UNIVERSITY
OF TRENTO

PhD Physics Workshop

02/12/2020

Neural Network on a Photonic Chip

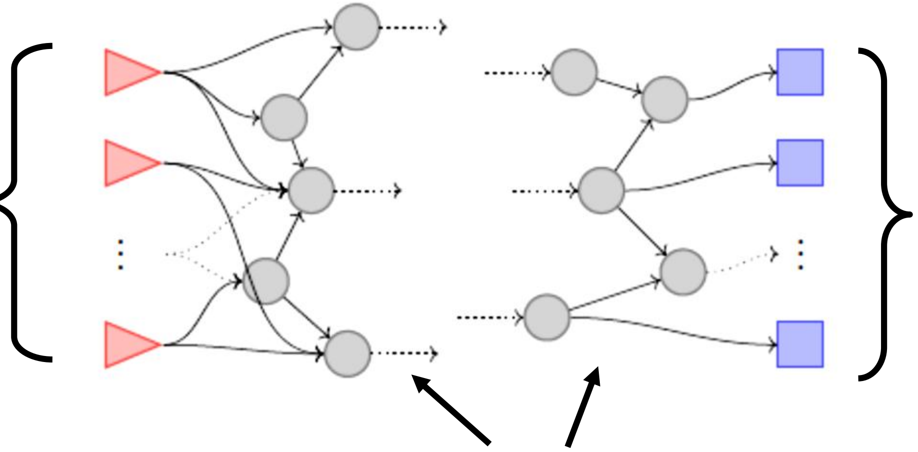
Dhouha Jemmeli

Overview

- Neural network
- Integrated photonics
- Chip design and SCISSOR definition
- Sequence of coupled resonators: experimental results
- Sequence of coupled resonators: Modelling

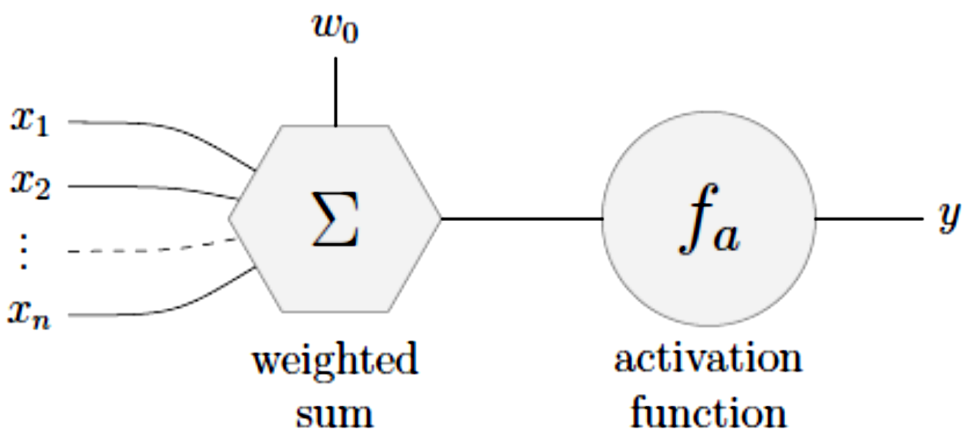
Neural Networks

Input nodes



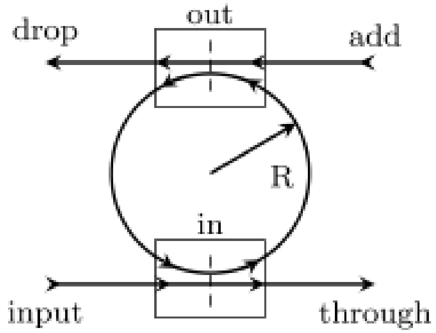
Output nodes

Hidden nodes



Preparation phase of neural network :

- Learning process
- Validation process
- Testing process



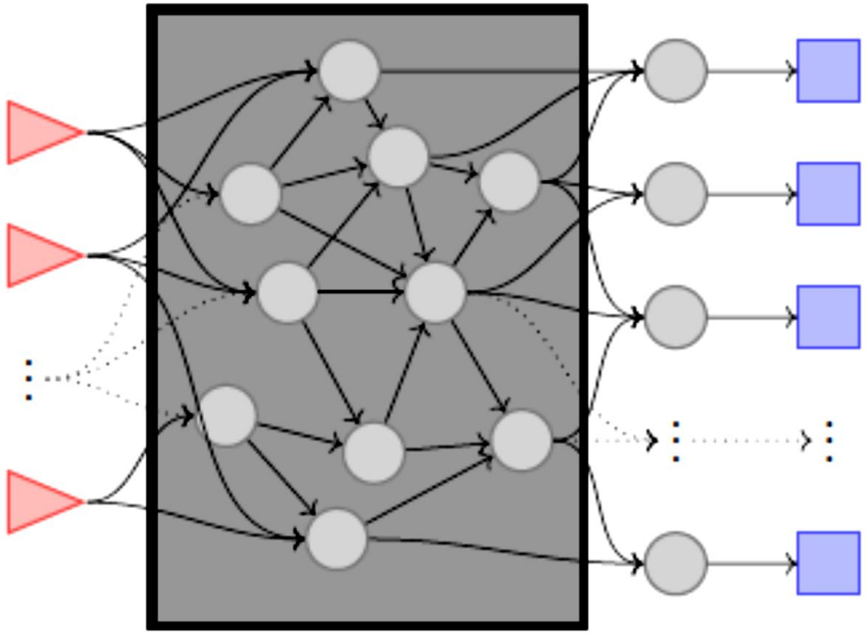
The nonlinear response of a micro-ring could be exploited in an all-optical node of a feedforward ANN

Reservoir Computing

Only the parameters of the output nodes are Learned

The "reservoir" increases the dimensionality of the input

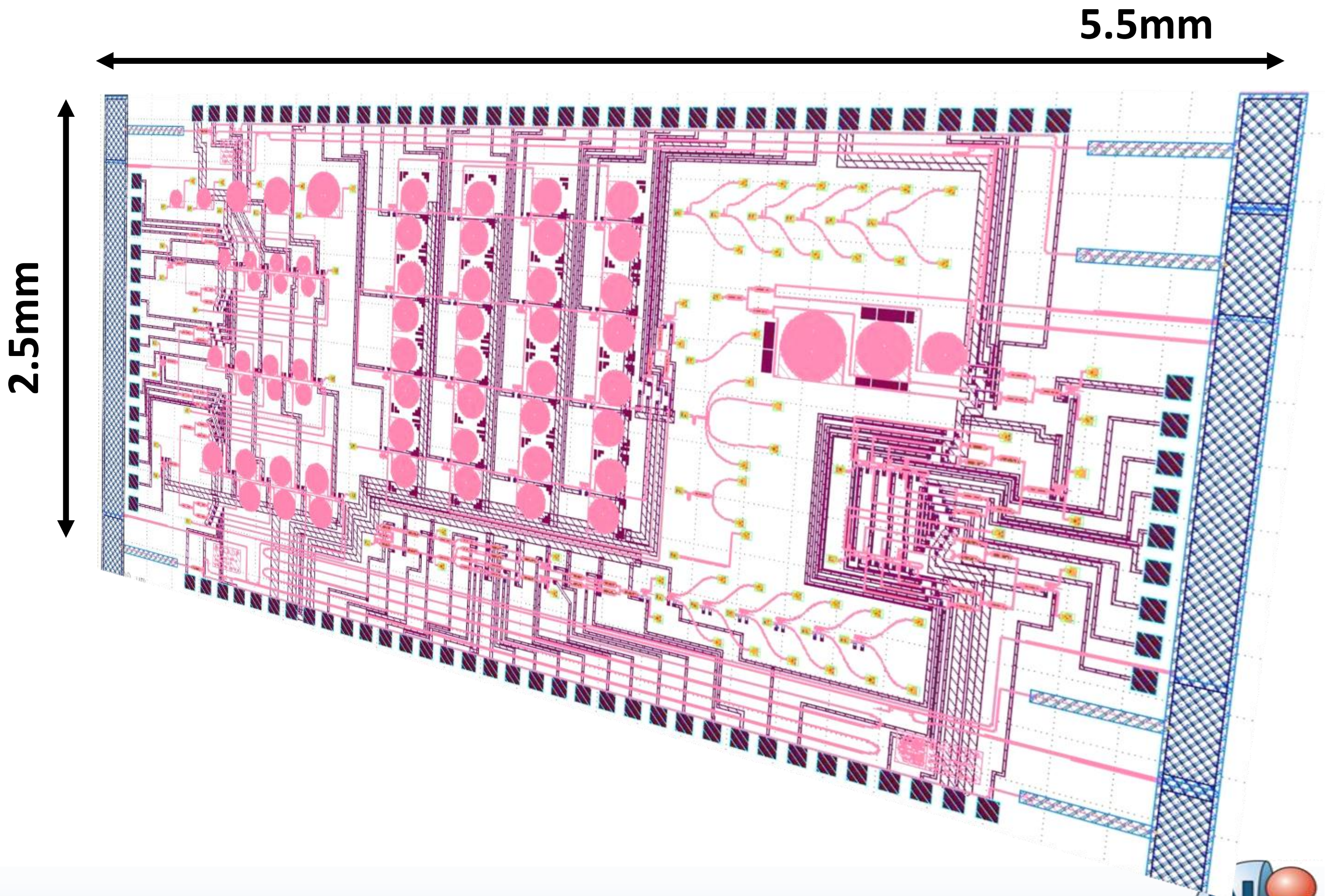
The output layer can more easily distinguish the inputs



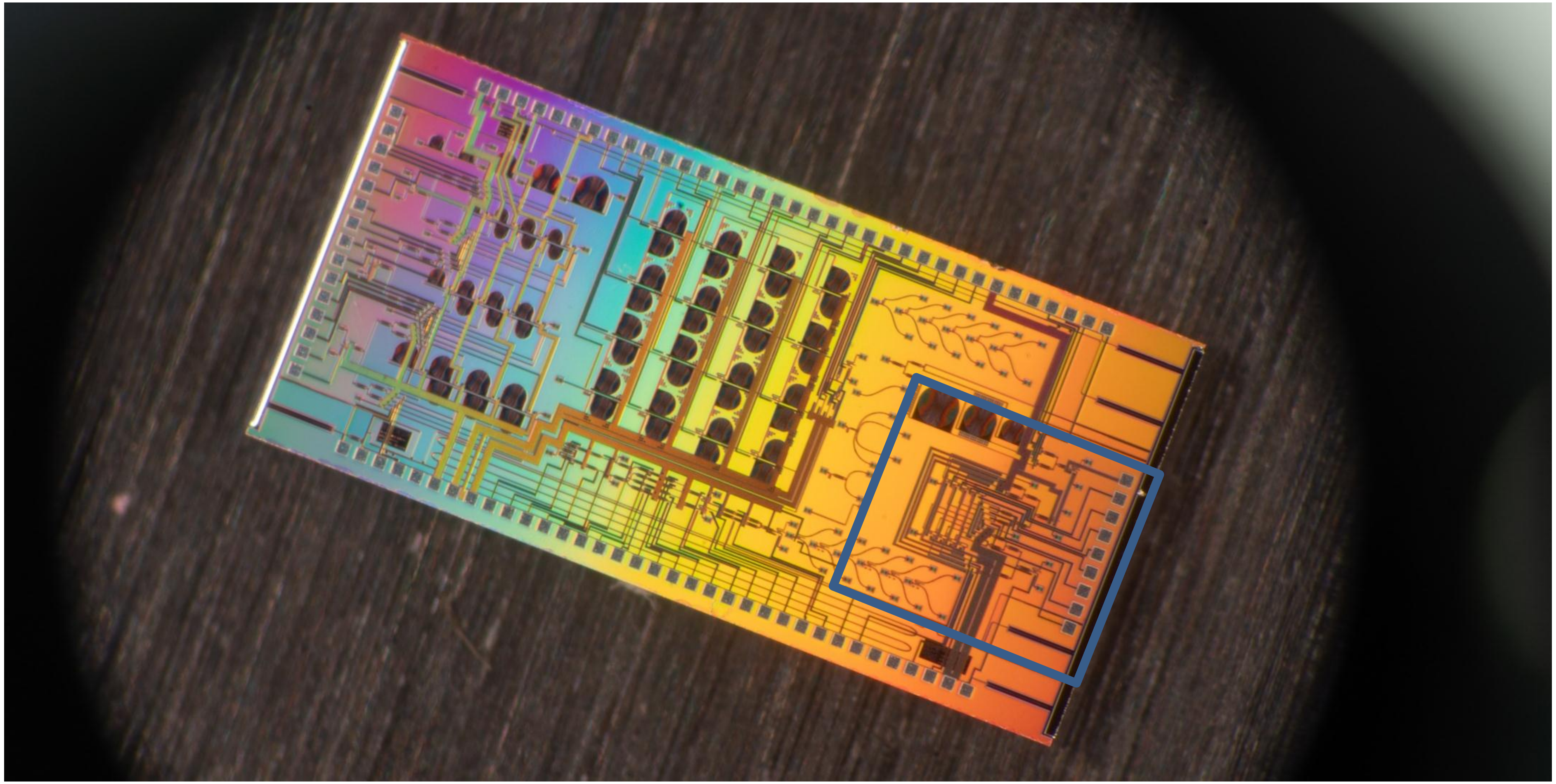
Integrated photonics applied to ANNs

Advantages of silicon photonics:

