Classical and Quantum Silicon Photonics: few examples

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European Research Council grantee

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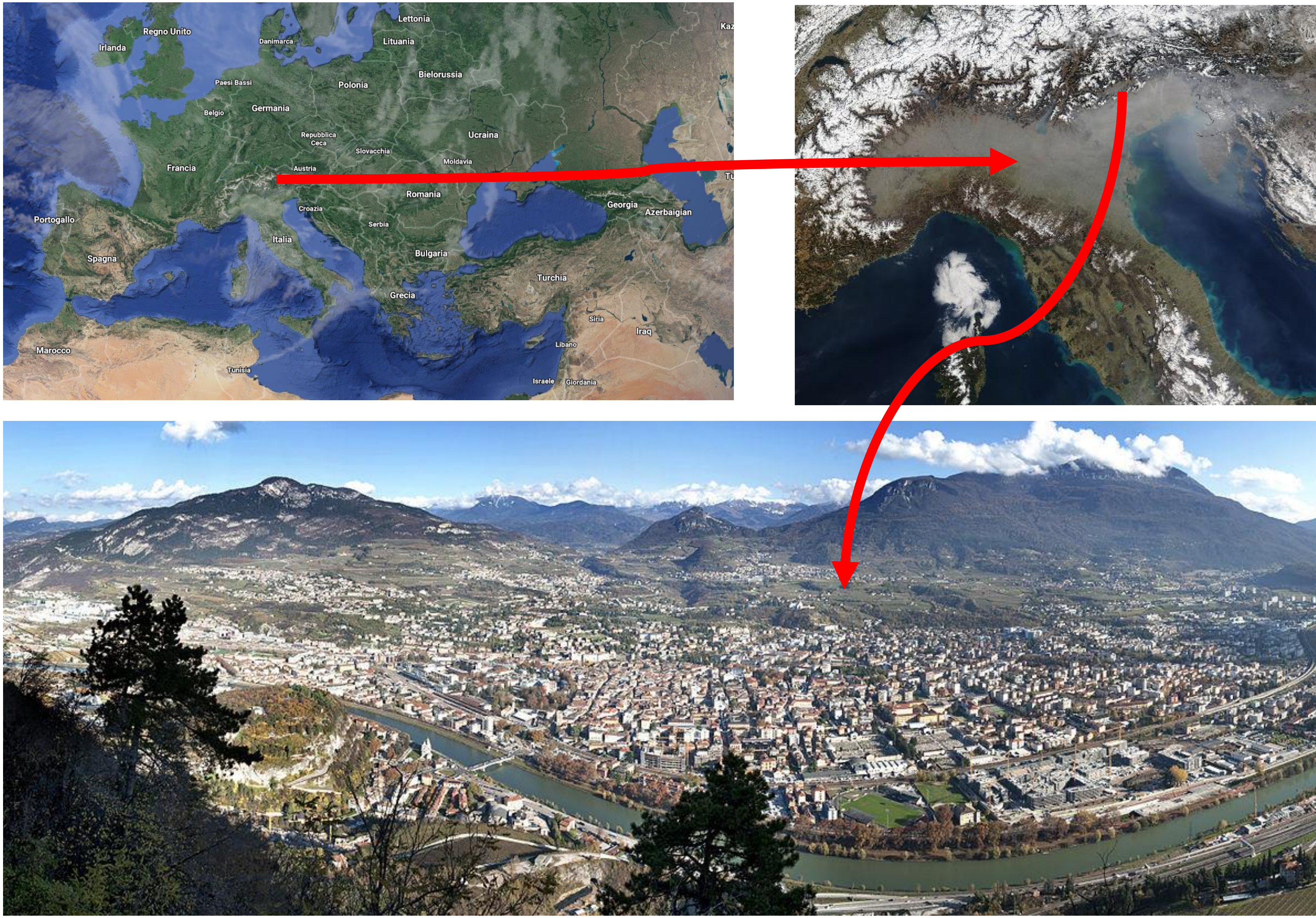

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http://nanolab.physics.unitn.it/

Quantum Photonics
Non-Hermitian Photonics
Neuromorphic Photonics

frontiers in Physics
REVIEW
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Thirty Years in Silicon Photonics: A Personal View

Lorenzo Pavesi *

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Silicon Photonics, the technology where optical devices are fabricated by the mainstream microelectronic processing technology, was proposed almost 30 years ago. I joined this research field at its start. Initially, I concentrated on the main issue of the lack of a silicon laser. Room temperature visible emission from porous silicon first, and from silicon nanocrystals then, showed that optical gain is possible in low-dimensional silicon, but it is severely counterbalanced by nonlinear losses due to free carriers. Then, most of my research focus was on systems where photons show novel features such as Zener

Nanoscience Laboratory

prof

researcher

staff

Post-doc

PhD

Master students

Q@TN

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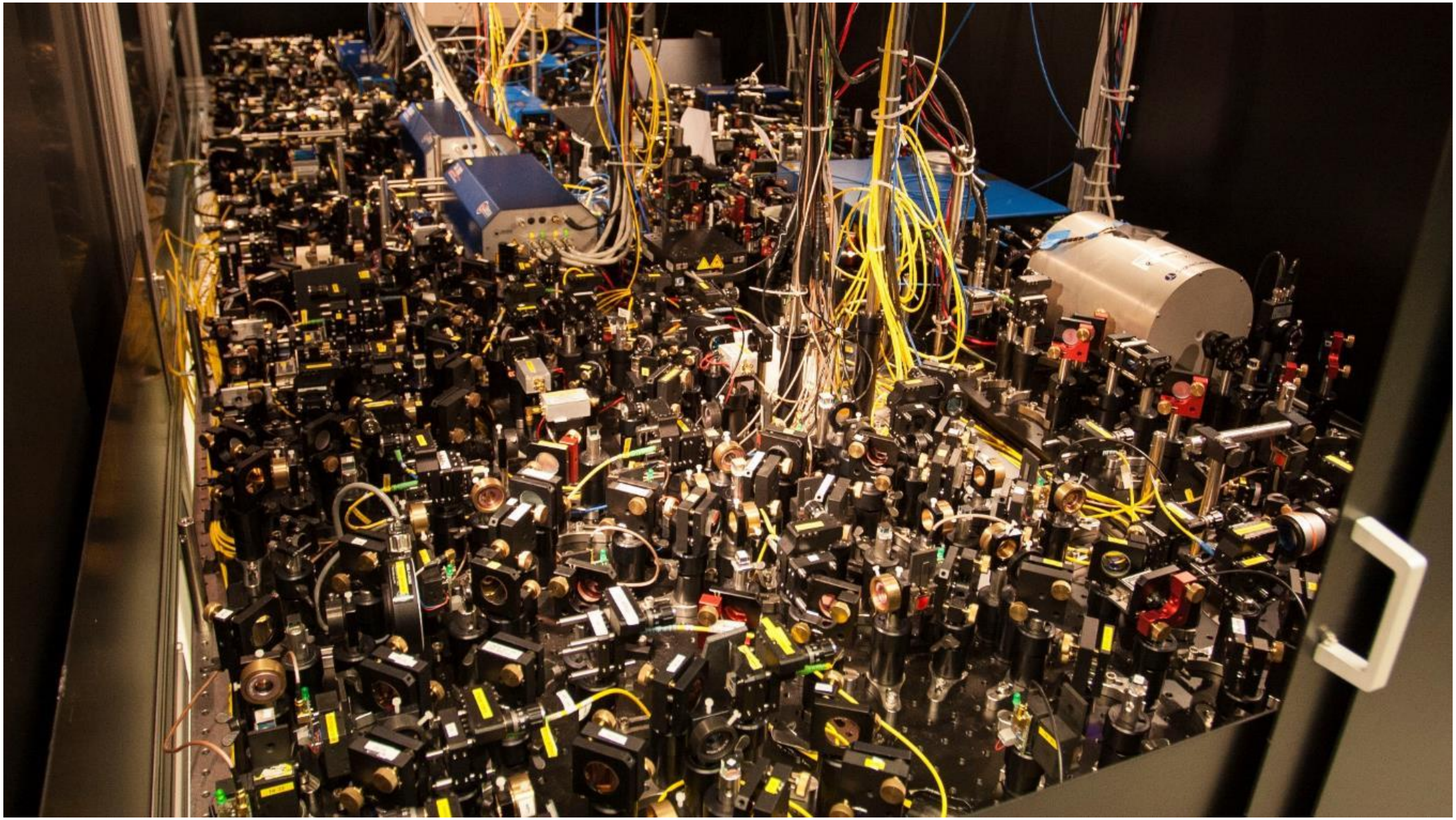
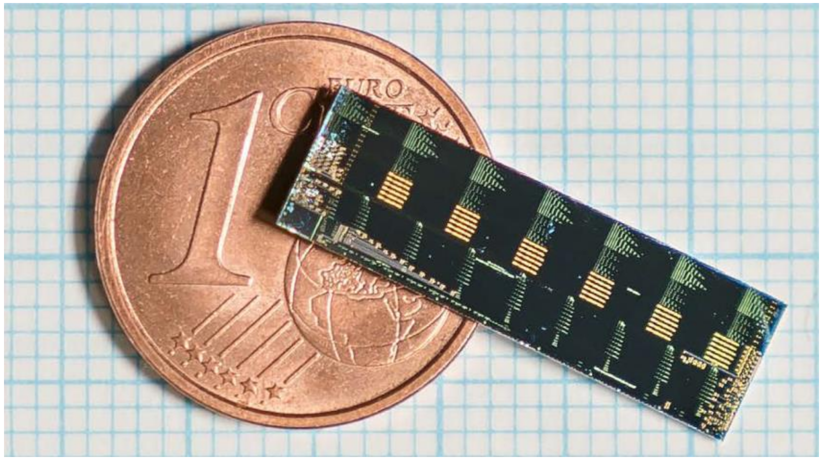
Integrated photonics



Integrated photonics

Photonic Integrated Circuit



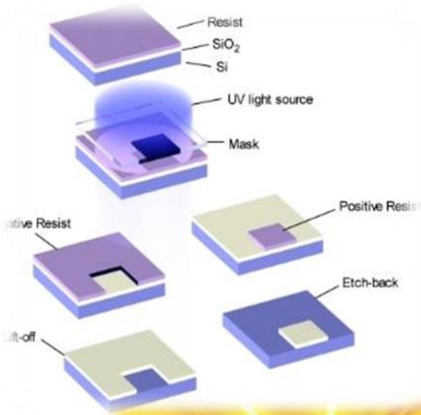
Widespread diffusion

- Lower dimensions
- Lower costs
- CMOS compatible

- More stable
- Lower noise
- Lower losses

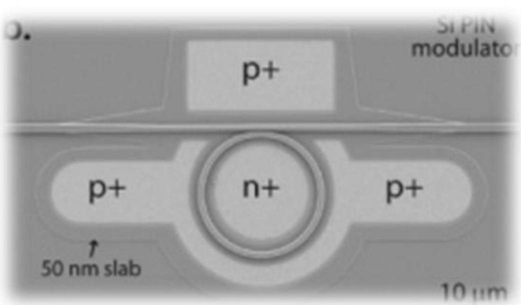
Efficient devices

Silicon Photonics



Photonic devices fabricated using Silicon and standard Silicon processing (Complementary Metal Oxyde Semiconductor technology)

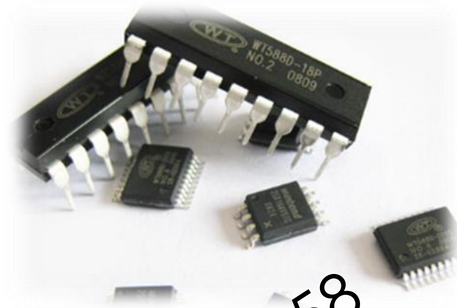
Mass manufacturability, low cost, high volumes and state of the art performances



Natural way of merging photonics and electronics on the same chip

A parallel paradigm to success..

Microelectronics



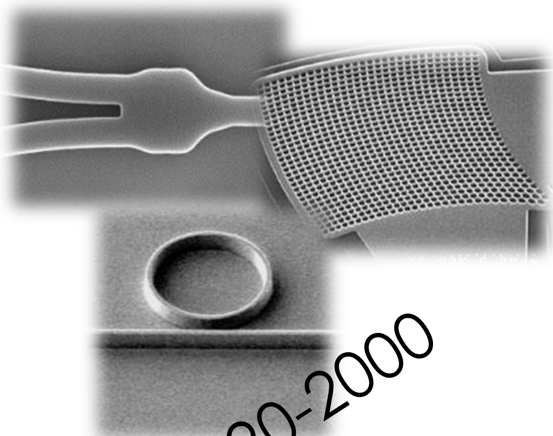
1948

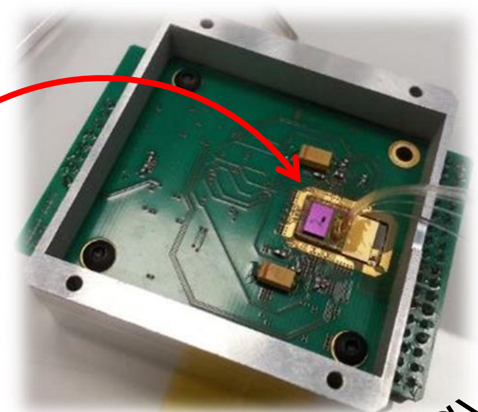
1958

today

Years

Integrated Photonics



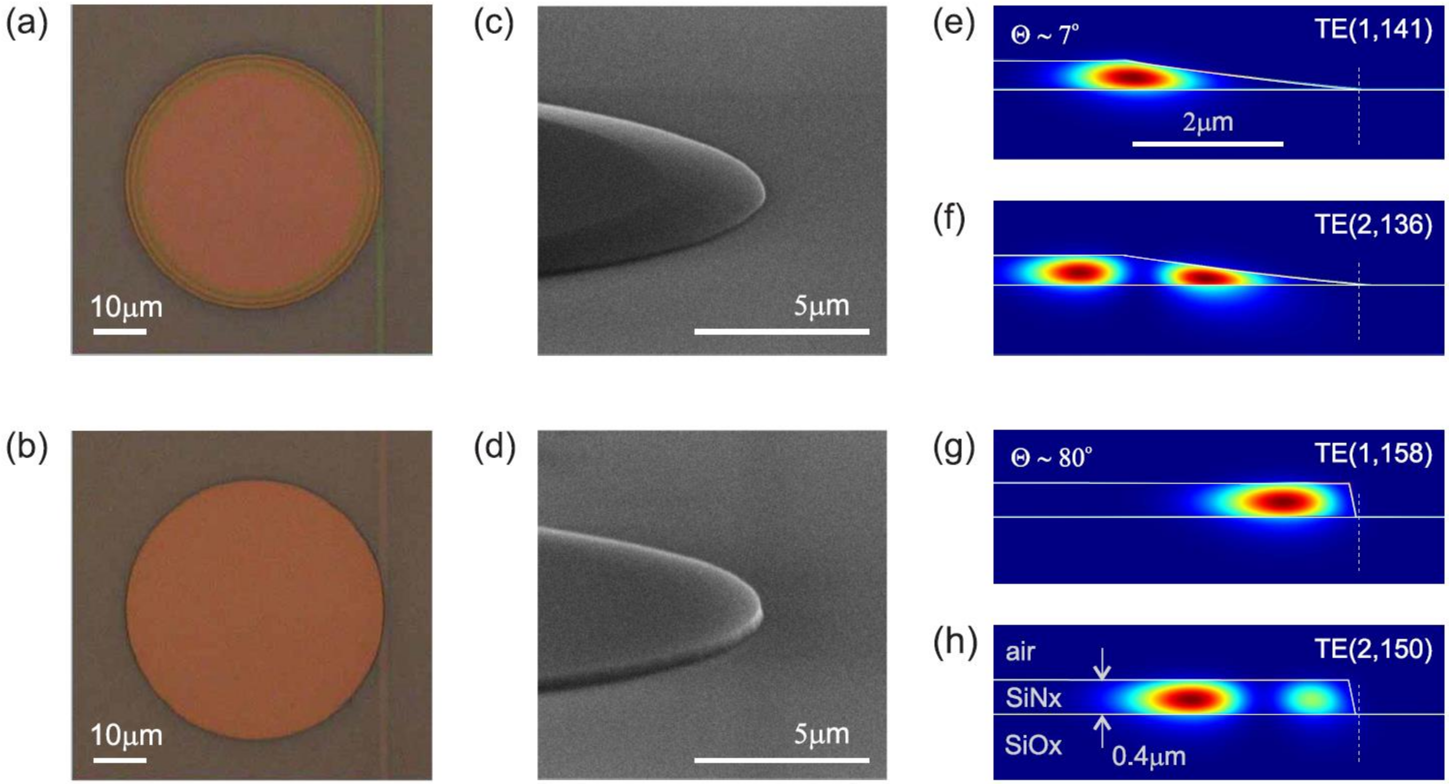


1990-2000

2000-2010

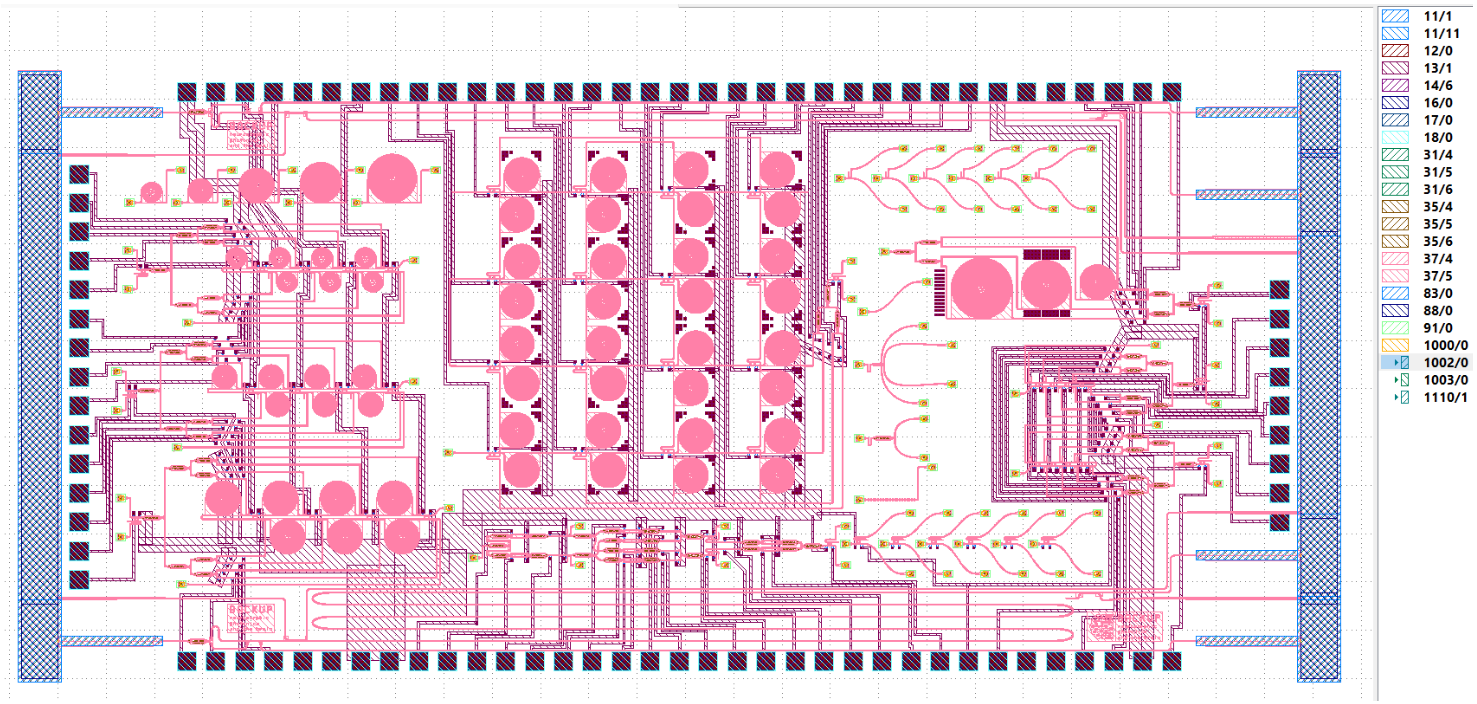
today

Integrated Silicon Photonics



1 DEVICE

Integrated Silicon Photonics

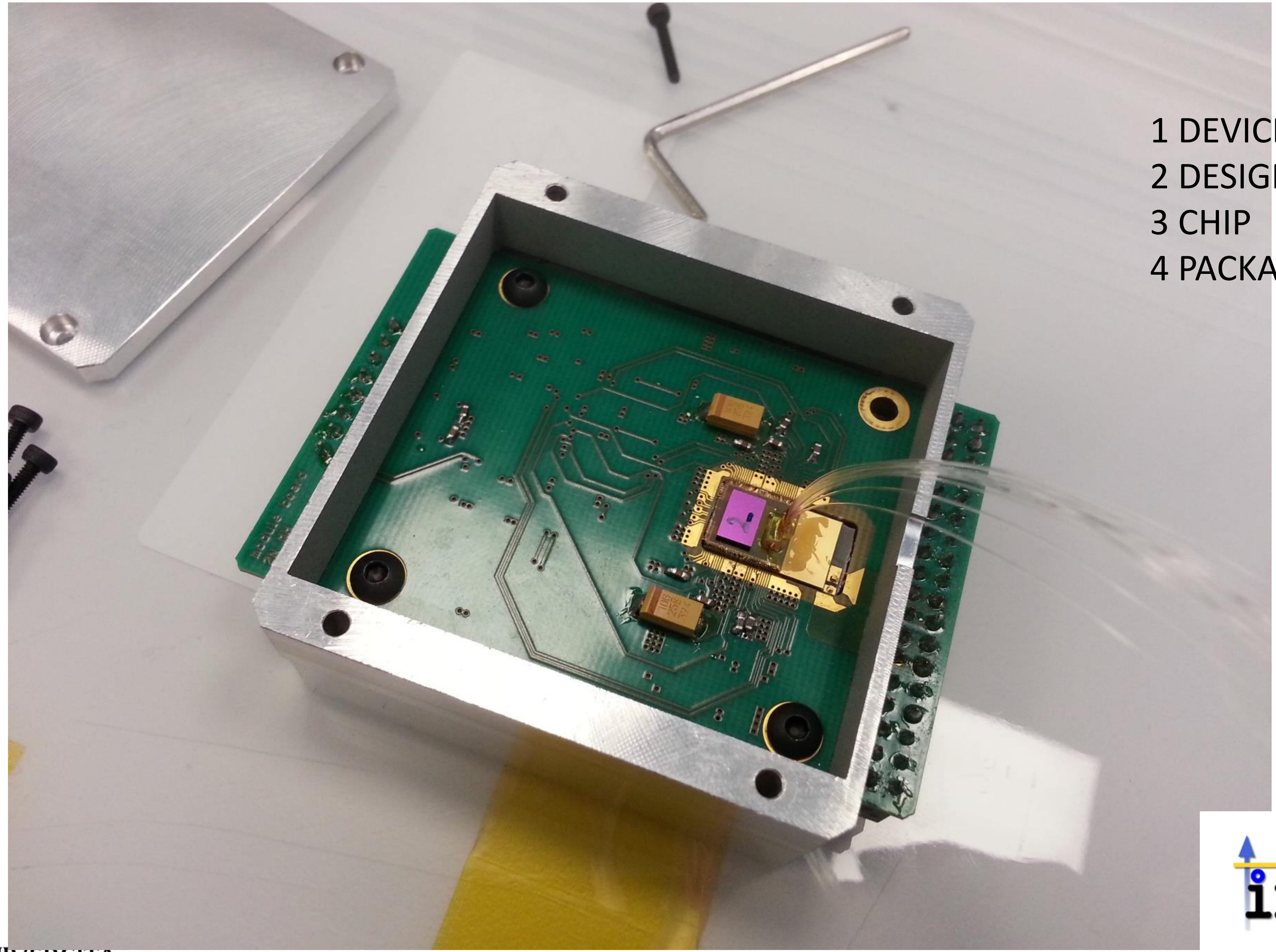


1 DEVICE
2 DESIGN

Integrated Silicon Photonics

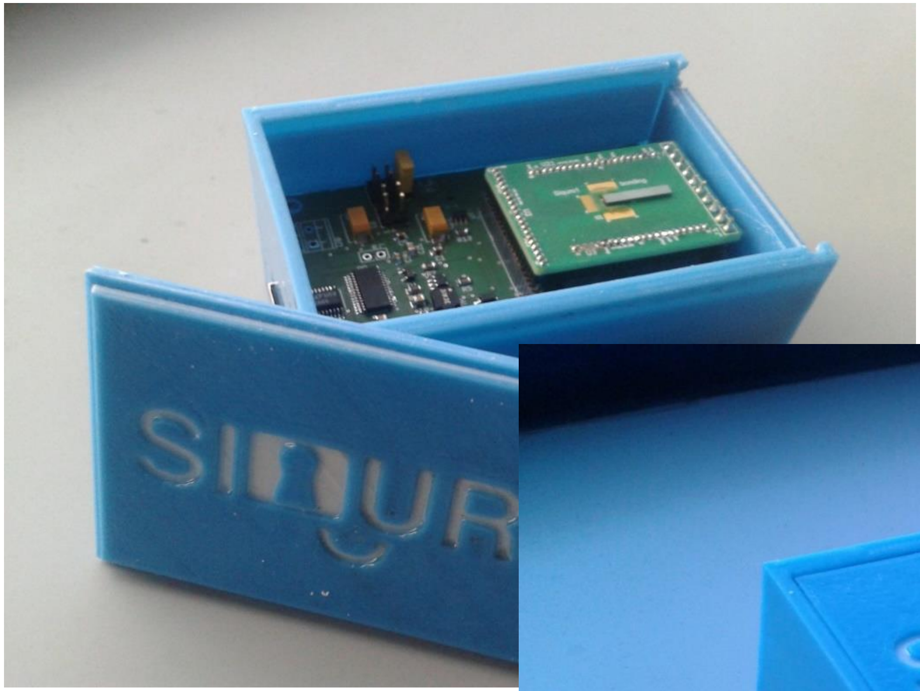
1 DEVICE
2 DESIGN
3 CHIP

Integrated Silicon Photonics



1 DEVICE
2 DESIGN
3 CHIP
4 PACKAGE

Integrated Silicon Photonics




1 DEVICE
2 DESIGN
3 CHIP
4 PACKAGE
5 SYSTEM

Integrated Silicon Photonics

1 DEVICE
2 DESIGN
3 CHIP
4 PACKAGE
5 SYSTEM

SYMPHONY

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PART 1 (classical=em theory)
Simple non-hermitian resonators

