Optical Neural Networks

- Optical Diode
- Polariton Circuits
- Perceptron

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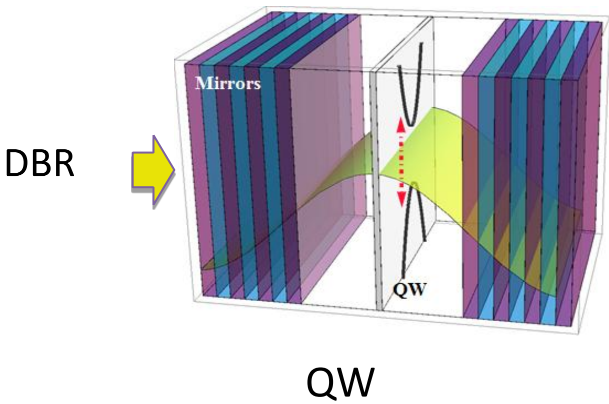
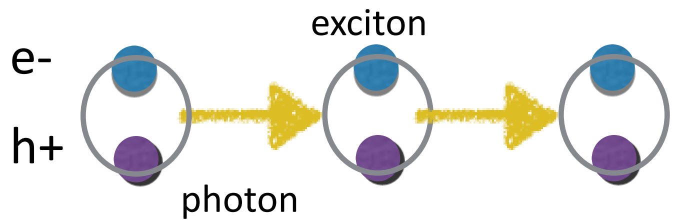
(2) University of Iceland

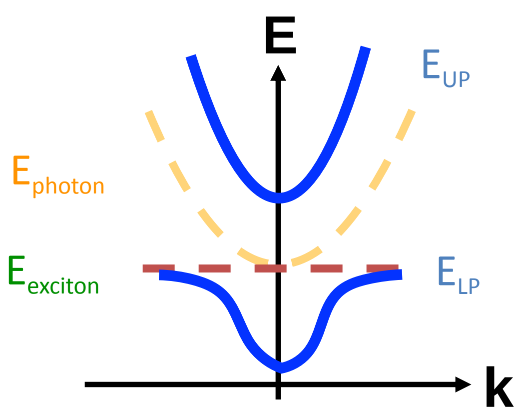
Polaritons=exciton+photon strongly coupled

Optical microcavity



Strong coupling: when the photon transform to an exciton before it decays and the exciton transform to a photon before it dephases.





$$H = E_{ck}\hat{\phi}_k^+\hat{\phi}_k + E_X\hat{\chi}^+\hat{\chi}_k + \Omega_R(\hat{\phi}_k^+\hat{\chi}_k + \hat{\chi}_k^+\hat{\phi}_k)$$

- Optical control.
- Nonlinear response due exciton nature.
- High speed signal transport would allow faster calculations.
- Low carrier resistance would reduce heat losses.

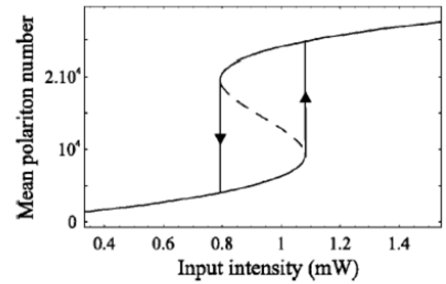
Optical Diode

Polarition bistability

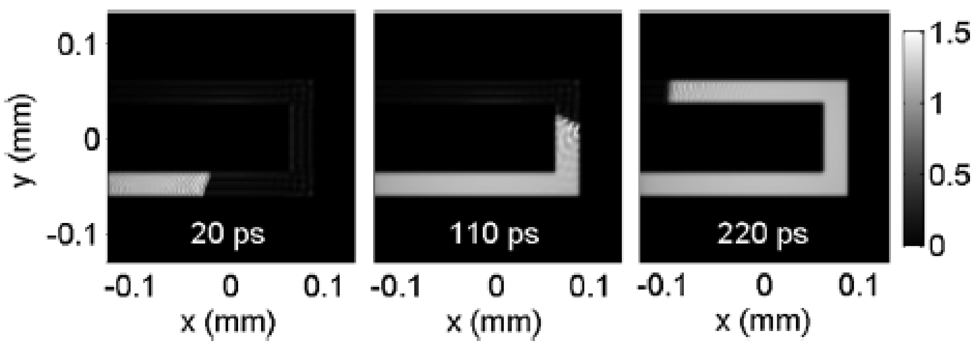
- Polaritons are bosons that might form a single coherent state composed of a macroscopic number of particles.

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(\widehat{E}_{LP}(\widehat{\mathbf{k}}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha|\Psi|^2\right)\Psi + \mathfrak{F}(\mathbf{r},t)e^{-\frac{i\varepsilon_p t}{\hbar}}.$$

- Lower polariton mode: provide kinetic energy
- Potential
- Polariton lifetime
- Exchange interactions due exciton components
- Optical pump



- D. M. Whittaker, Phys. Rev. B **71**, 115301 (2005).
- A. Baas, J. Ph. Karr, H. Eleuch, and E. Giacobino, Phys. Rev. A **69**, 023809 (2004).
- N. A. Gippius *et al.*, Europhys. Lett. **67**, 997 (2004).



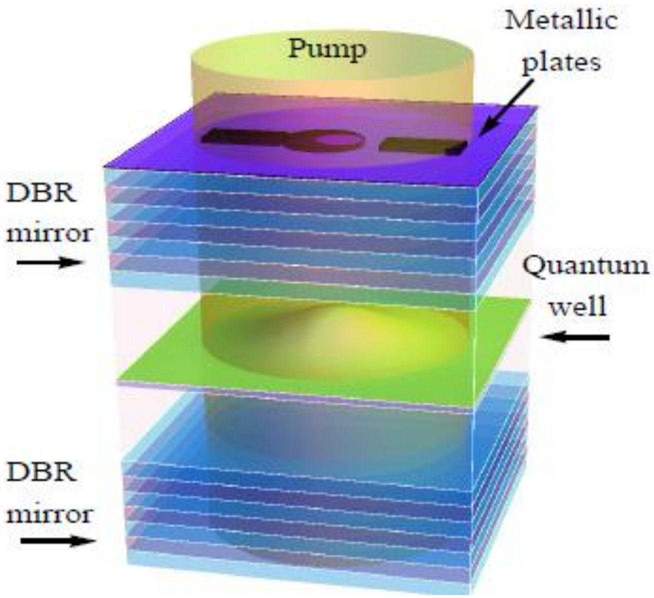
$$|\mathfrak{F}|^2 = \left[\left(\varepsilon_p - V(\mathbf{r}) - \alpha|\Psi|^2\right)^2 + \frac{\hbar^2}{4\tau^2}\right]|\Psi|^2$$

