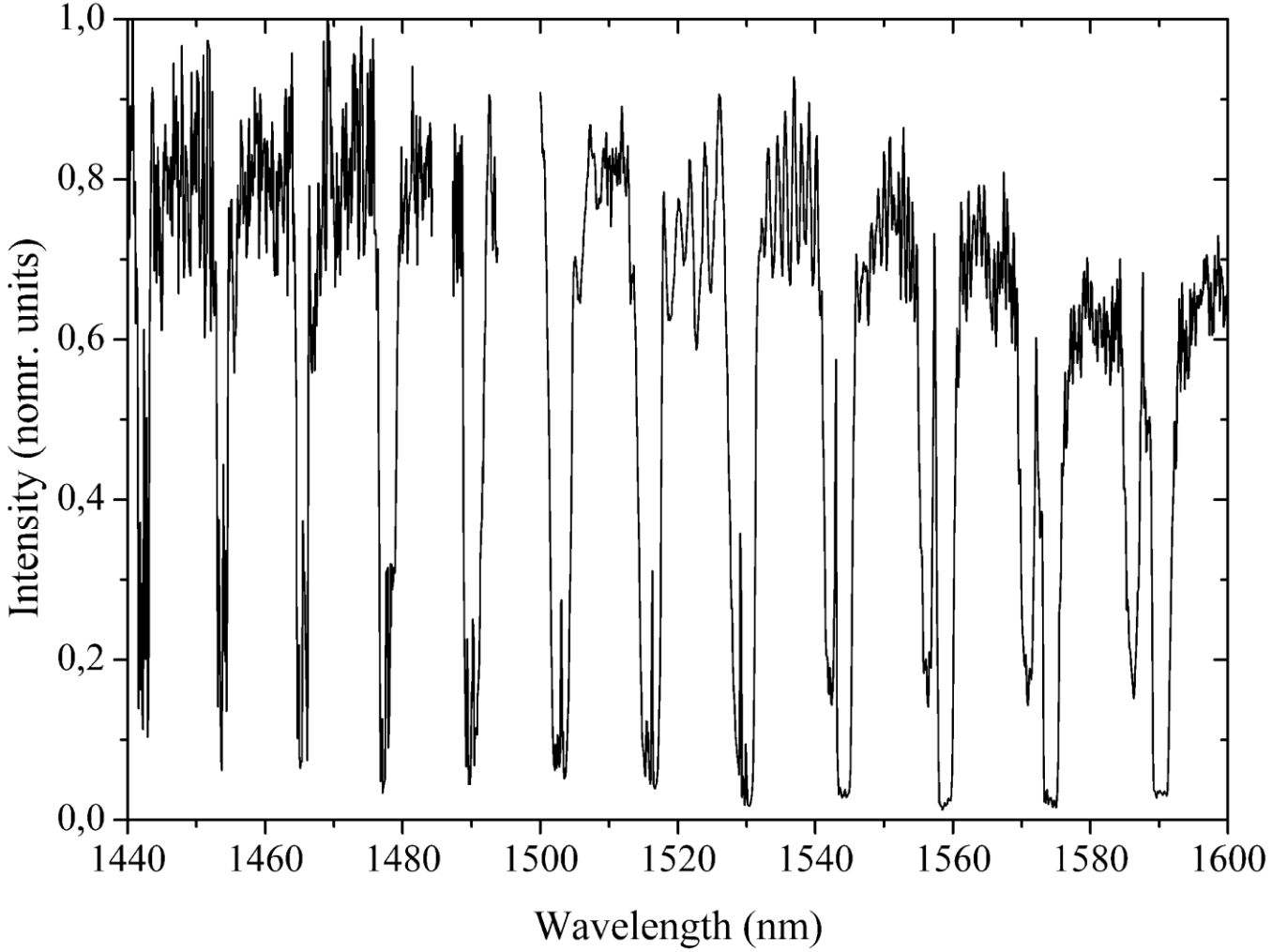
Ring-like and **Bragg**-like



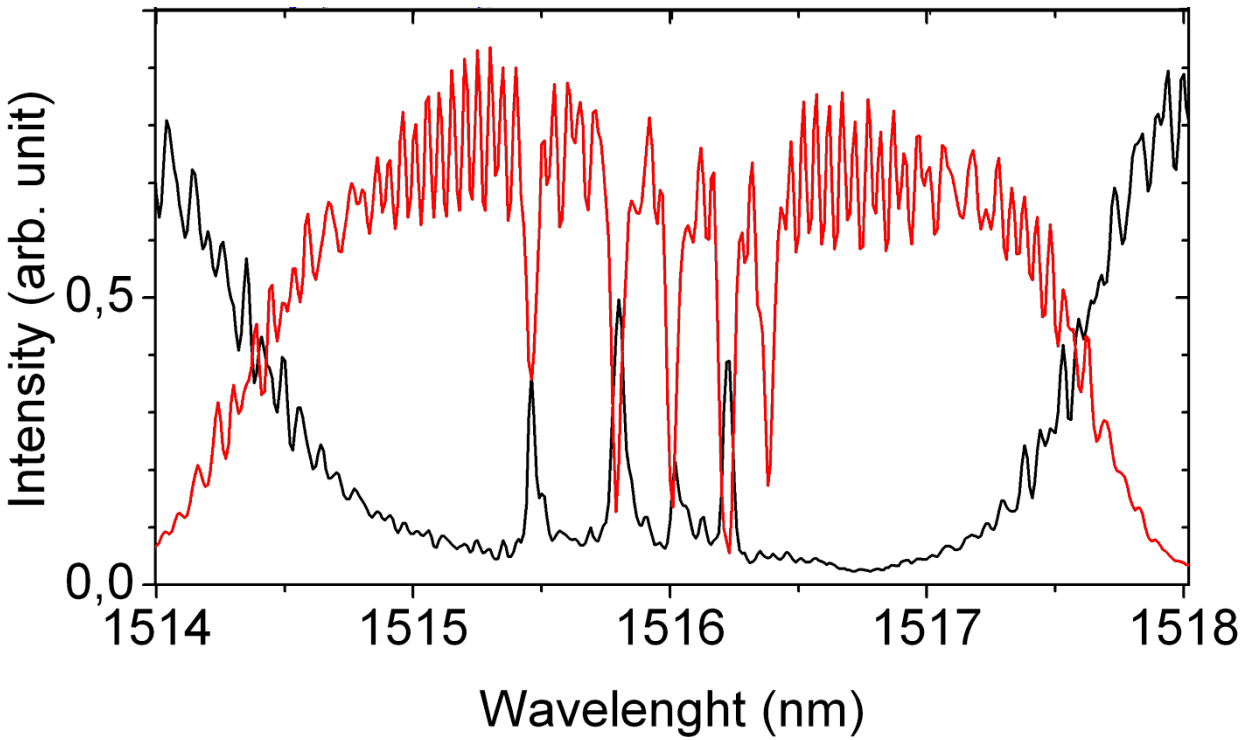
RB: $m\lambda_R = n_{eff} \cdot 2\pi r$

BB: $n\dfrac{\lambda_B}{2} = n_{eff} \cdot L$

Through port transmission spectra



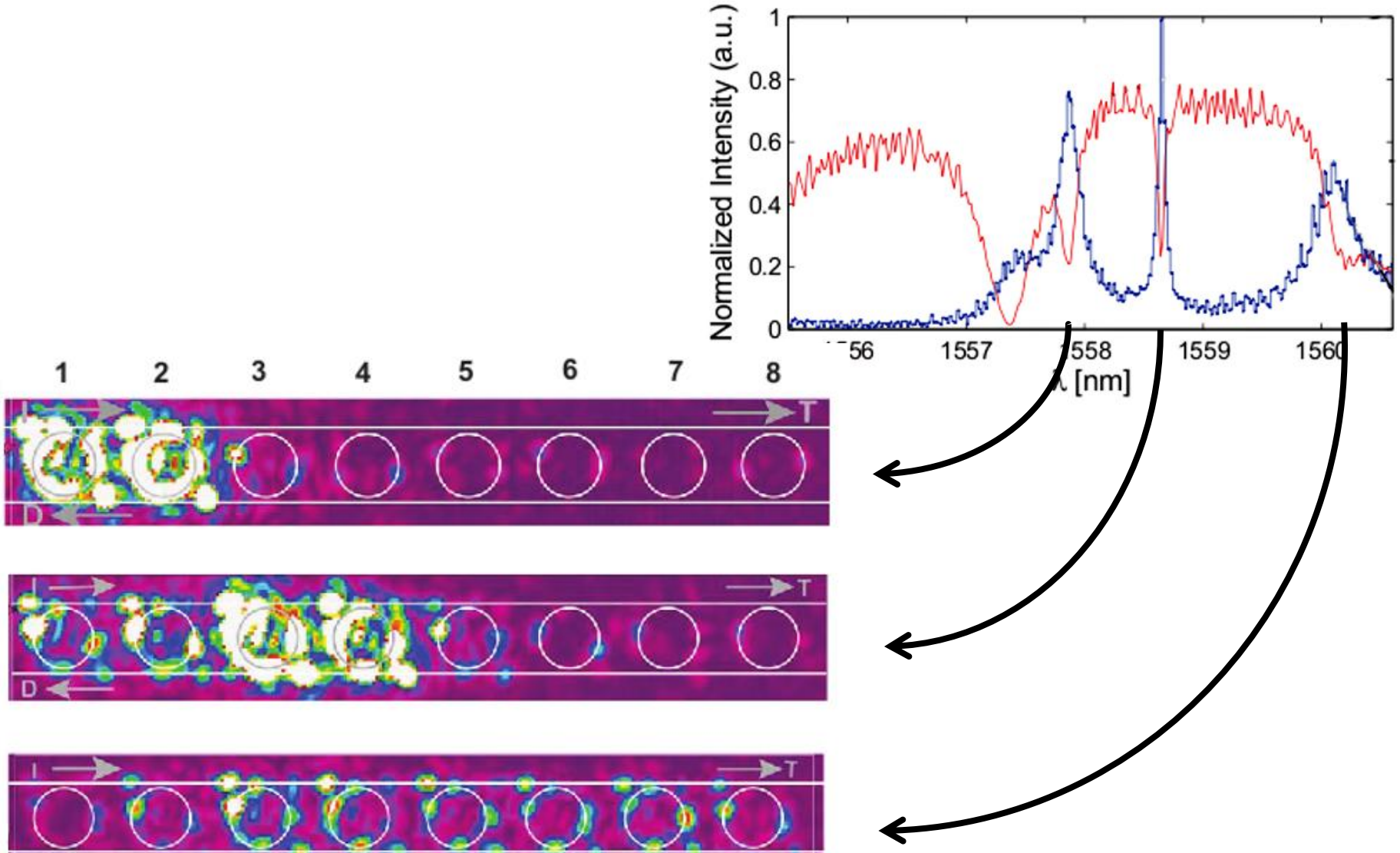
Unexpected resonances...