PART 2 (quantum=qm theory)
(Non local) photonic entanglement and its use in ghost spectroscopy

Simple non-hermitian resonators show extra sensitivities

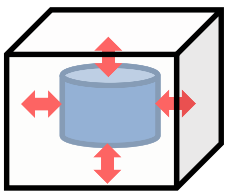
PART 1

The slides in this chapter are by Stefano Biasi and Riccardo Franchi

Hermitian and Non-Hermitian Hamiltonians

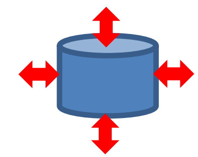
Hermitian

Commonly describing **non-dissipative physics** with **time-reversal** symmetry



Non-Hermitian

Commonly describing **dissipative physics** with **anti-unitary** symmetry



Hermitian matrices for a two level system

$$\boldsymbol{H} = \boldsymbol{H}^{\dagger}$$

$$\mathbf{C} = \begin{pmatrix} \omega & \beta \\ \beta & \omega \end{pmatrix} = \boldsymbol{C}^{\dagger}$$

One-parameter

Non-Hermitian matrices

$$\boldsymbol{H} \neq \boldsymbol{H}^{\dagger}$$

$$\mathbf{D} = \begin{pmatrix} \omega & \beta_{12} \\ \beta_{21} & \omega \end{pmatrix} \neq \boldsymbol{D}^{\dagger}$$

Photonics is affected by losses, therefore its physics is non-hermitian

Hermitian and Non-Hermitian Hamiltonians

Hermitian

Commonly describing **non-dissipative physics** with **time-reversal** symmetry

$$\mathbf{C} = \begin{pmatrix} \boldsymbol{\omega} & \boldsymbol{\beta} \\ \boldsymbol{\beta} & \boldsymbol{\omega} \end{pmatrix} = \boldsymbol{C}^{\dagger}$$

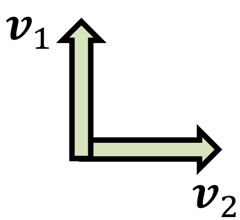
Real eigenvalues

$$\mathbf{C}\, \boldsymbol{v}_{1,2} = \lambda_{1,2}\, \boldsymbol{v}_{1,2}$$

Linear

$$\lambda_{1,2} = \boldsymbol{\omega} \pm \boldsymbol{\beta}$$

$$<\ \boldsymbol{v}_1 \mid \boldsymbol{v}_2 > = \mathbf{0}$$



Non-Hermitian

Commonly describing **dissipative physics** with **anti-unitary** symmetry

$$\mathbf{D} = \begin{pmatrix} \boldsymbol{\omega} & \boldsymbol{\beta}_{12} \\ \boldsymbol{\beta}_{21} & \boldsymbol{\omega} \end{pmatrix} \neq \boldsymbol{D}^{\dagger}$$

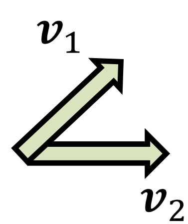
Can be Complex

$$\boldsymbol{D}\, \boldsymbol{v}_{1,2} = \lambda_{1,2}\, \boldsymbol{v}_{1,2}$$

Square root

$$\lambda_{1,2} = \boldsymbol{\omega} \pm \sqrt{\boldsymbol{\beta}_{12}\boldsymbol{\beta}_{21}}$$

$$<\ \boldsymbol{v}_1 \mid \boldsymbol{v}_2 > \neq \mathbf{0}$$



Main difference approaching the **degeneracies**: $\lambda_1 = \lambda_2$

$$\boldsymbol{\beta} \rightarrow \mathbf{0} \Rightarrow \lambda_1 = \lambda_2$$

and

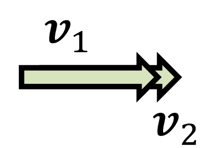
$$<\ \boldsymbol{v}_1 \mid \boldsymbol{v}_2 > = \mathbf{0}$$

Diabolic Point

$$\boldsymbol{\beta}_{12} \rightarrow \mathbf{0} \Rightarrow \lambda_1 = \lambda_2$$

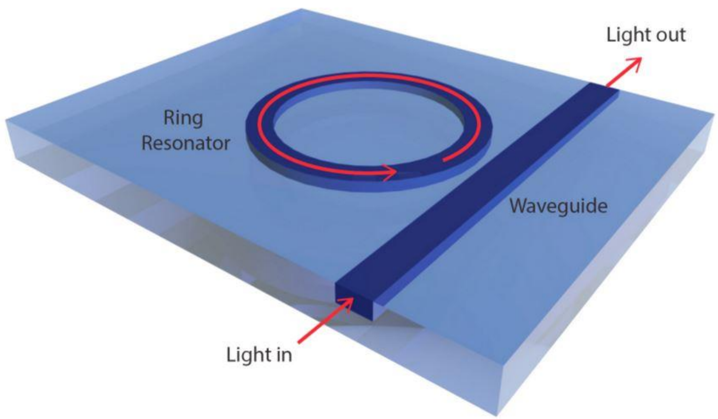
and

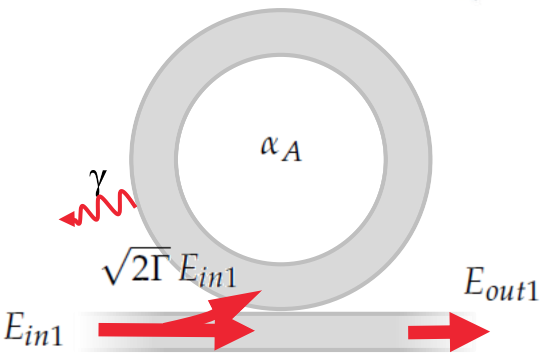
$$<\ \boldsymbol{v}_1 \mid \boldsymbol{v}_2 > = \mathbf{1}$$



Exceptional Point

A microring resonator: stationary response





The light coming from the input port **couples into the** resonator with the resonance mode α_A

The dynamic of the system can be described thanks to the **temporal mode theory** (TMT):

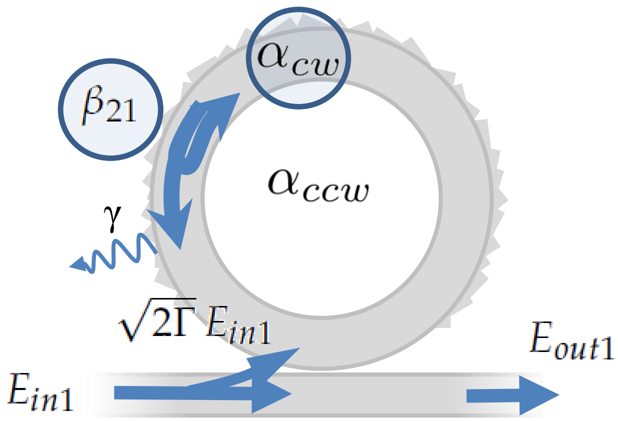
$$\frac{d\alpha_A}{dt} = (i\omega - \gamma - \Gamma)\,\alpha_A + i\sqrt{2\Gamma}\,E_{in1}$$

$$\frac{E_{out1}}{E_{in1}} = t = 1 + i\sqrt{2\Gamma}\,\alpha_A$$

The **Outgoing field** assumes the typical **Lorentzian shape:**

$$t = 1 - \frac{2\Gamma}{[i\Delta\omega + \gamma + \Gamma]}$$

A microring resonator: surface-wall roughness



Considering the **backscattering:**

- **Forward** propagation
- **Backward** propagation

Temporal **coupled mode** equations

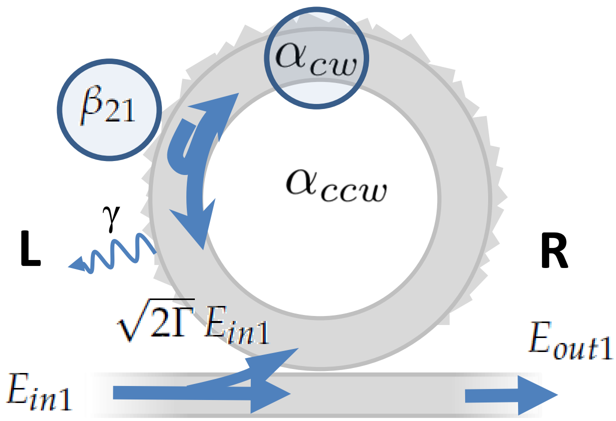
$$\begin{cases} \dfrac{d\alpha_{ccw}}{dt} = (i\omega - \gamma - \Gamma)\alpha_{ccw} - \beta_{12}\alpha_{cw} + i\sqrt{2\Gamma}E_{in1} \\ \dfrac{d\alpha_{cw}}{dt} = (i\omega - \gamma - \Gamma)\alpha_{cw} - \beta_{21}\alpha_{ccw} \end{cases}$$

$$\frac{E_{out1}}{E_{in1}} = t = 1 + i\,\sqrt{2\Gamma}\,\alpha_{ccw}$$

$\beta_{12/21}$

Are the **complex** coupling coefficients

A microring resonator: surface-wall roughness



Writing in the equations in a matrix form **(two-level system):**

$$i\,\frac{d}{dt}\begin{pmatrix}\alpha_{\rm ccw}\\ \alpha_{\rm cw}\end{pmatrix} = \boldsymbol{H}_0\begin{pmatrix}\alpha_{\rm ccw}\\ \alpha_{\rm cw}\end{pmatrix} + \boldsymbol{H}_c\begin{pmatrix}\alpha_{\rm ccw}\\ \alpha_{\rm cw}\end{pmatrix} - \sqrt{2\Gamma}\begin{pmatrix}E_{\rm in,L}\\ E_{\rm in,R}\end{pmatrix} \quad \text{where} \quad \boldsymbol{H}_0 = \begin{pmatrix}\omega_0 - i(\gamma+\Gamma) & 0\\ 0 & \omega_0 - i(\gamma+\Gamma)\end{pmatrix}$$

$$\boldsymbol{H}_c = \begin{pmatrix}0 & -i\,\beta_{12}\\ -i\,\beta_{21} & 0\end{pmatrix}$$

A microring resonator: surface-wall roughness

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$$\boldsymbol{H}_c = \begin{pmatrix}0 & -i\,\beta_{12}\\ -i\,\beta_{21} & 0\end{pmatrix}$$ if $\beta_{12} = -\beta_{21}^* = \beta$ ⇒ **Hermitian** $\boldsymbol{H}_c = \boldsymbol{H}_c^\dagger$ ⇒ $\lambda_{1,2} = \omega_0 \pm |\beta| - i(\gamma+\Gamma)$, $<\boldsymbol{v}_1|\boldsymbol{v}_2> = 0$

A microring resonator: surface-wall roughness

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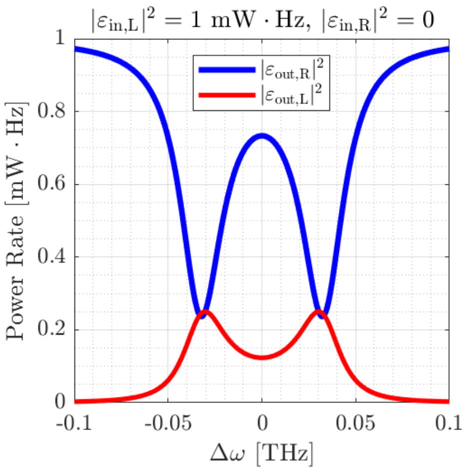
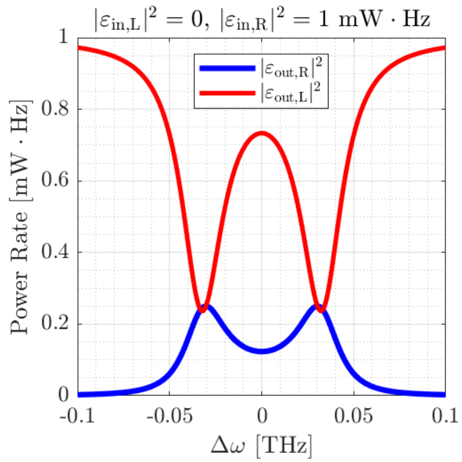
if $\beta_{12} = -\beta_{21}^{*} = \beta$ ⇒ **Hermitian** $\boldsymbol{H}_c = \boldsymbol{H}_c^{\dagger}$ ⇒ $\boldsymbol{t}_{\boldsymbol{l-r}} = \boldsymbol{t}_{\boldsymbol{r-l}}$, $|\boldsymbol{r}_{\boldsymbol{l-r}}|^2 = |\boldsymbol{r}_{\boldsymbol{r-l}}|^2$

Hermitian and non-Hermitian Physics - integrated microresonators





Continuous exchange of the **same energy** between the **forward** and **backward** mode: the doublet is **balanced.**

A microring resonator: surface-wall roughness

Writing in the equations in a matrix form **(two-level system):**

$$i\,\frac{d}{dt}\begin{pmatrix}\alpha_{\mathrm{ccw}}\\ \alpha_{\mathrm{cw}}\end{pmatrix} = \boldsymbol{H}_0\begin{pmatrix}\alpha_{\mathrm{ccw}}\\ \alpha_{\mathrm{cw}}\end{pmatrix} + \boldsymbol{H}_c\begin{pmatrix}\alpha_{\mathrm{ccw}}\\ \alpha_{\mathrm{cw}}\end{pmatrix} - \sqrt{2\Gamma}\begin{pmatrix}E_{\mathrm{in,L}}\\ E_{\mathrm{in,R}}\end{pmatrix}$$

where

$$\boldsymbol{H}_0 = \begin{pmatrix}\omega_0 - i(\gamma+\Gamma) & 0\\ 0 & \omega_0 - i(\gamma+\Gamma)\end{pmatrix}$$

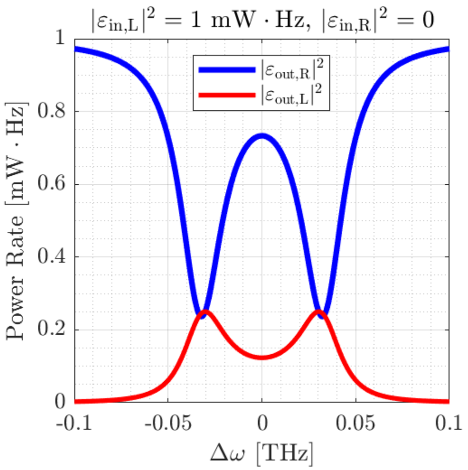
$$\boldsymbol{H}_c = \begin{pmatrix}0 & -i\,\beta_{12}\\ -i\,\beta_{21} & 0\end{pmatrix}$$

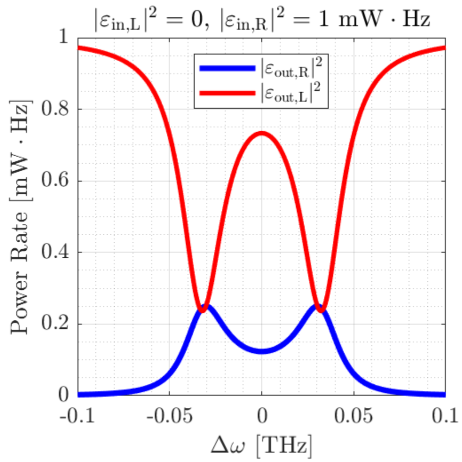
if $\beta_{12} \neq -\beta_{21}^*$ ⇒ **Non-Hermitian** $\boldsymbol{H}_c \neq \boldsymbol{H}_c^\dagger$ ⇒

$$\lambda_{1,2} = \omega_0 \pm \sqrt{-\beta_{12}\beta_{21}} - i(\gamma+\Gamma)$$

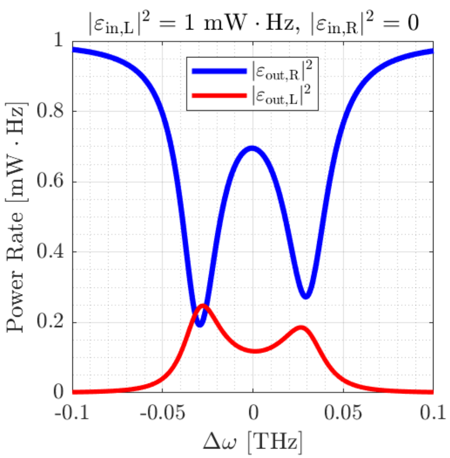
$$< \boldsymbol{v}_1|\boldsymbol{v}_2 > \neq 0$$

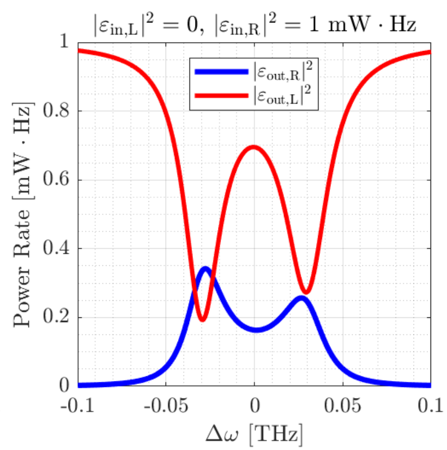
Hermitian and non-Hermitian Physics - integrated microresonators





Continuous exchange of the **same energy** between the **forward** and **backward** mode: the doublet is **balanced.**

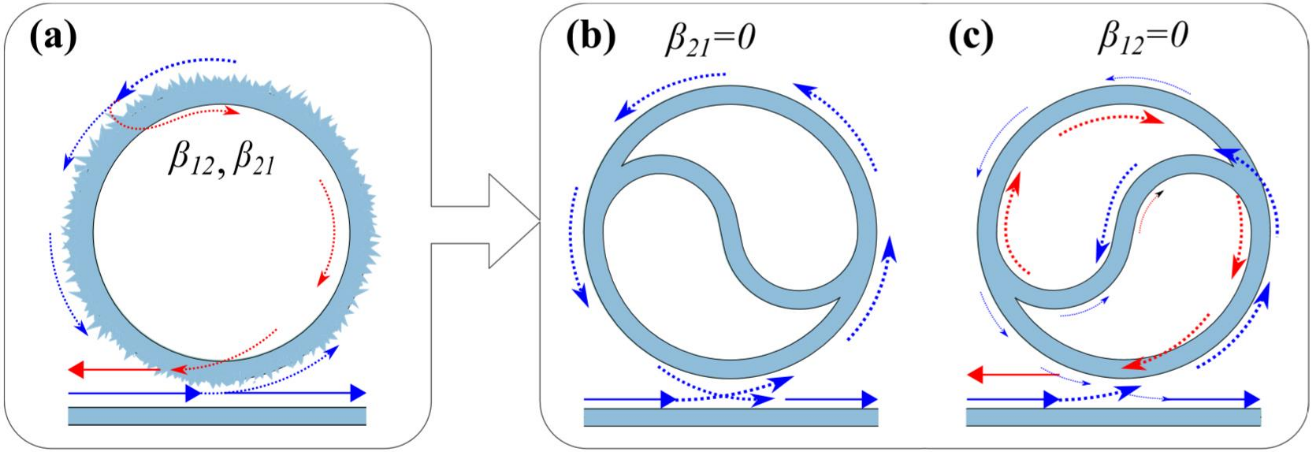




A microring resonator: surface-wall roughness

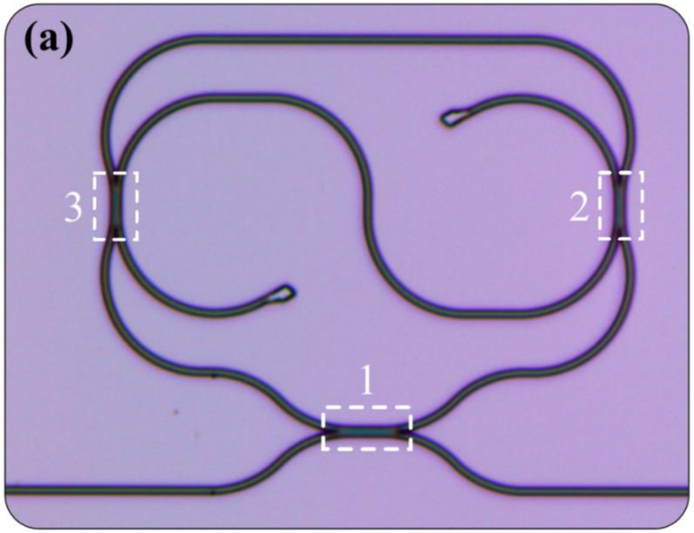
In the case of the **Backscattering** the **off-diagonal β coefficients are stochastic!**