T. C. H. Liew, A. V. Kavokin, and I. A. Shelykh, Phys. Rev. Lett. **101**, 016402 (2008).

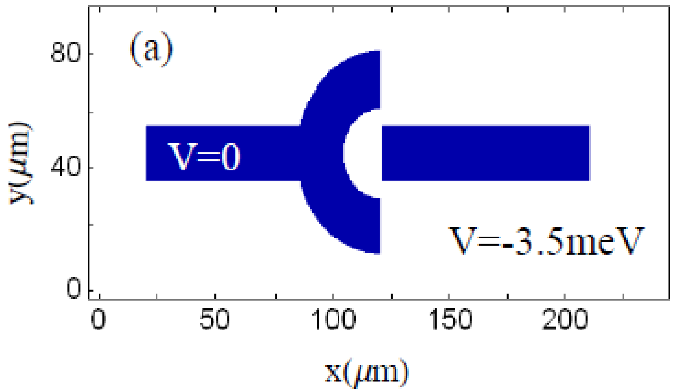
Optical Diode

Optical Diode

- **Ideal Diode**: The forward signal is fully transmitted while the transmission in the reverse direction tends to zero.

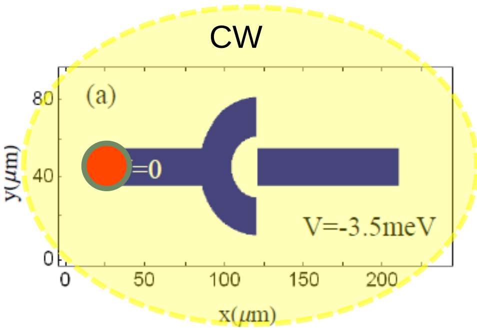


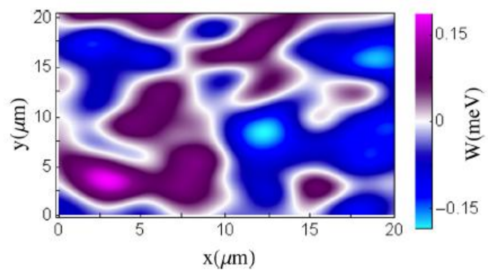
Potential will favour tunneling of particles in one direction.



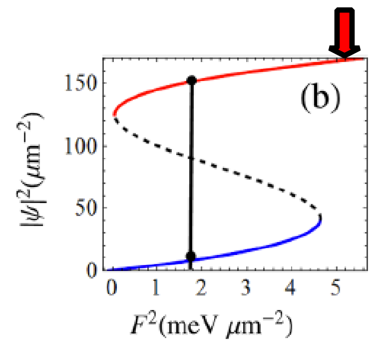
Mechanism

Numerical results using Gross-Pitaevskii equation in presence of disorder



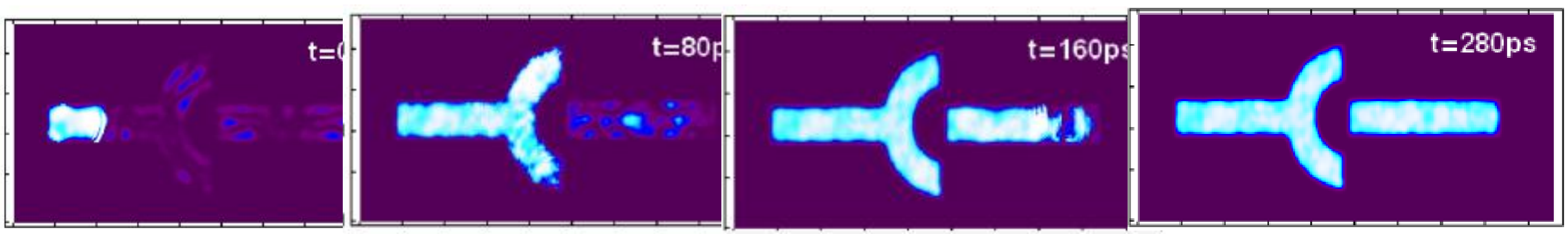


fast pulse

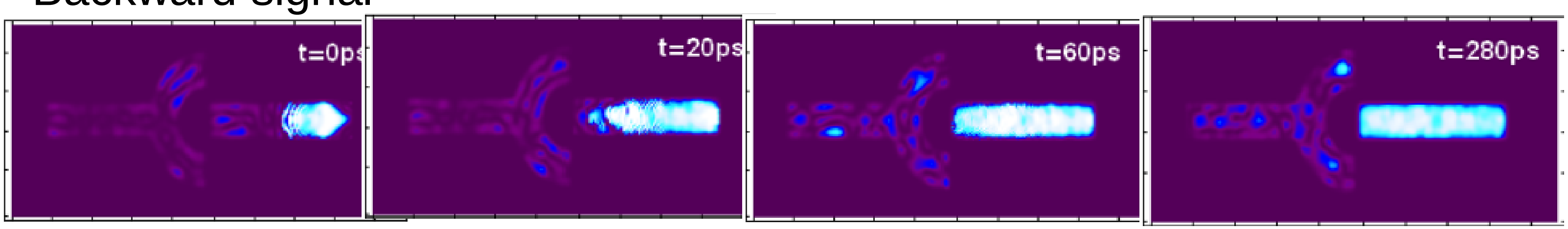


continuous pump

Forward signal



Backward signal



Optical Diode

Summary

- Without any additional external control, the forward signal is fully transmitted while the transmission in the reverse direction tends to zero.

- Compatible with propagating polariton neurons, useful element to reduce feedback

- The system proves to be robust to the presence of disorder.

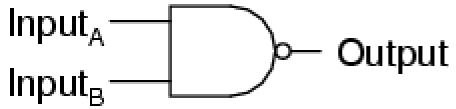
T. Espinosa-Ortega,T. C. H. Liew and I. A. Shelykh, Appl. Phys. Lett. 103, 191110 (2013).

Polaritonic Circuits

Logic circuits requirements

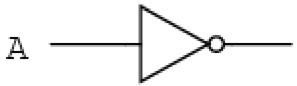
1) **Universal Logic**. Both AND- and NOT-type gates.