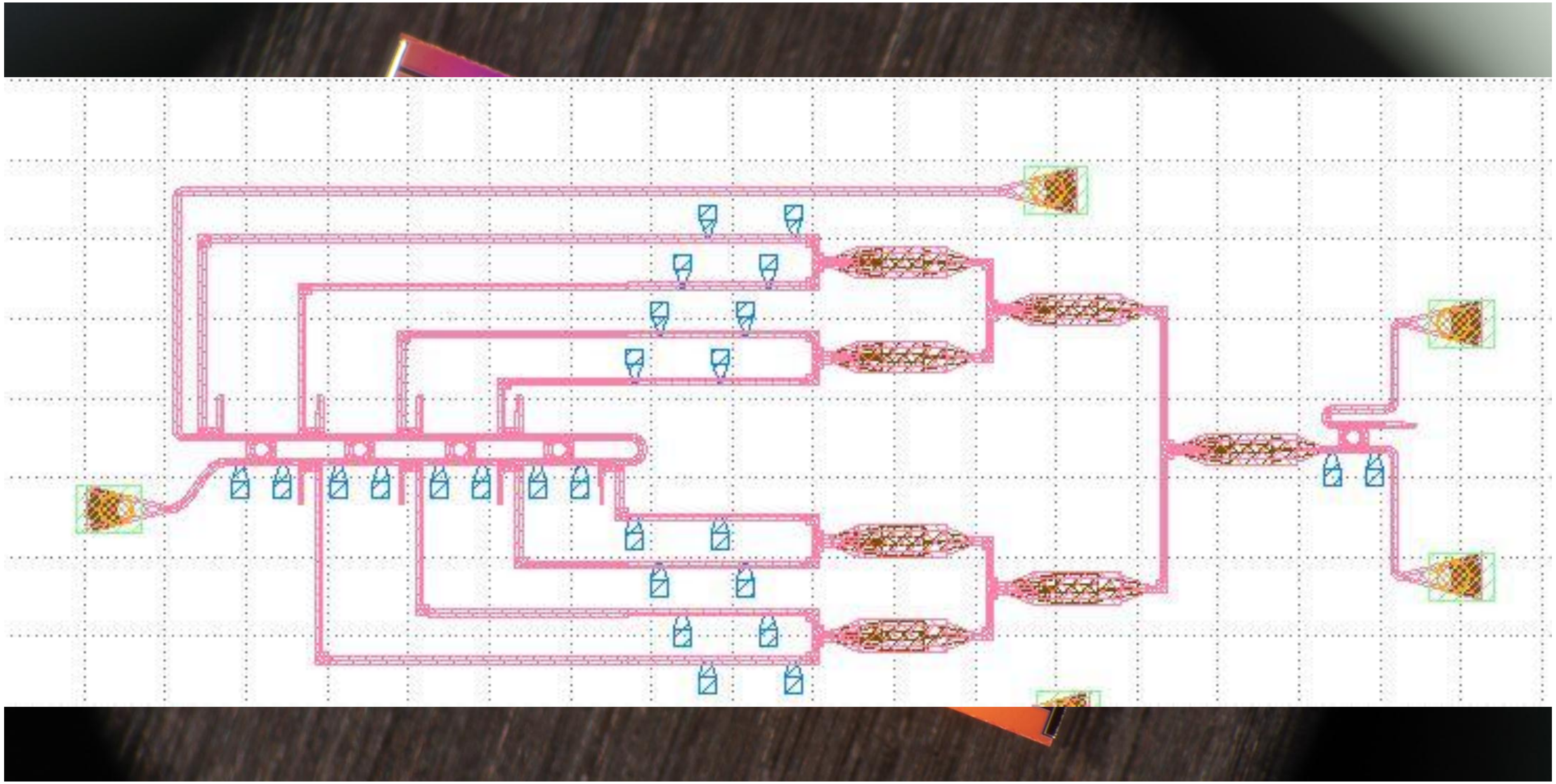
- Stable, well-understood material
- Relatively low-cost substrates
- High refractive index means short devices
- High thermal conductivity means tolerance to high-power devices or to high packing density
- Thermo-optic effect means a second possibility for optical modulation exists