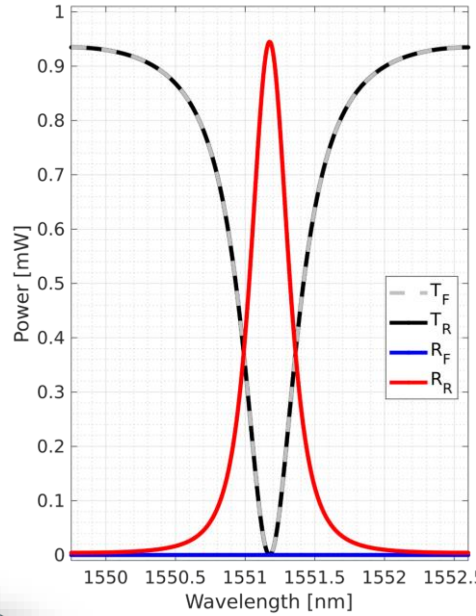
We need to introduce a **non-reciprocal loss** inside the cavity:



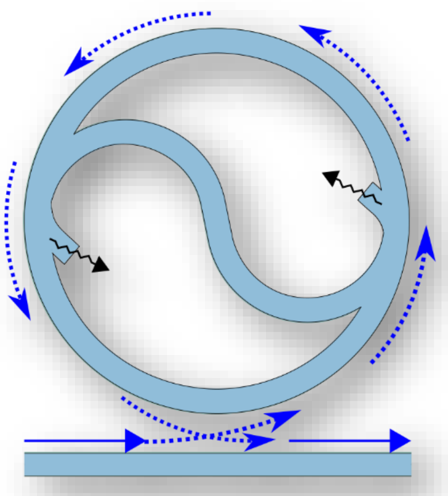
S-shaped additional crossover waveguide element that **selectively couples** counter-propagating modes in a **propagation-direction-dependent way**

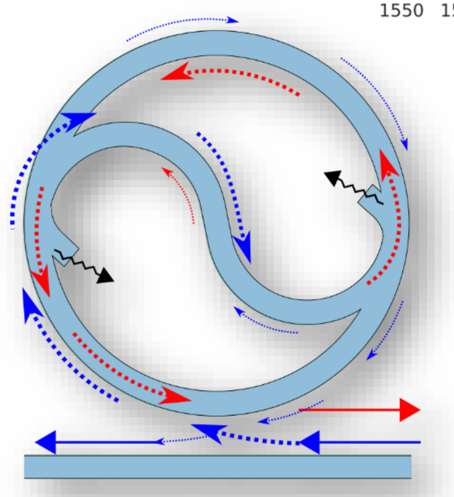
A Taiji microresonator





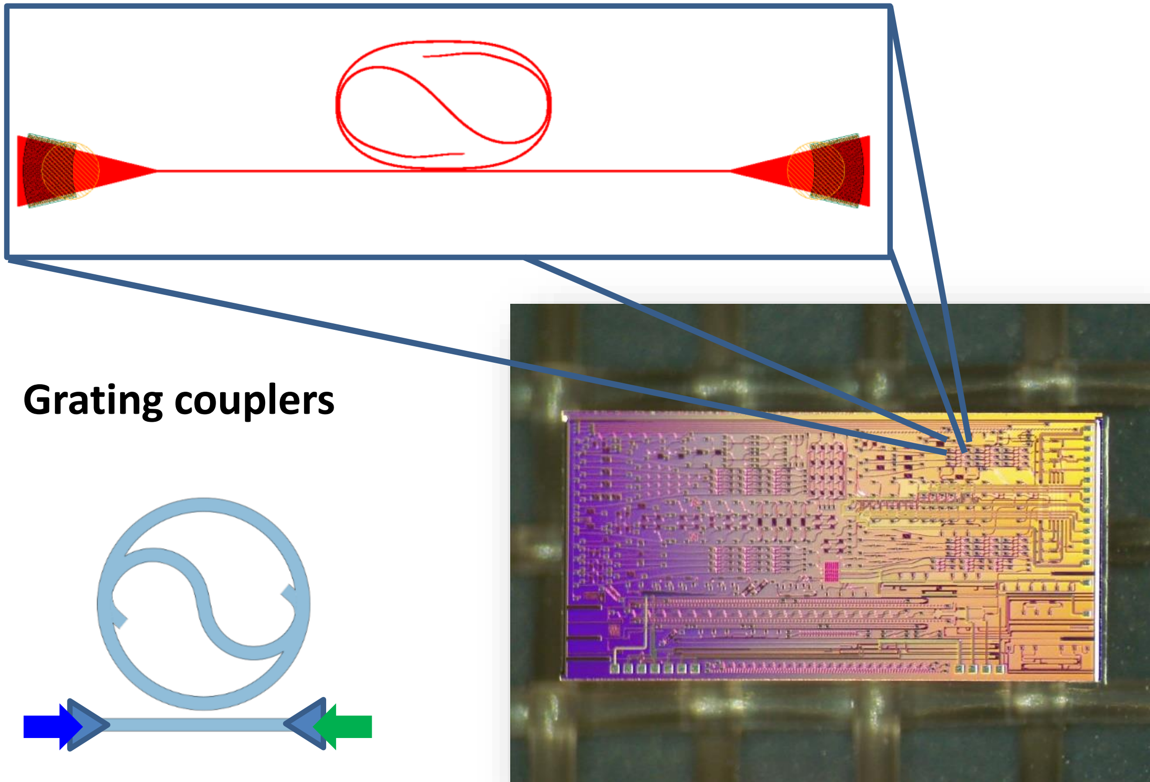
Taiji



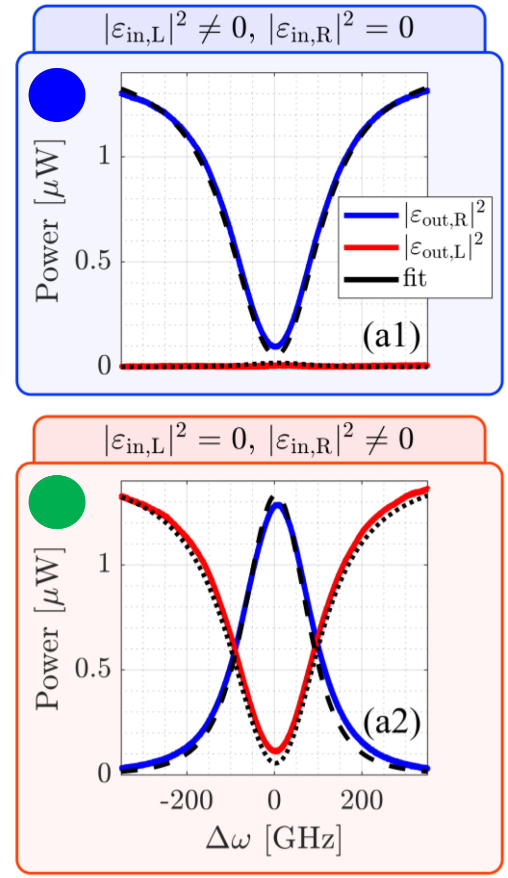


- **Forward** and **Reverse** have **different reflections**
- **The Lorentz reciprocity theorem ensures the same transmissions**
- **Work in an Exceptional Point**

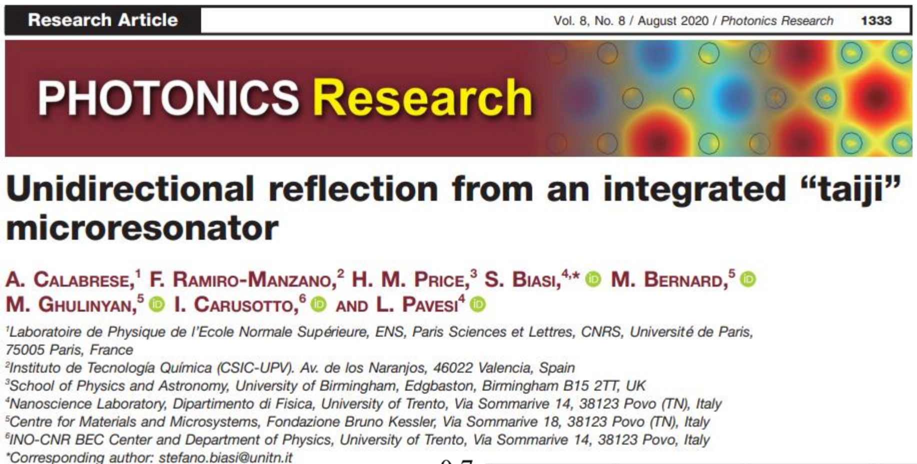
Taiji: unidirectional reflection



Grating couplers



Taiji: unidirectional reflection


Research Article
Vol. 8, No. 8 / August 2020 / Photonics Research 1333
PHOTONICS Research

Unidirectional reflection from an integrated "taiji" microresonator

A. Calabrese,[1] F. Ramiro-Manzano,[2] H. M. Price,[3] S. Biasi,[4,*] M. Bernard,[5] M. Ghulinyan,[5] I. Carusotto,[6] and L. Pavesi[4]

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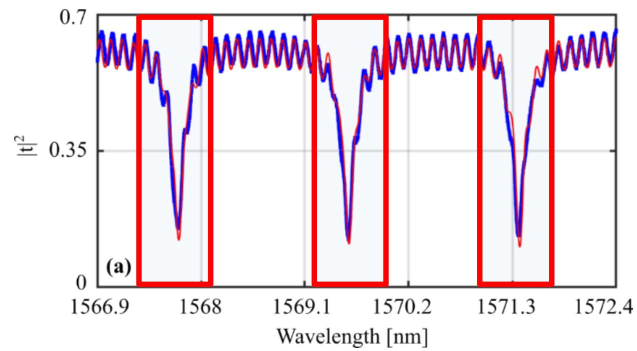
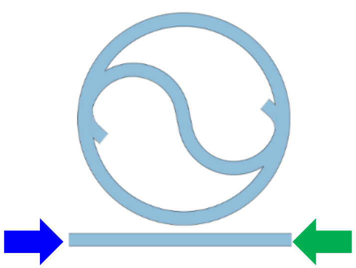
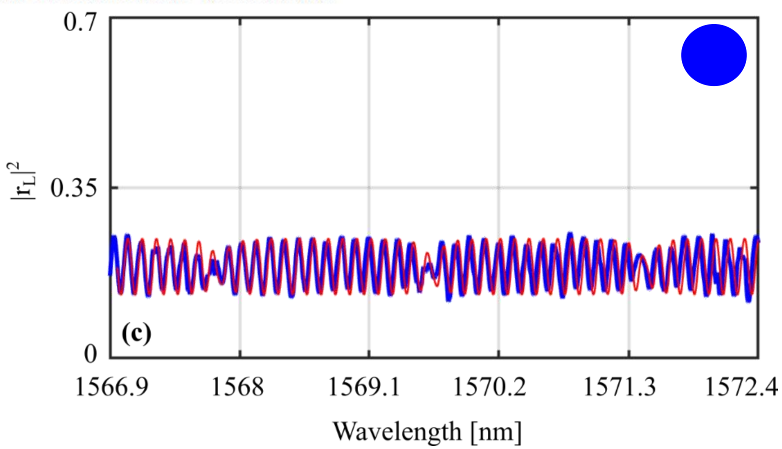
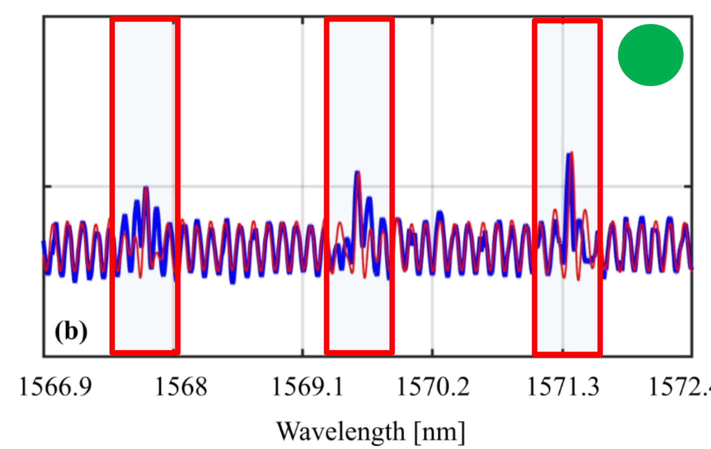
[2]Instituto de Tecnología Química (CSIC-UPV). Av. de los Naranjos, 46022 Valencia, Spain
[3]School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[4]Nanoscience Laboratory, Dipartimento di Fisica, University of Trento, Via Sommarive 14, 38123 Povo (TN), Italy
[5]Centre for Materials and Microsystems, Fondazione Bruno Kessler, Via Sommarive 18, 38123 Povo (TN), Italy
[6]INO-CNR BEC Center and Department of Physics, University of Trento, Via Sommarive 14, 38123 Povo, Italy
*Corresponding author: stefano.biasi@unitn.it

Taiji microresonator experimental results:









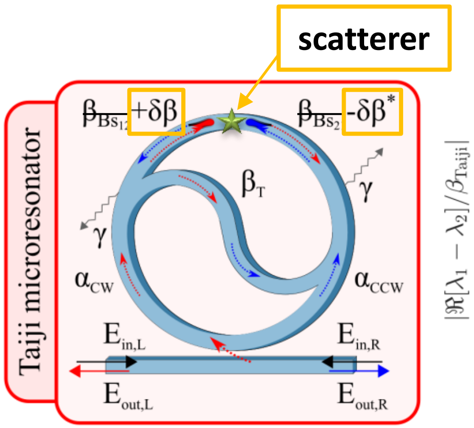
Taiji as a sensor on Exceptional point

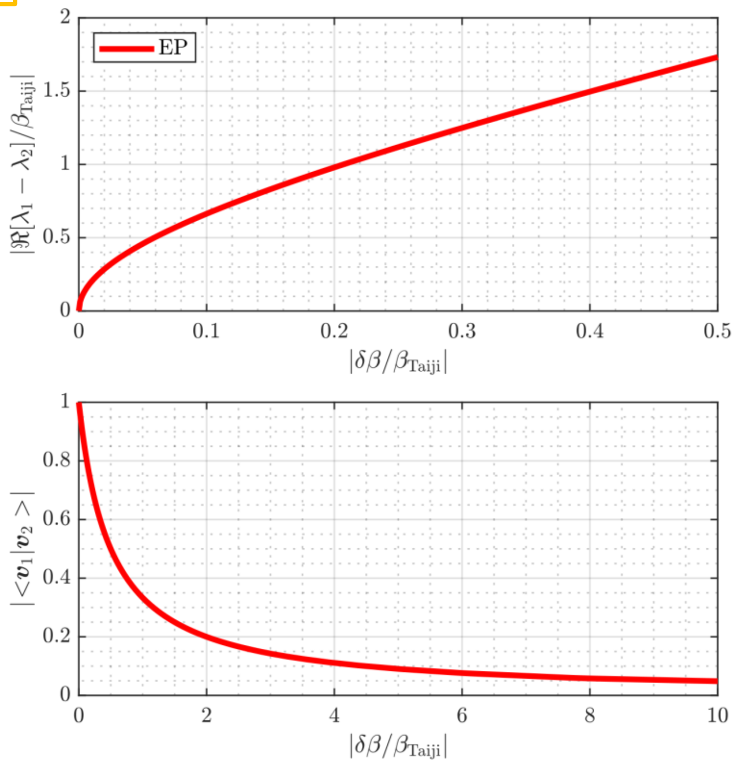
$$\beta_{12} = \beta_T + \cancel{\beta_{BS_{12}}} + \delta\beta$$

$$\beta_{21} = 0 + \cancel{\beta_{BS_{21}}} - \delta\beta^*$$

$$\beta_T = \beta_{Taiji} \gg \delta\beta \geq 0$$

$$\Re[\lambda_{1,2}] = \omega_0 \pm \sqrt{\beta_T \delta\beta^* + |\delta\beta|^2}$$





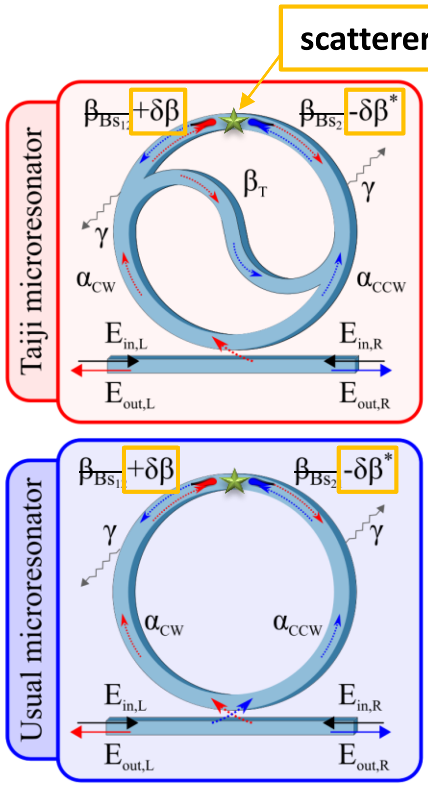
Taiji as a sensor on Exceptional point

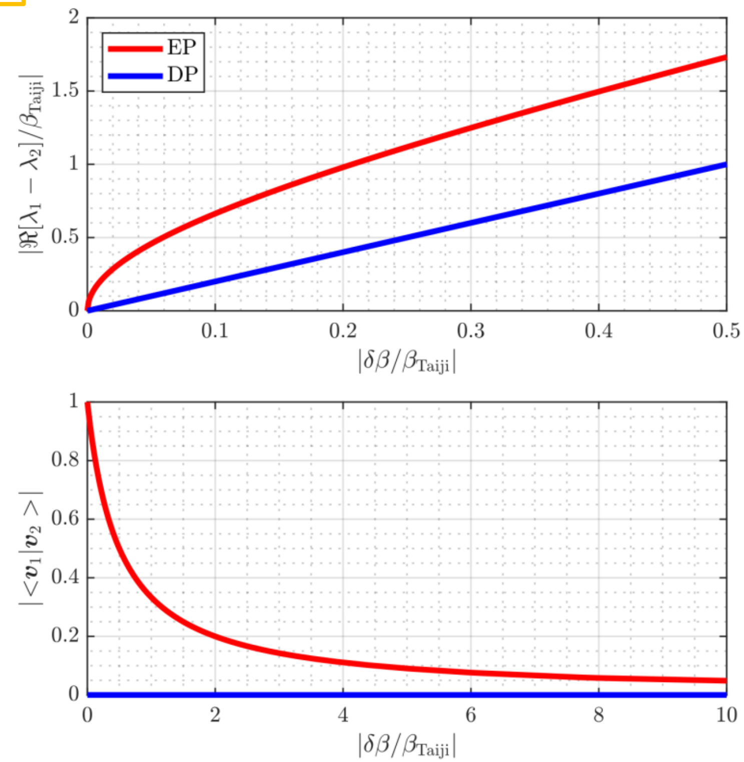
$$\beta_{12} = \beta_T + \cancel{\beta_{BS_{12}}} + \delta\beta$$

$$\beta_{21} = 0 + \cancel{\beta_{BS_{21}}} - \delta\beta^*$$

$$\beta_T = \beta_{Taiji} \gg \delta\beta \geq 0$$

$$\Re[\lambda_{1,2}] = \omega_0 \pm \sqrt{\beta_T \delta\beta^* + |\delta\beta|^2}$$





$$\beta_{12} = 0 + \cancel{\beta_{BS_{12}}} + \delta\beta$$

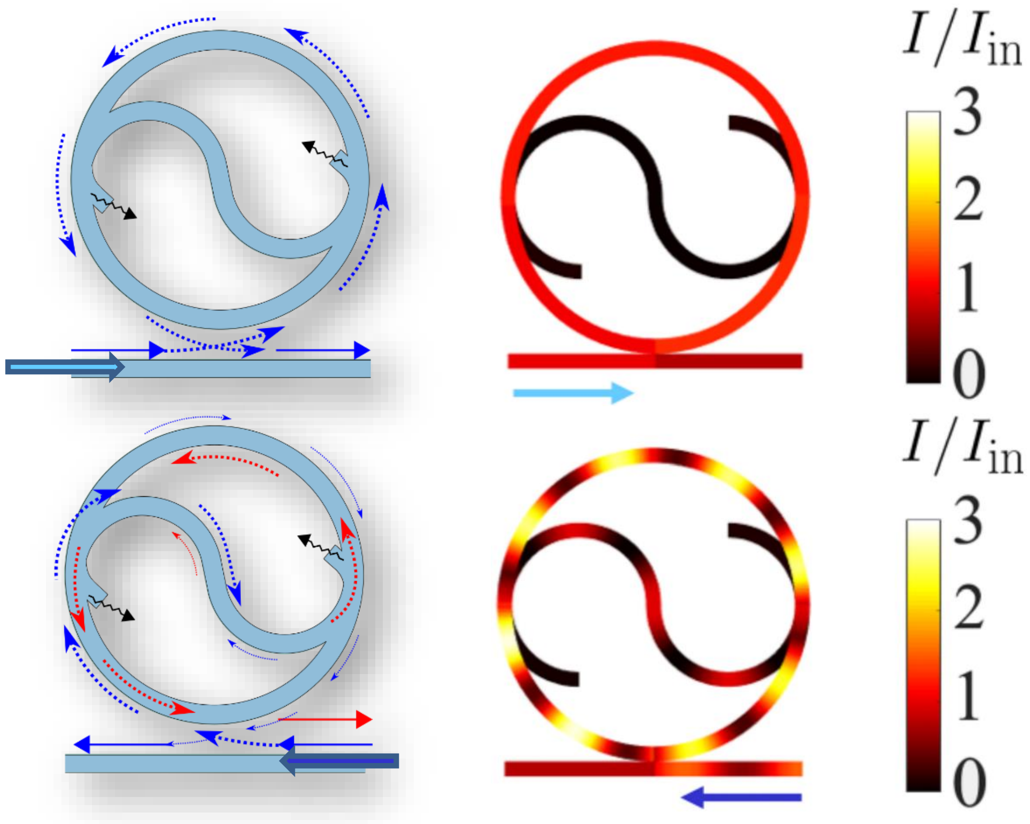
$$\beta_{21} = 0 + \cancel{\beta_{BS_{21}}} - \delta\beta^*$$

$$\delta\beta \geq 0$$

$$\Re[\lambda_{1,2}] = \omega_0 \pm |\delta\beta|$$

Taiji: breaking the Lorentz Reciprocity Theorem

energy inside the microresonator



A. Munoz de las Heras et al,Physical Review Applied **15**, 054044 (2021).

Riccardo Franchi et al, Optics Express 29, 29615-29630 (2021)