NAND gate



A	B	Output
0	0	1
0	1	1
1	0	1
1	1	0

NOT gate



A	Output
0	1
1	0

Polariton's spin as Input/Output of the system

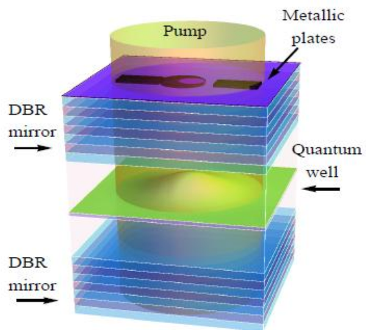
Logic circuits requirements

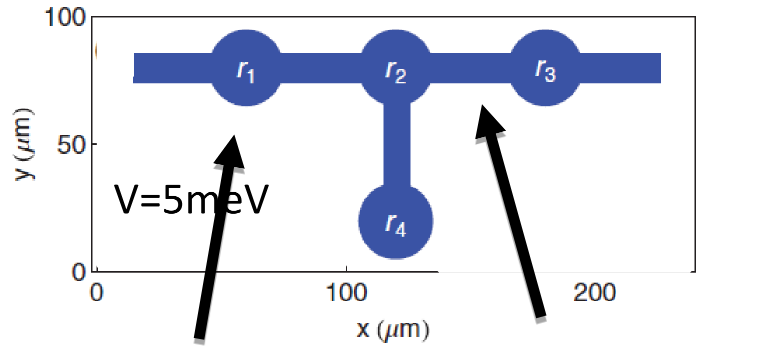
1) **Universal Logic**. Both AND- and NOT-type gates.
2) **Cascadability**. The output of one gate must be able to drive the next;
3) **Fan Out.** It must be possible to split and duplicate signals;
4) **Amplification**. Loss must be fully compensated such that signals are maintained at the logic level;
5) **Input-Output Isolation**. The circuit must operate in one direction only, with no significant feedback effects from the output.

Polariton's spin as Input/Output of the system

Arquitecture

- Confinement potential





CW pump at nodes

Channels ballistic transport

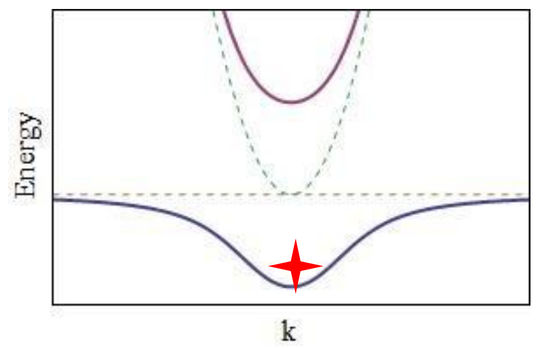
- Gross Pitaevskii equation for polaritons with **right** and **left** circular polarization

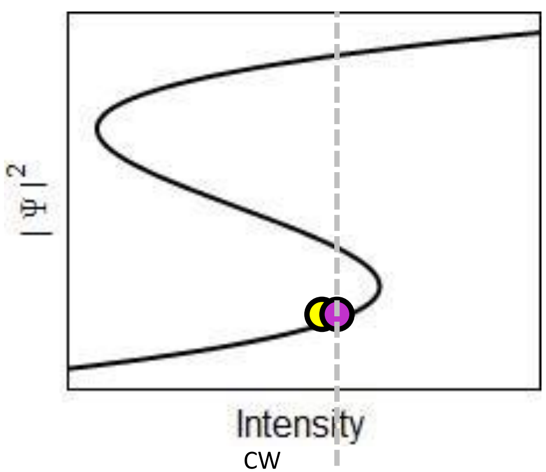
$$i\hbar \frac{\partial \Psi_+}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_+|^2 + \alpha_2|\Psi_-|^2]\Psi_+ + \Delta(\mathbf{r})\Psi_- + \mathfrak{F}_+(t,\mathbf{r}),$$

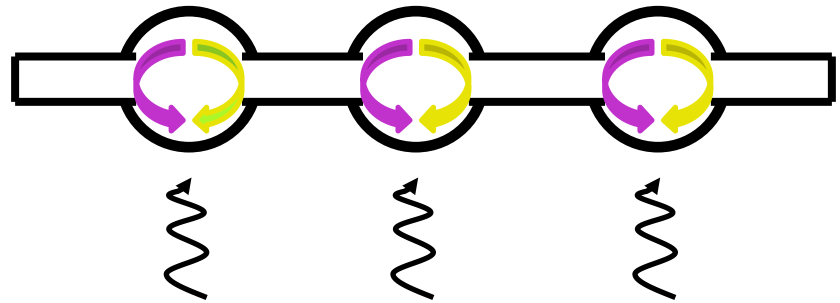
$$i\hbar \frac{\partial \Psi_-}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_-|^2 + \alpha_2|\Psi_+|^2]\Psi_- + \Delta(\mathbf{r})\Psi_+ + \mathfrak{F}_-(\mathbf{r},t),$$

- There will be multi stability at the nodes
- There will be spin precession in the channels

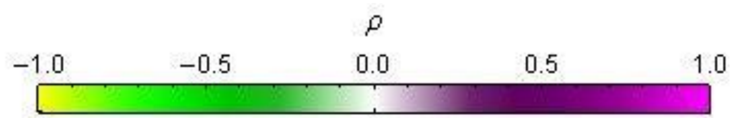
Circuit dynamics







$$\mathfrak{F}_s(\mathbf{r},t) = \sum_{i=1} F_s Exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{l^2} - \frac{i\varepsilon_p t}{\hbar}\right]$$



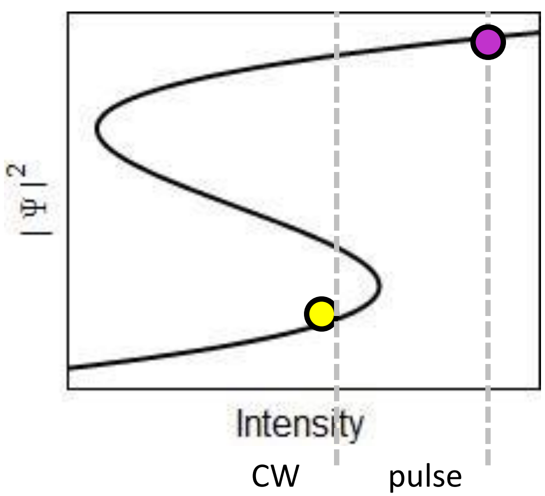
$$\rho = \frac{|\Psi_+|^2 - |\Psi_-|^2}{|\Psi_+|^2 + |\Psi_-|^2}$$