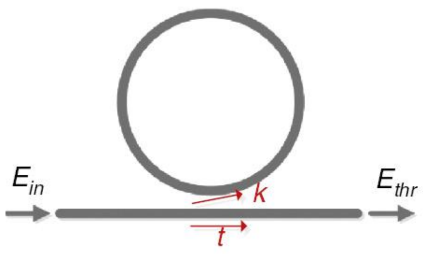
Chip design and SCISSOR definition



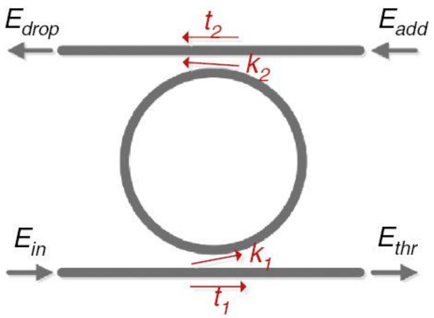
Chip design and SCISSOR definition



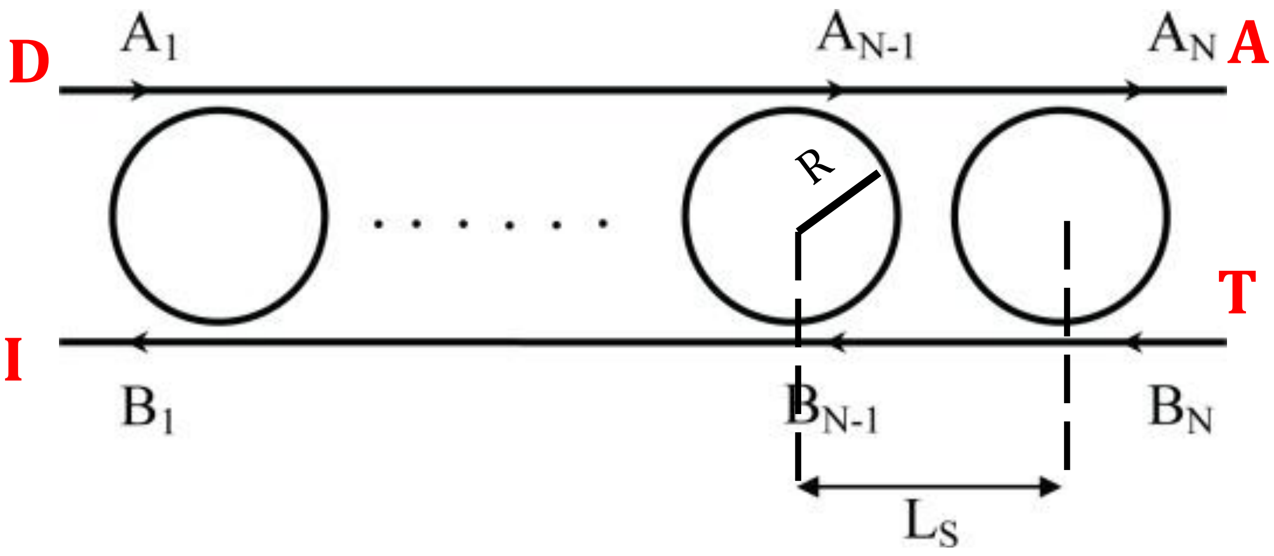
Chip design and SCISSOR definition

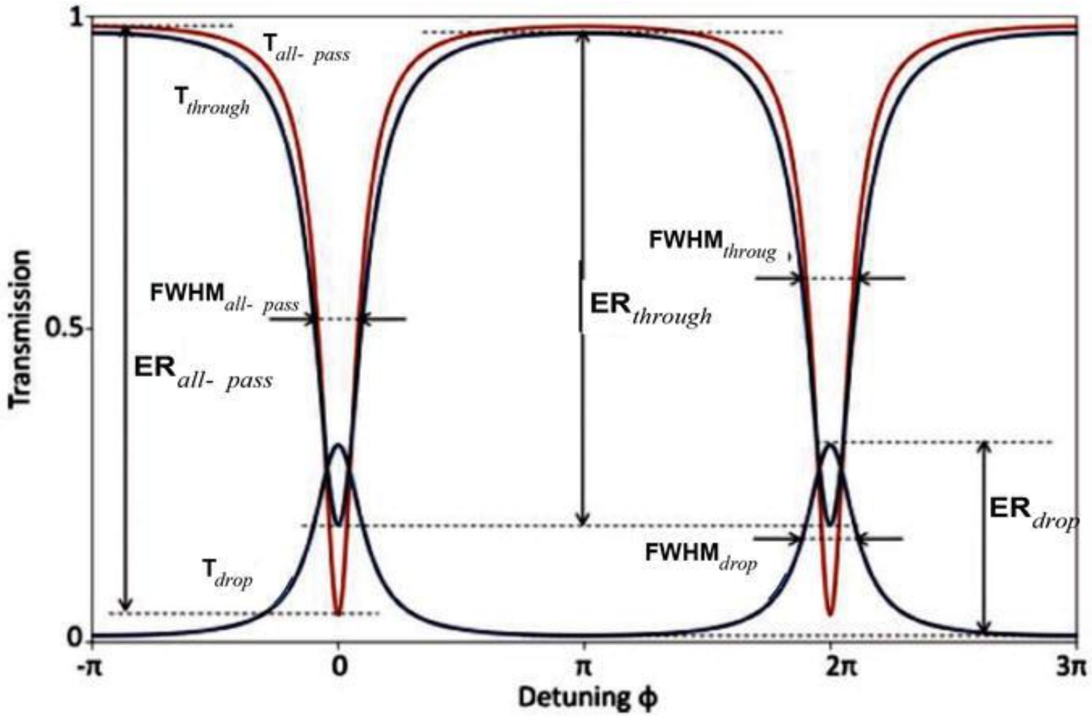


All-pass ring resonator



Add-drop ring resonator

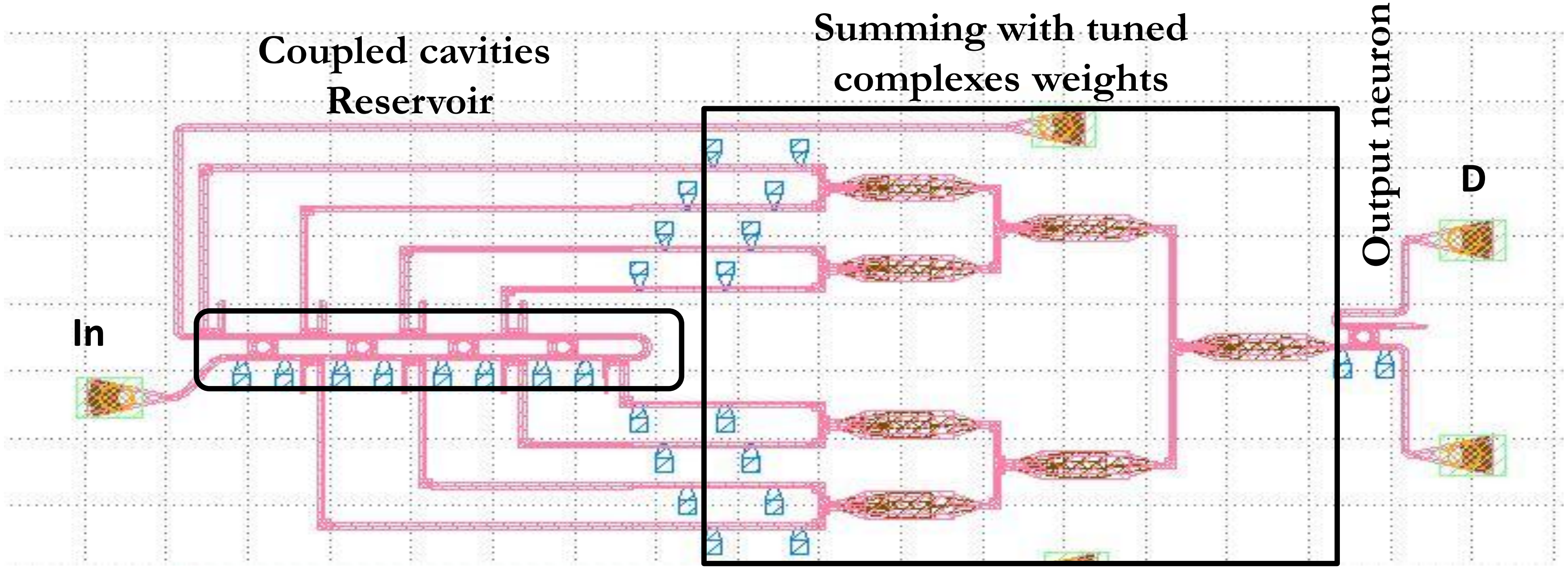




Transmission spectrum of an all-pass ring and the two outputs of add-drop ring

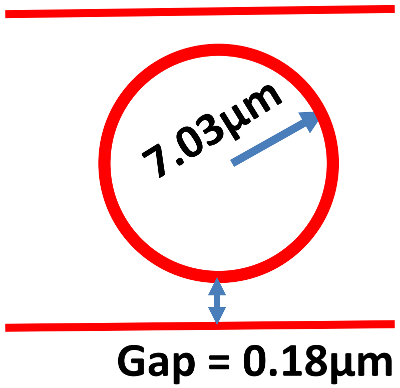
$$FSR_{\lambda_m} \simeq \frac{\lambda_m^2}{n_{eff}^g(\lambda_m)\, 2\pi R} \qquad Q := \frac{\omega_m}{FWHM_{\omega_m}} = \frac{\lambda_m}{FWHM_{\lambda_m}}$$

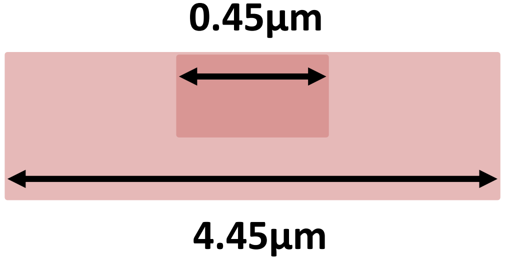
Chip design and SCISSOR definition



The reservoir is an optical cavity composed by series of coupled ring resonators

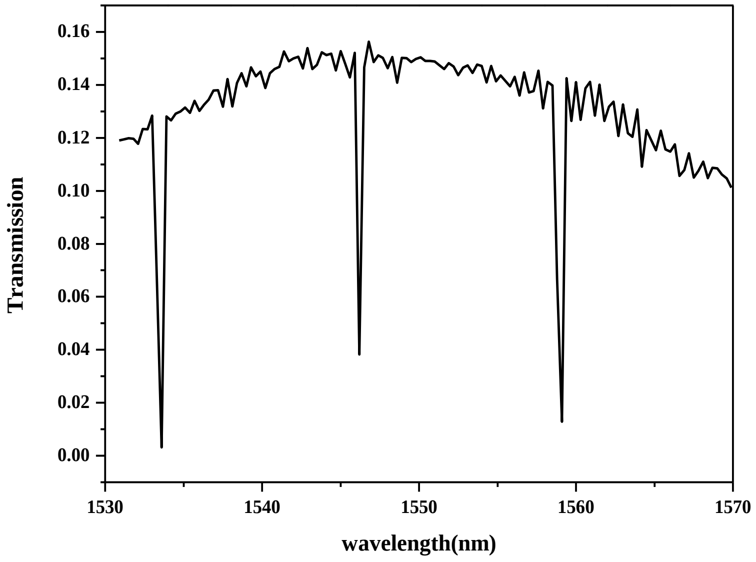
The field inside the cavity is probed by a number of waveguides and sent to the perceptron.