Taiji: breaking the Lorentz Reciprocity Theorem

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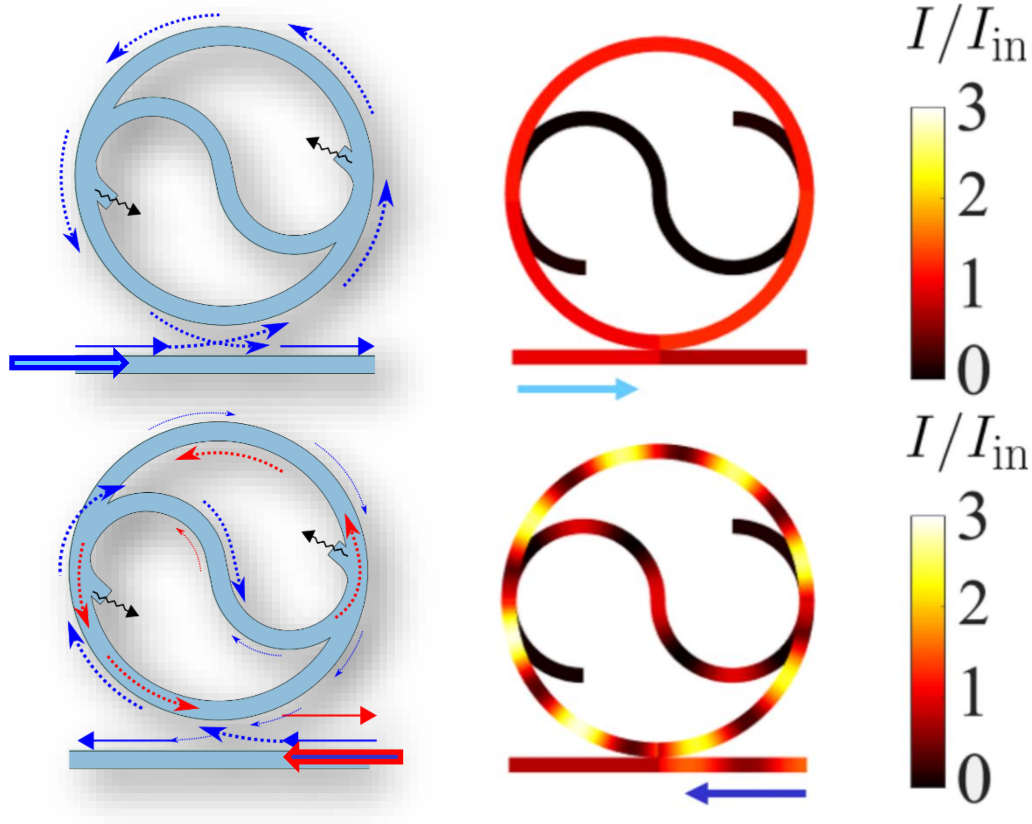

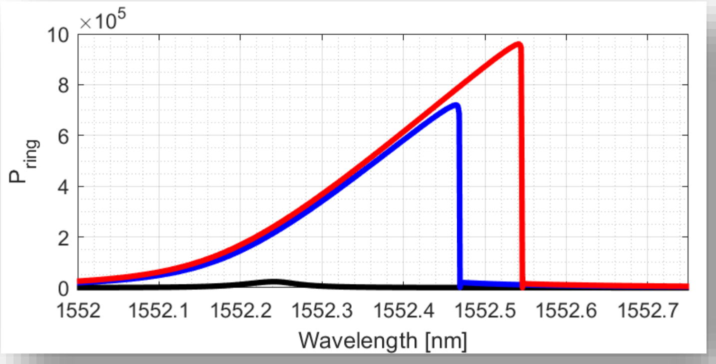

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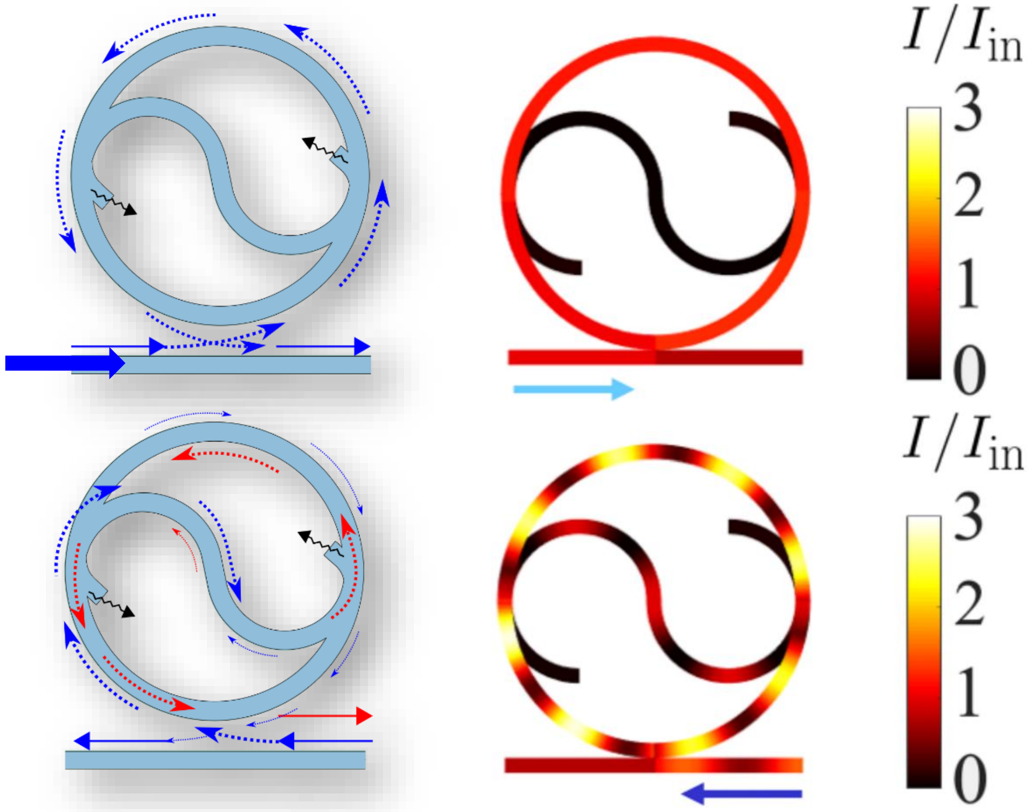
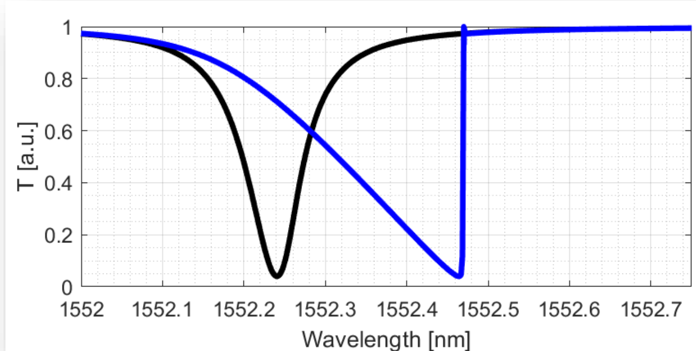
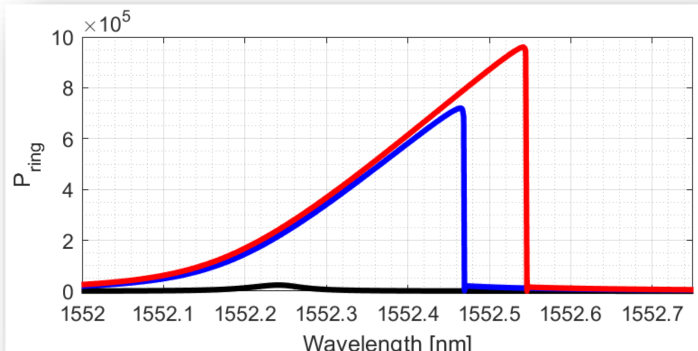


Transmission





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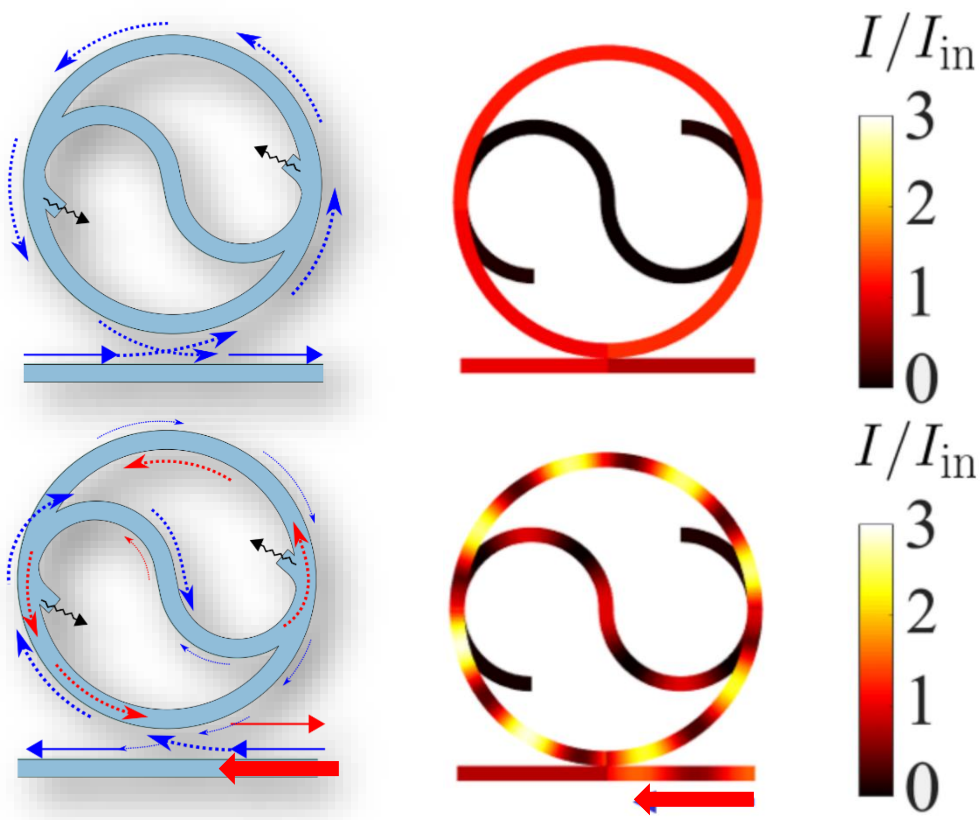
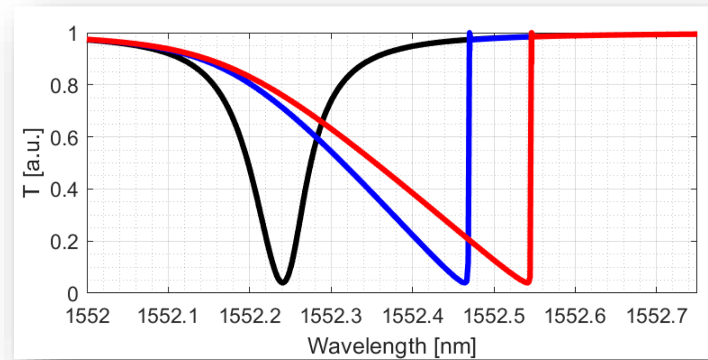
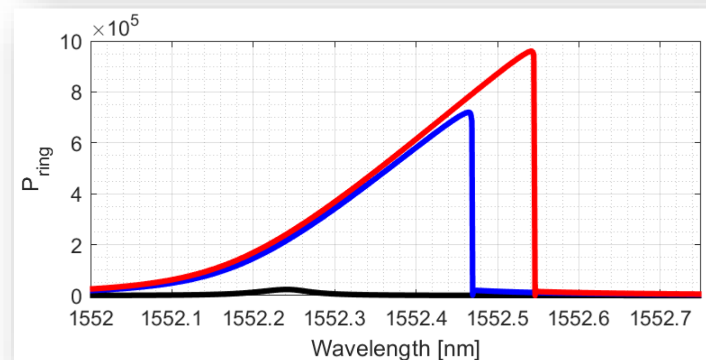
energy inside the microresonator



Transmission





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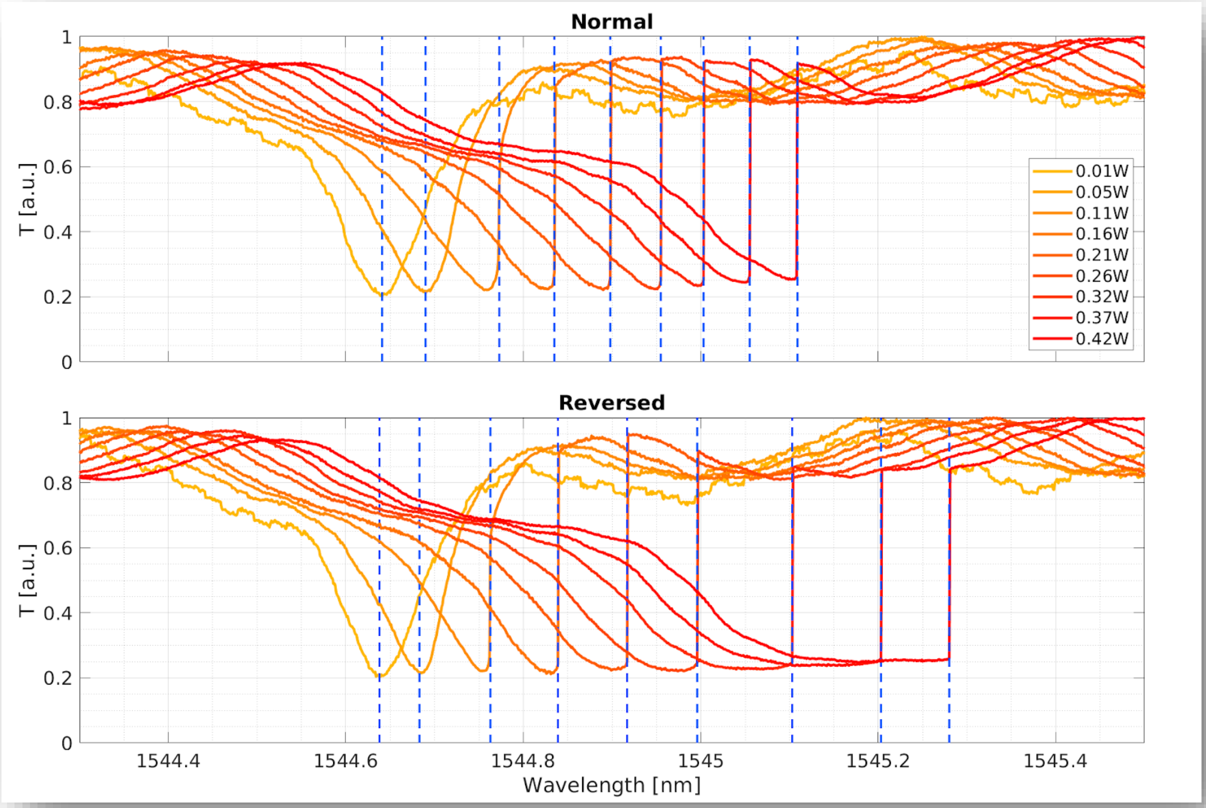
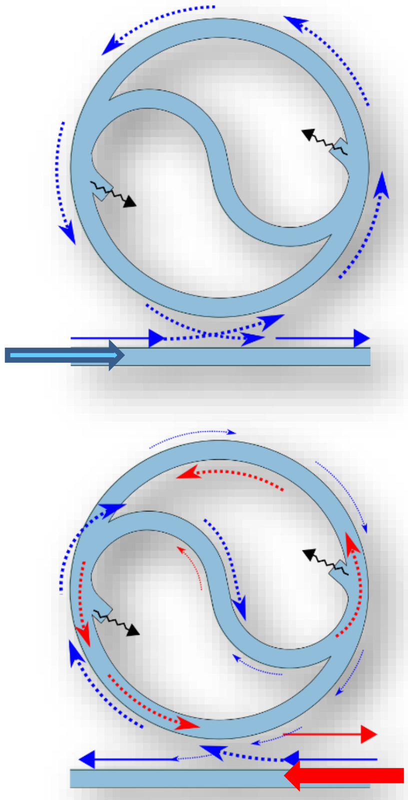
Taiji: breaking the Lorentz Reciprocity Theorem





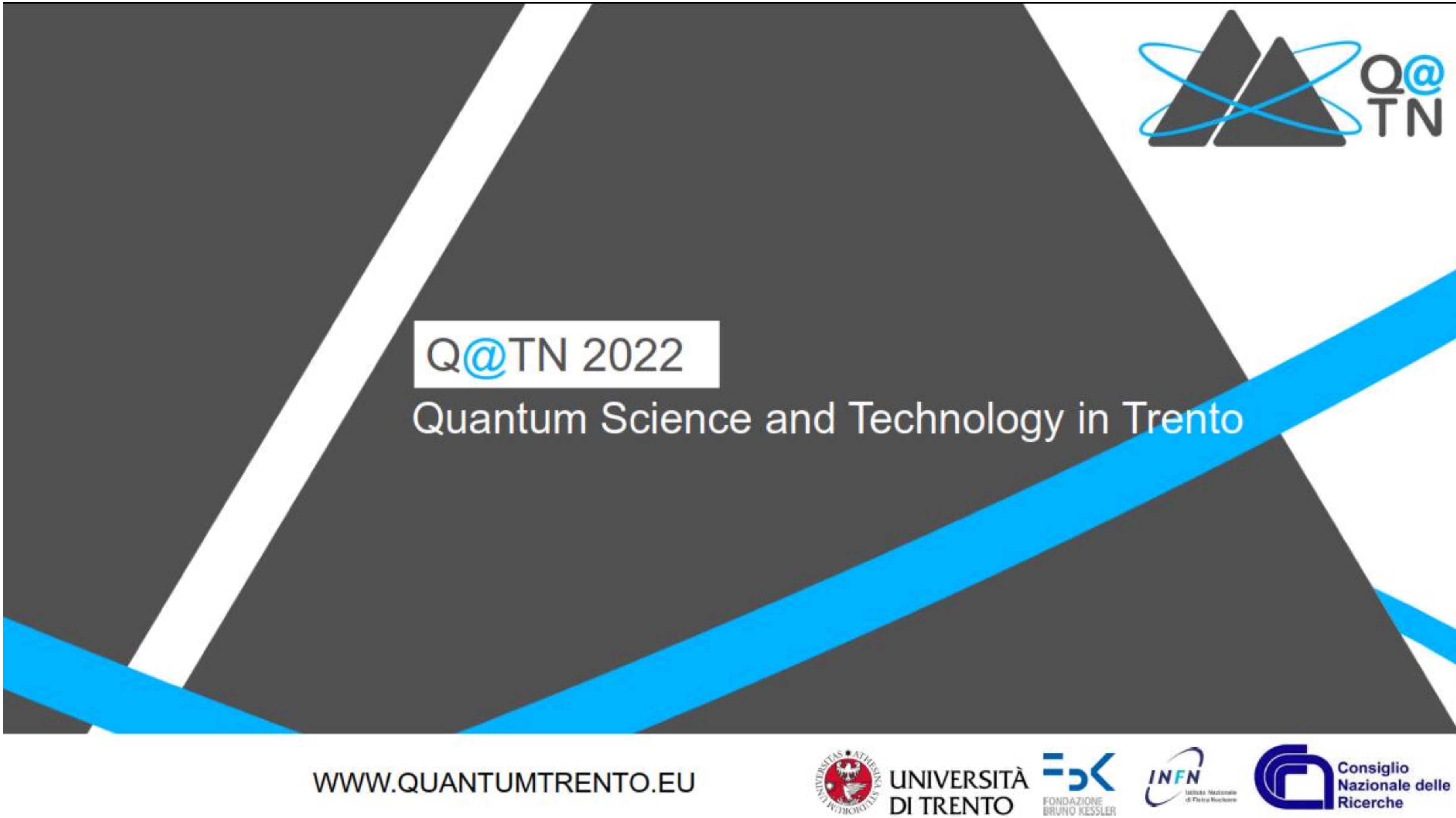
A. Munoz de las Heras et al,Physical Review Applied **15**, 054044 (2021).

Riccardo Franchi et al, Optics Express 29, 29615-29630 (2021)

(Non local) photonic entanglement and its use in ghost spectroscopy

PART 2

Quantum at Trento

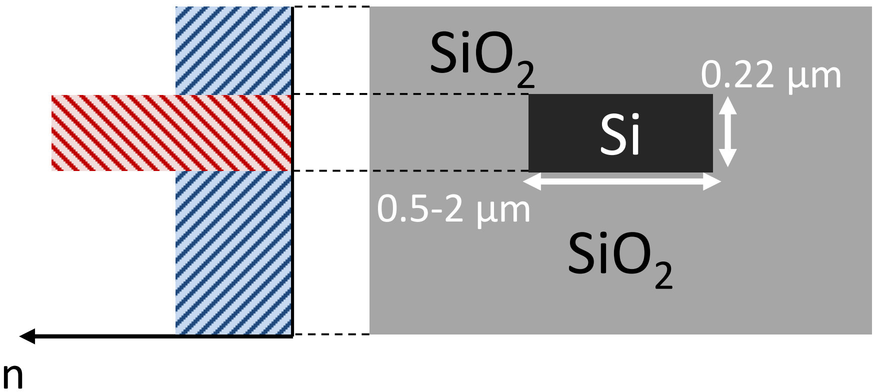


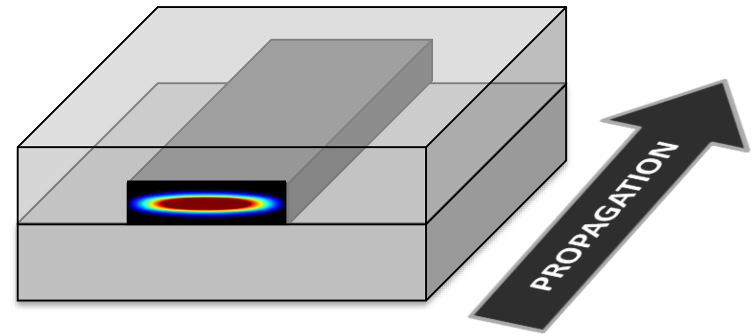
Part 2

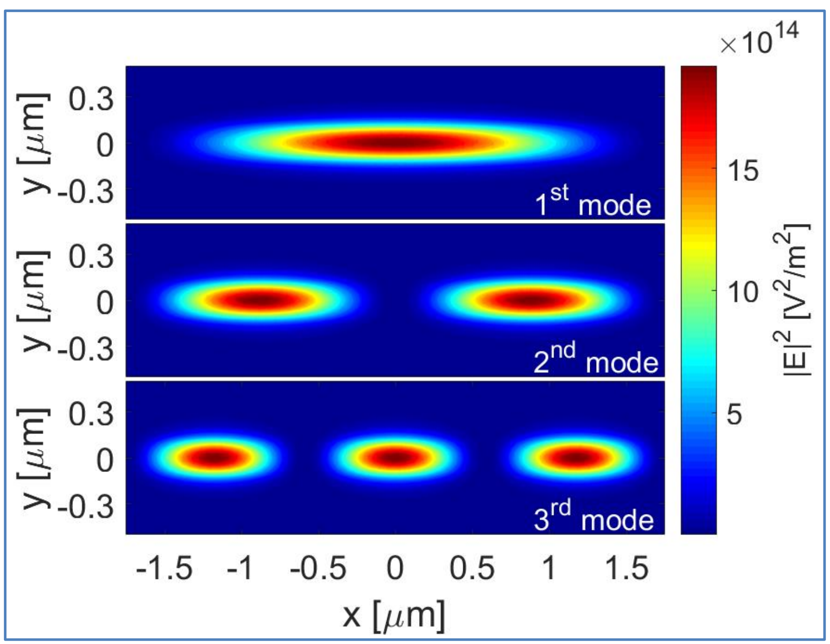
- The basic building blocks
- Intermodal FWM
- Ultra pure heralded single photon source
- Ghost spectroscopy in the MIR

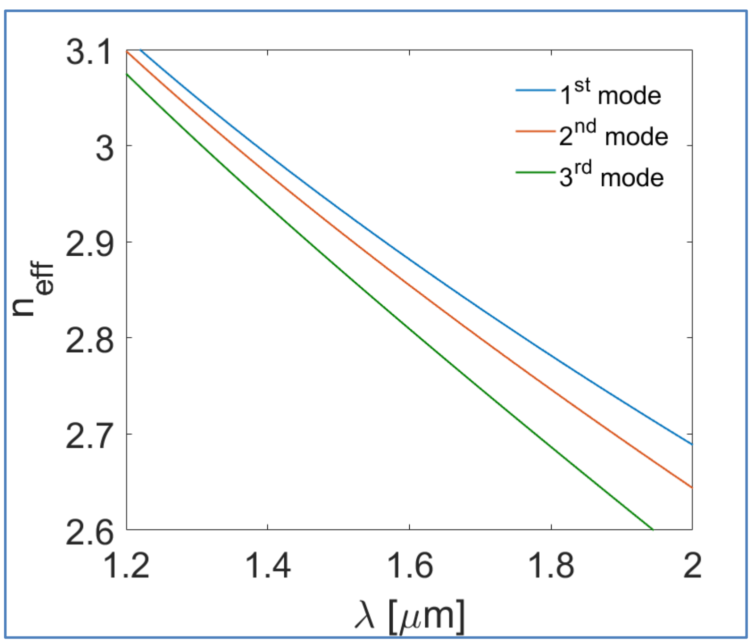
The basic building blocks

WAVEGUIDES









The basic building blocks

NONLINEAR OPTICS

Polarization

$$\boldsymbol{P} = \varepsilon_0 (\chi^{(1)} \boldsymbol{E}_\mathrm{i} + \chi^{(2)} \boldsymbol{E}_\mathrm{i} \boldsymbol{E}_\mathrm{j} + \chi^{(3)} \boldsymbol{E}_\mathrm{i} \boldsymbol{E}_\mathrm{j} \boldsymbol{E}_\mathrm{l})$$

$\chi^{(2)}$

- No-Centrosymmetry

Unless one breaks the centrosymmetry!