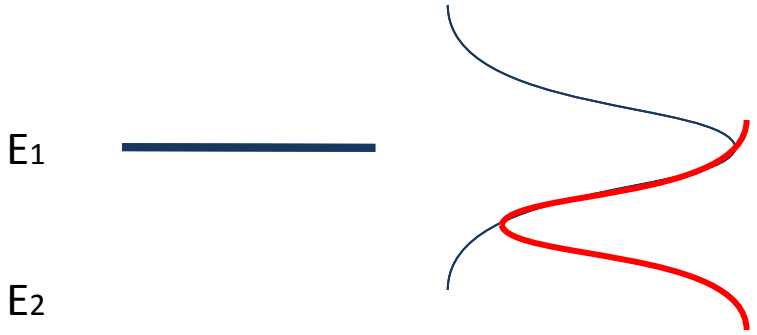
Q: 10^4-10^5

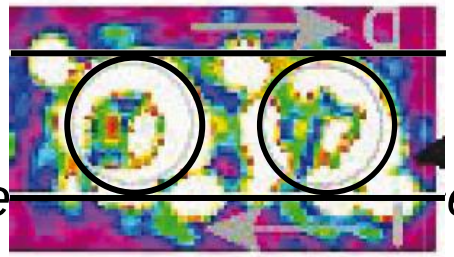
Peaks spacing: 25 GHz

Localized states

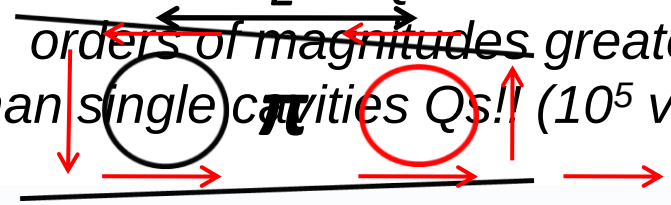


Where do they come from?

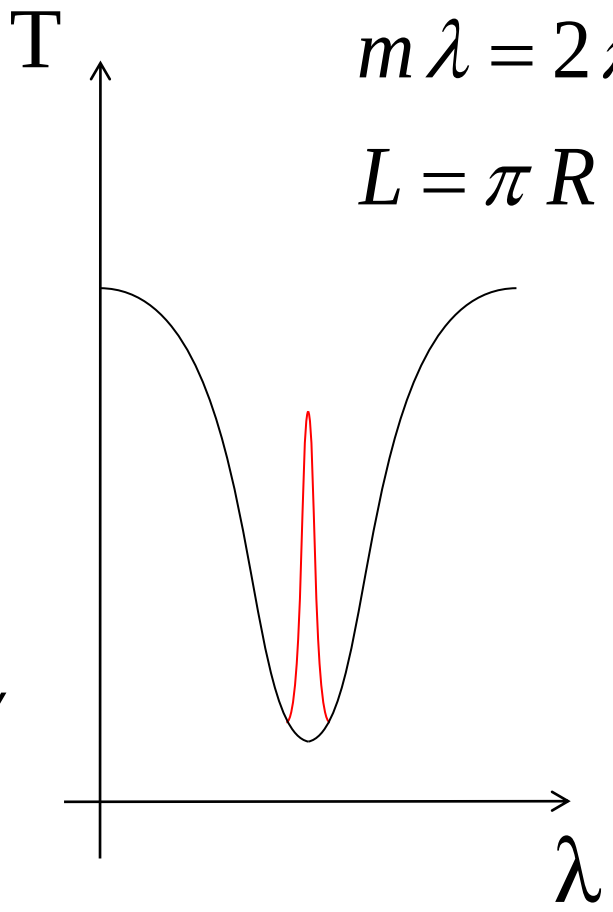




Coupled Resonator Induced Trasparency



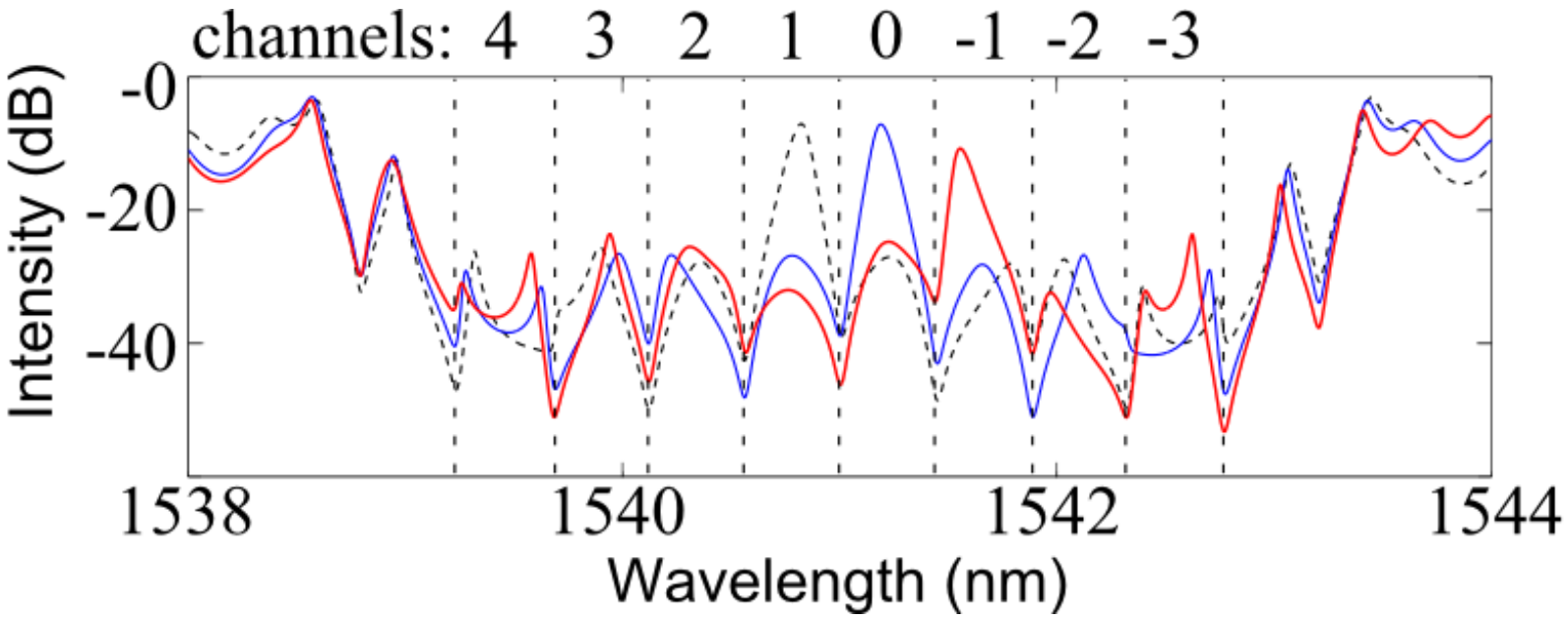
CRIT Qs are orders of magnitudes greater than single cavities Qs!! (10^5 vs 10^3)