σ+ , σ- polaritons injected at the nodes using a CW pump

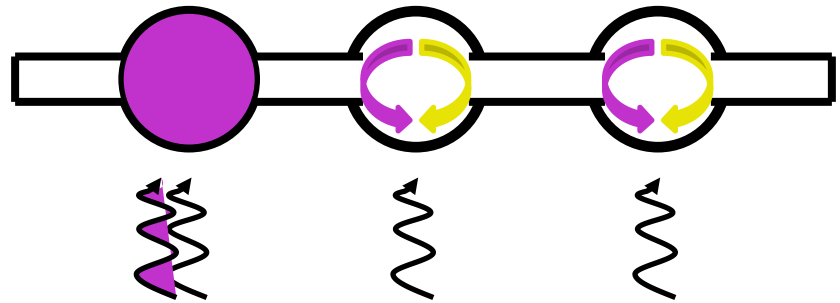
Circuit dynamics

Fast pulse σ+ on first node (INPUT)

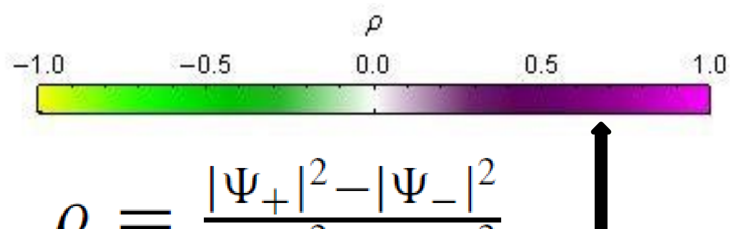
first node:



INPUT



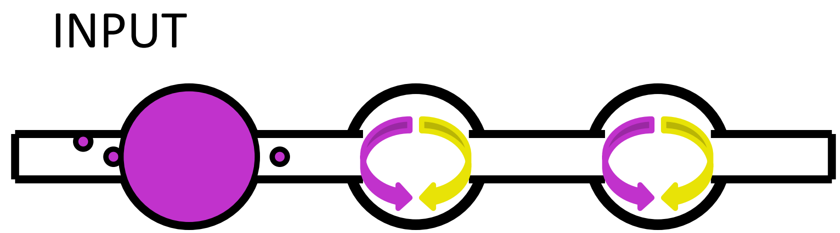
$$\mathfrak{F}_s(\mathbf{r},t) = \sum_{i=1}^{4} F_s Exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{l^2} - \frac{i\varepsilon_p t}{\hbar}\right] + \mathcal{P}_s(\mathbf{r},t),$$



$$\rho = \frac{|\Psi_+|^2 - |\Psi_-|^2}{|\Psi_+|^2 + |\Psi_-|^2}$$

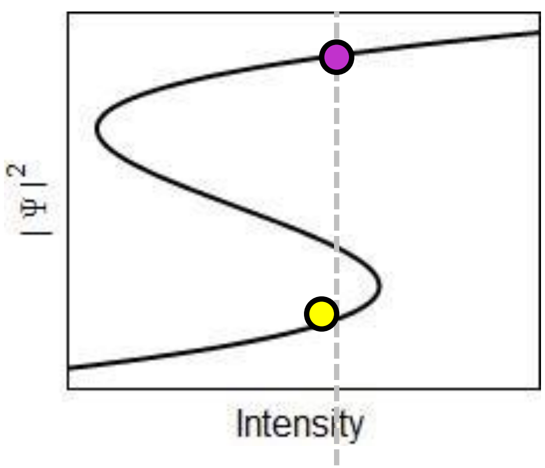
First node polarization

Circuit dynamics



First node: **increment of potential energy**, polaritons will be ejected to the channels.

first node:



In channels there is no CW

-> ballistic transport

$$i\hbar\frac{\partial\Psi_+}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_+|^2 + \alpha_2|\Psi_-|^2]\Psi_+ + \Delta(\mathbf{r})\Psi_- + \mathfrak{F}_+(t,\mathbf{r}),$$

$$i\hbar\frac{\partial\Psi_-}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_-|^2 + \alpha_2|\Psi_+|^2]\Psi_- + \Delta(\mathbf{r})\Psi_+ + \mathfrak{F}_-(\mathbf{r},t),$$

$$\alpha_1 >> \alpha_2$$

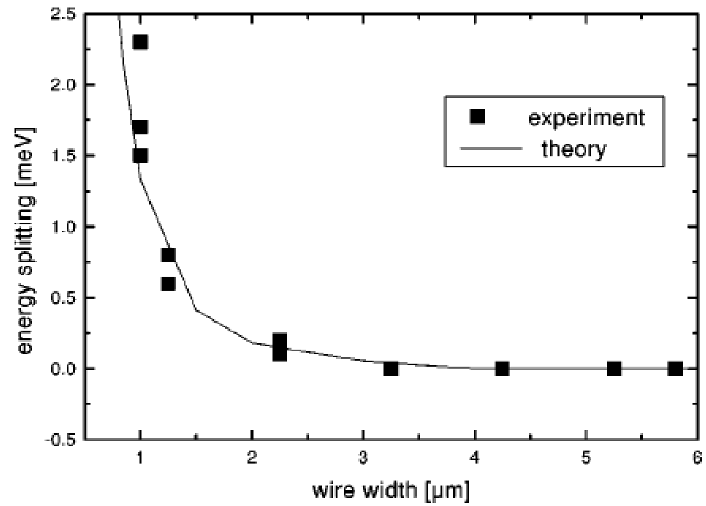
Ballistic transport in channels

E splitting of optical modes in wires with polarization ⊥ and ıı to wire

A. Kuther, et. al, Phys. Rev. B (1991).

E splitting of exciton polaritons

G. Dasbach, et. al., Rev. B (2005).



$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\Psi_+\\ \Psi_-\end{pmatrix}=\frac{1}{2}\begin{pmatrix}E_0 & \Delta\\ \Delta & E_0\end{pmatrix}\begin{pmatrix}\Psi_+\\ \Psi_-\end{pmatrix}$$