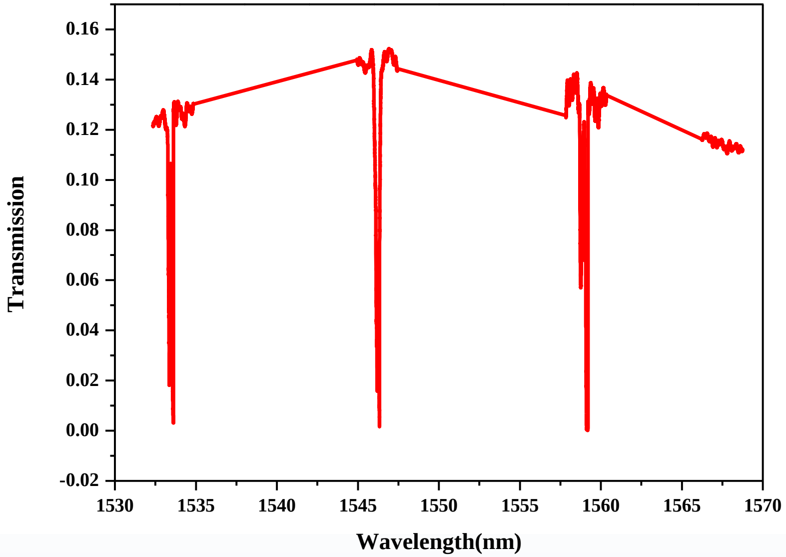


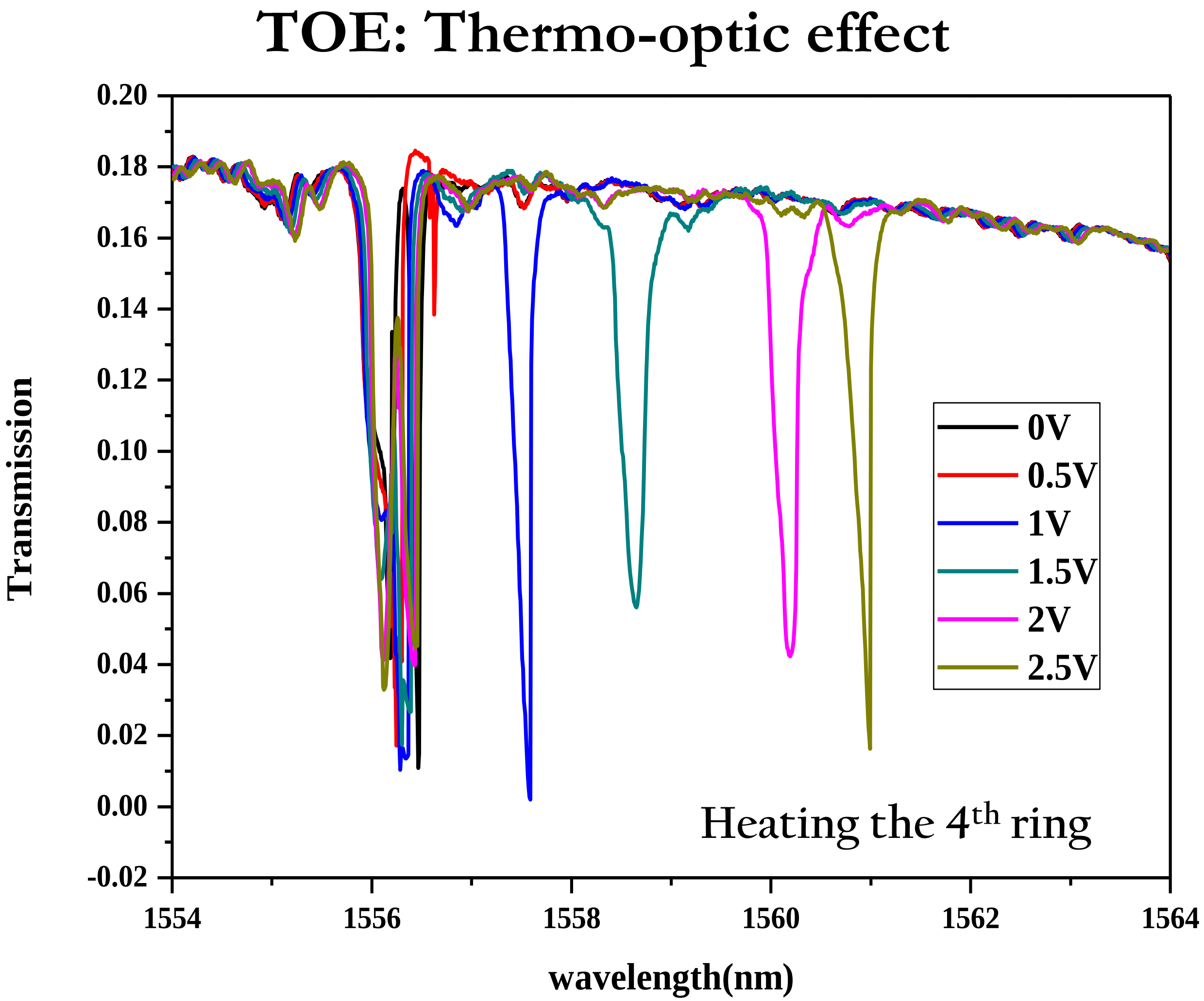


Cross-section of the waveguide

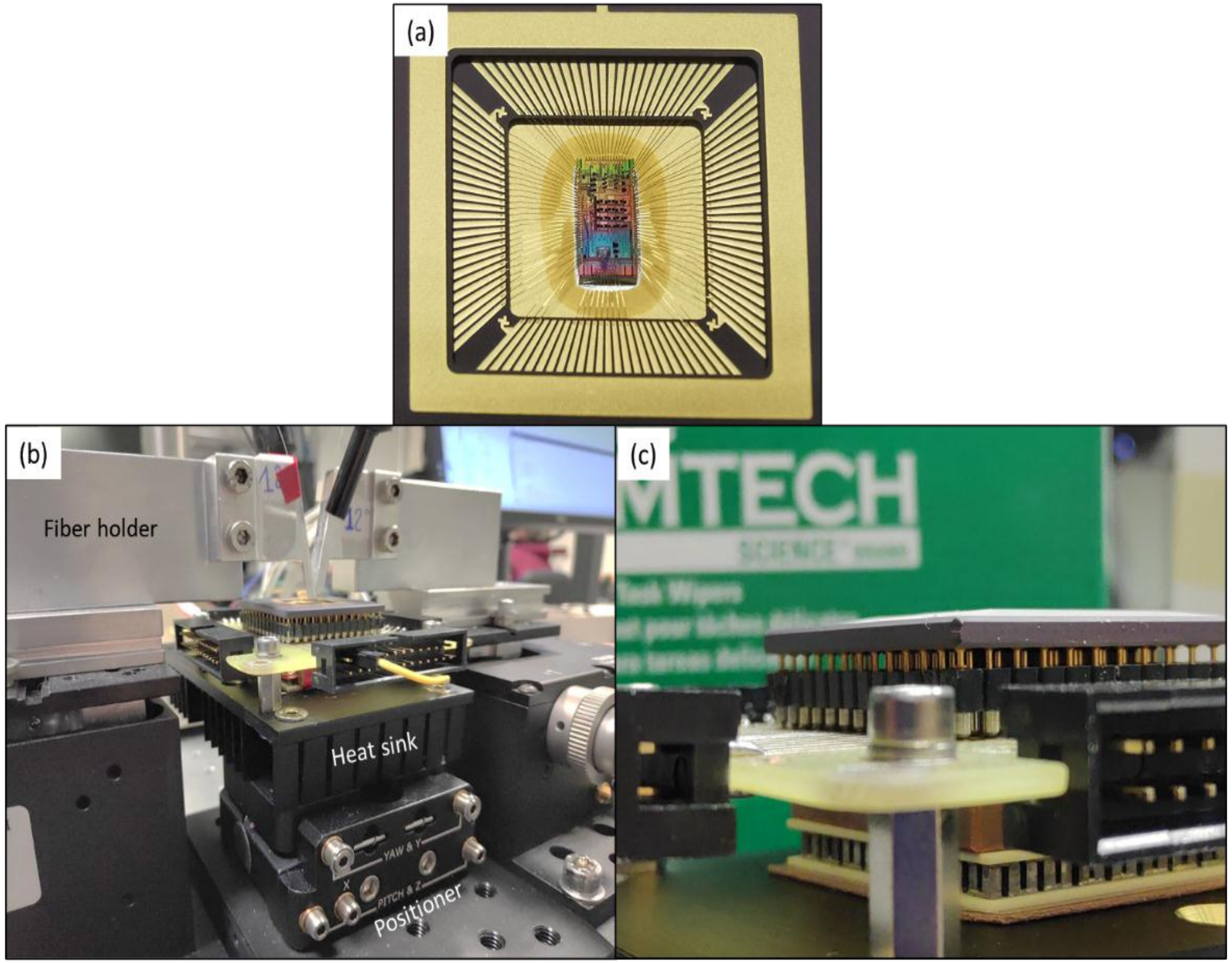
Sequence of coupled resonators: experimental results

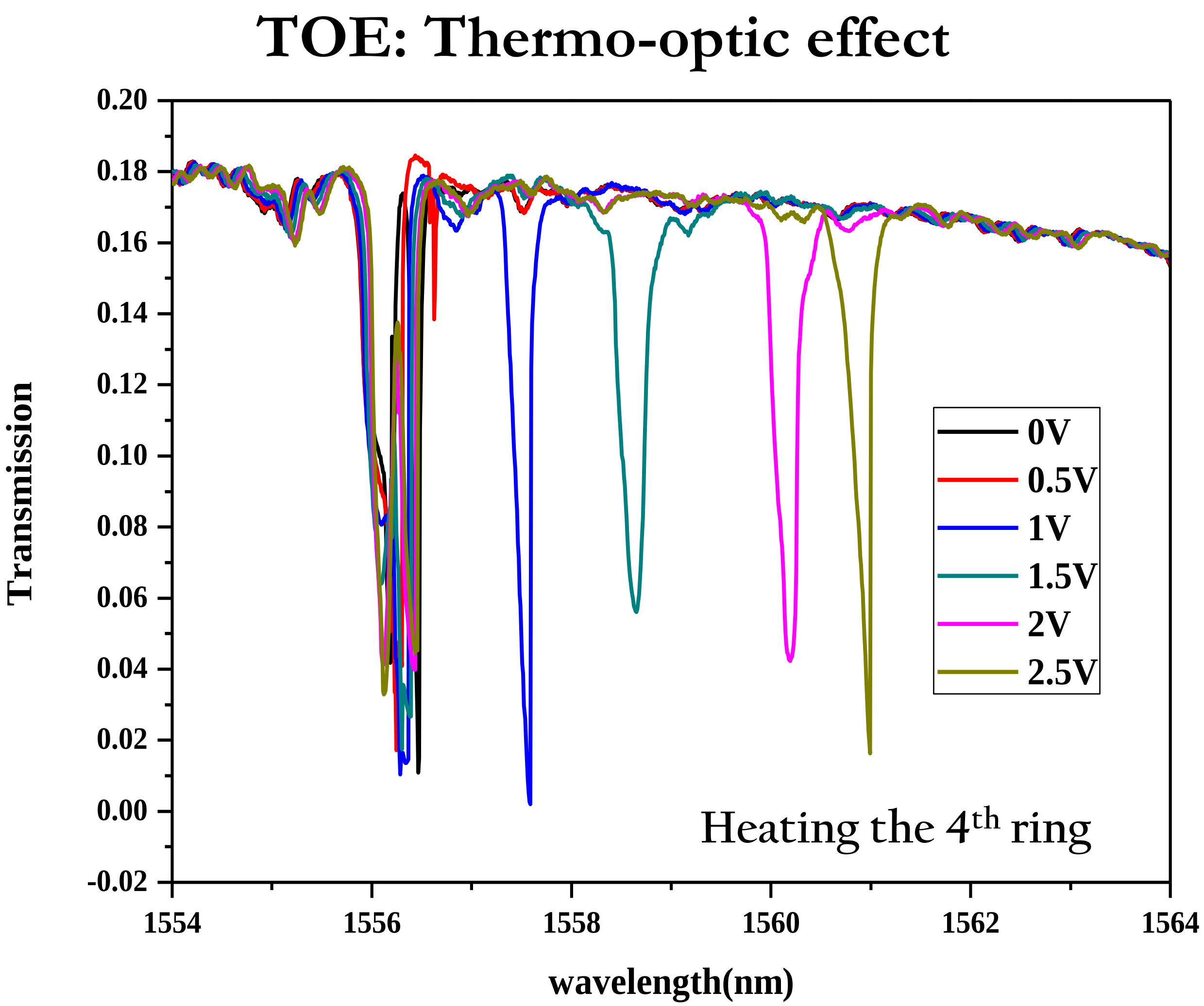






Sequence of coupled resonators: experimental results





Sequence of coupled resonators: experimental results

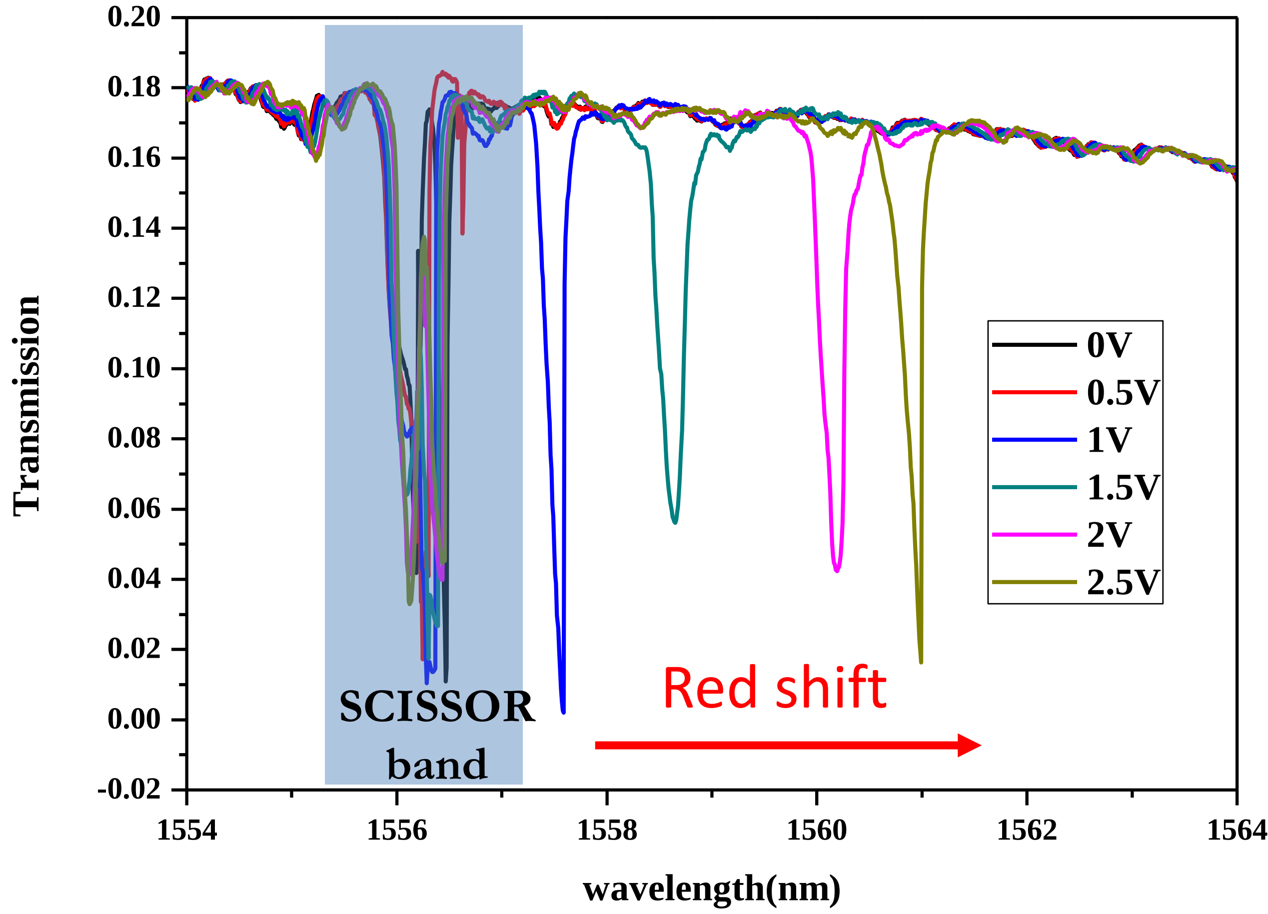
Resonance frequency shift induced by thermo optic effect