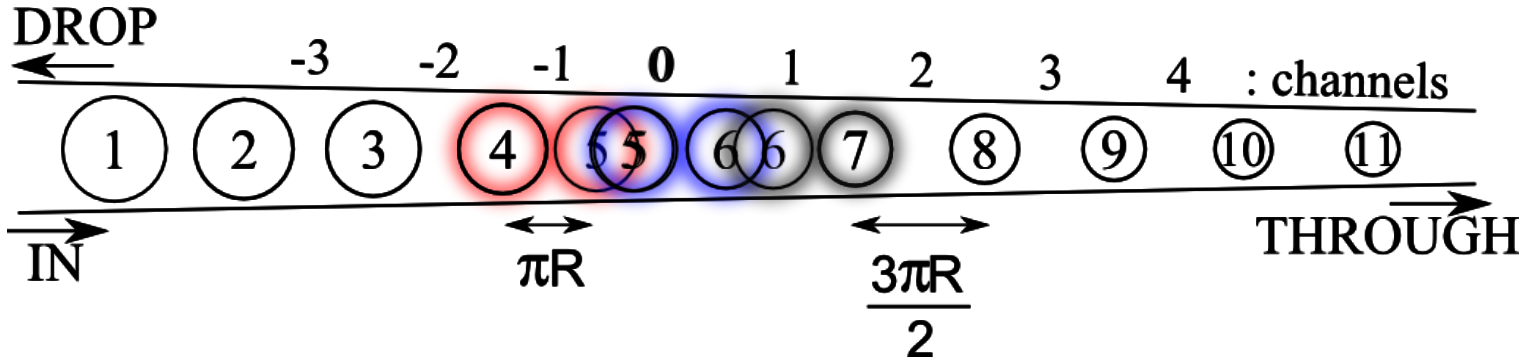


$$m\lambda = 2\pi n R$$

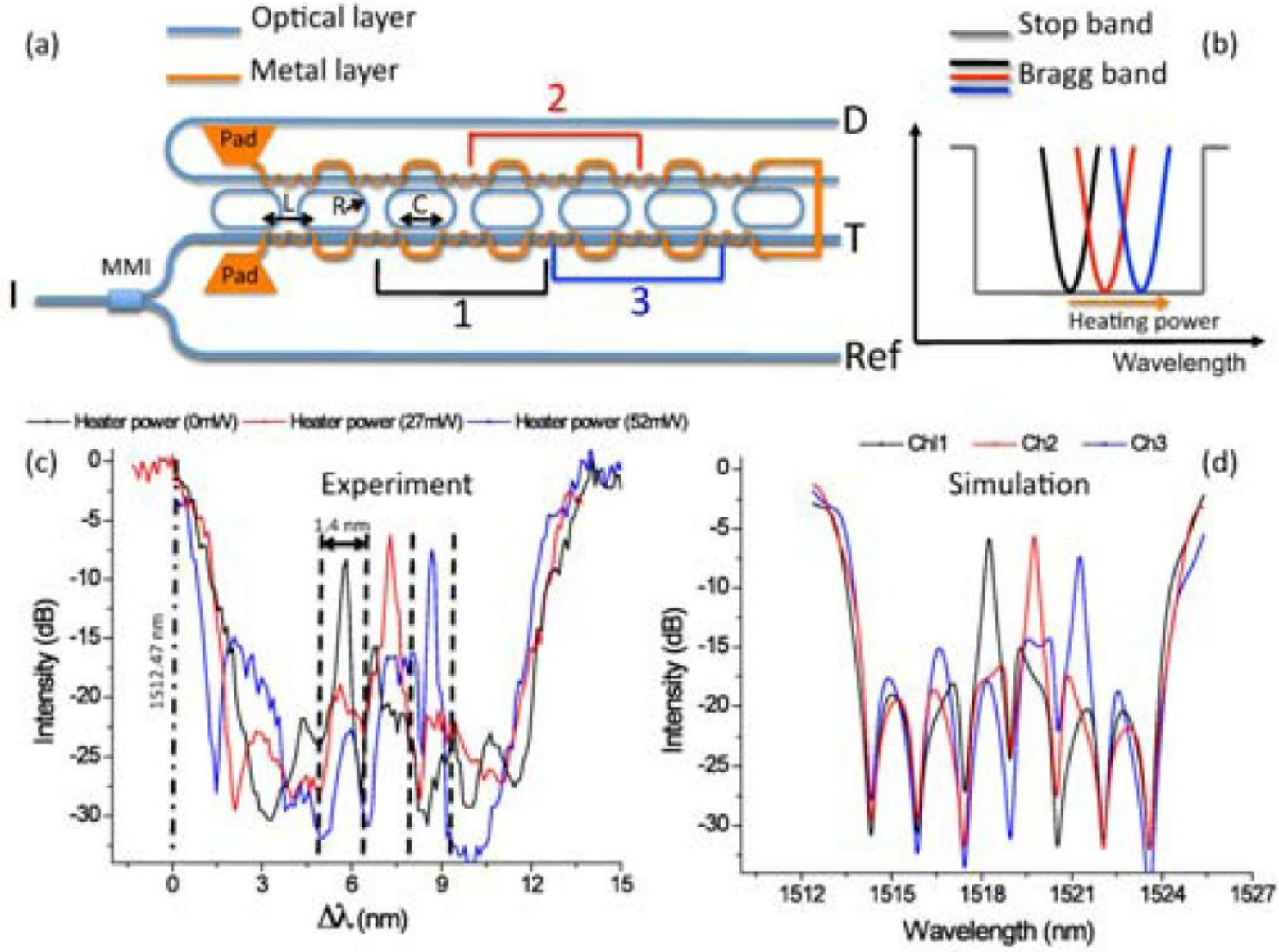
$$L = \pi R$$

Tapered SCISSOR

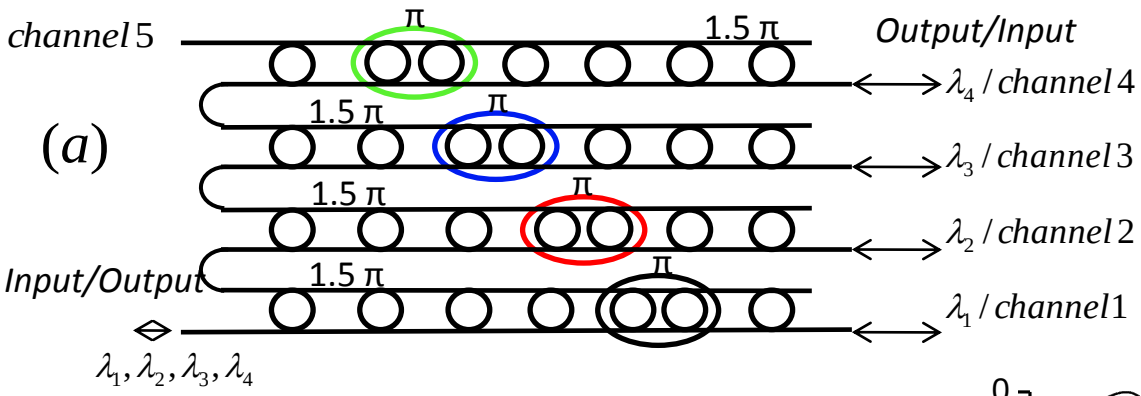


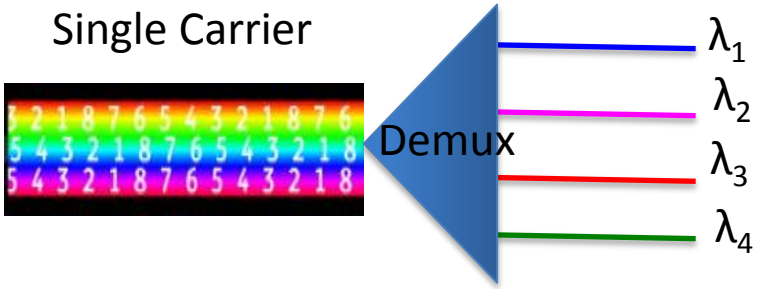


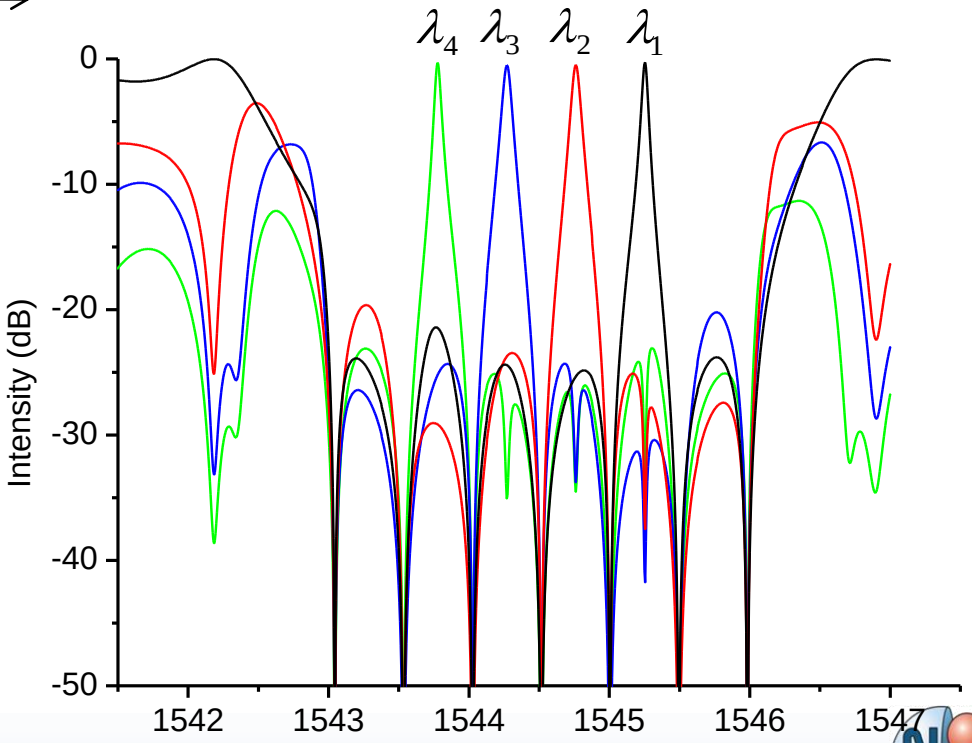
experiments



Structure realized: Dense WDM Mux/Demux





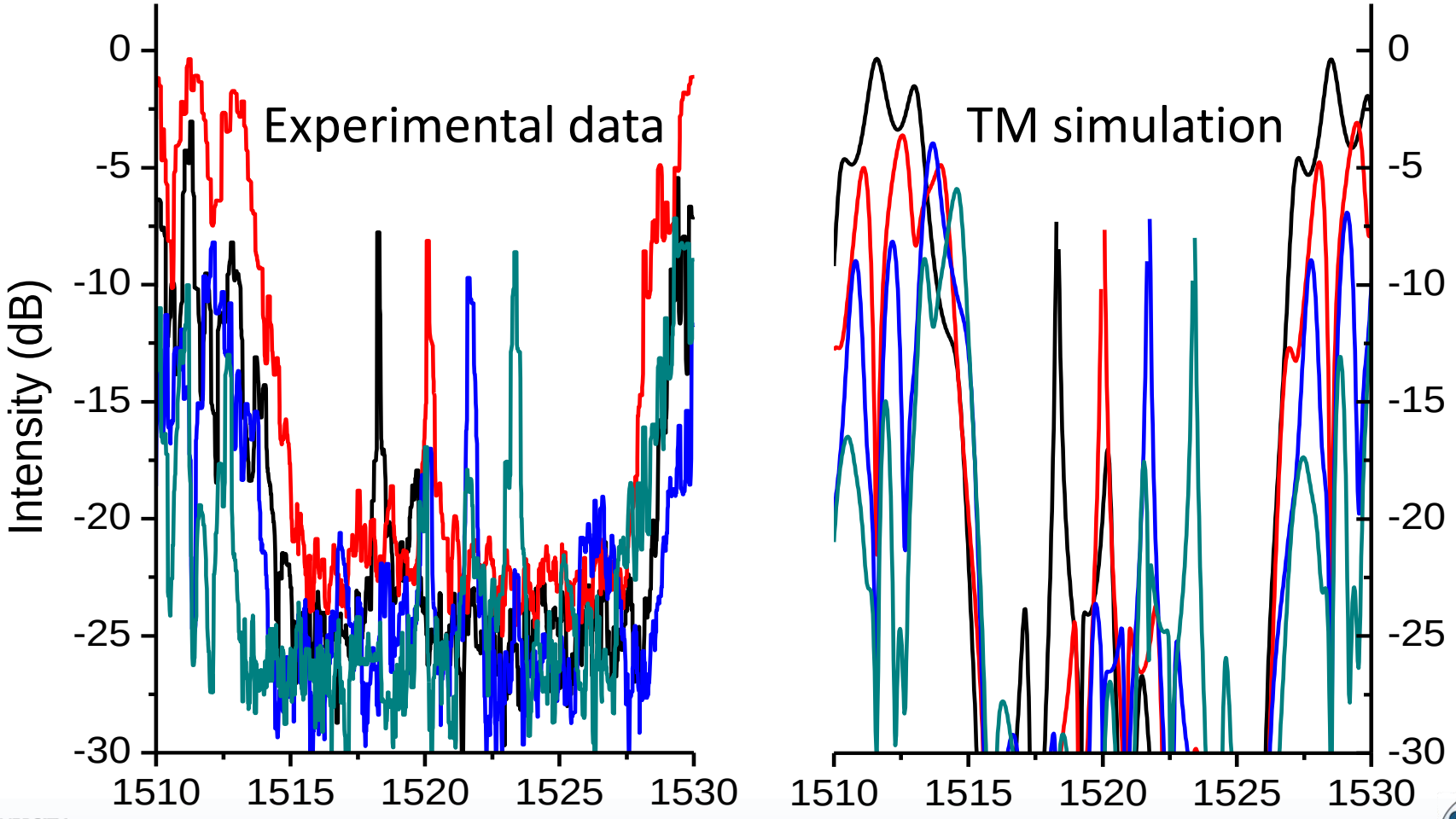


Structure realized: Mux/Demux, First experimental proof of this design!

7 racetrack based SCISSOR with radius of 3.25 μm

Channels bandwidth: 6-7 GHz (Q – 20000/30000) ***Good balance between channels***

Crosstalk < 10 dB ***Channel losses: 7-8 dB***