$\chi^{(3)}$

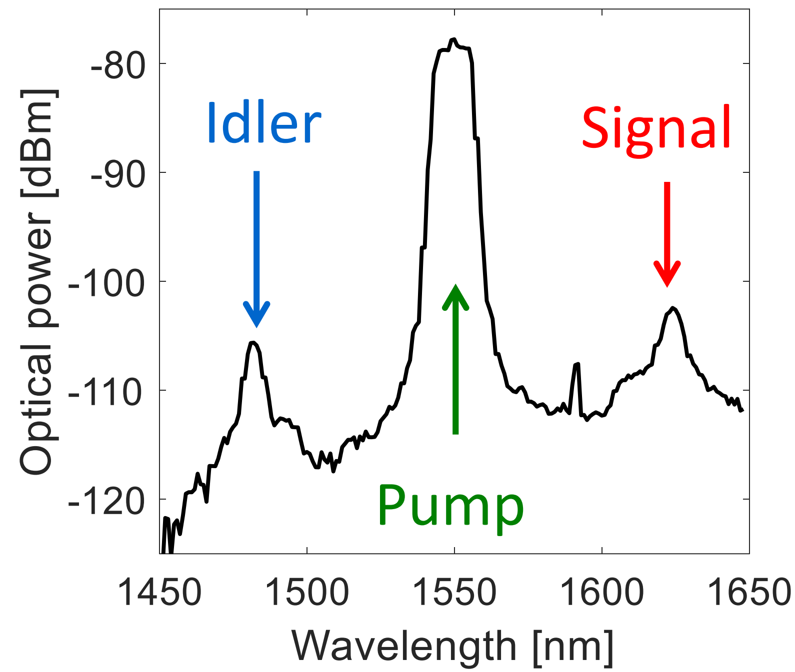
- Centrosymmetry

Silicon crystal

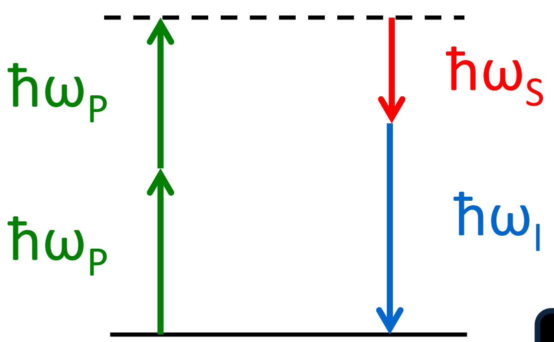
Part 2

- The basic building blocks
- Intermodal FWM
- Ultra pure heralded single photon source
- Ghost spectroscopy in the MIR

Spontaneous Four Wave Mixing (FWM)



ENERGY DIAGRAM



Max efficiency	Phase mismatch	Wave vector
$\Delta k = 0$	$\Delta k = k_P + k_P - k_S - k_I$	$k = \frac{\omega}{c} n_{eff}(\omega)$

Intermodal phase matching

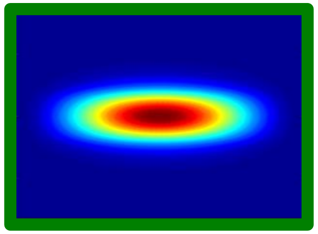
Max efficiency	Phase mismatch	Wave vector
$\Delta k = 0$	$\Delta k = k_P + k_P - k_S - k_I$	$k = \frac{\omega}{c} n_{eff}(\omega)$

j, q, l, m are the mode orders

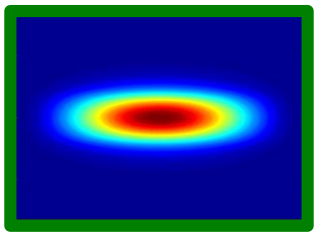
$$\Delta k = \frac{1}{c}\left(\omega_P\, n_{eff}^{j}(\omega_P) + \omega_P\, n_{eff}^{q}(\omega_P) - \omega_S\, n_{eff}^{l}(\omega_S) - \omega_I\, n_{eff}^{m}(\omega_I)\right)$$

Control the modes ⇨ Control the phase matching

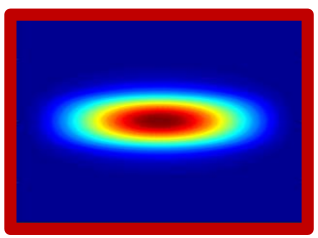
intramodal FWM vs intermodal FWM



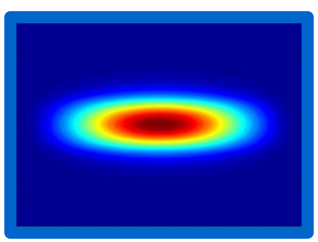
PUMP



PUMP



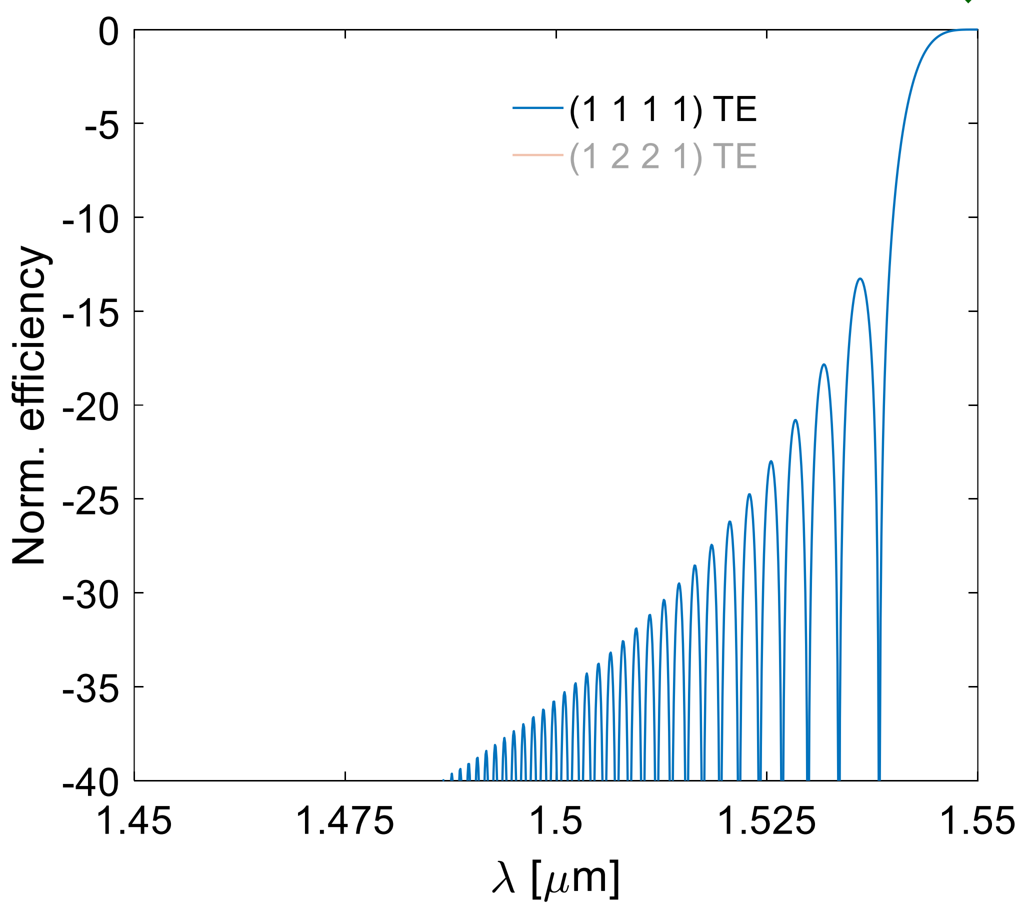
SIGNAL



IDLER

SIMULATION

λ Pump



Intermodal phase matching

Max efficiency	Phase mismatch	Wave vector
$\Delta k = 0$	$\Delta k = k_P + k_P - k_S - k_I$	$k = \frac{\omega}{c} n_{eff}(\omega)$

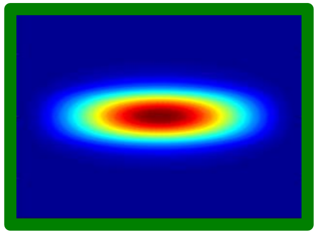
↓

$\boldsymbol{j, q, l, m}$ are the mode orders

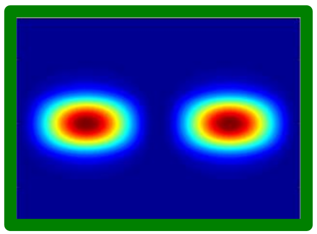
$$\Delta k = \frac{1}{c}\left(\omega_P\, n_{eff}^{j}(\omega_P) + \omega_P\, n_{eff}^{q}(\omega_P) - \omega_S\, n_{eff}^{l}(\omega_S) - \omega_I\, n_{eff}^{m}(\omega_I)\right)$$

Control the modes ⇨ Control the phase matching

intramodal FWM vs intermodal FWM



PUMP



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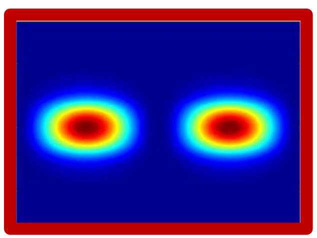
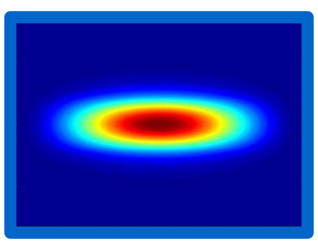


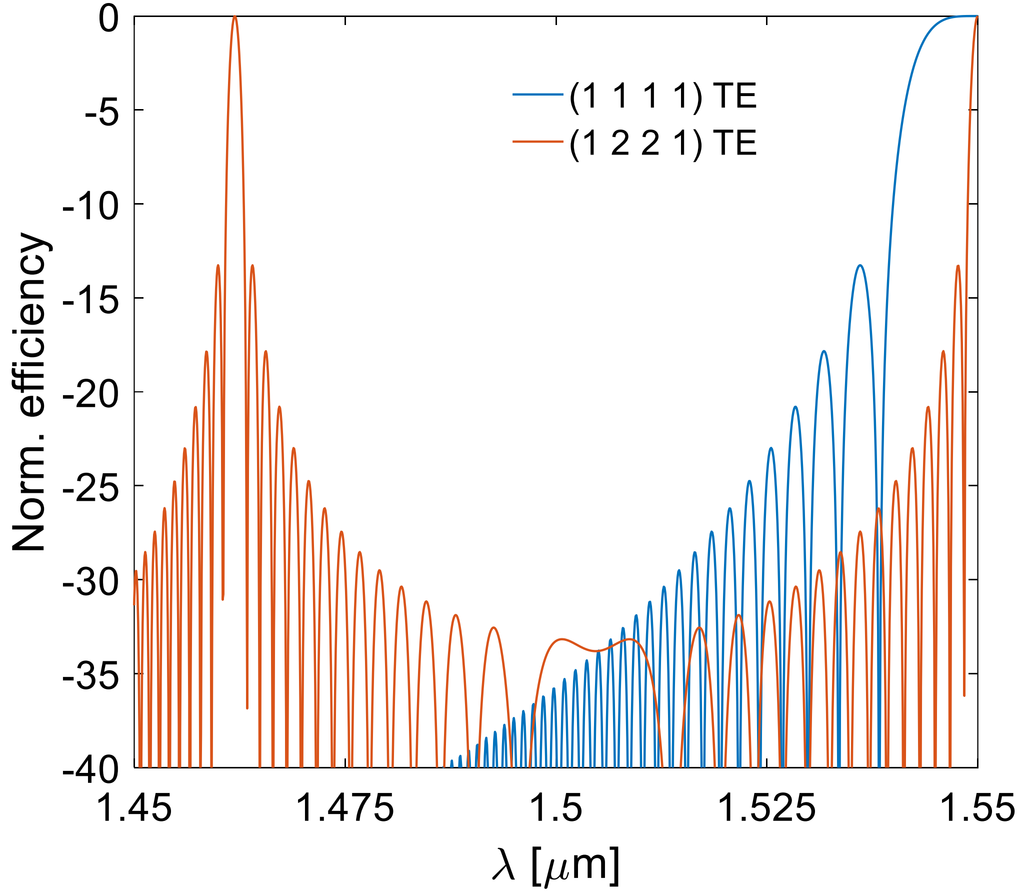
SIGNAL



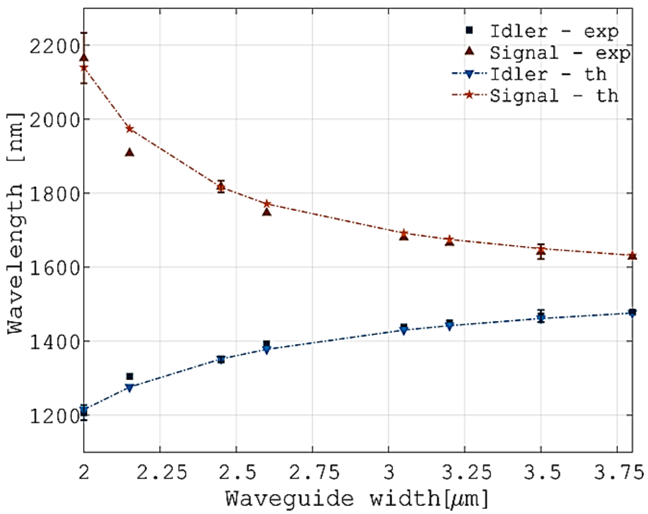
IDLER

SIMULATION

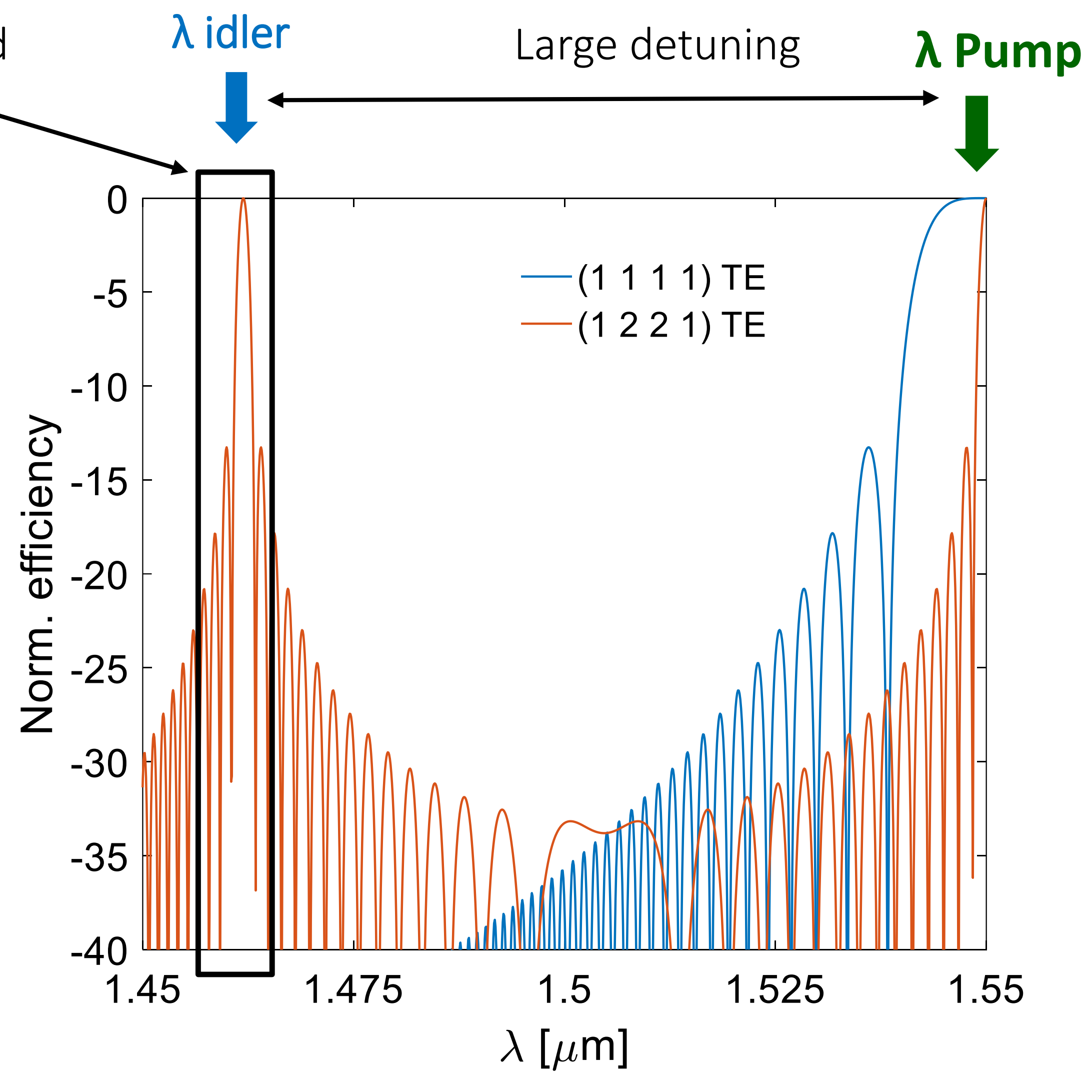
λ Pump



intramodal FWM vs intermodal FWM

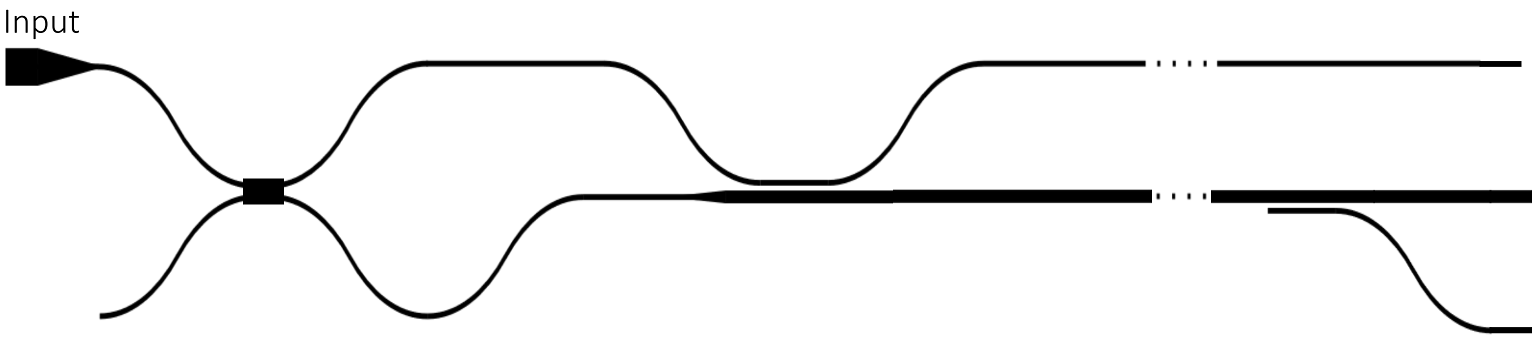


Wavelength tuning

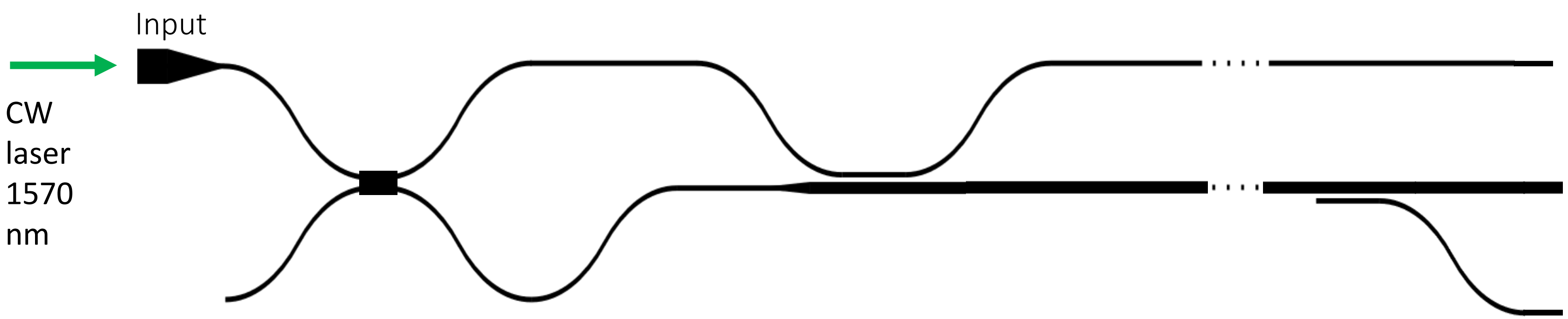


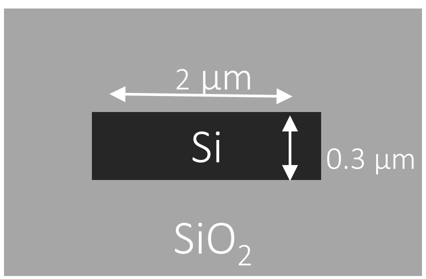
How do we implement Spontaneous intermodal FWM on a chip?