otential mixing σ+ and σ-

Splitting is inversely proportional the channel width

$$\Delta = E_x - E_y$$

$$E_0 = E_x + E_y$$

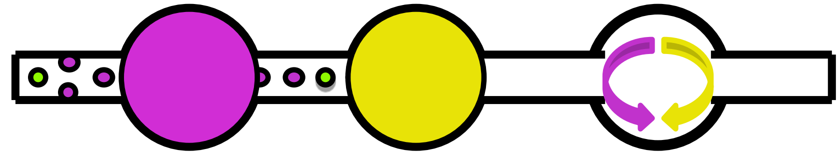
Polaritonic circuits

Circuit dynamics

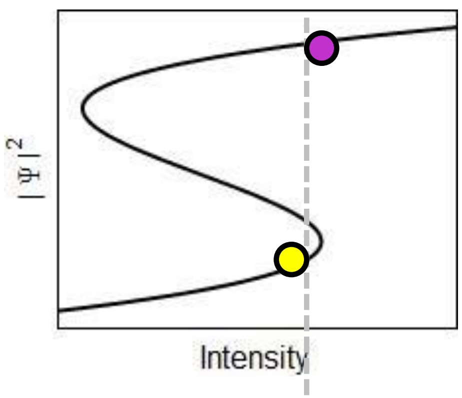
INPUT OUTPUT

Potential Δ will induce

spin precession in channels

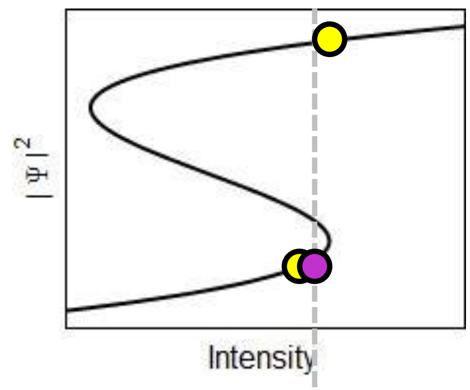


first node



cw

second node



cw

Neighbor nodes work like

NOT Gate

Input **+**

Output **-**

$$i\hbar\frac{\partial\Psi_+}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_+|^2 + \alpha_2|\Psi_-|^2]\Psi_+ + \Delta(\mathbf{r})\Psi_- + \mathfrak{F}_+(t,\mathbf{r}),$$

$$i\hbar\frac{\partial\Psi_-}{\partial t} = [E_{LP}(\mathbf{k}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha_1|\Psi_-|^2 + \alpha_2|\Psi_+|^2]\Psi_- + \Delta(\mathbf{r})\Psi_+ + \mathfrak{F}_-(\mathbf{r},t),$$