Benifits of the new design

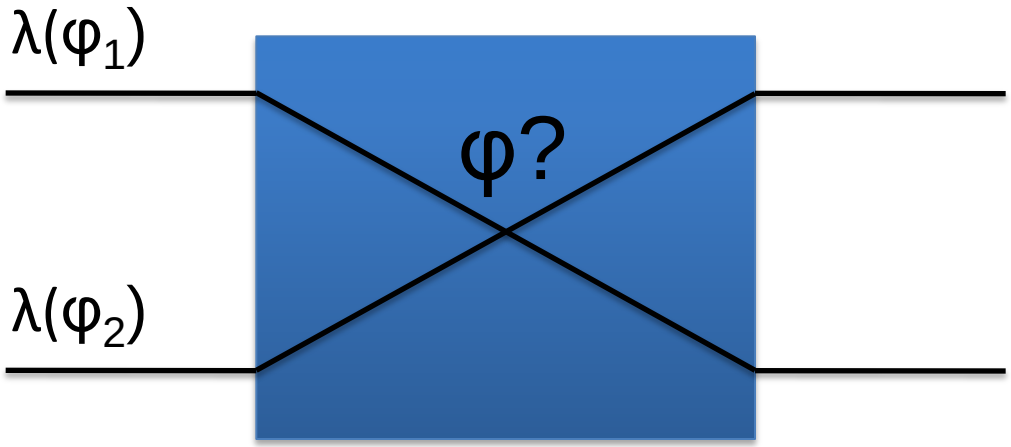
- Allows to reach **small bandwidth** (<25 GHz)
  - Possibility to handle more channels (more data) in the same telecom window
- **Robust** to manufacturing defects (more than the classic SCISSOR)
- ***Switchable channels*** by means a small refractive index variation ($<10^{-3}$)

outline

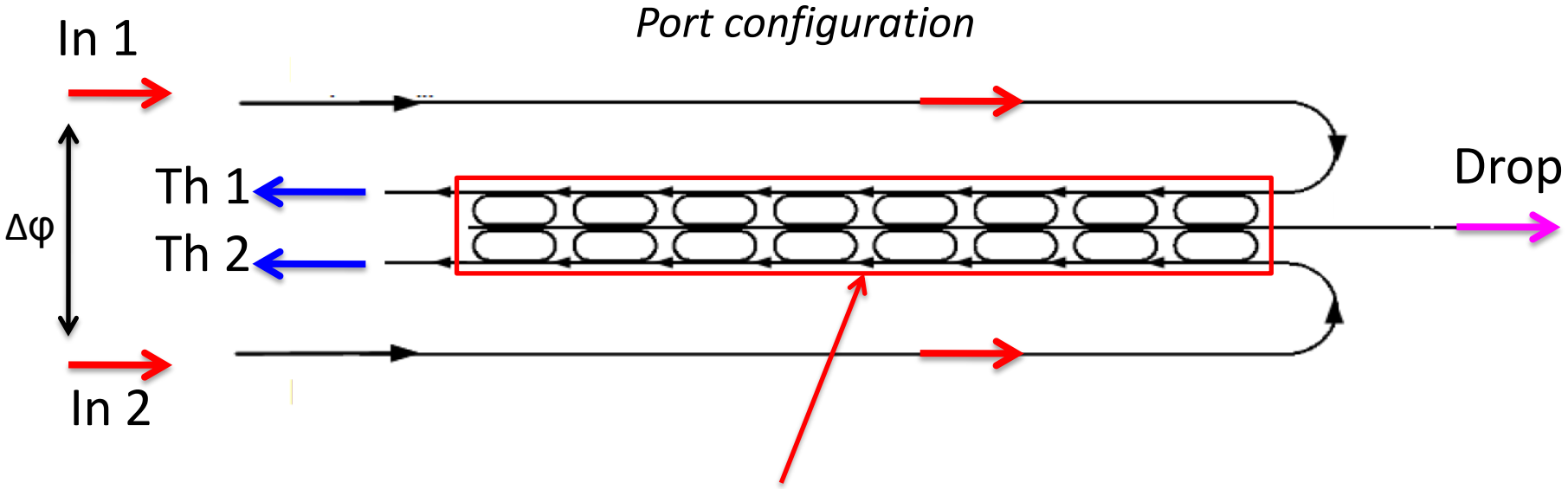
- Introduction
- Nanophotonics: vertical coupled microcavities
- Nanophotonics: coupled resonator induced transparency
- Nanophotonics: interferometric switching
- conclusions