$$\Delta n_{TOE}\,(r) = \frac{dn}{dT}\Delta T$$

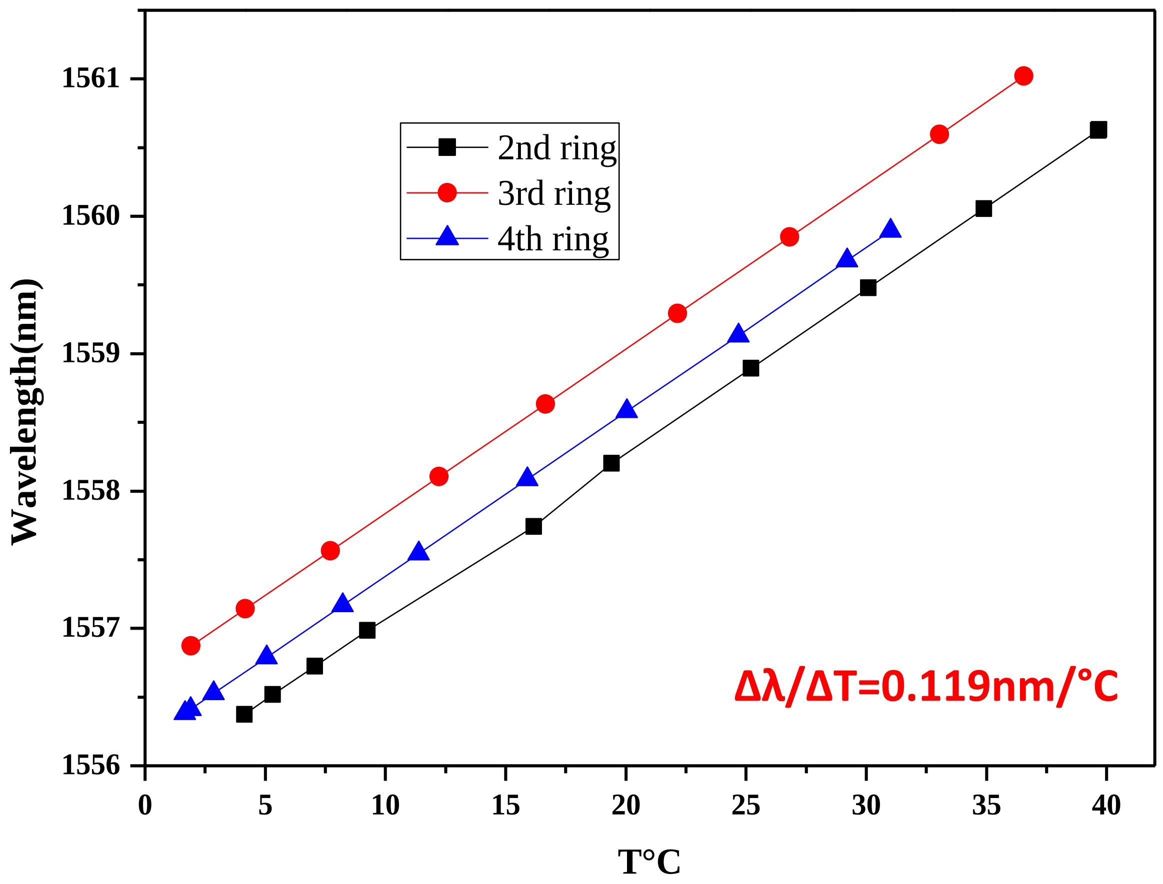
TOE: Thermo-optic effect

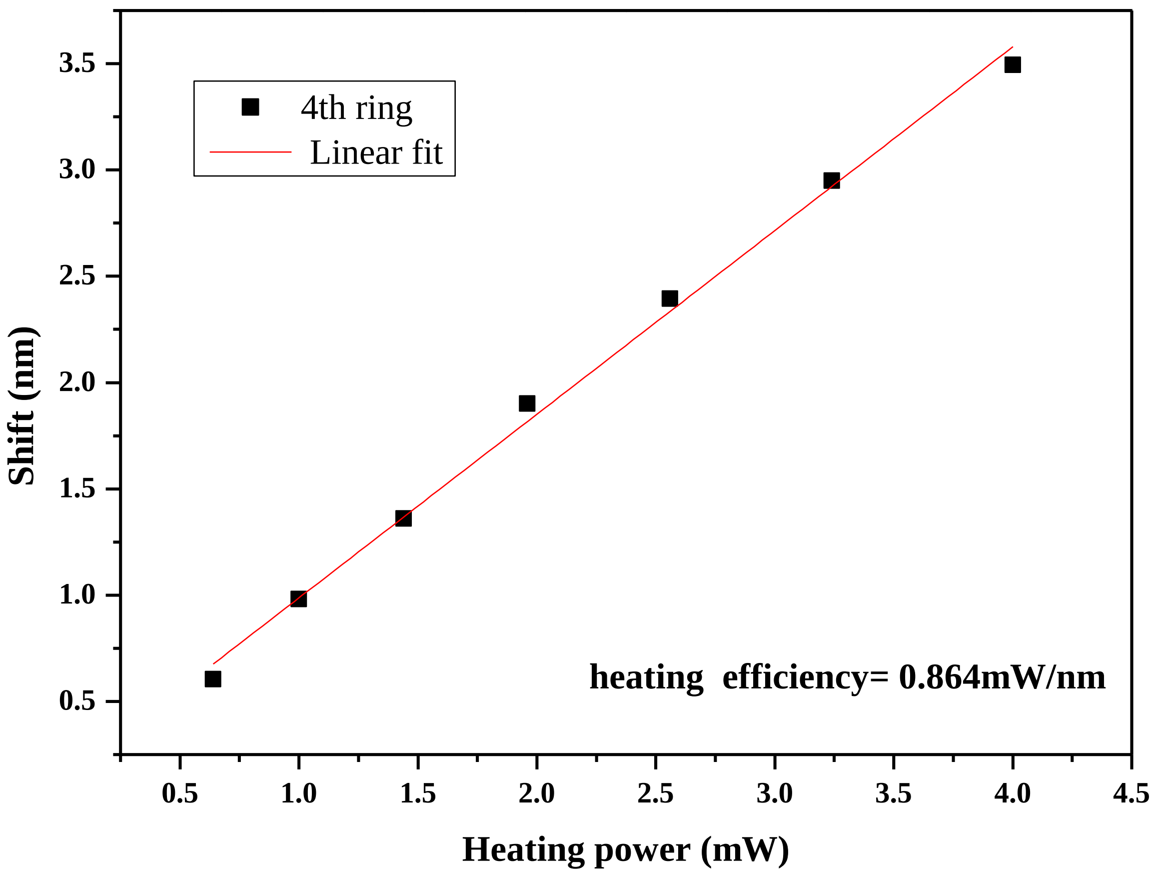
$\Delta n_{TOE} > 0$ Red shift

$$\Delta T = \frac{n_{eff}}{k_{toe}}\,\frac{\Delta\lambda}{\lambda_m}$$



Sequence of coupled resonators: experimental results

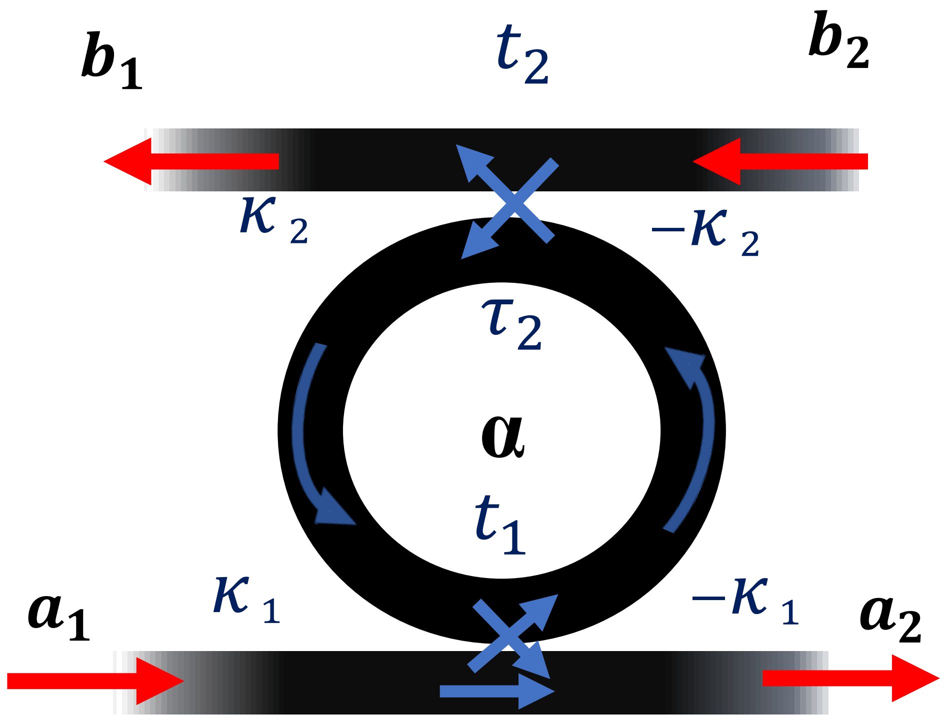




Cold Resonant Frequency

- **1555.86 nm (3rd ring)**
- **1556.64 nm (4th ring)**
- **1556.18 nm (2nd ring)**

Add-Drop Filter



$$\begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = \mathrm{K1*P*K2} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \equiv \mathrm{M} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

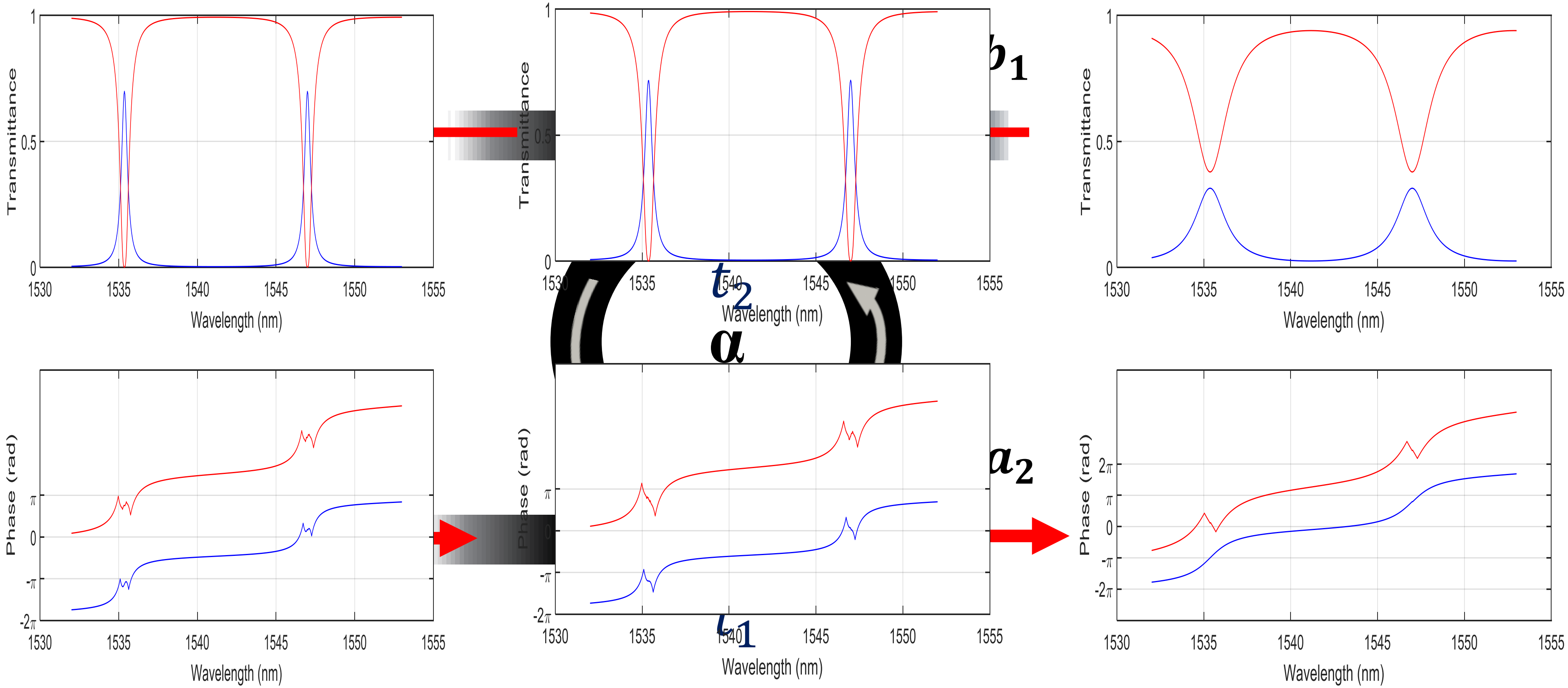
$$\mathrm{K2} = \frac{1}{ik2} \begin{pmatrix} -t2 & 1 \\ -1 & t2 \end{pmatrix}; \quad \mathrm{K1} = \frac{1}{ik1} \begin{pmatrix} -t1 & 1 \\ -1 & t1 \end{pmatrix}; \quad \mathrm{P} = \begin{pmatrix} 0 & \frac{1}{\gamma} e^{-i\theta} \\ \gamma e^{i\theta} & 0 \end{pmatrix}$$