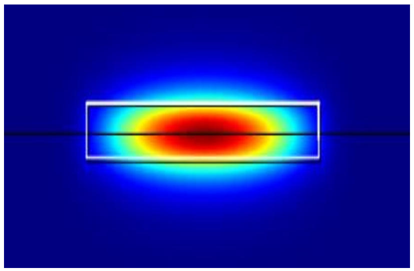
Photonic circuit



Photonic circuit

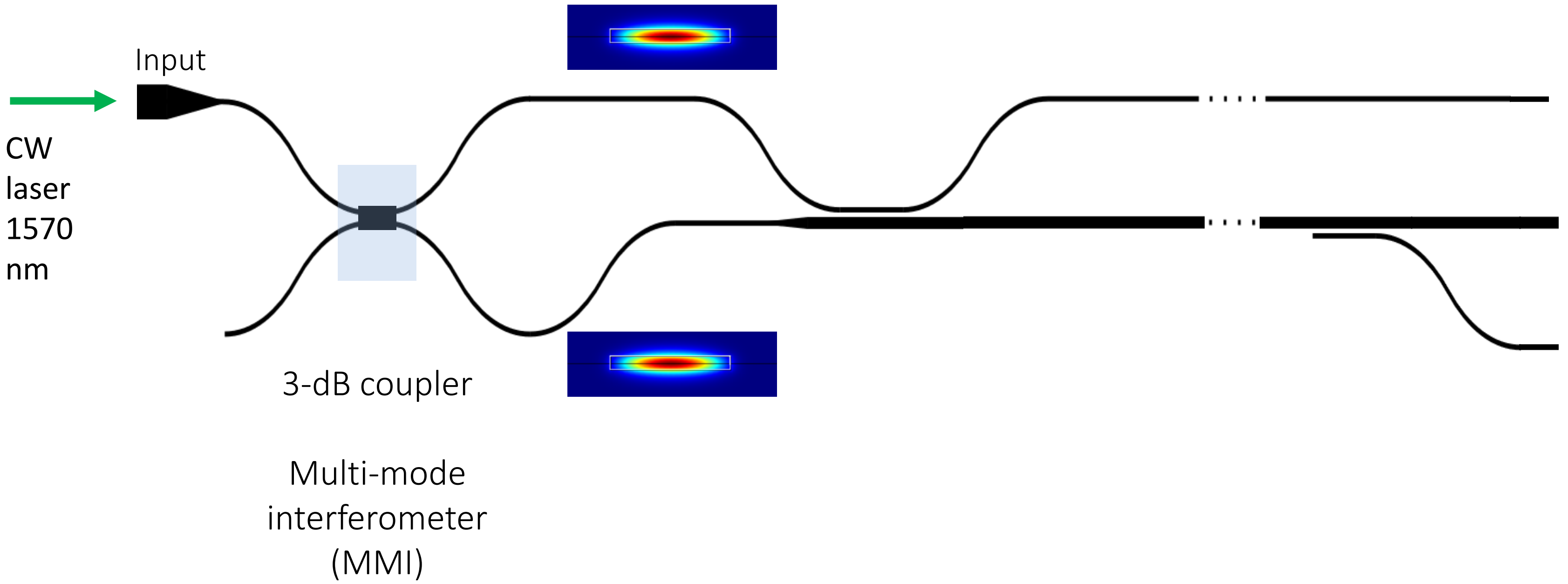






(2019) Frontiers in Physics, 7 , art. no. 128 doi:10.3389/fphy.2019.00128

Photonic circuit



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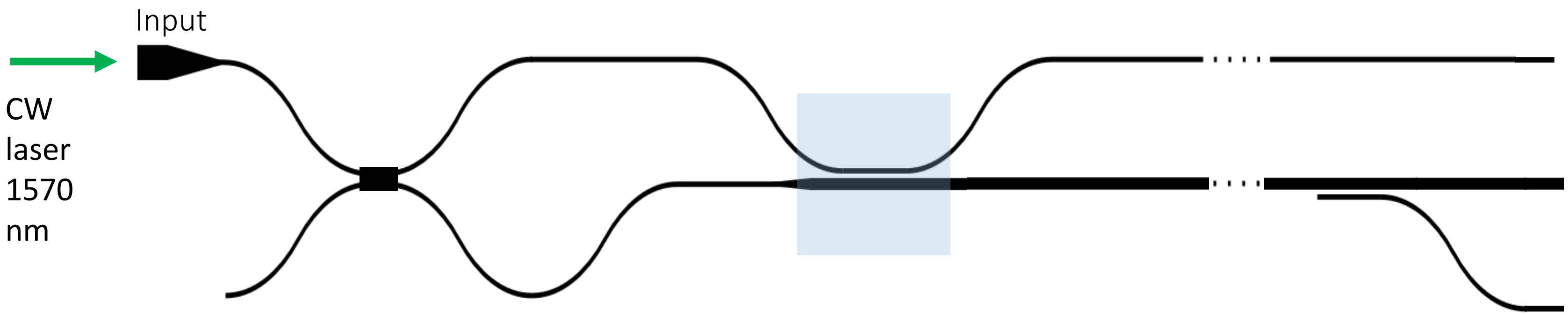
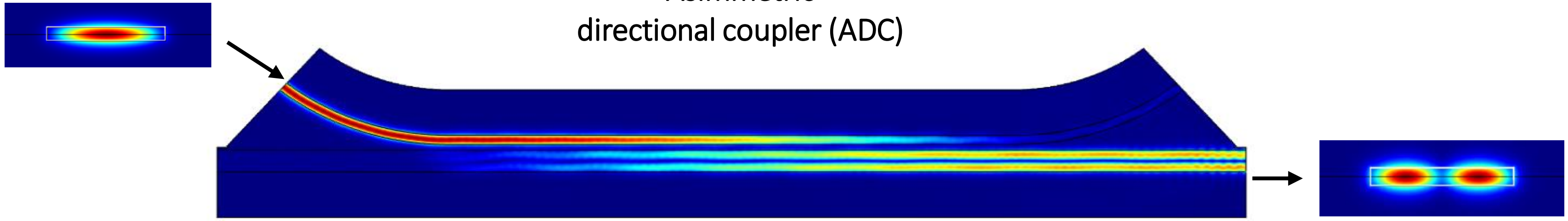
Photonic circuit





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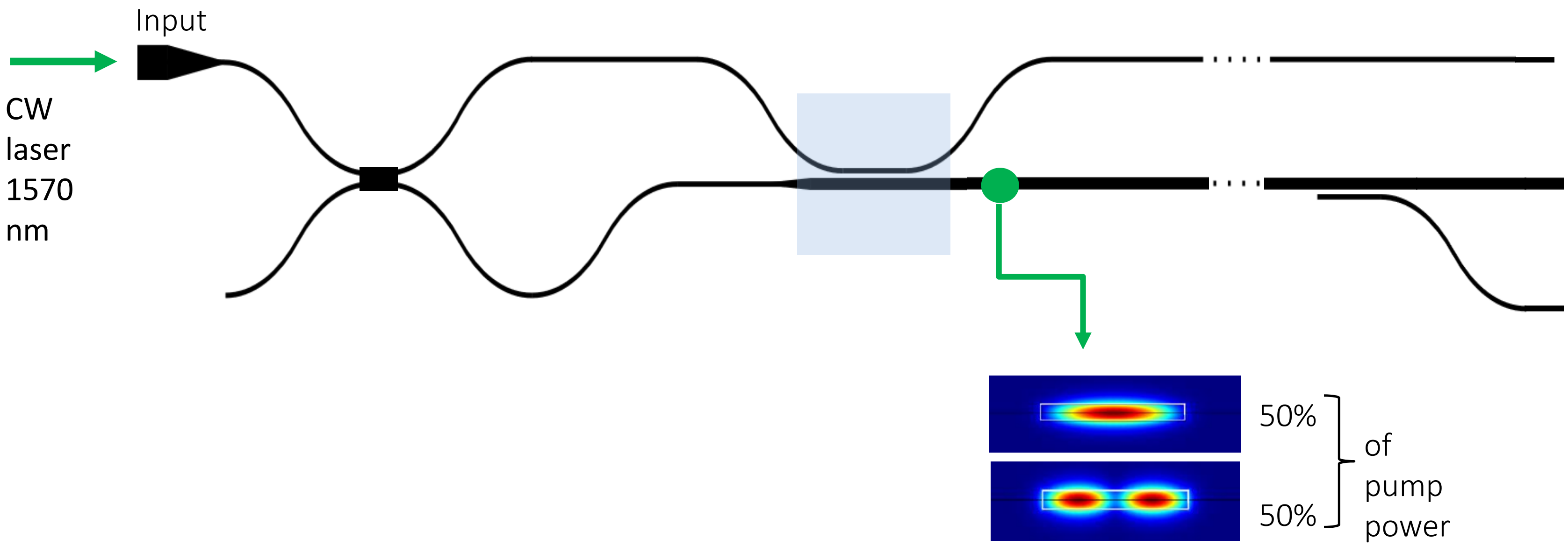
Photonic circuit



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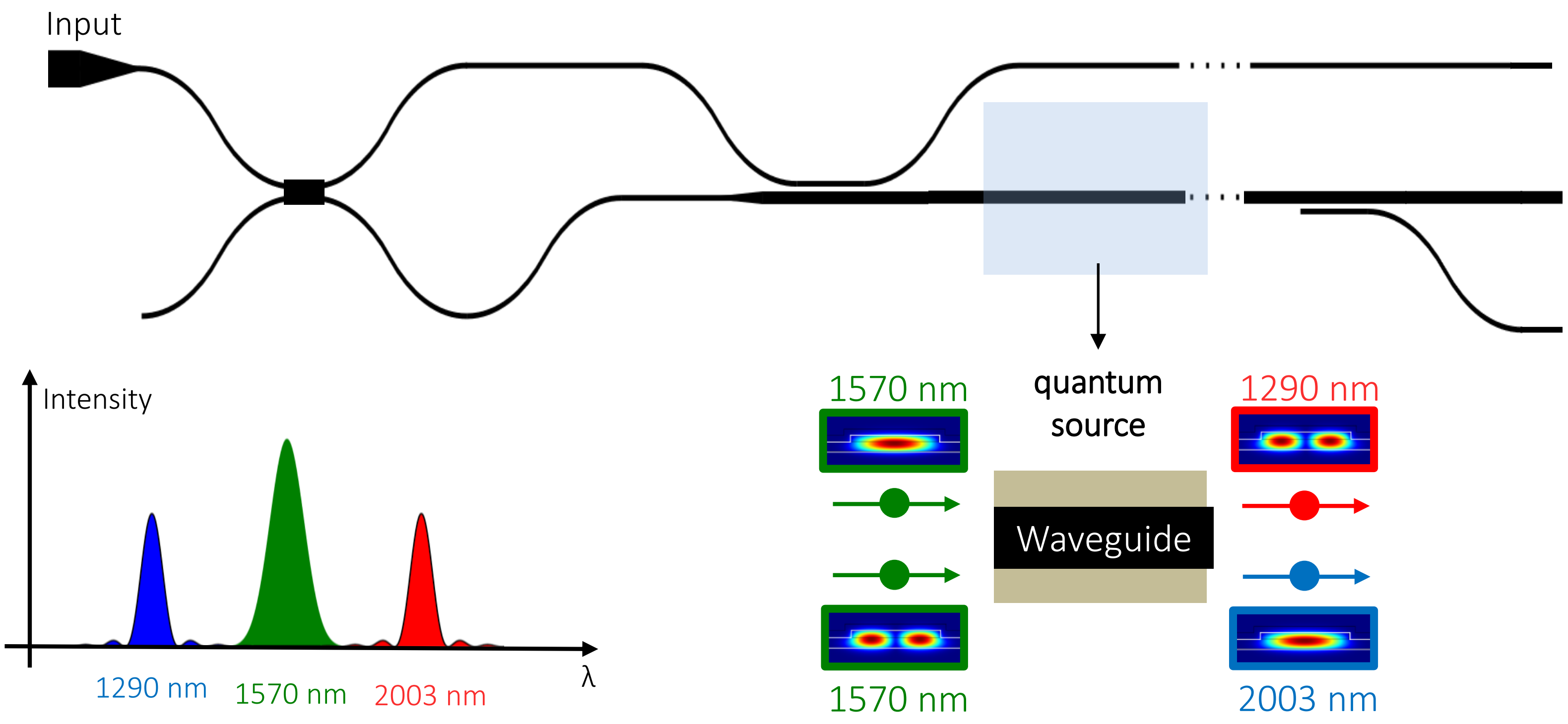
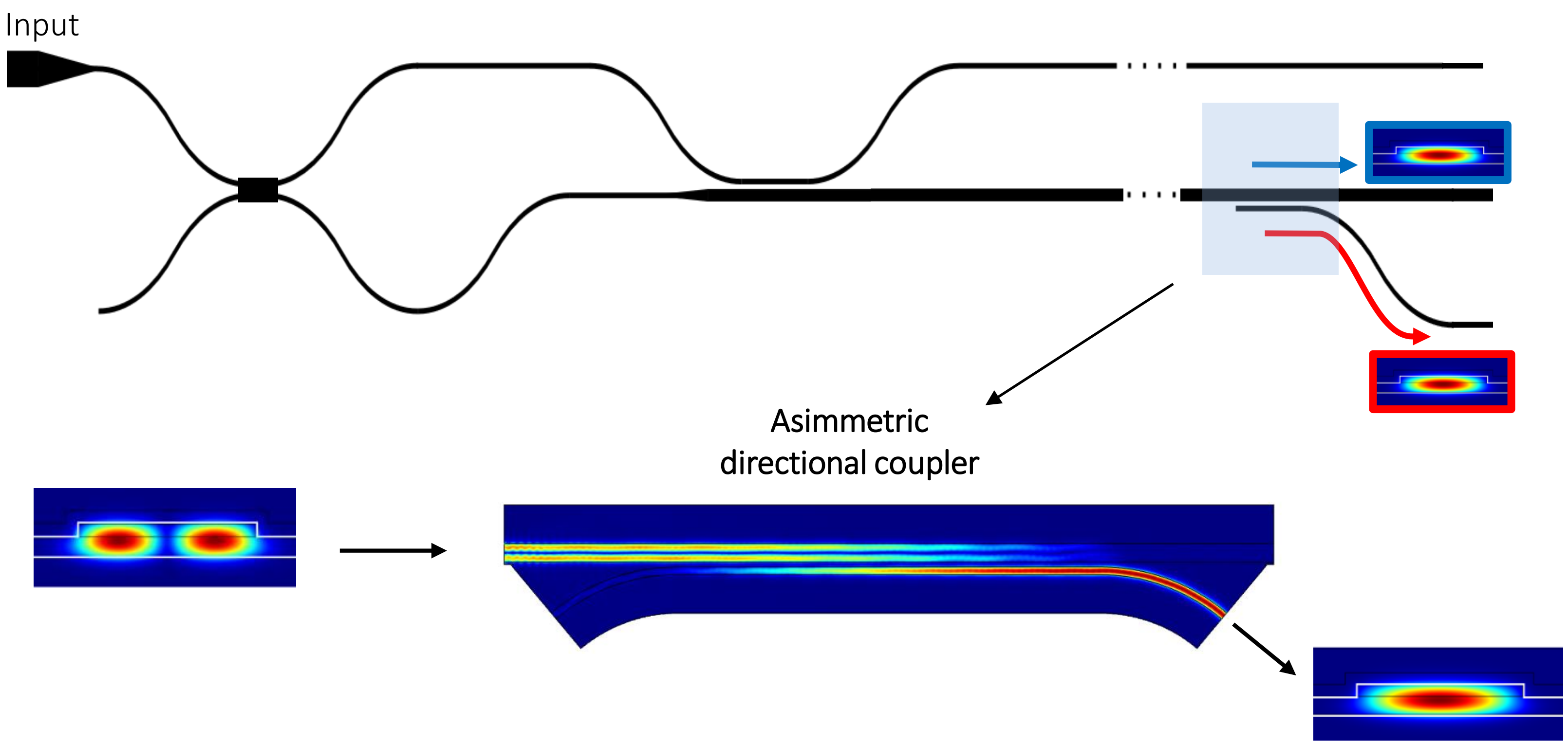
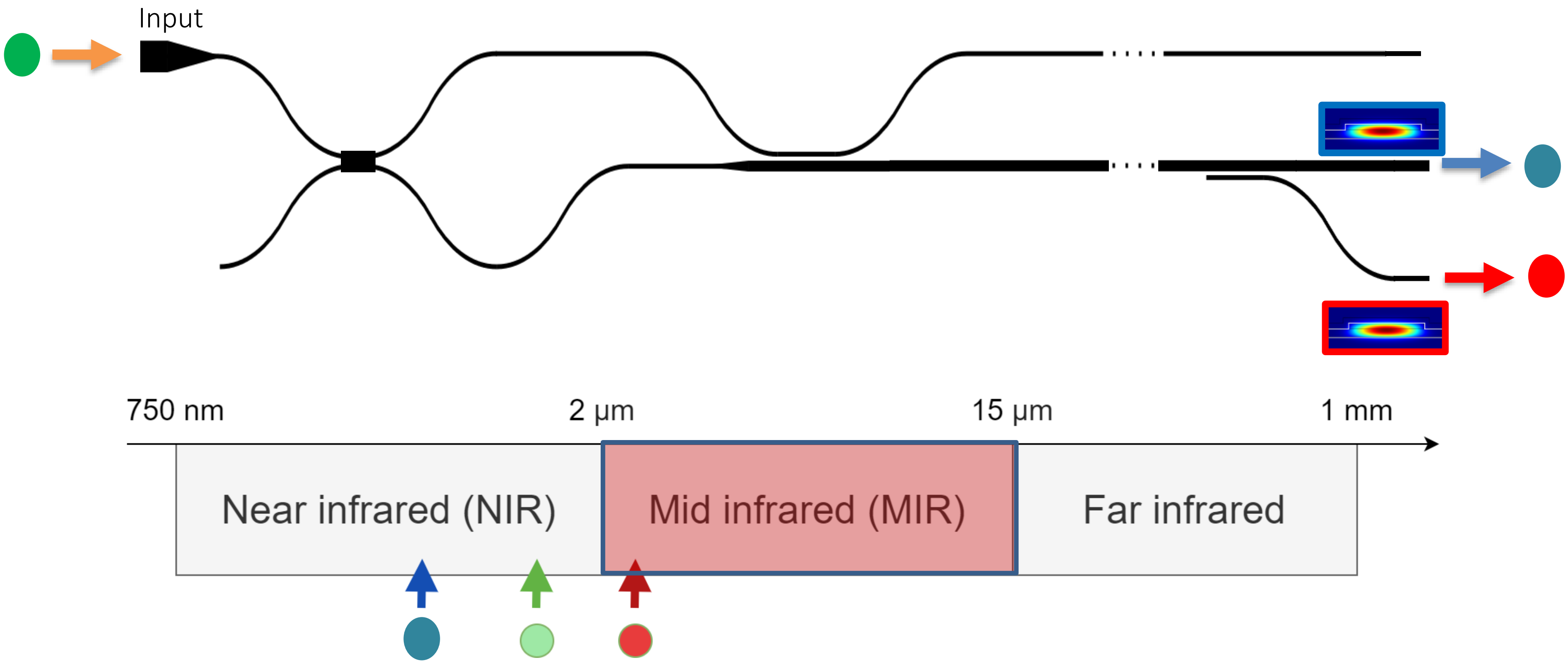
Photonic circuit



Photonic circuit



Photonic circuit

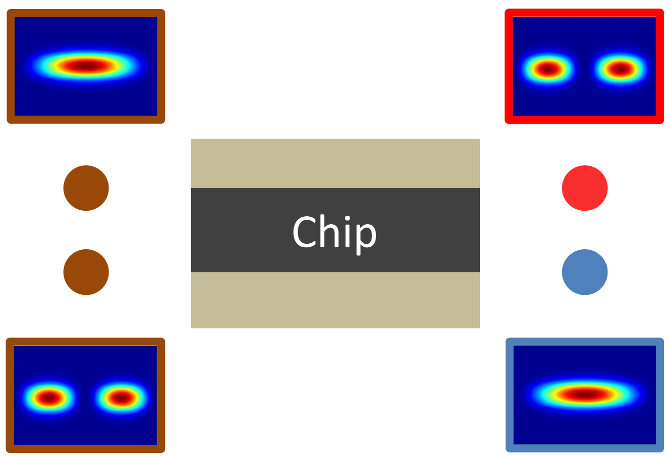


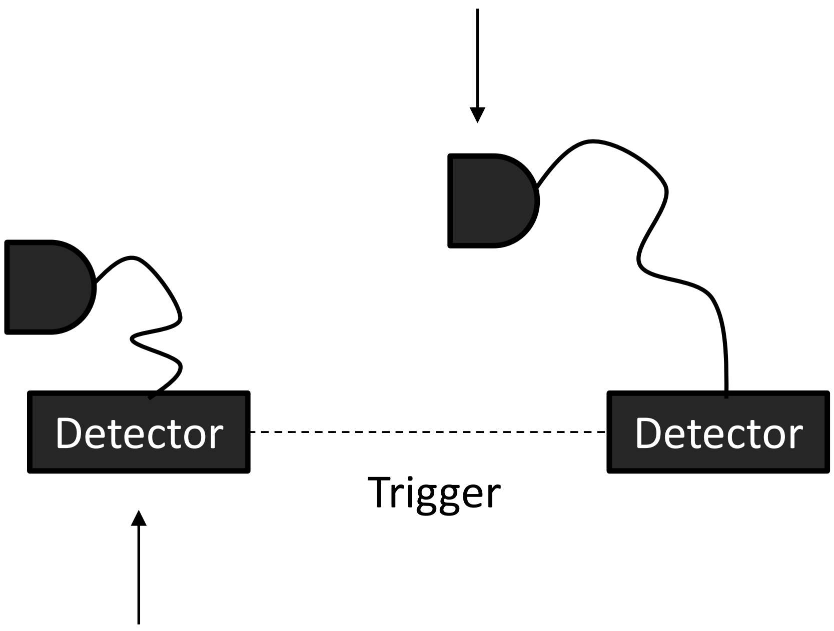
Part 2

- The basic building blocks
- Intermodal FWM
- Ultra pure heralded single photon source
- Ghost spectroscopy in the MIR