New concept in DWDM routing

- Routing protocol based on the phase
- Routing of bands



Phase switch: Port configuration

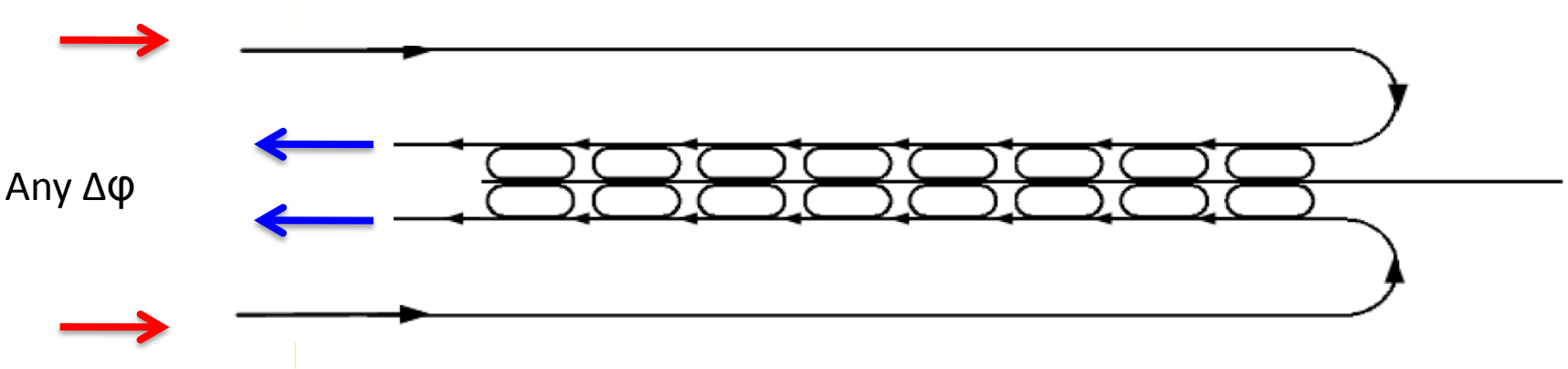


The signals interfere inside the 2 SCISSOR

Phase switch

	Spectral behaviour		
Phase behaviour		Res	Out of Res
	φ=0		Ths
	φ=π		Ths

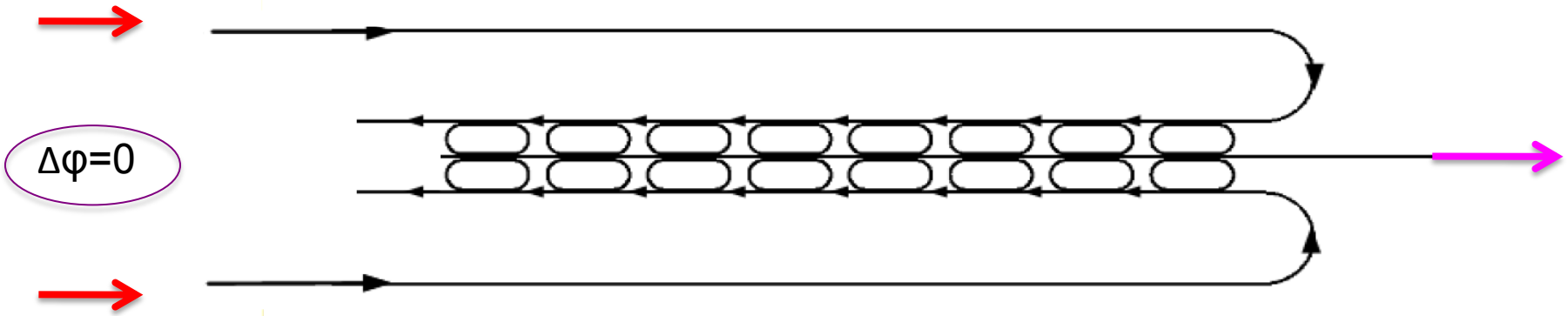
State 1: Out of resonance



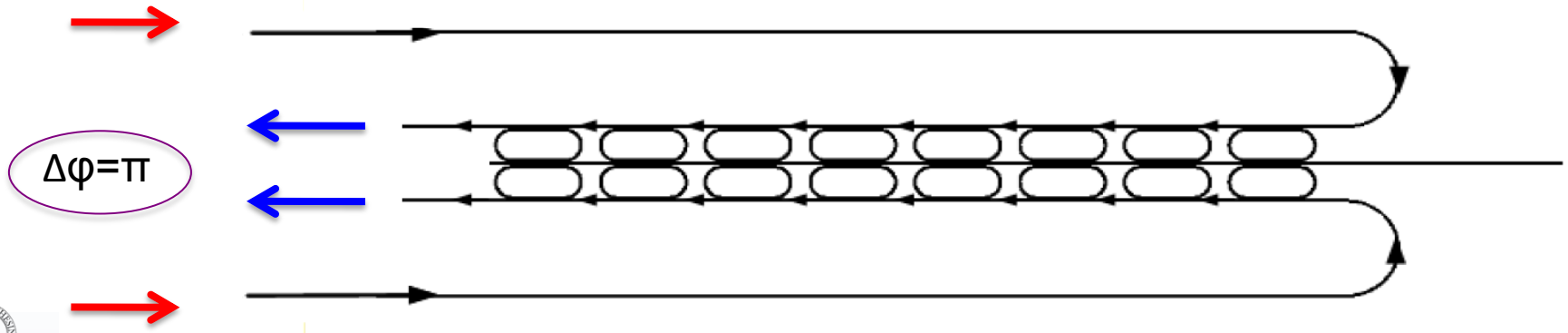
Phase switch

	Spectral behaviour		
Phase behaviour		Res	Out of Res
	φ=0	Drop	
	φ=π	Ths	

State 2a: In resonance, constructive phase condition



State 2b: In resonance, destructive phase condition

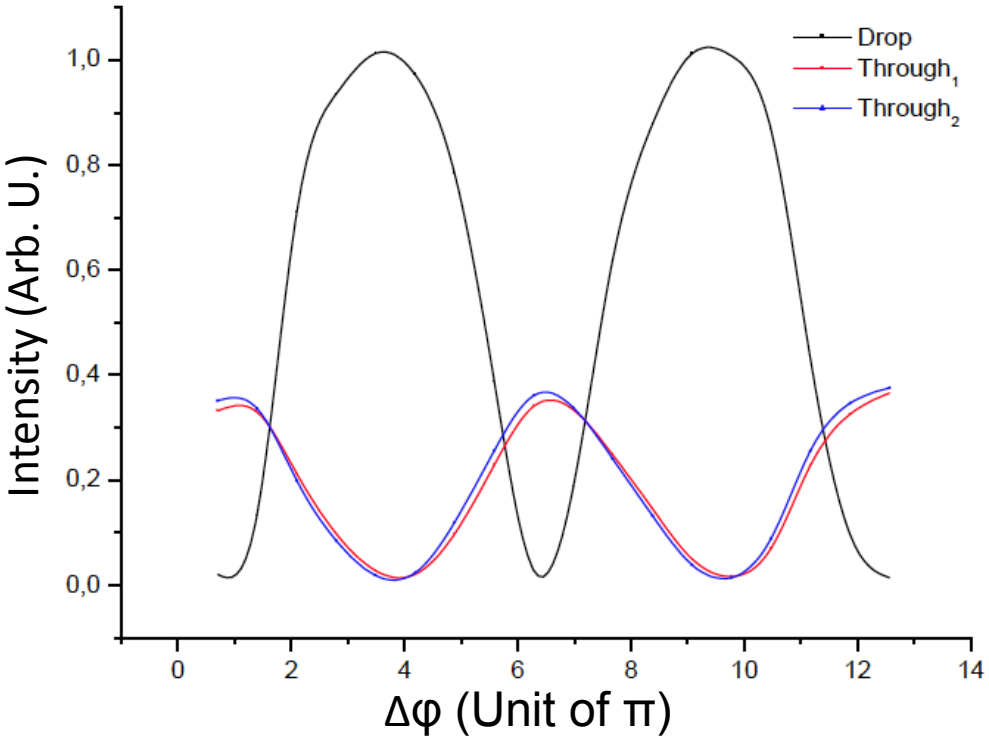


Experimental results

- First demonstration of working principle: phase switching achieved
- Mach Zehnder like response
- Opposite phase behaviour of drop and through ports as expected

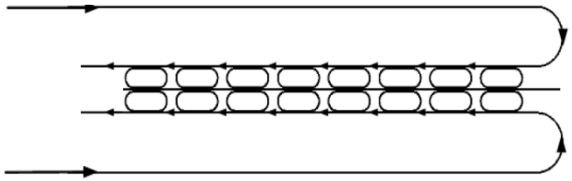
	Spectral behaviour		
Phase behaviour		Res	Out of Res
	φ=0	Drop	Ths
	φ=π	Ths	Ths

Resonant

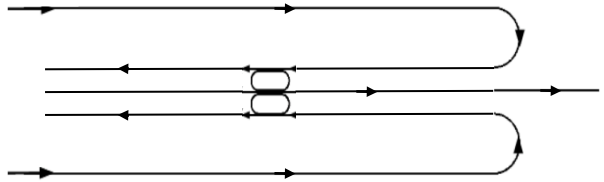


Why SCISSOR?

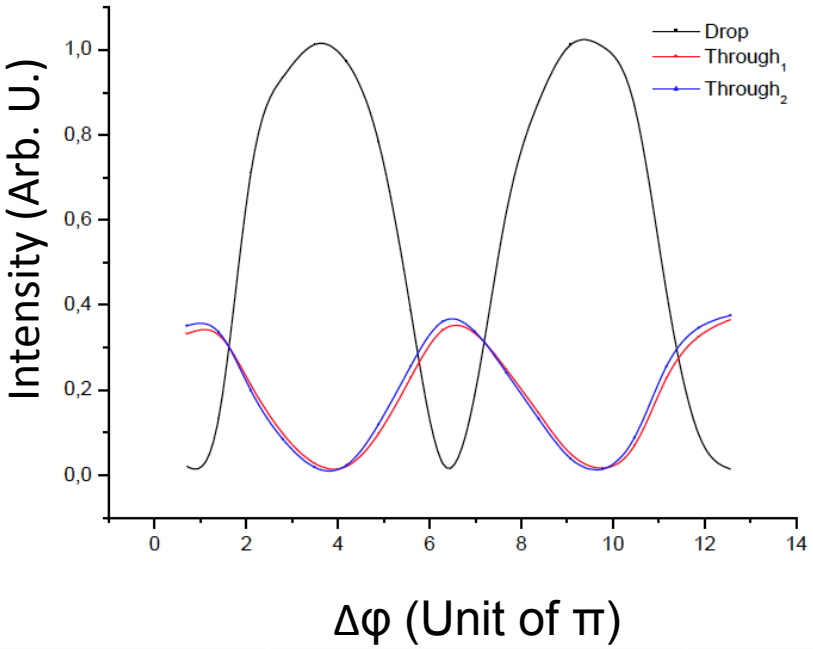
- Robust to fabrication errors: small deviations from nominal sizes are averaged out
- Less sensitive to inputs unbalance thanks to the optical feedback