$$\begin{pmatrix} b_1 \\ a_2 \end{pmatrix} = \frac{1}{M_{22}} \begin{pmatrix} -M_{22} & 1 \\ -\det(M) & M_{12} \end{pmatrix} \begin{pmatrix} a_1 \\ b_2 \end{pmatrix} \equiv \mathrm{M'} \begin{pmatrix} a_1 \\ b_2 \end{pmatrix}$$

$$T = \left|\frac{b_1}{a_1}\right|^2 = \left|\frac{\det(M')}{M'_{22}}\right|^2$$

$$D = \left|\frac{a_2}{a_1}\right|^2 = \left|-\frac{M'_{21}}{M'_{22}}\right|^2$$

Sequence of coupled resonators: Modelling



$t_1 > \alpha^2 t_2$: over coupling

$t_1 = 0.95$; $t_2 = 0.9$

$\alpha = 0.99$

$t_1 = \alpha^2 t_2$: critical coupling

$t_1 = 0.95$; $t_2 = 0.931$

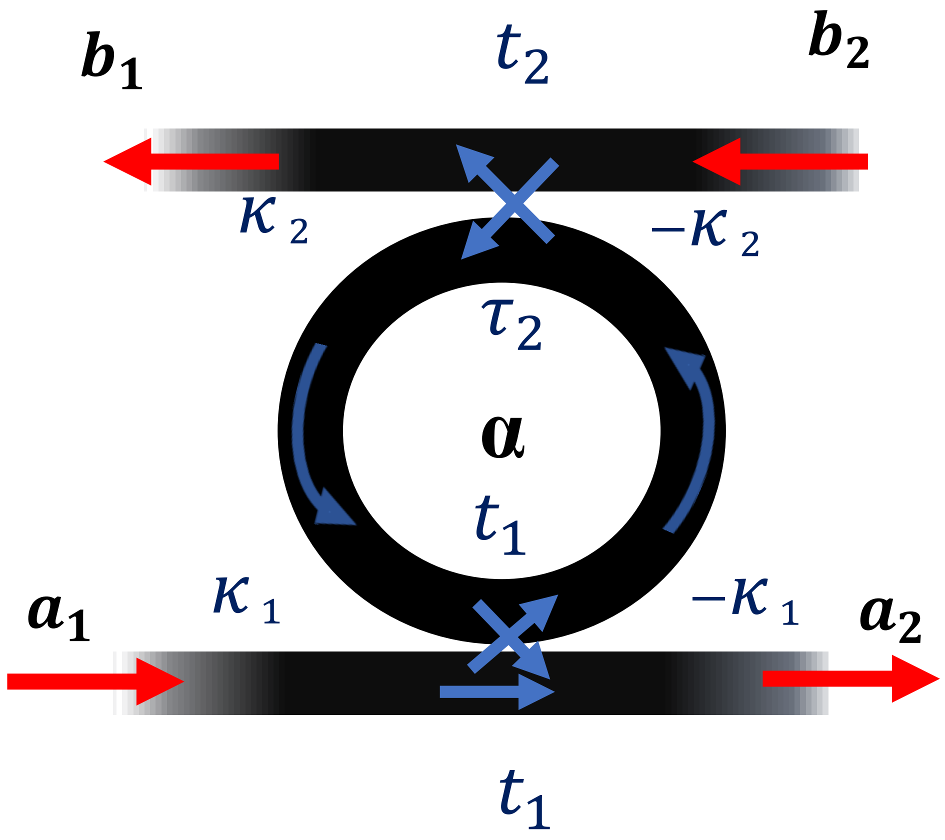
$\alpha = 0.99$

$t_1 < \alpha^2 t_2$: under coupling

$t_1 = 0.95$; $t_2 = 0.6$

$\alpha = 0.99$

Add-Drop Filter



$$\begin{pmatrix} b_2 \\ b_1 \end{pmatrix} = \text{K1*P*K2} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \equiv \text{M} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

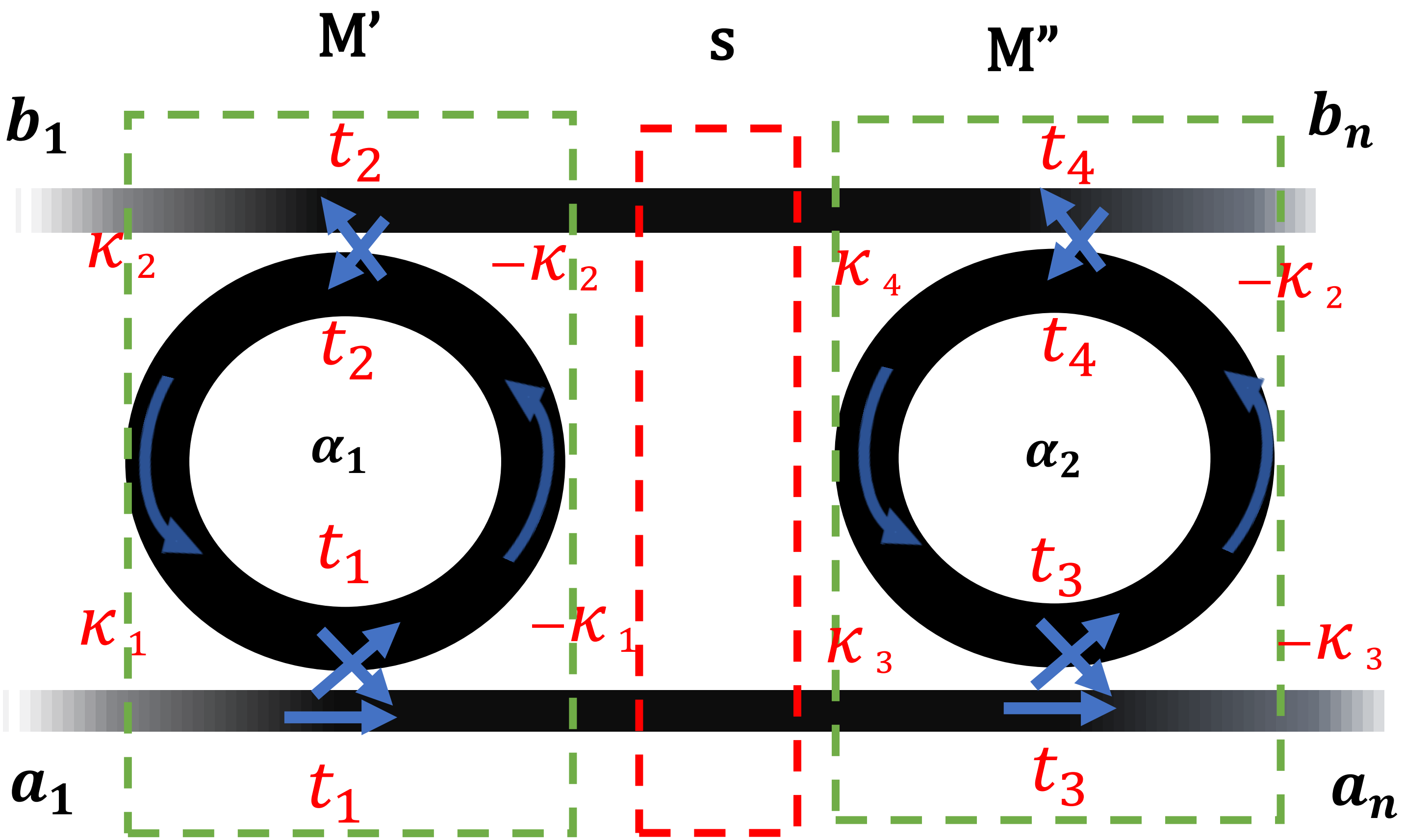
$$\text{K2} = \frac{1}{ik2} \begin{pmatrix} -t2 & 1 \\ -1 & t2 \end{pmatrix}; \quad \text{K1} = \frac{1}{ik1} \begin{pmatrix} -t1 & 1 \\ -1 & t1 \end{pmatrix}; \quad \text{P=} \begin{pmatrix} 0 & \frac{1}{\gamma} e^{-i\theta} \\ \gamma e^{i\theta} & 0 \end{pmatrix}$$

$$\begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = \frac{1}{M_{22}} \begin{pmatrix} -M_{22} & 1 \\ -\det(M) & M_{12} \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \equiv \text{M'} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

$$T = \left| \frac{a_2}{a_1} \right|^2 = \left| \frac{\det(M')}{M'_{22}} \right|^2$$

$$D = \left| \frac{b_1}{a_1} \right|^2 = \left| - \frac{M'_{21}}{M'_{22}} \right|^2$$

Sequence of coupled resonators: Modelling



$$S=\begin{pmatrix} e^{-i\varphi} & 0 \\ 0 & e^{i\varphi} \end{pmatrix}$$

$$\begin{pmatrix} a_n \\ b_n \end{pmatrix} \equiv M'' .S .M' \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

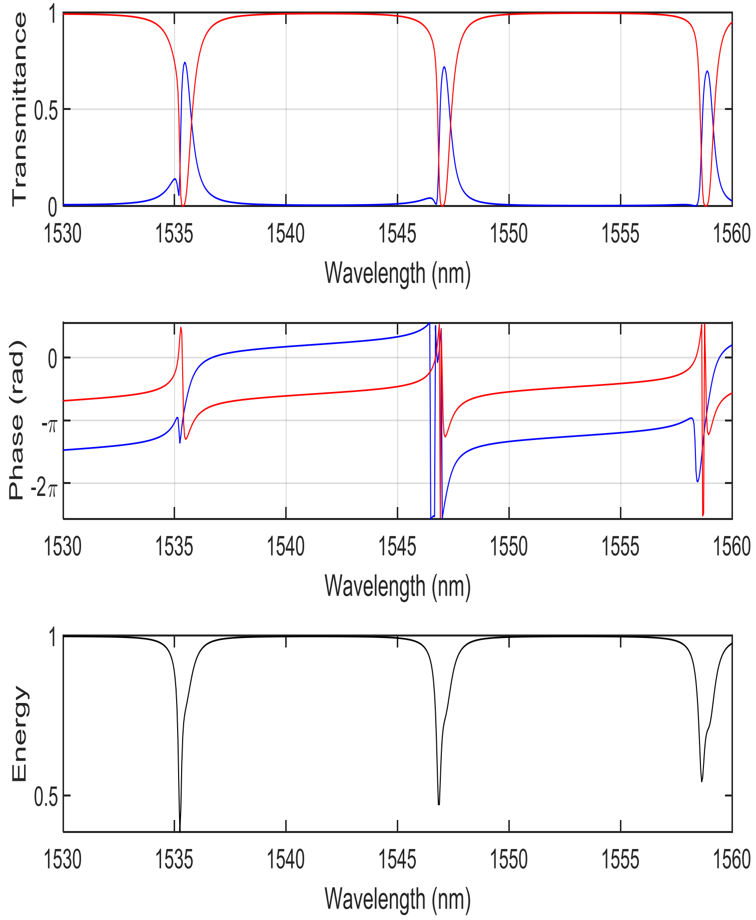
$$\begin{pmatrix} a_n \\ b_n \end{pmatrix} \equiv N \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

$$T = \left|\frac{a_n}{a_1}\right|^2 = \left|\frac{\det(N)}{N_{22}}\right|^2$$

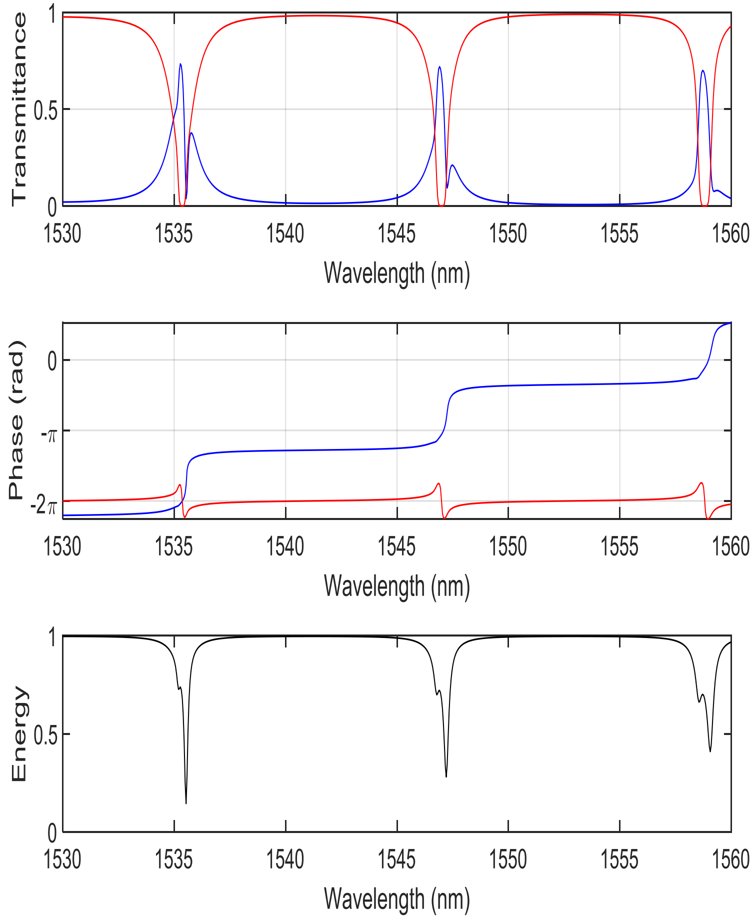
$$D = \left|\frac{b_1}{a_1}\right|^2 = \left|-\frac{N_{21}}{N_{22}}\right|^2$$