- Need of single photons for different applications

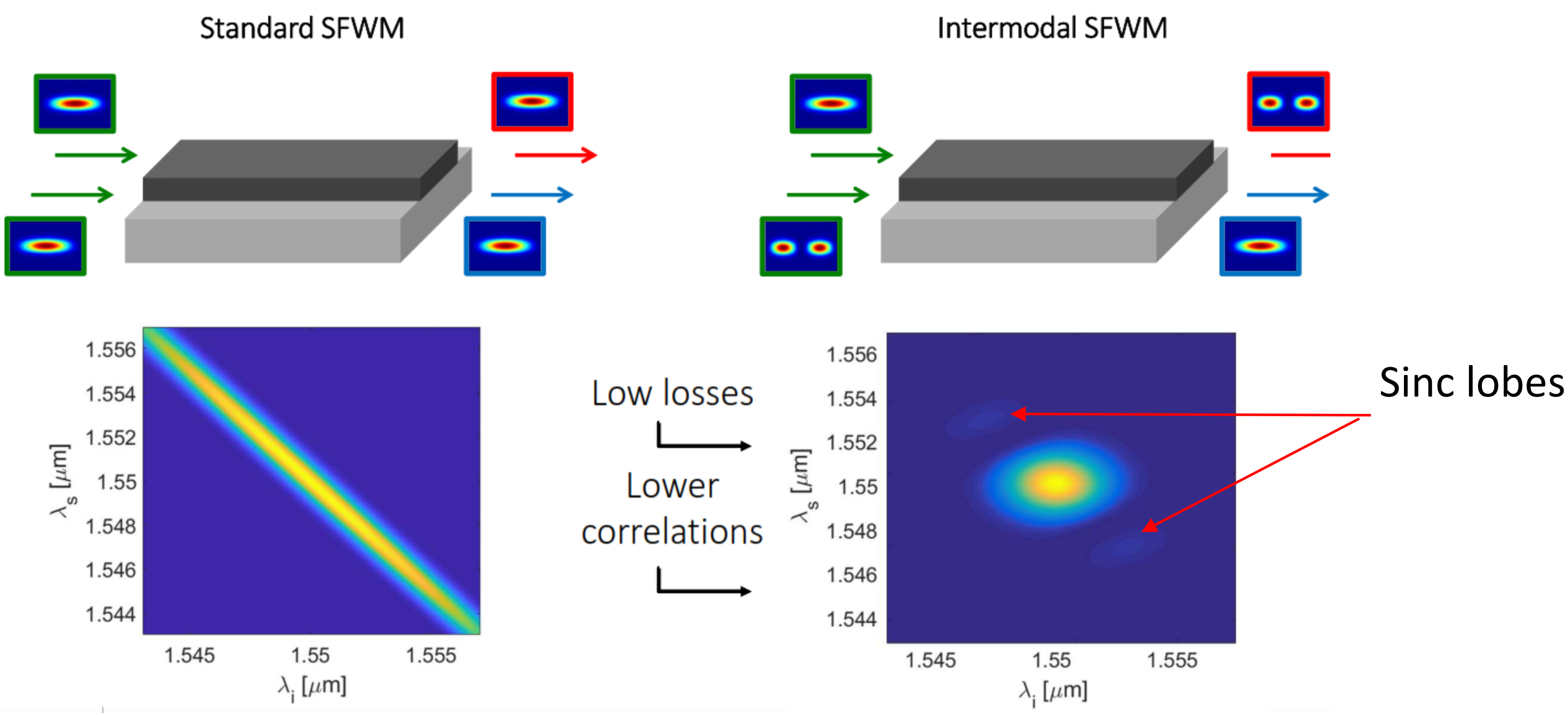
Basic on-chip heralded source





Ideal single photon source: the measure of the heralder does not determine the heralded state

High purity heralded single photon source

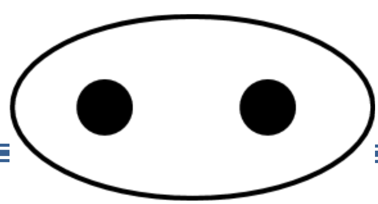


Entangled photons

Non separable biphoton wavefunction

$$|\Psi\rangle \sim |\varphi_1\rangle_i|\psi_1\rangle_s + |\varphi_2\rangle_i|\psi_2\rangle_s$$

Low purity

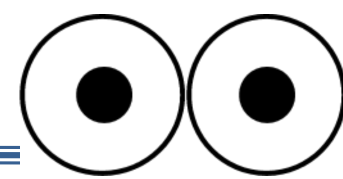


Single photons

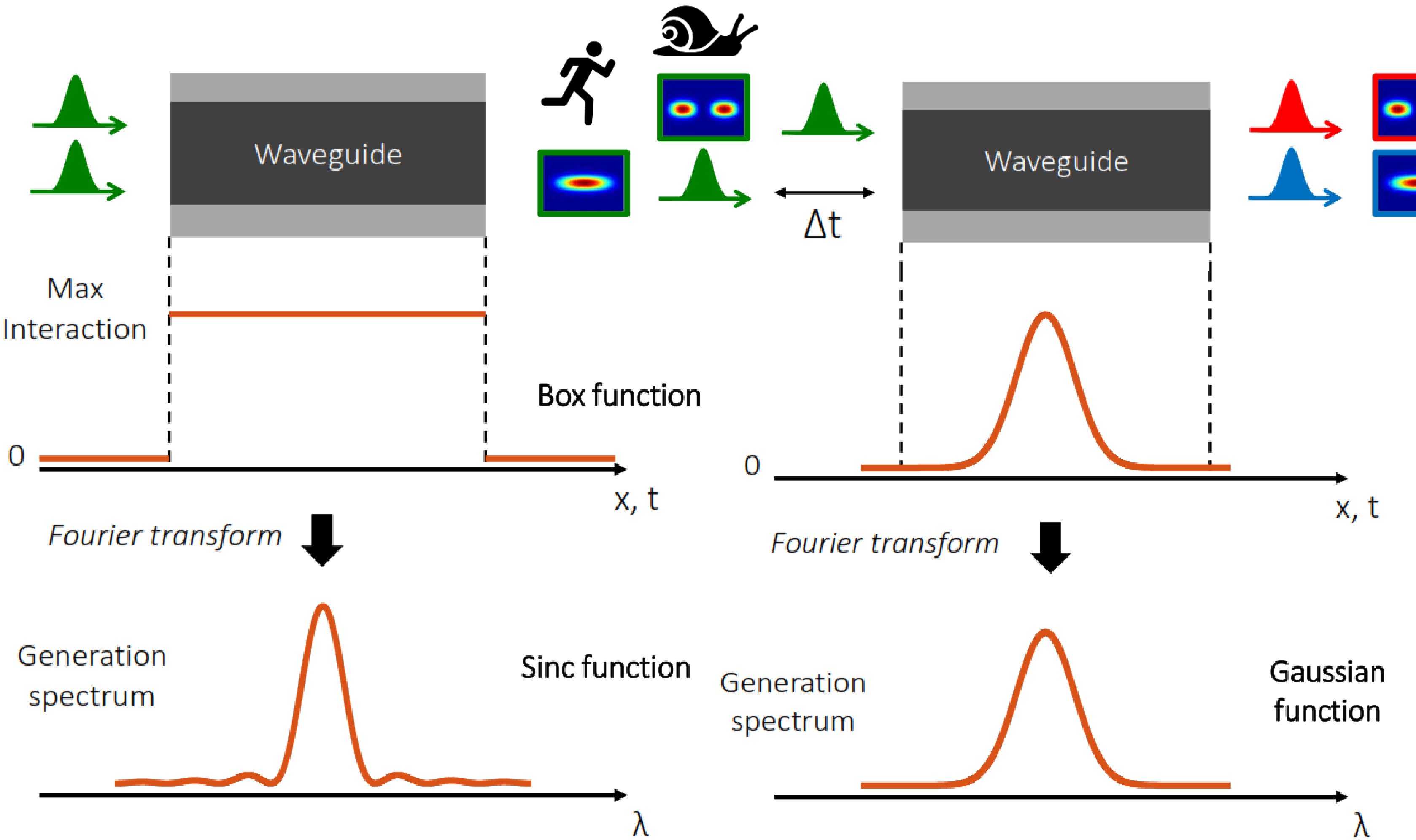
Separable biphoton wavefunction

$$|\Psi\rangle \sim |\varphi\rangle_A|\psi\rangle_B$$

High purity P ~ 76%

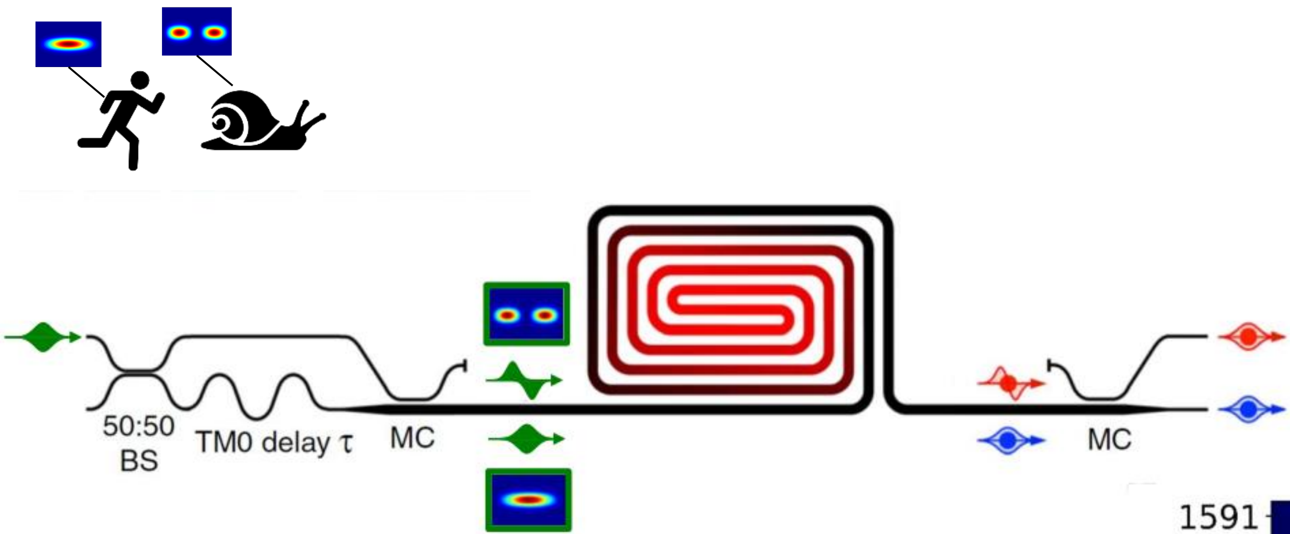


High purity heralded single photon source



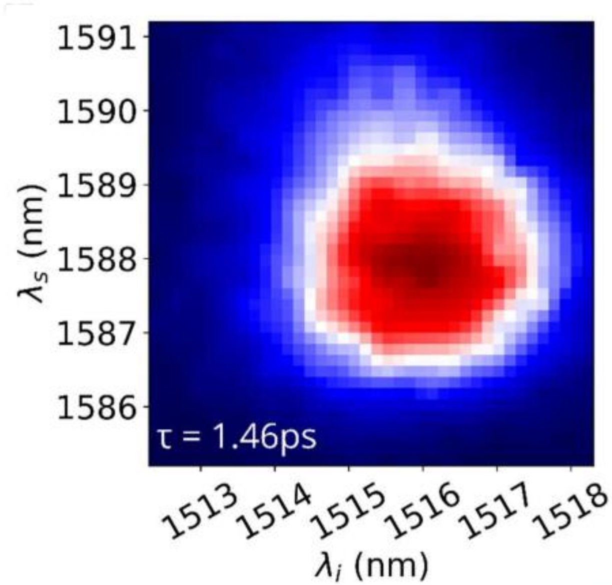
adiabatic turn on of Spontaneous Four Wave mixing

High purity heralded single photon source

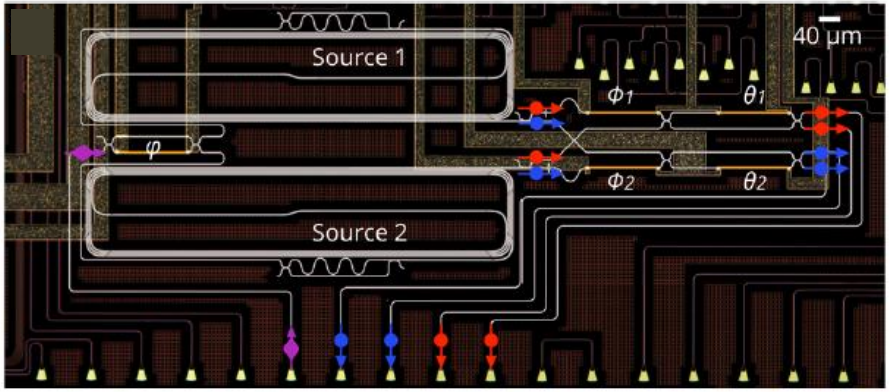


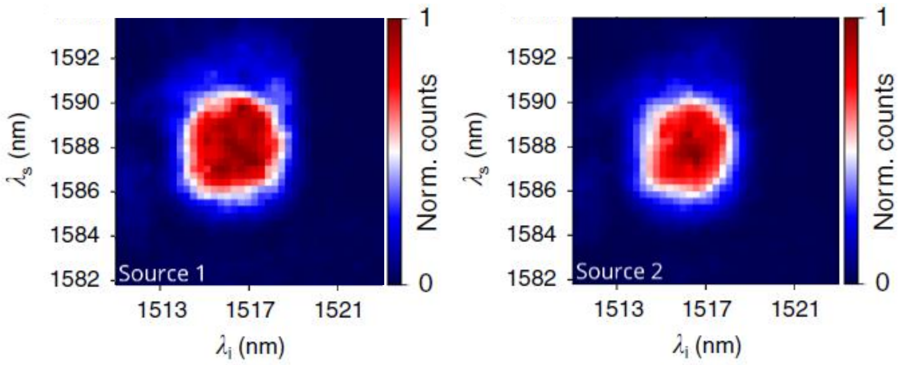
P = 99.04(6)% -> extremely low correlations

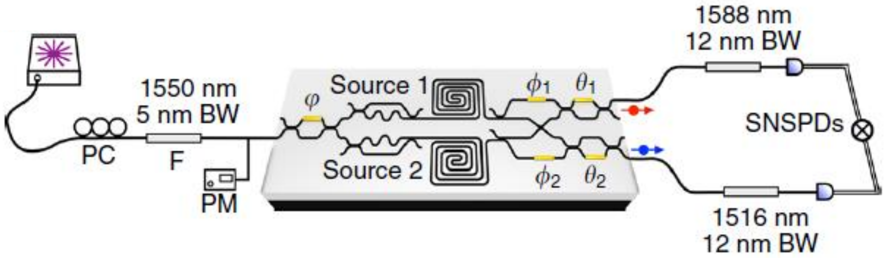
Heralding efficiency = 91(9)% -> extremely low losses



High purity heralded single photon source







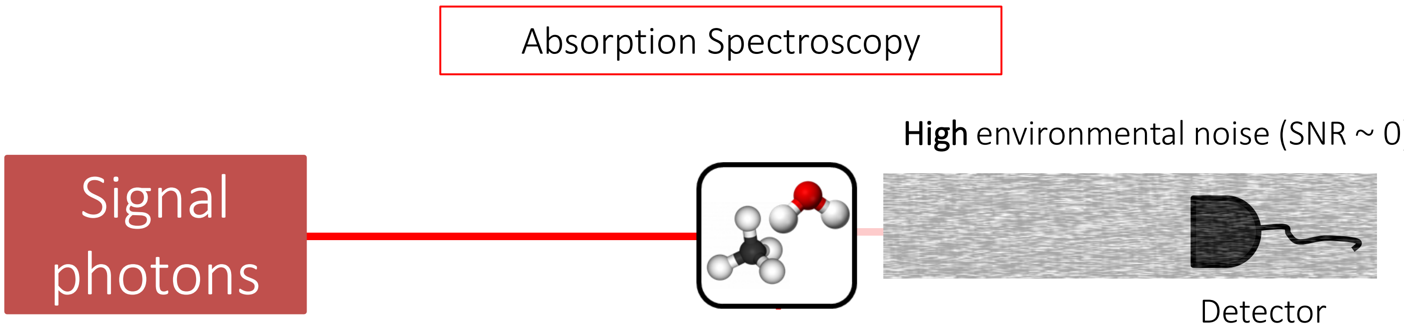
- 99.9% SINGLE MODE EMISSION
- 98.5 % INDISTINGUISHABILITY
- 91% INTRINSIC HERALDING EFFICIENCY

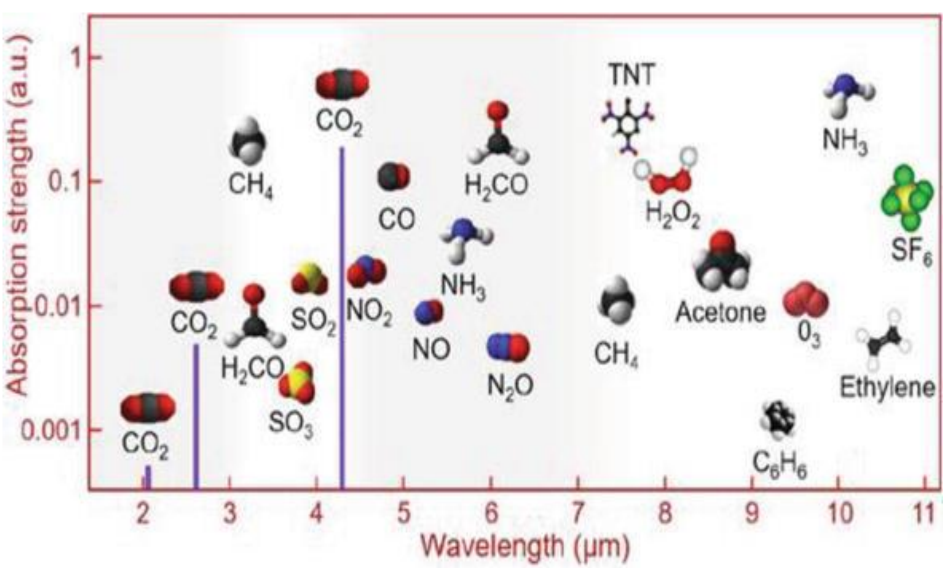
- > 50 PHOTONS
  COMPLEXITY REGIME IN BOSON SAMPLING

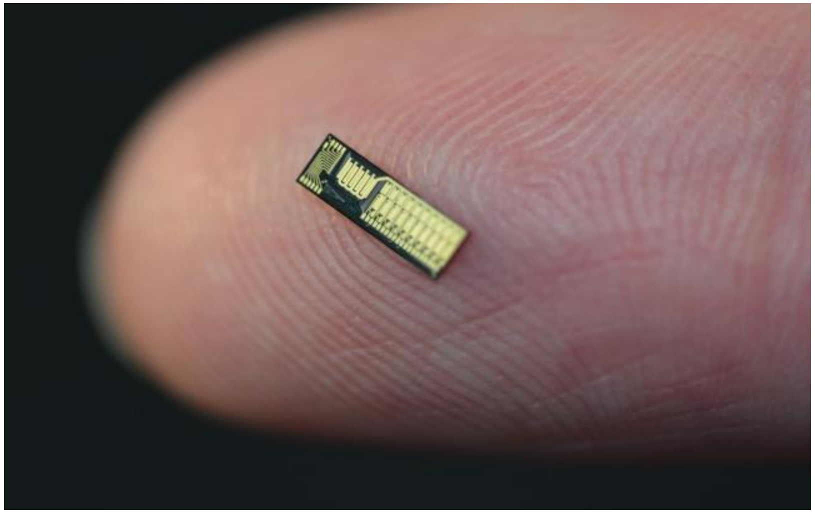
Part 2

- The basic building blocks
- Intermodal FWM
- Ultra pure heralded single photon source
- Ghost spectroscopy in the MIR

MIR sensing via Ghost Spectroscopy







An heralded single photon source in the MIR

$$\mathrm{CAR} = \frac{\text{good coincidences } (\Delta t = 0)}{\text{accidental coinc. } (\Delta t > 0)}$$

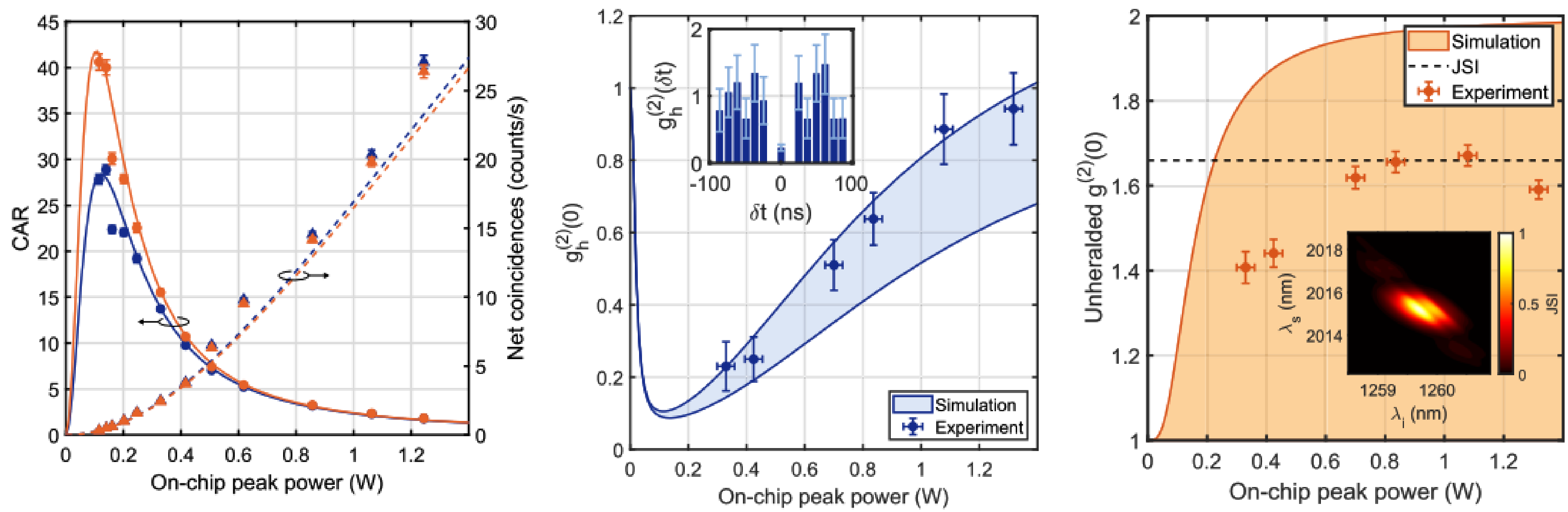
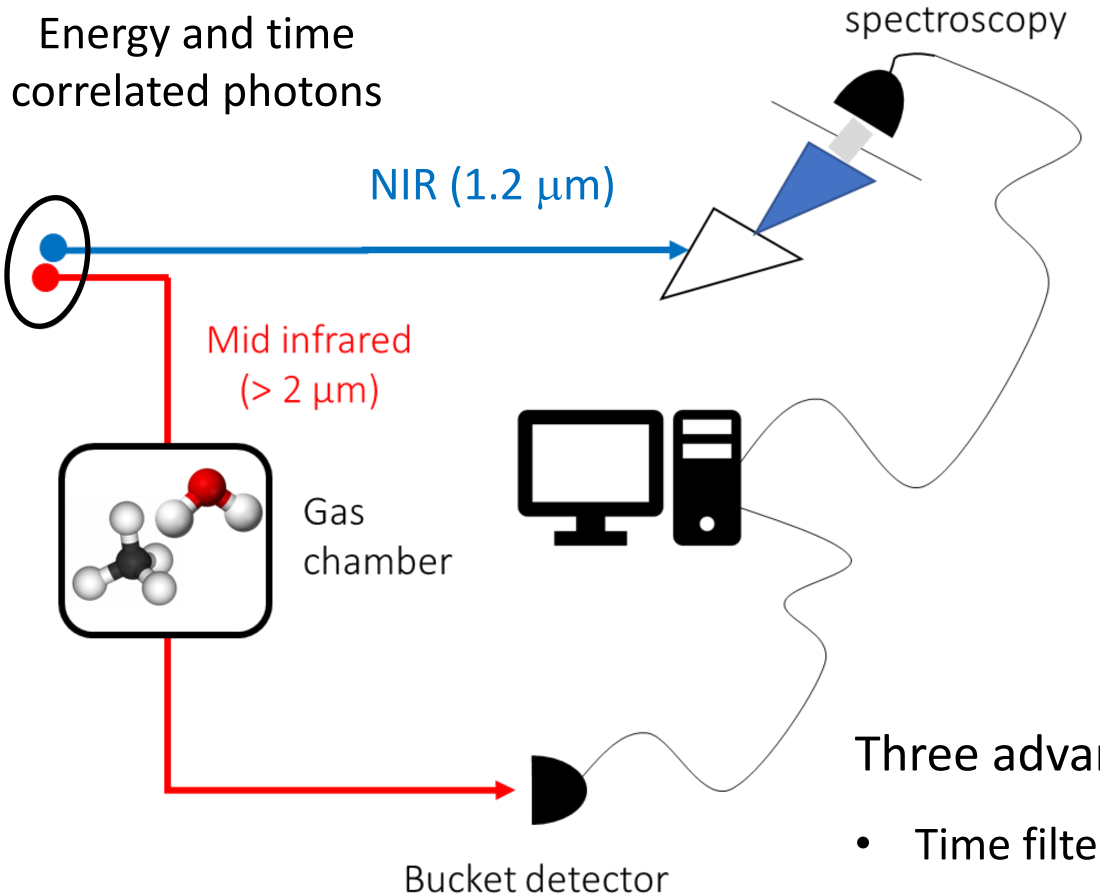
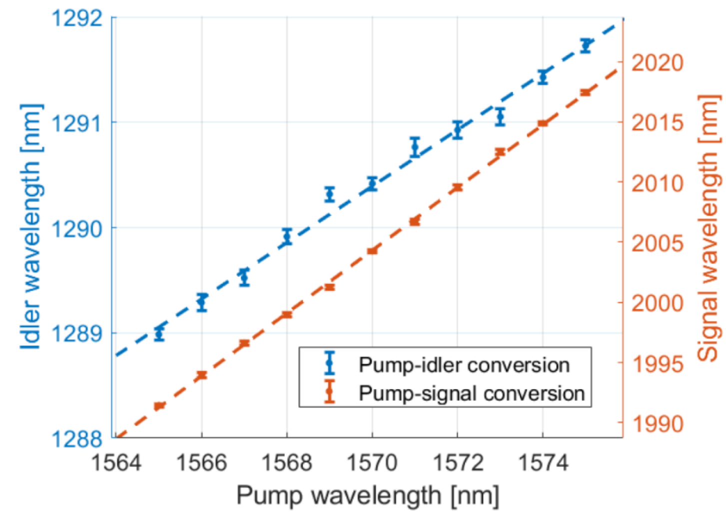


TABLE I. Comparison with state-of-the-art MIR heralded sources.