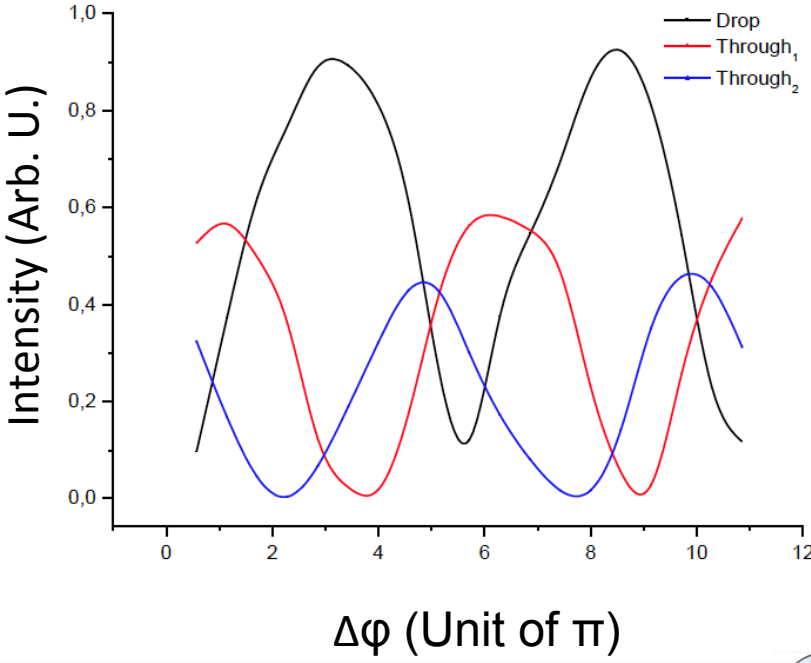


SCISSOR



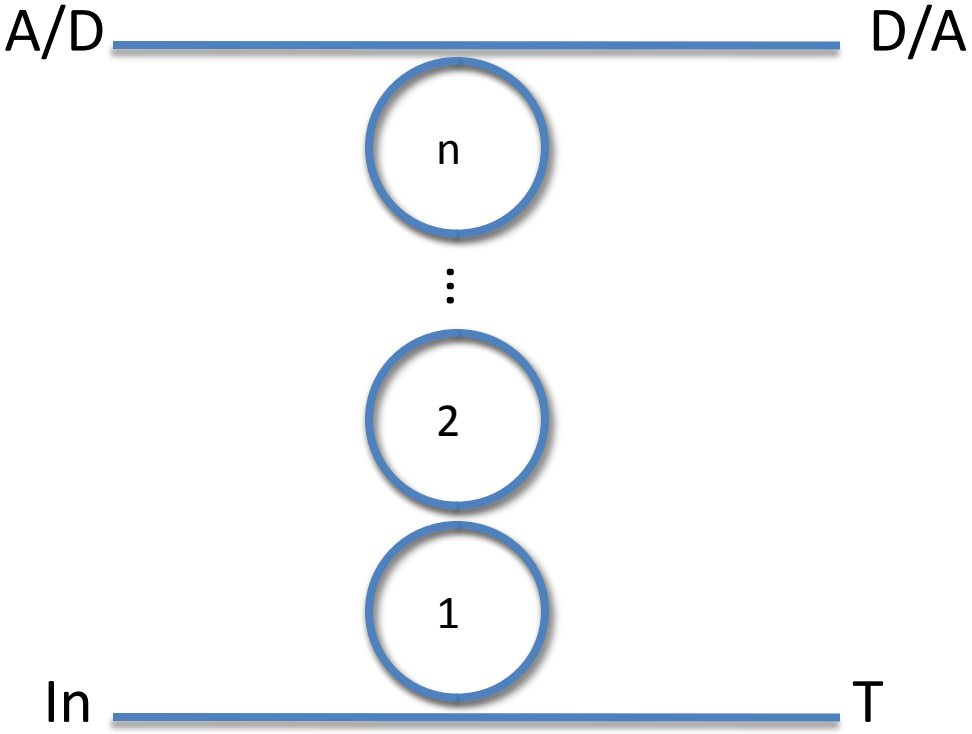
Single resonator

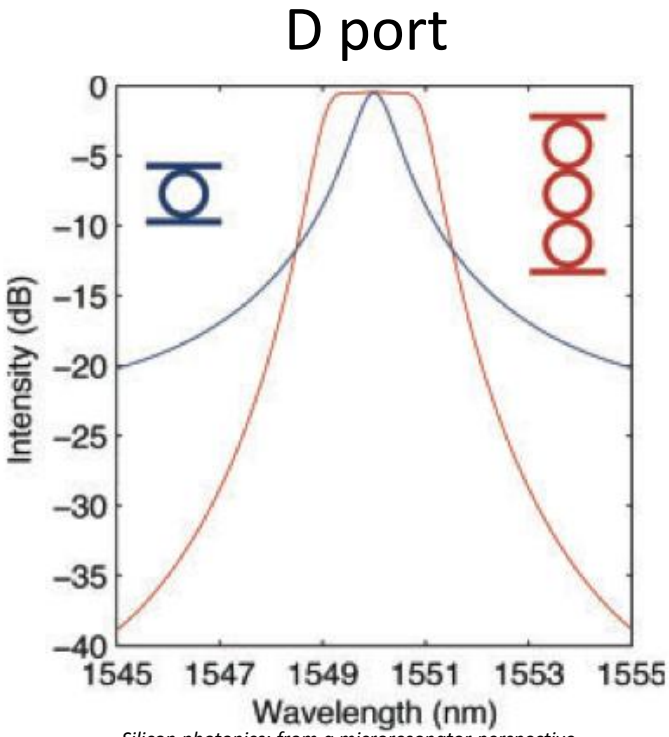




Multiple resonators: CROW

- Resonators in series:
  - CROW, Coupled Resonators Optical Waveguides
  - Typical applications: Flat box filter

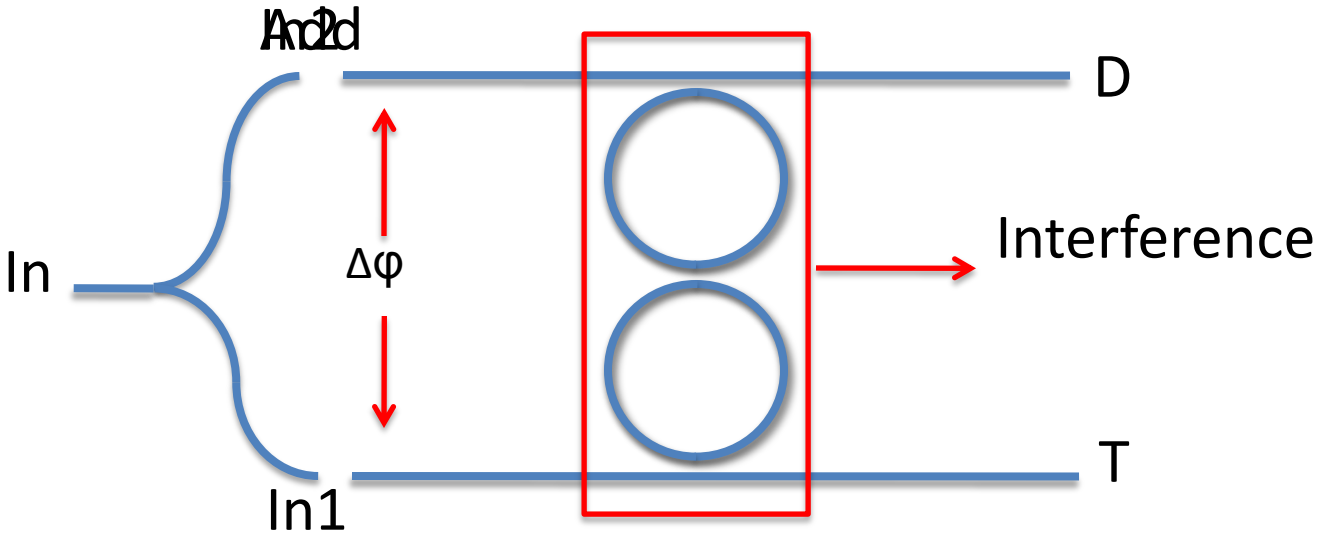




Silicon photonics: from a microresonator perspective, Shaoqi Feng, Ting Lei, Hui Chen, Hong Cai, Xianshu Luo and Andrew W. Poon

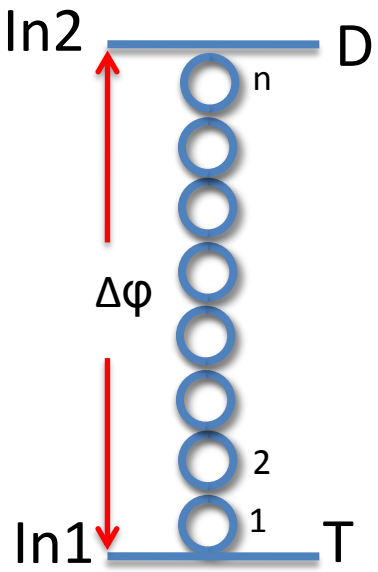
New way to use CROW

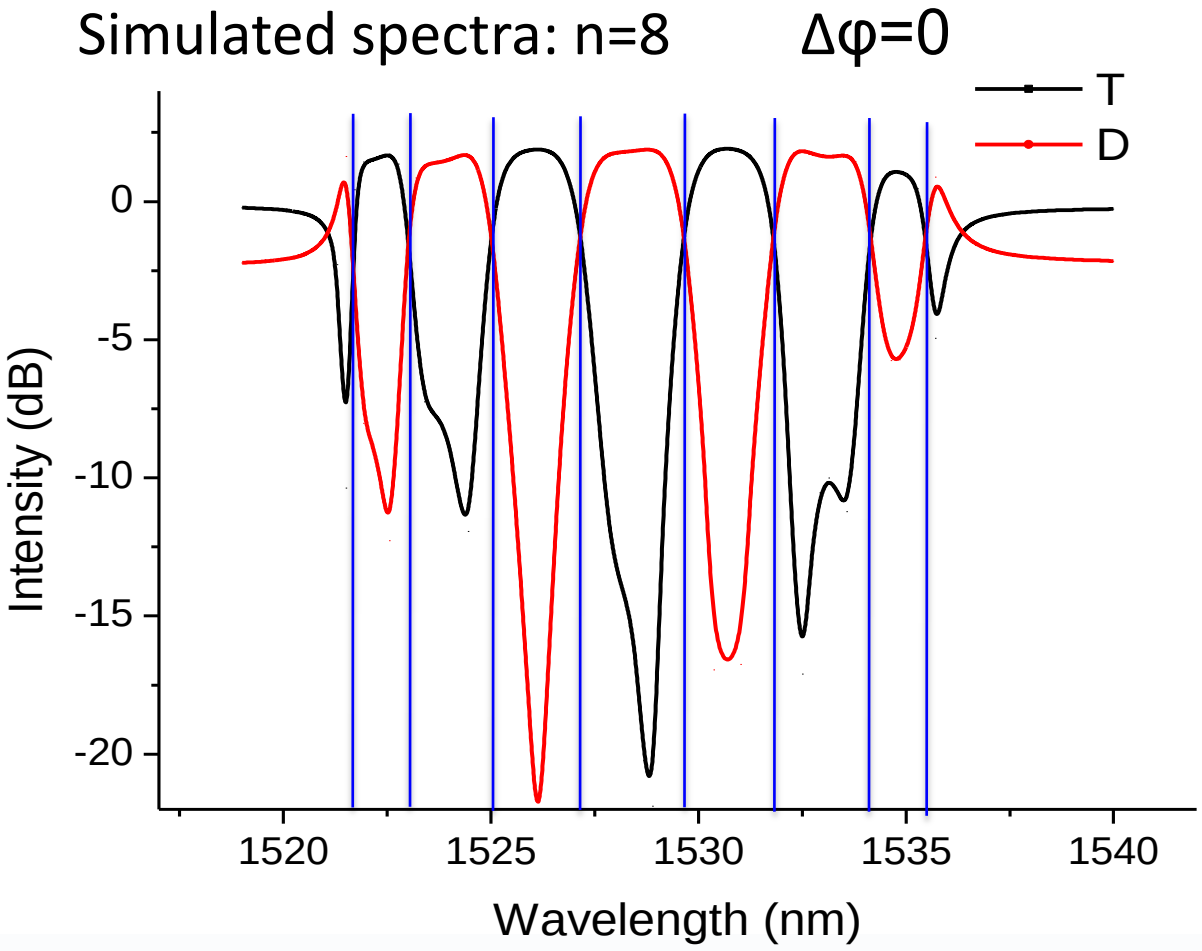
- Use the In and Add port as a single input: Add=In2
- The In1-In2 Phase relation allows to tune the spectrum response
- 3 ports device: In, T,and D