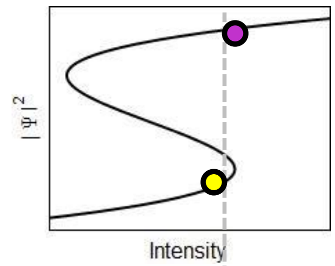
Polaritonic circuits

NOT Gate

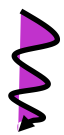
Calculations using GP

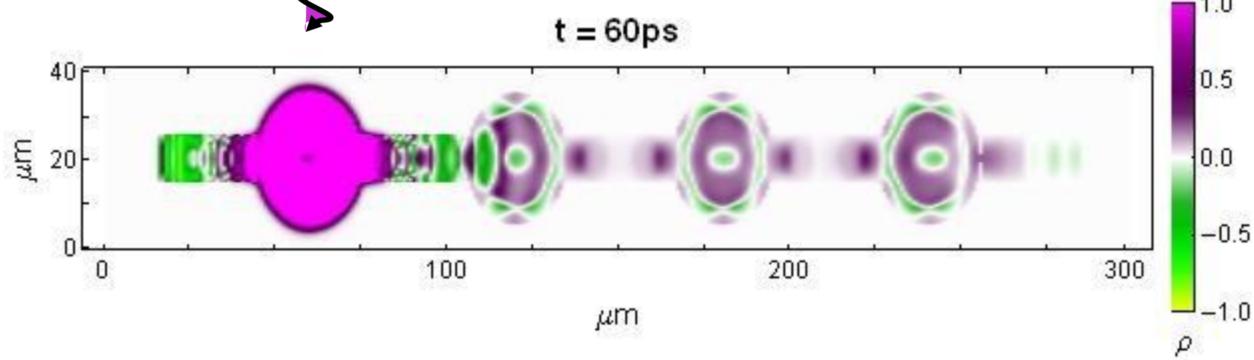
INPUT	OUTPUT
+/−	−/+

first node



Input σ+





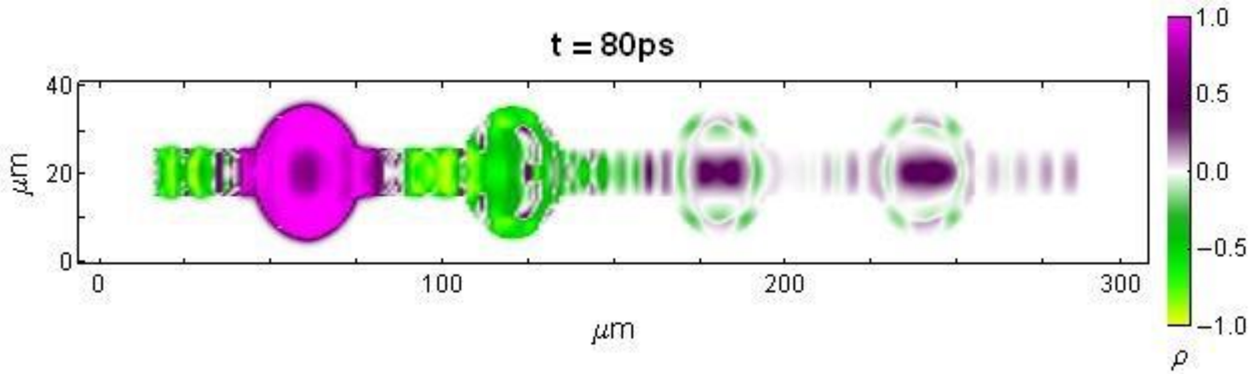
CW pump slightly polarized towards σ+

T. Espinosa-Ortega, T.C.H. Liew, Phys. Rev. B 87, 195305 (2013).

NOT Gate

Calculations using GP

INPUT	OUTPUT
+/−	−/+



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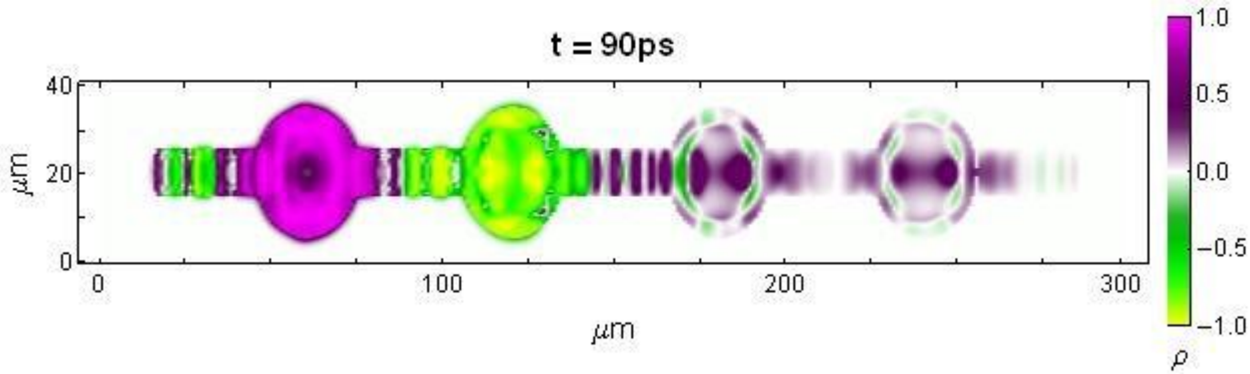
NOT Gate

Calculations using GP

INPUT	OUTPUT
+/−	−/+



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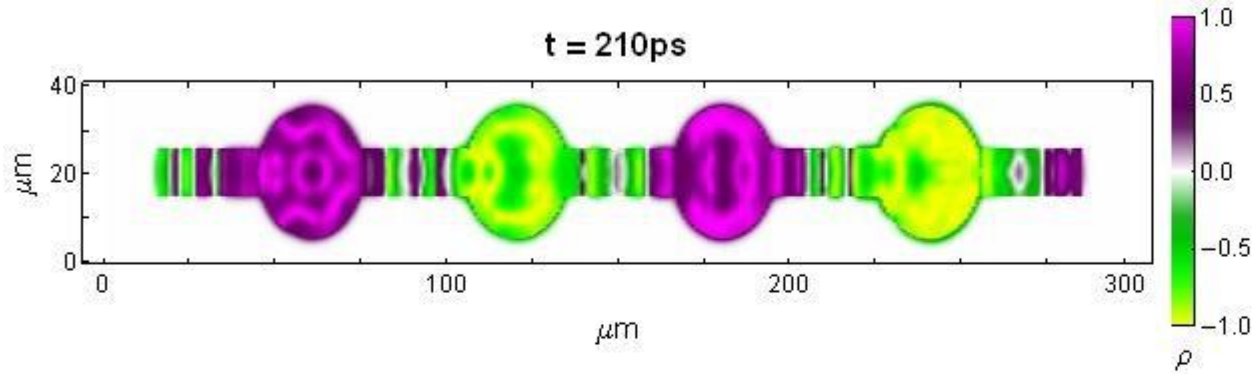
NOT Gate

Calculations using GP

INPUT	OUTPUT
+/−	−/+



CW pump slightly polarized towards σ+

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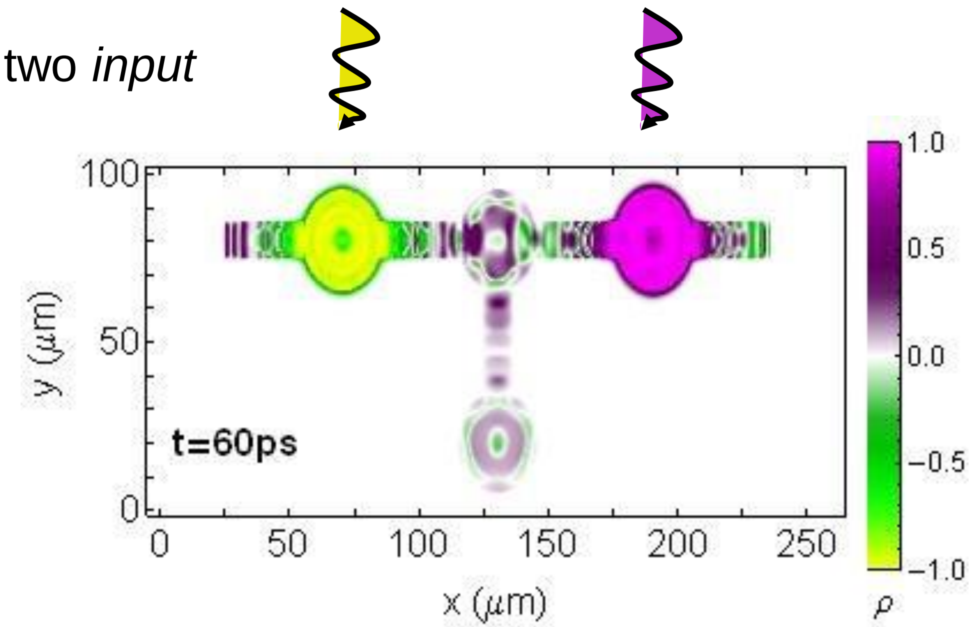
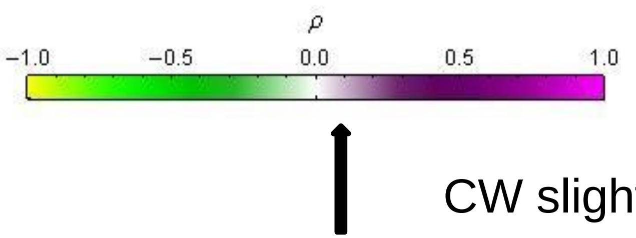
AND Gate