Platform	Process	Generation probability (W^{-2})	CAR max	CAR at $N_{si}^{net} \sim 1$ Hz	$g_h^{(2)}(0)$	η_I (%)	References
Mg:PPLN	SPDC	...	180 ± 50	...	...	...	19
SOI	Intra-modal SFWM	0.28	25.7 ± 1.1	25.7 ± 1.1	...	5	21
SOI	Inter-modal SFWM	0.70 ± 0.10	40.4 ± 0.9	27.9 ± 0.5	0.23 ± 0.08	59 ± 5	This work

MIR sensing via Ghost Spectroscopy

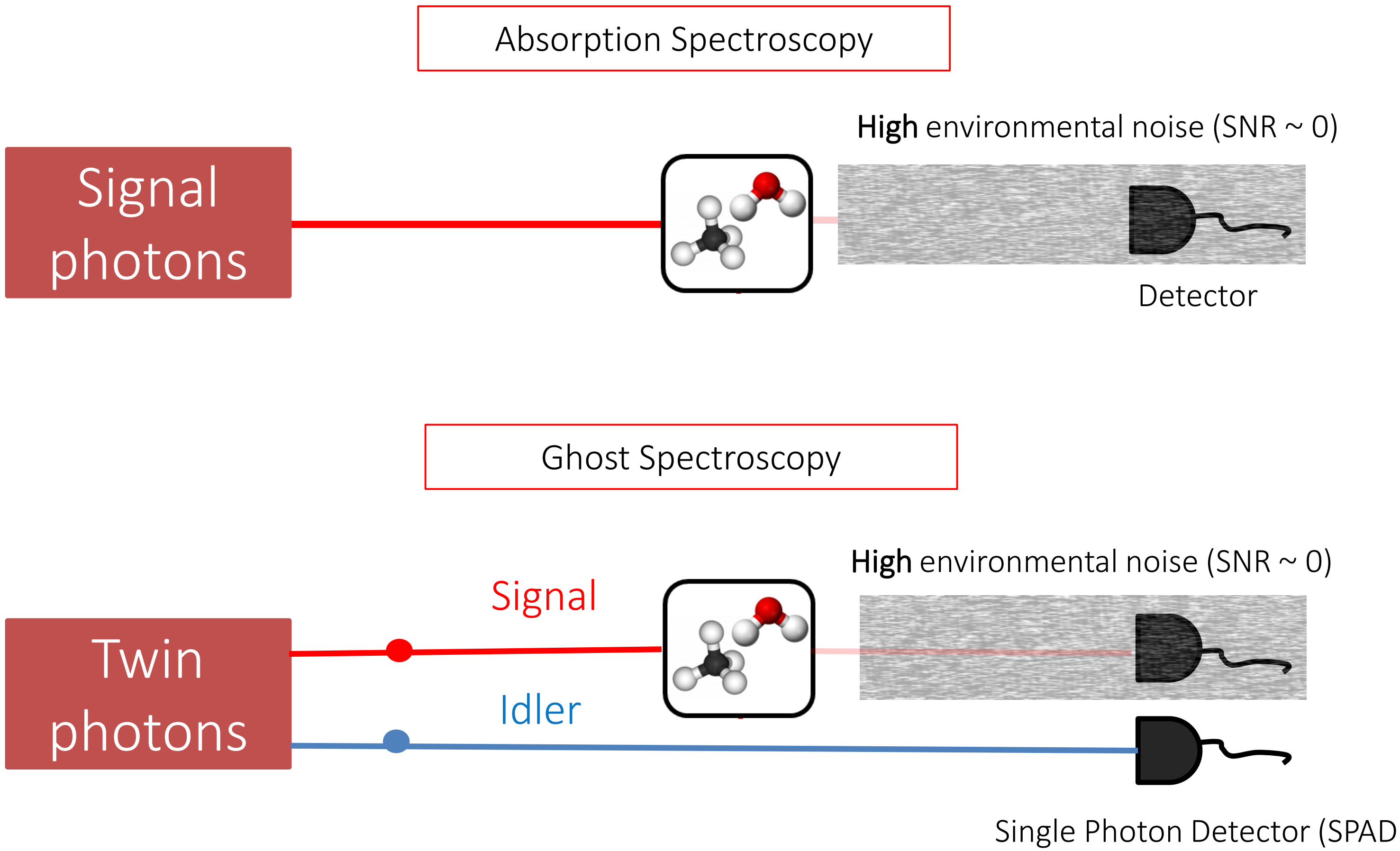




Three advantages:

- Time filtering (correlation)
- Ghost information translation (entanglement)
- Large spectral shift between the twin photons

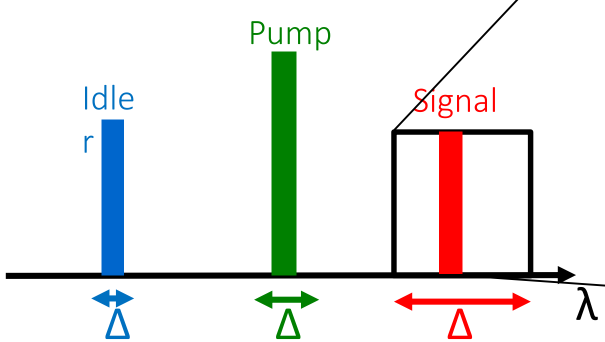
MIR sensing via Ghost Spectroscopy



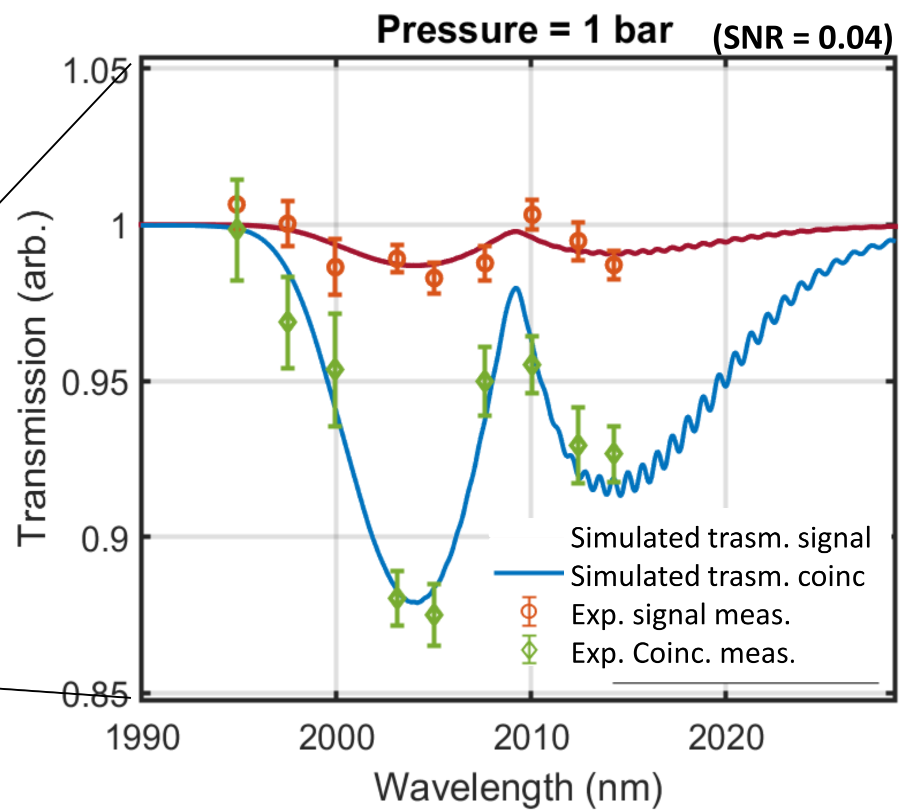
Ghost spectroscopy

High environmental noise (SNR = 0.04)

- Spectrum of CO_2
- Pressure variation measurement



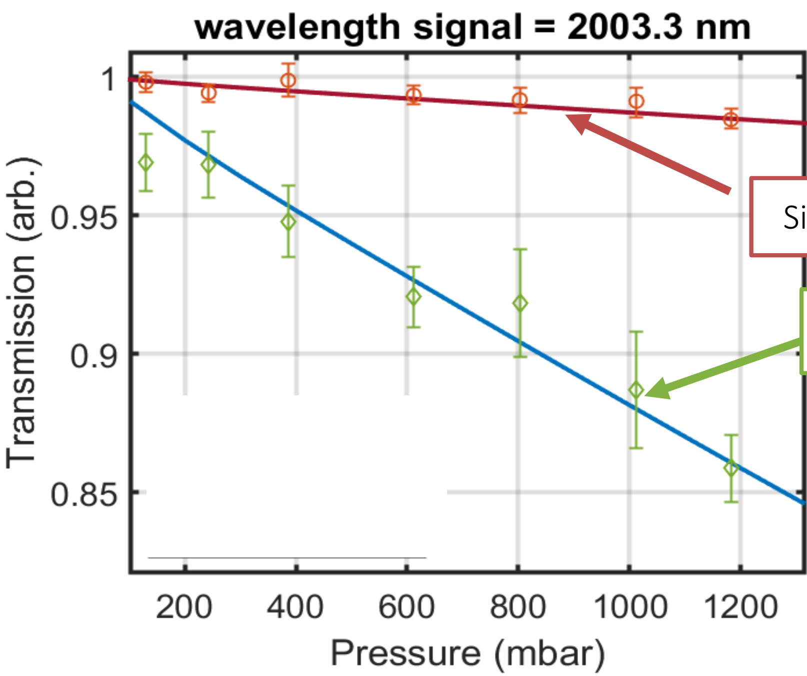
$$2\hbar\omega_P = \hbar\omega_S + \hbar\omega_I$$

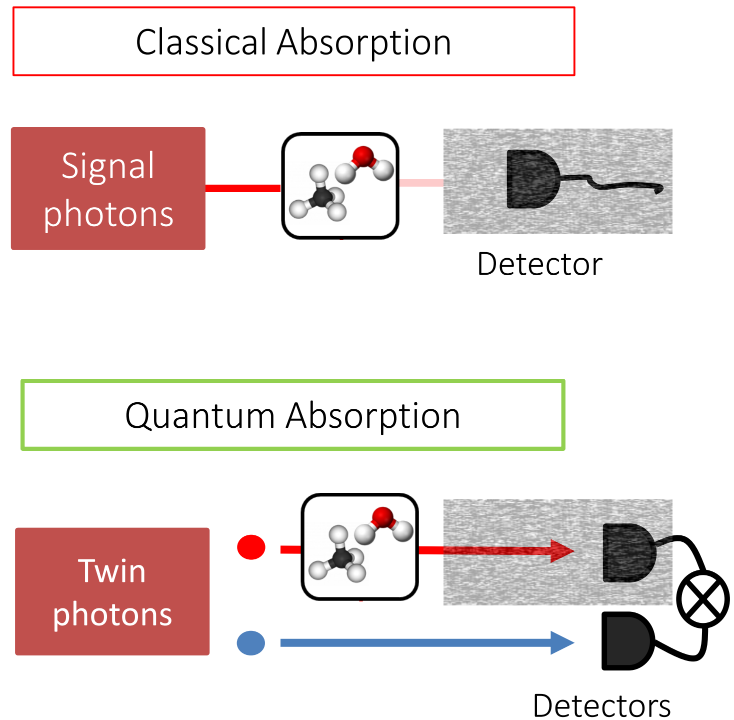


Time filtering

Ghost spectroscopy

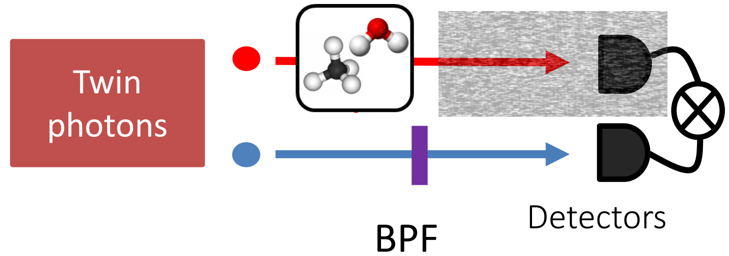
High environmental noise (SNR = 0.04)

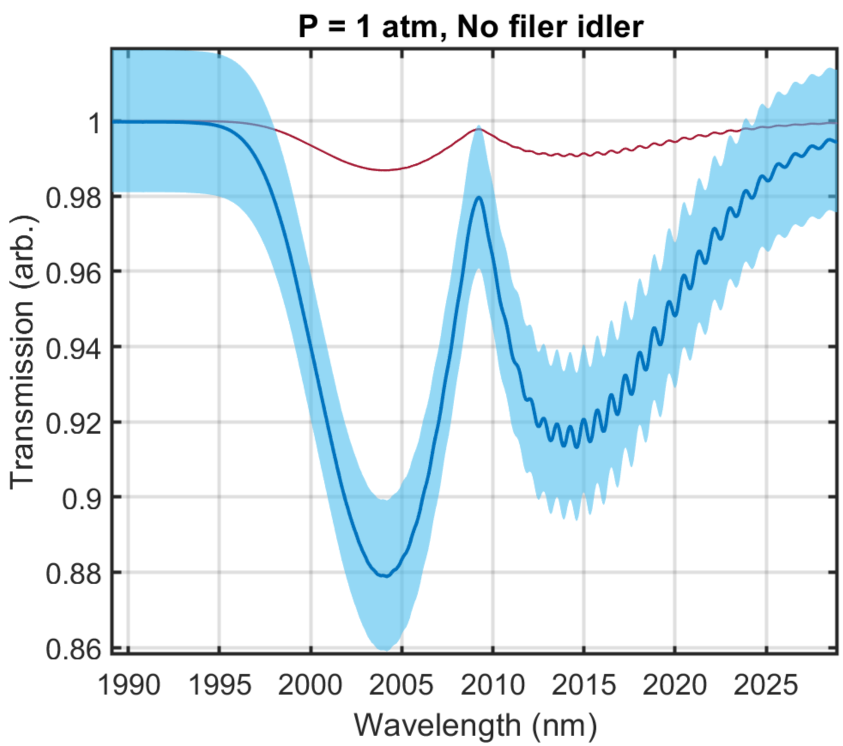


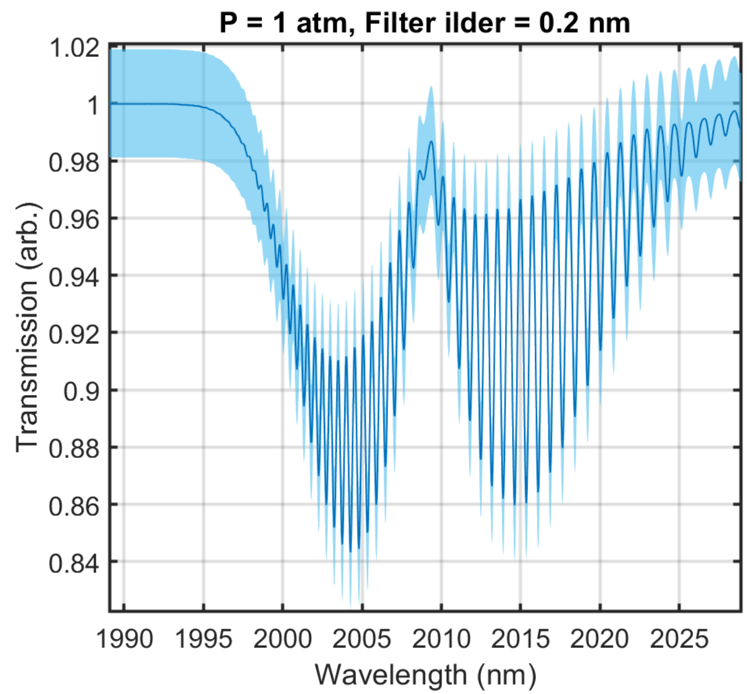


Time filtering

Ghost spectroscopy







- Ghost information translation

Conclusions

- Few examples of physics and applications of silicon photonics integrated circuits
- interesting phenomena and application in simple structures
- Silicon nonlinearities are enabling phenomena
- Exciting perspectives for further developments when one moves from single device to matrices of differently interconnected structures

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- Neuromorphic photonics

PELM

ISLAND read and write neurons

BACKUP neuromorphic photonics and the brain

erc European Research Council

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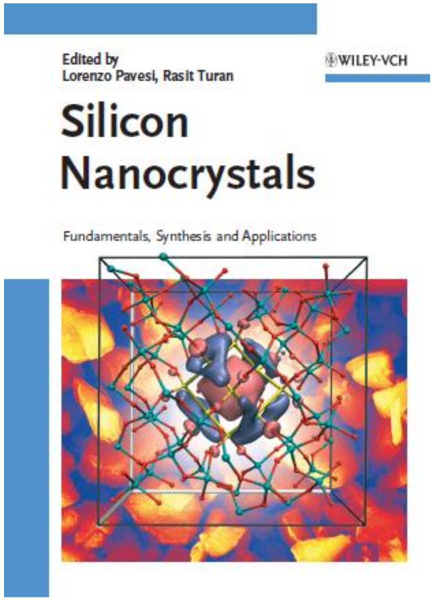
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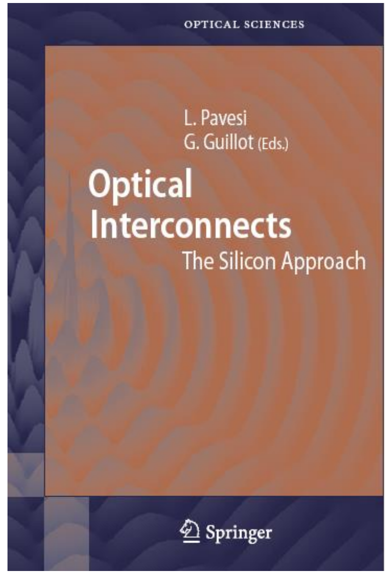
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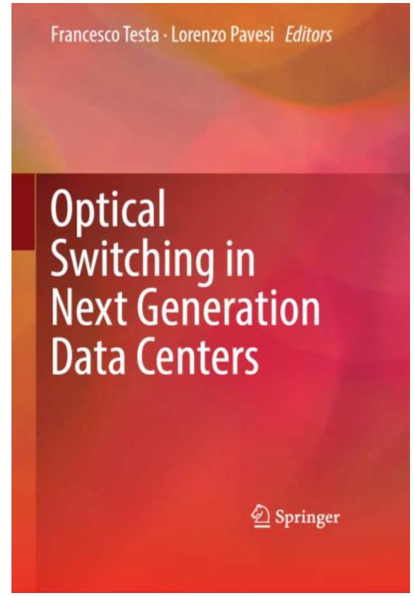
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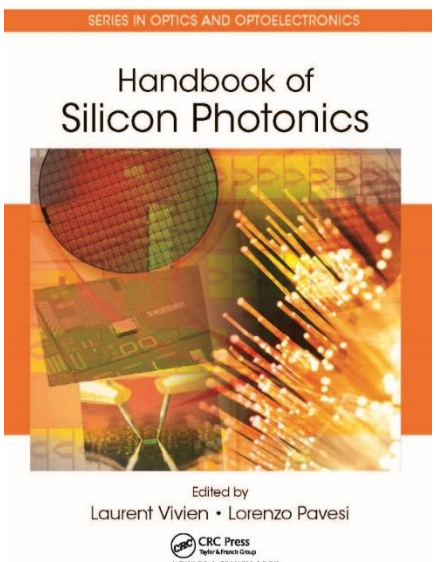
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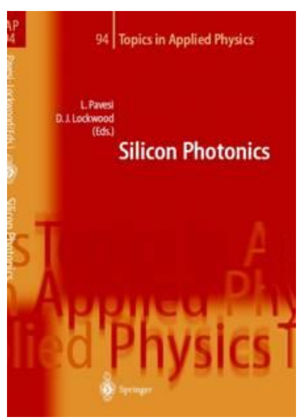
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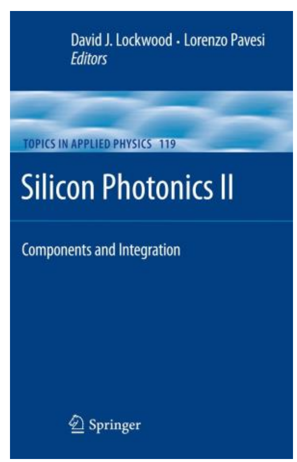
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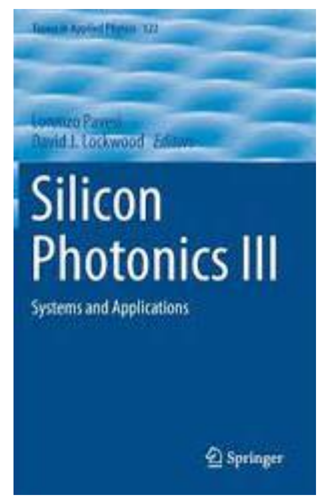
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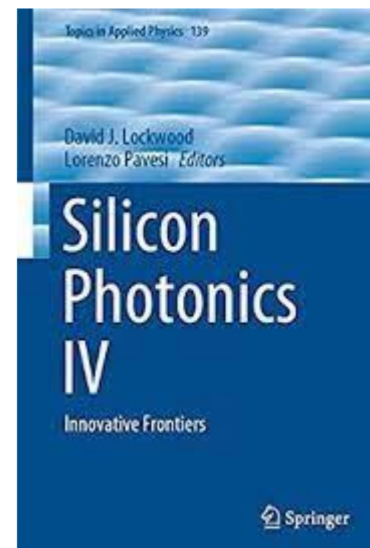
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