Device features: fixed phase

- The spectrum is composed of n-1 box-like bands





Device features: fixed phase

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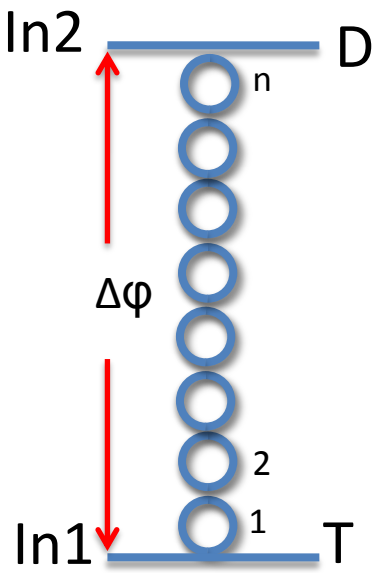
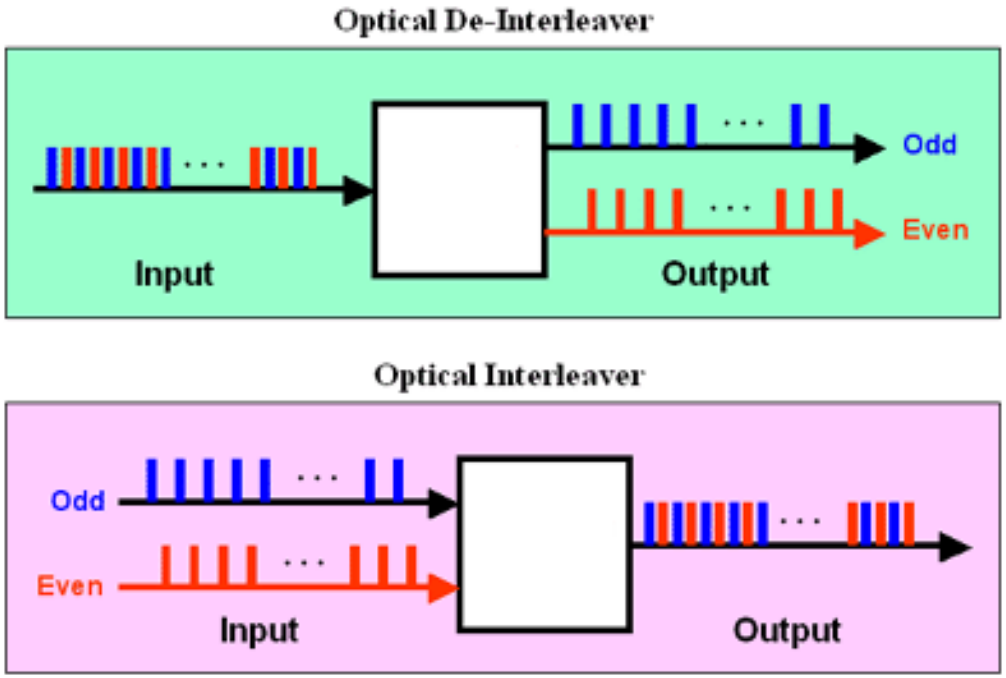
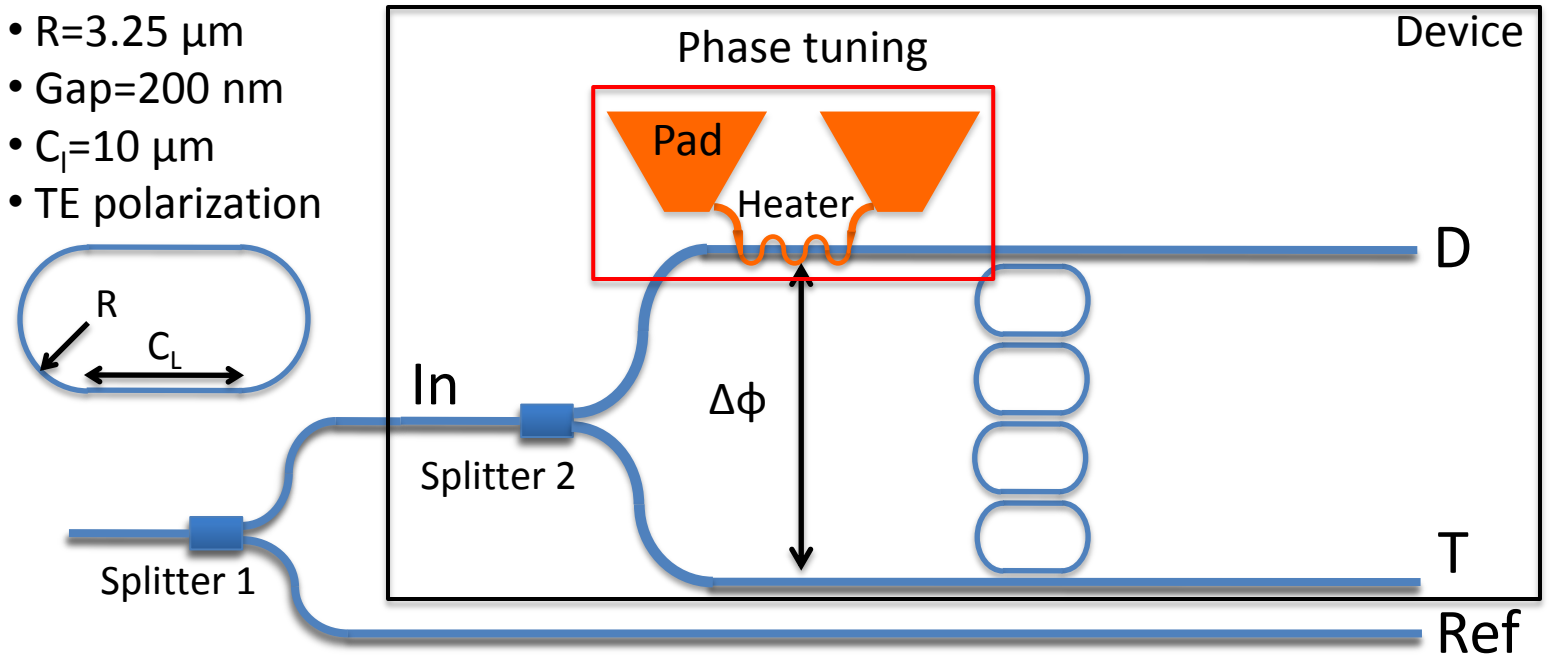