AND & OR gate two *input*



INPUT	OUTPUT
{−,+}	+

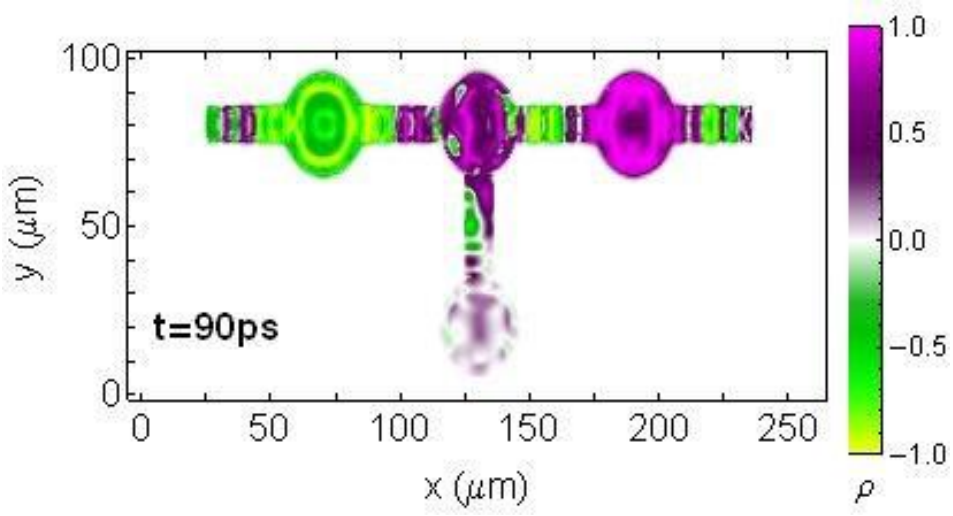


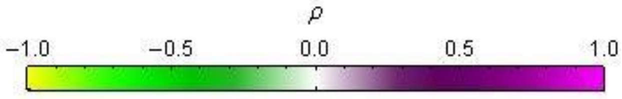
CW slightly bias σ+

AND Gate

AND & OR gate two *input*

INPUT	OUTPUT
{−,+}	+



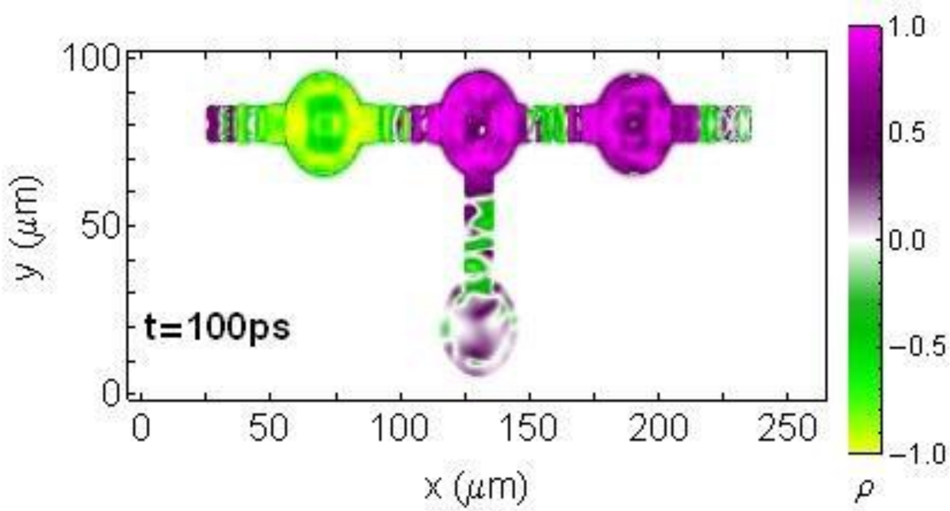


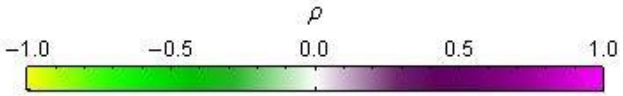
CW slightly bias $\sigma+$

AND Gate

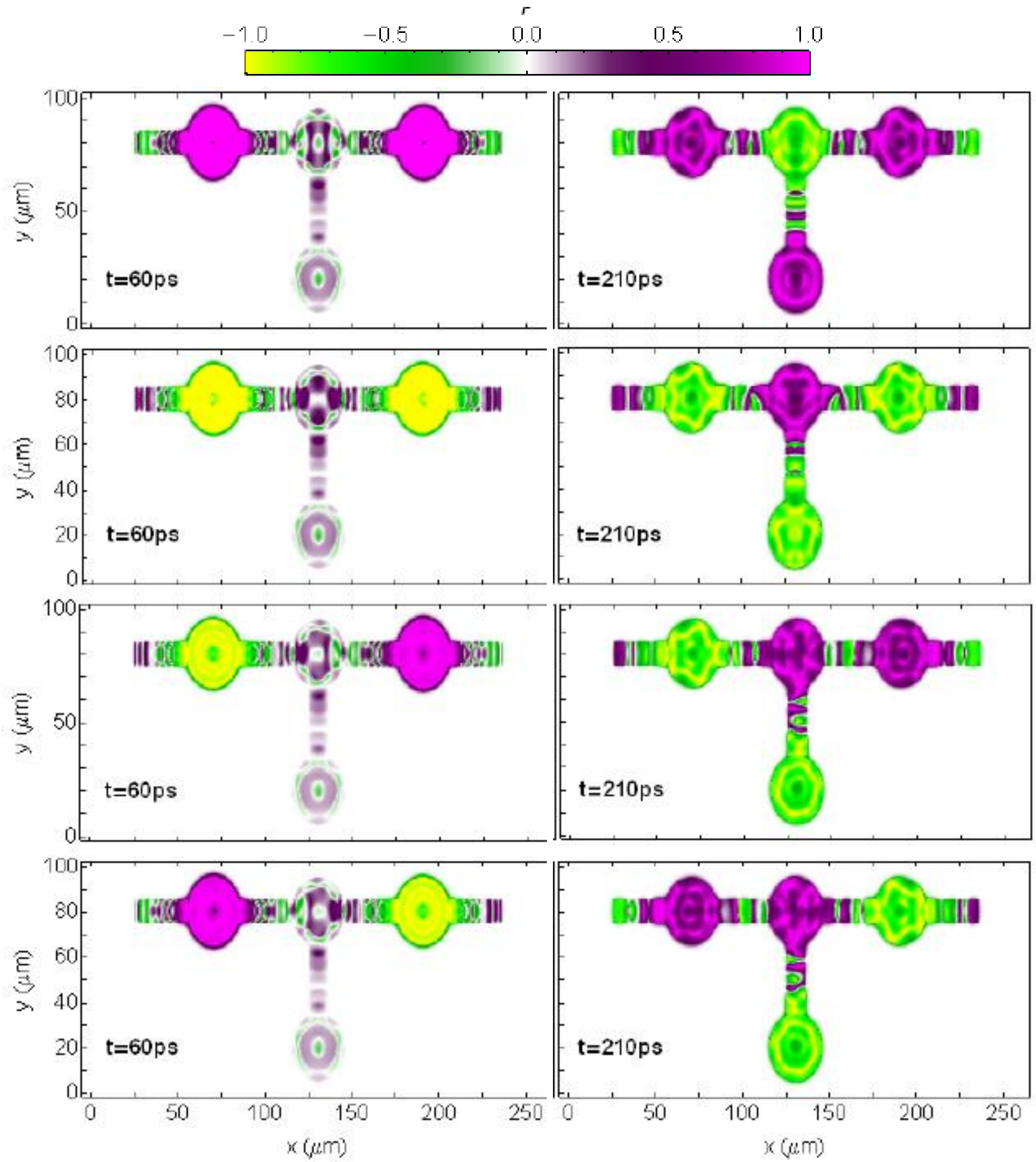
AND & OR gate two *input*

INPUT	OUTPUT
{−,+}	+





CW slightly bias σ+



A	B	Output
0	0	1
0	1	1
1	0	1
1	1	0

Polaritonic circuits

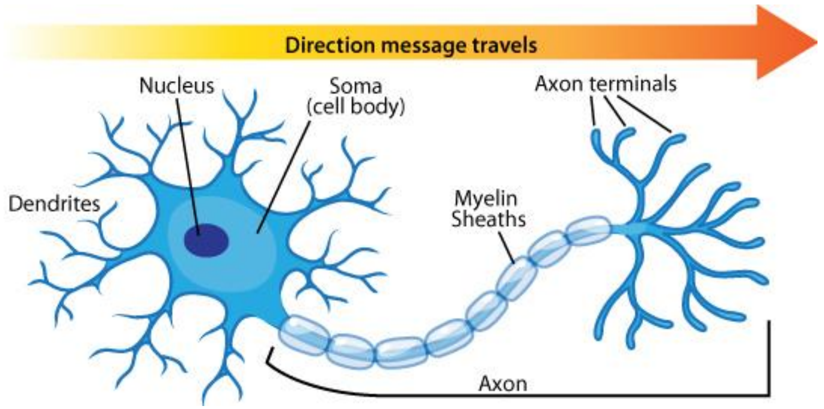
Summary

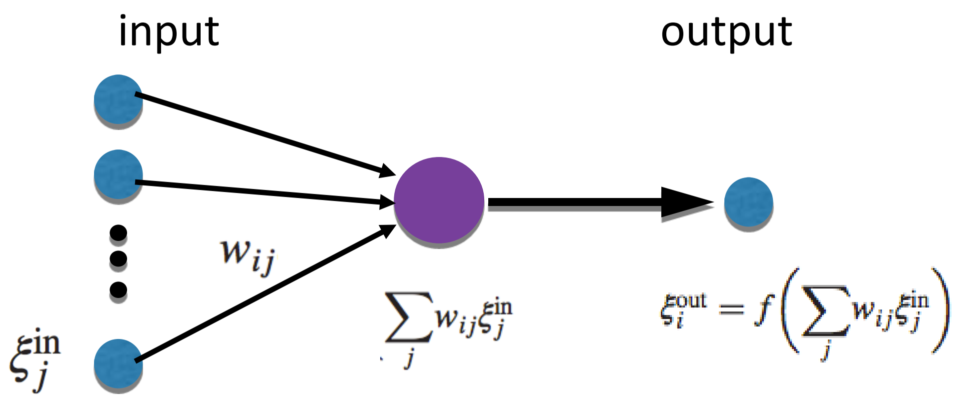
- We have presented a scheme for the realization of **complete photonic integrated circuits** in a single, compact solid-state system that **don't requite the use of external electric fields.**

T. Espinosa-Ortega and T. C. H. Liew, Phys. Rev. B, **87**, 195305 (2013) .

Perceptron:
Two layer neural network

Neuron



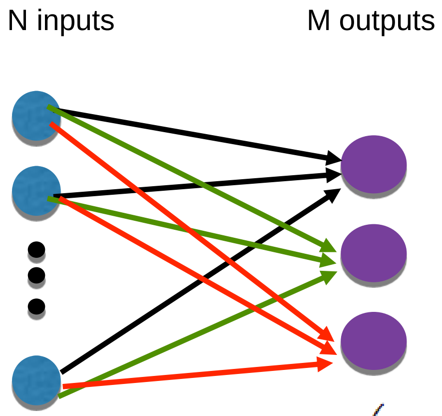


Perceptron

Neural networks

- Large number of interconnections.
- Possibility of different weights for each interconnection
- Flexibility in the choice of weights to allow learning.