Sequence of coupled resonators: Modelling

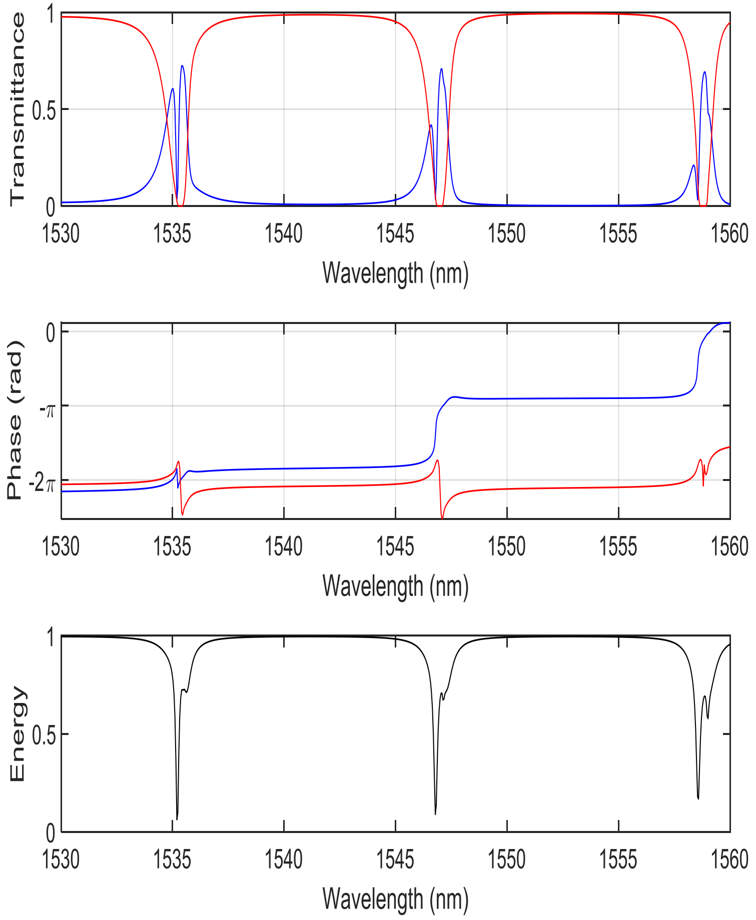
Two rings



Three rings

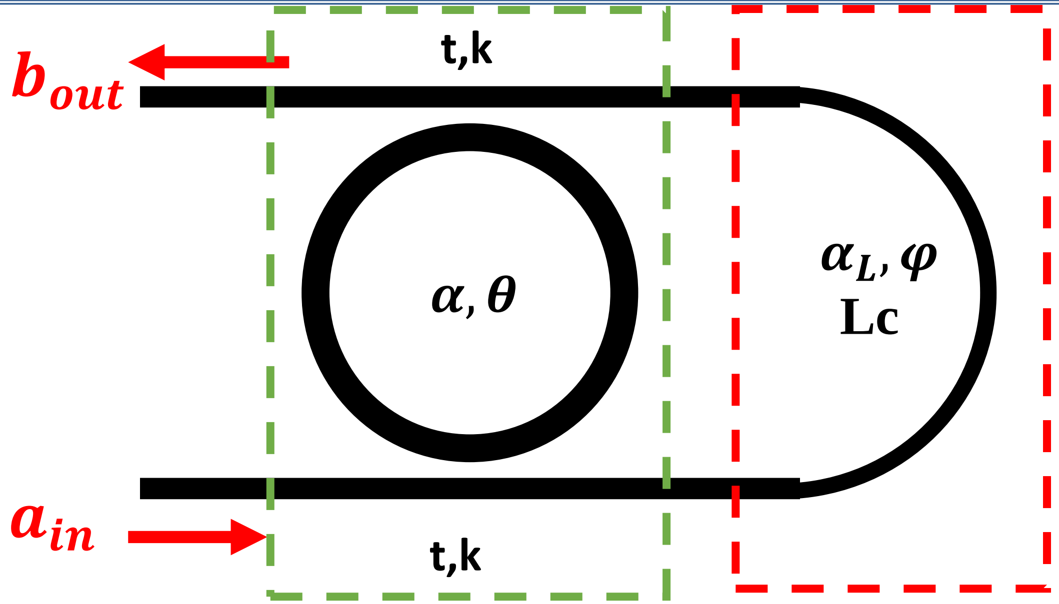


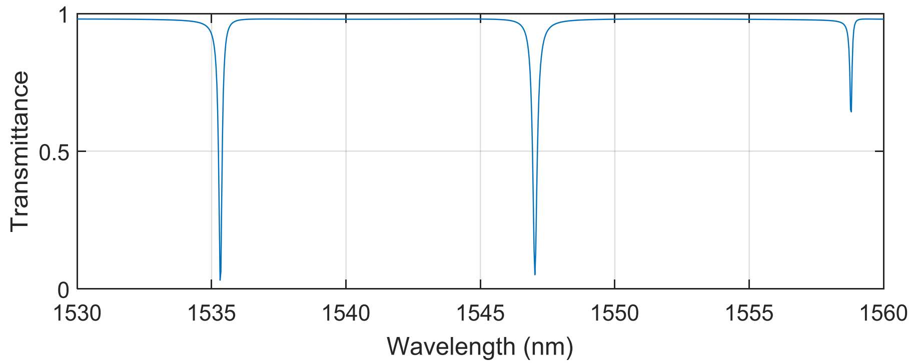
Four rings

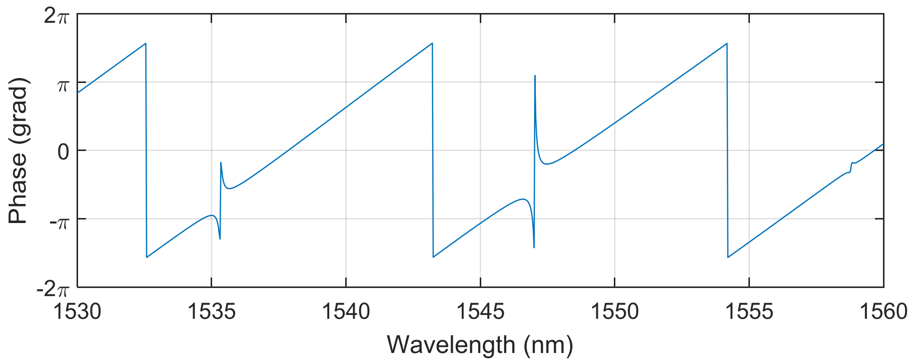


t_i =0.95; U = 3μm
$R_i = 6.5\mu m$; α_i=0.99 (i=1,2,3,4)

Feedback coupled waveguide (FCW)