Interleaver function

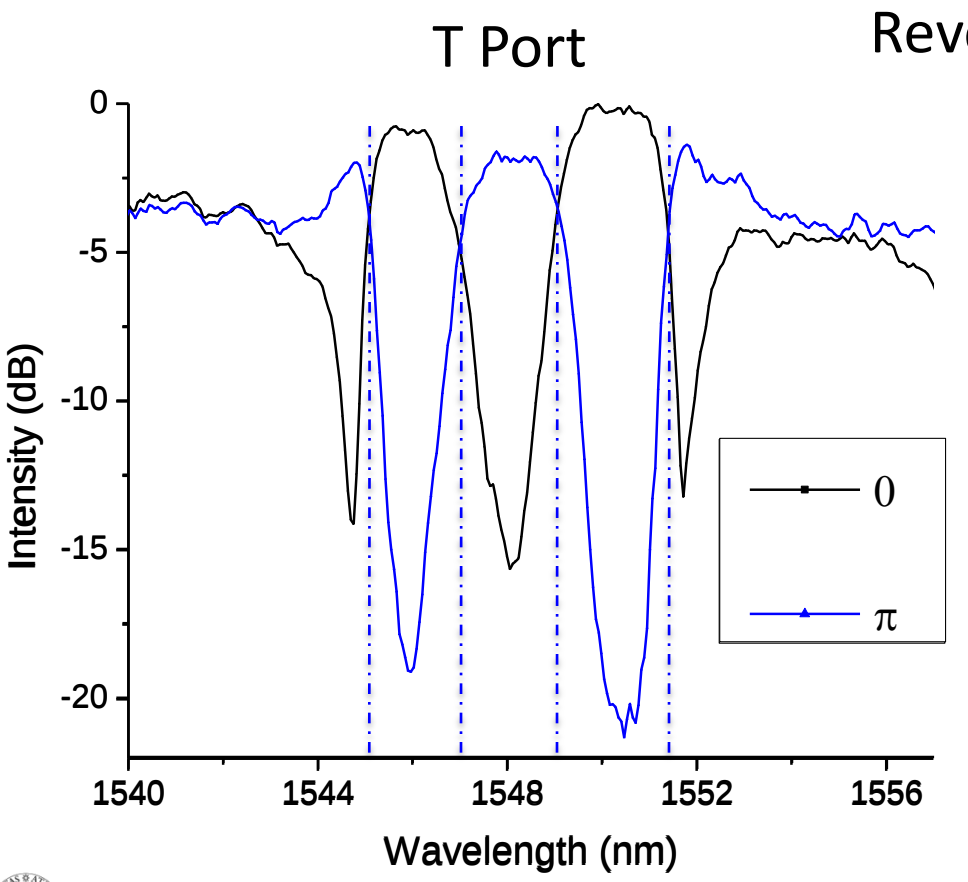
Device under test

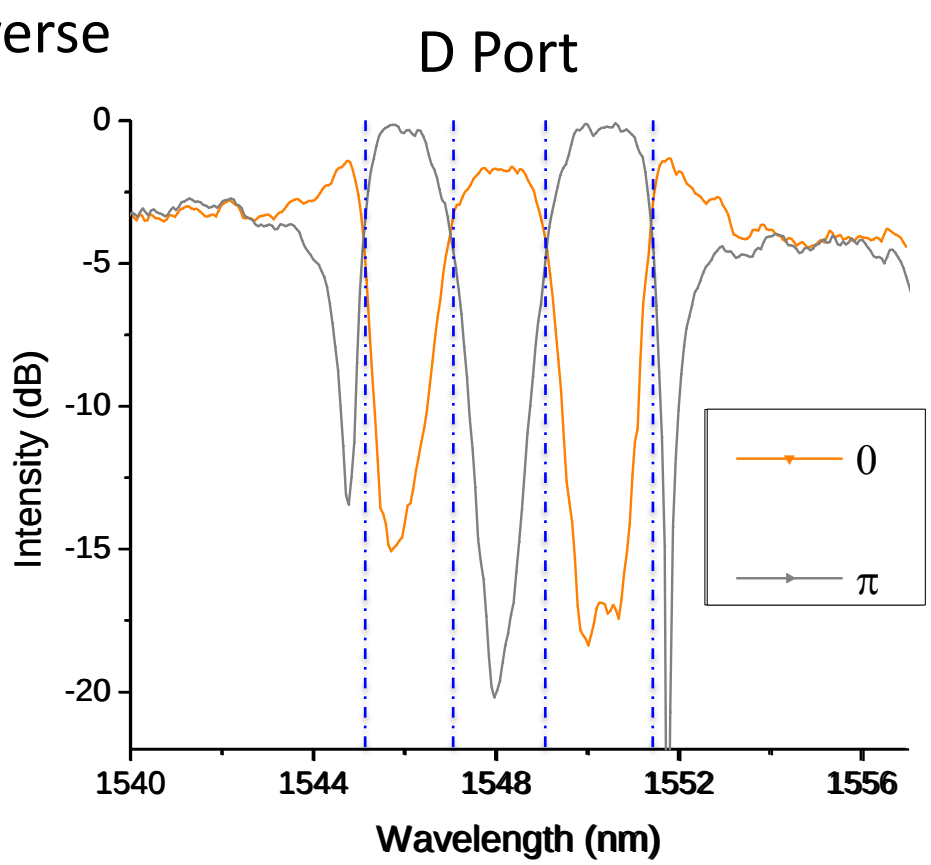
- Racetrack based CROW: 2,4,8 resonators
- Integrated metal heater for active refractive index tuning (Phase variation)



Experimental: CROW 4

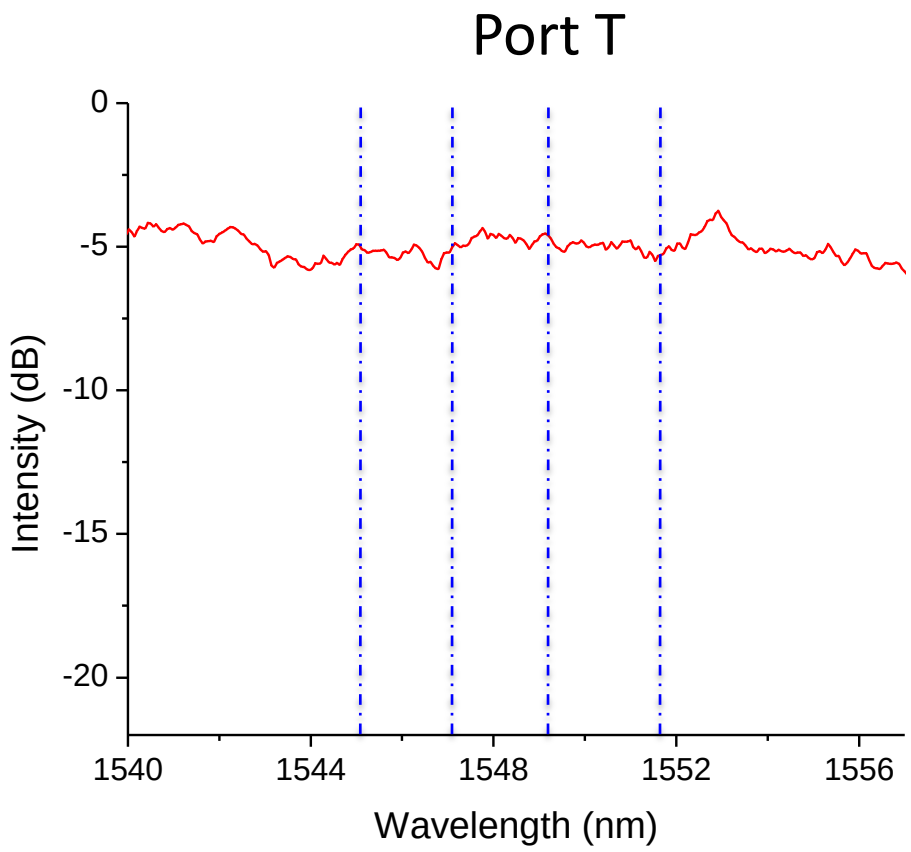
- $\Delta\varphi=0,\pi$: T and D ports are complementary
  - $\Delta\varphi=0$: Normal
  - $\Delta\varphi=\pi$: Reverse

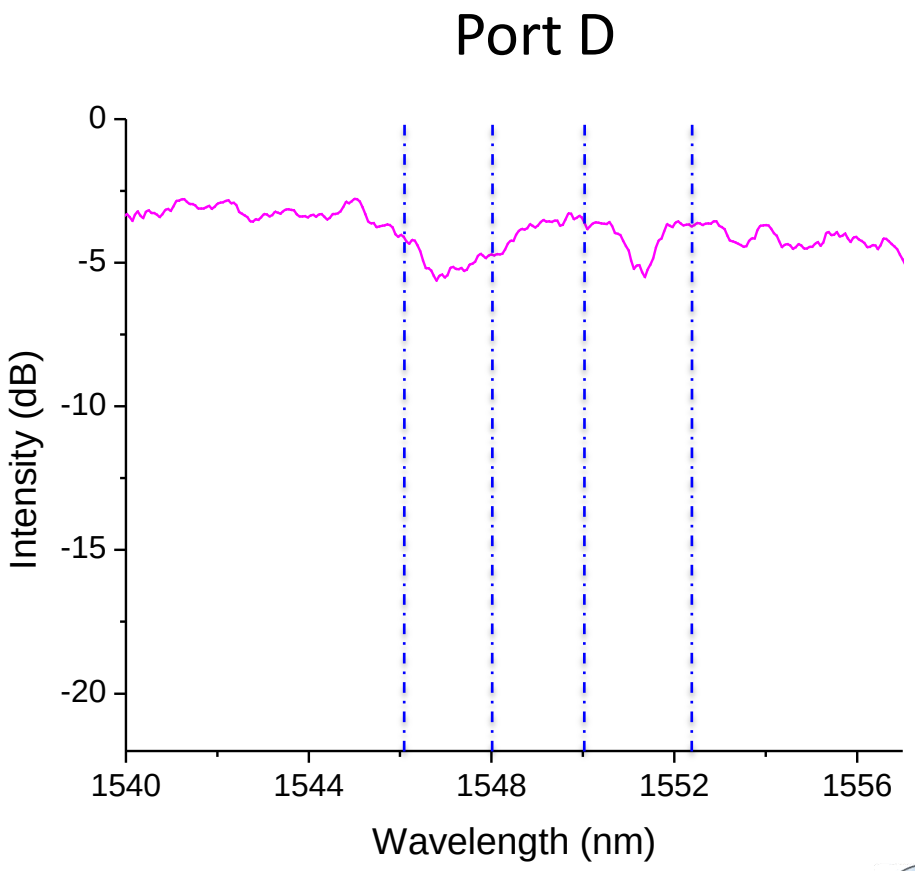




Experimental: CROW 4

- $\Delta\varphi=\pi/2$: Inhibition of resonances for both ports





…. therefore

- Interferometric controlled CROW
  - Reconfigurable interleaver with a beam splitter added functionalities

outline

- Introduction
- Nanophotonics: vertical coupled microcavities
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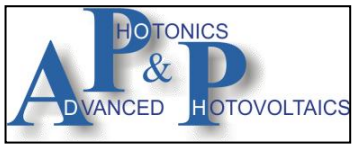
- Conclusions

Conclusions

- Silicon photonics is already at the industrial development and commercialization stage
- University groups cannot compete on the integration level
- Still by studying new physical phenomena new functionalities can be enabled
- There is still a lot of fun in this field….

Acknowledgments