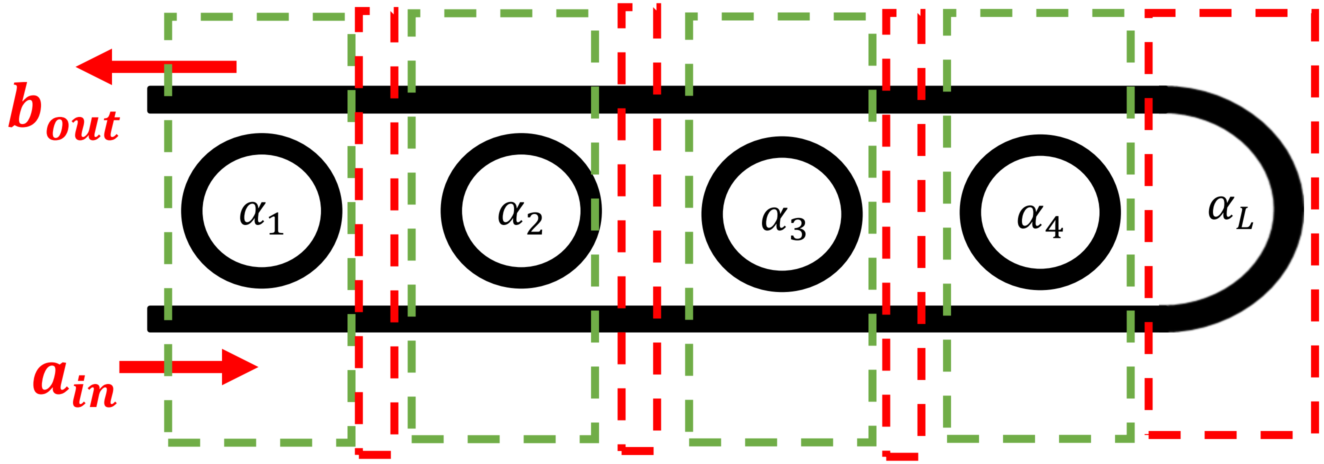


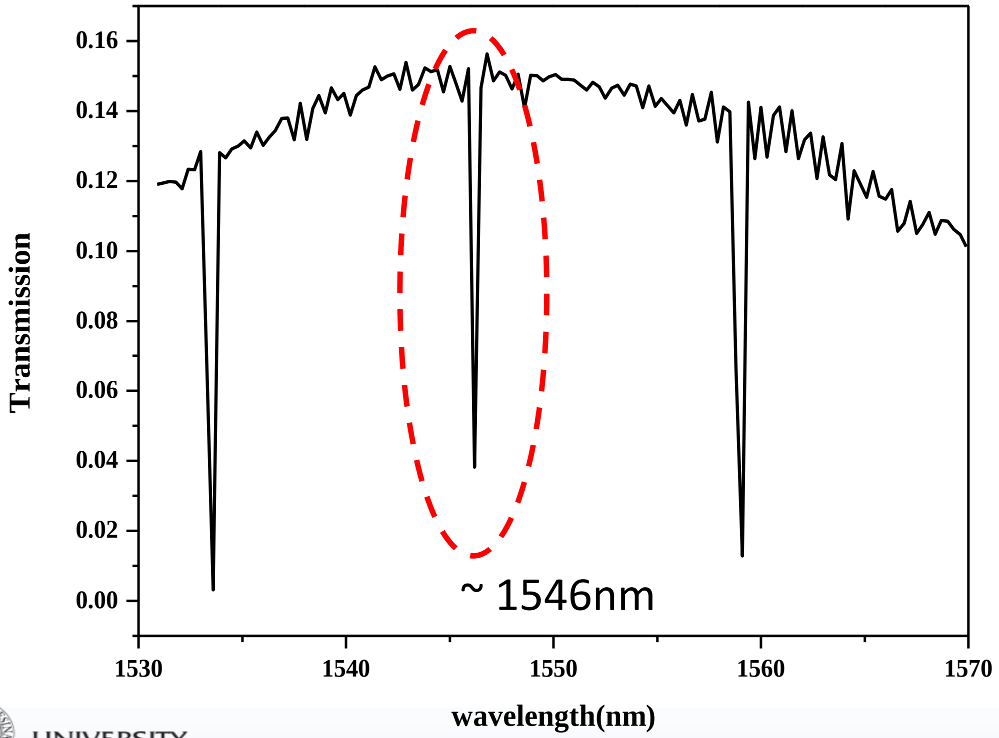


$$C = \alpha_L e^{i\varphi}$$

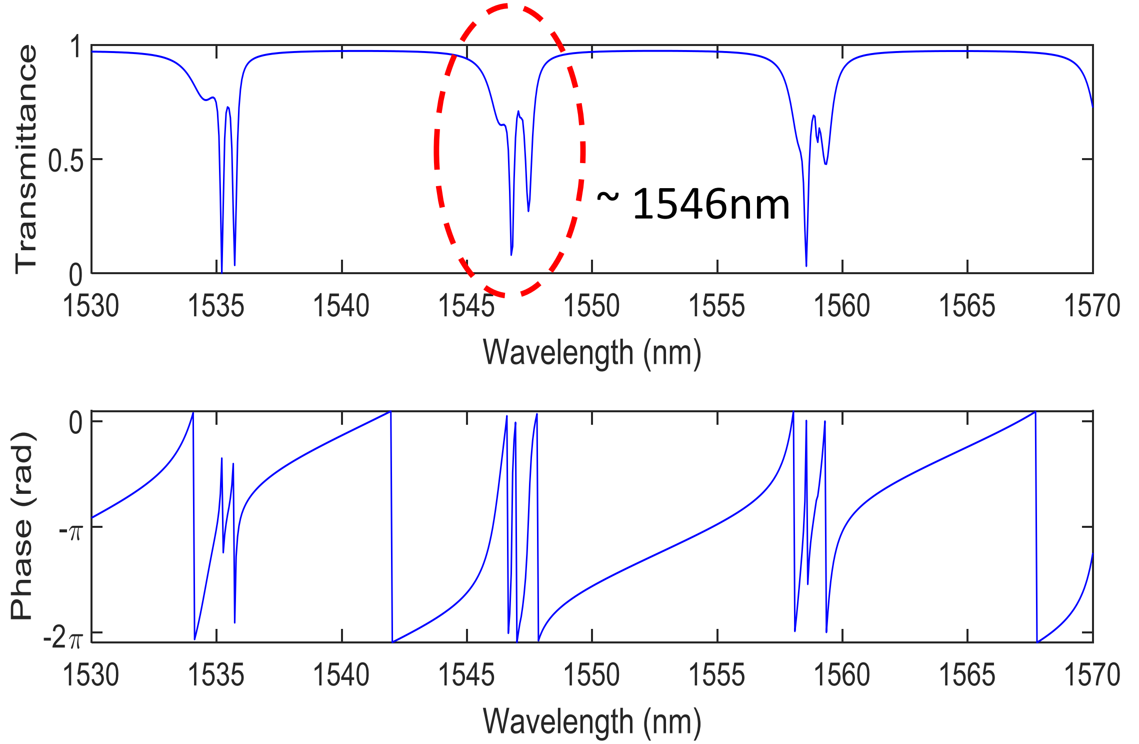
$$D = \left|\frac{b}{a}\right|^2 = \left|\frac{(CN_{11} - N_{21})}{N_{22} - CN_{12}}\right|^2$$

Sequence of coupled resonators: Simulations

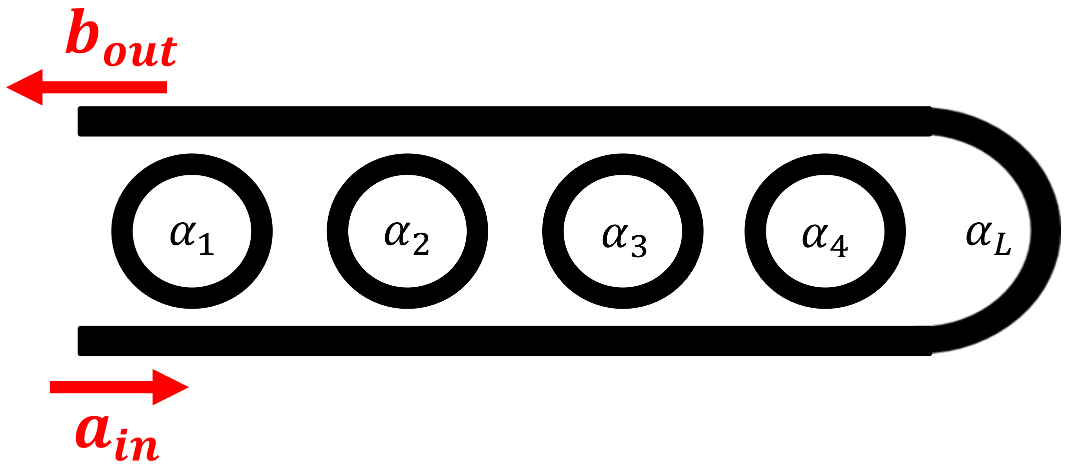




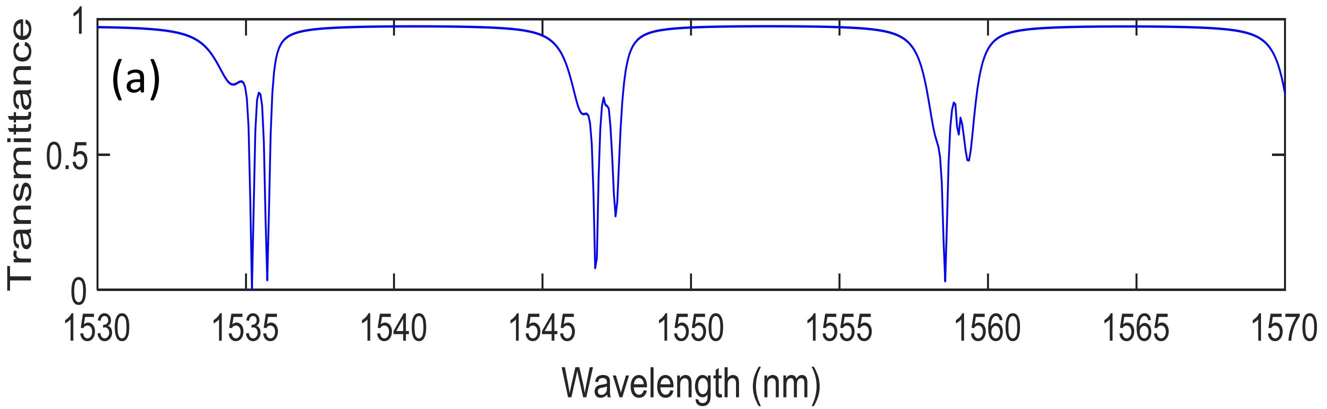
Transmission spectra of b_{out}

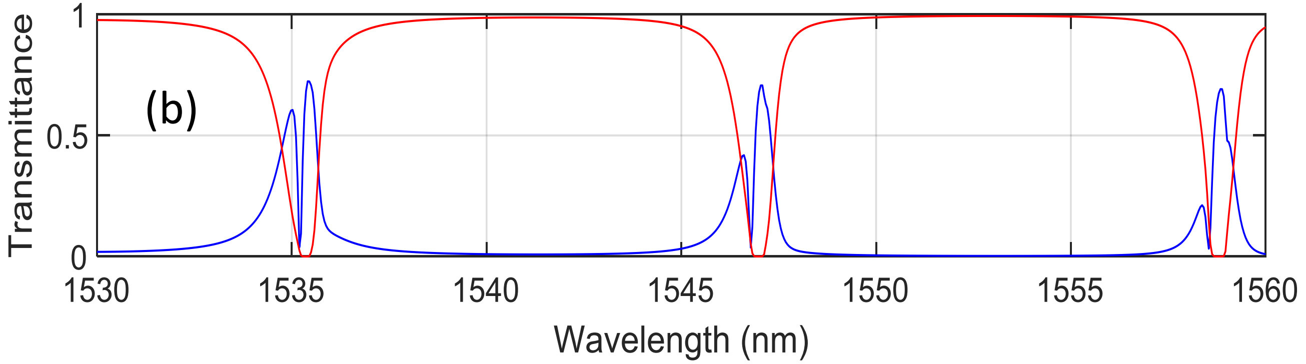


Sequence of coupled resonators: Simulations



Transmission spectra of (a)SCISSOR with FCW(b) and SCISSOR without FCW

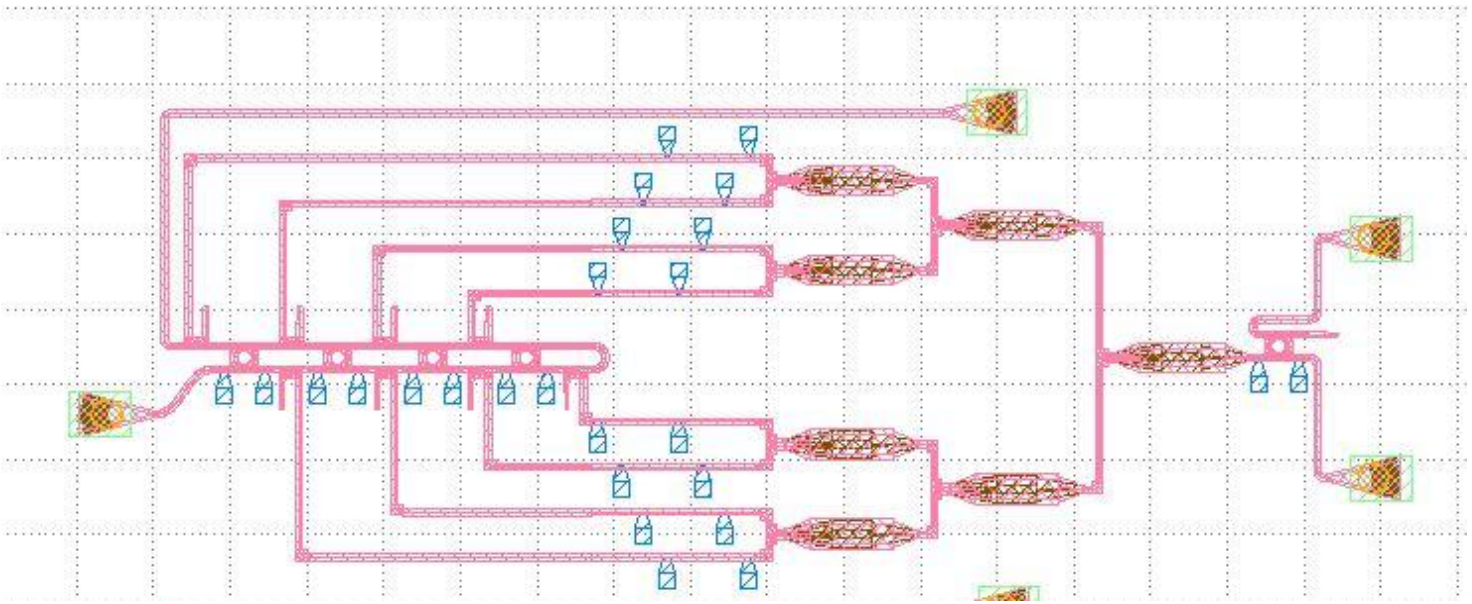




Conclusion and perspectives

- Modelling tool able to model the properties of the SCISSOR: the SCISSOR simulation reproduce almost the same experimental results

- Start to simulate the neural network based on our SCISSOR



Thank you for your attention