Perceptron: a device that via supervised learning allows to classify a set of inputs—>Pattern recognition



$$\xi_i^{out} = f\left(\sum_j w_{ij}\xi_j^{in}\right)$$

A two layer network of N inputs and M outputs requires NxM interconnections.

Simply/compact system

Perceptron

Perceptron based on wave ensembles

$$i\hbar\frac{\partial\psi}{\partial t} = (\hat{E} - i\hat{\Gamma} + V(\mathbf{x}))\psi + F(\mathbf{x})$$

Fourier space

$$i\hbar\frac{\partial\psi_i}{\partial t} = (E_0 - i\Gamma_0)\psi_i + \sum_j V_{ij}\psi_j + F_i,$$

$$V(\mathbf{x}) = \sum_{ij} V_{ij}\cos\left[(\mathbf{k}_i - \mathbf{k}_j).\mathbf{x}\right]$$

Divide the reciprocal space in two sets intputs and outputs

inputs dominated by driven field $\{F_i\}$

$$\psi_i = -\frac{F_i}{E_0 - i\Gamma}$$

outputs dominated by potential scattering

$$\psi_i = -\frac{\sum_{ij} V_{ij}\psi_j}{E_0 - i\Gamma} = \frac{\sum_j V_{ij}F_j}{(E_0 - i\Gamma)^2}.$$

neural network weights = Vij

$$\xi_i^{\text{out}} = f\left(\sum_j w_{ij}\xi_j^{\text{in}}\right)$$

Perceptron

Neural networks have 2 phases

• Training

The desired weights (Vij) are created

$V_{i,j}$ weights lifetime, depents in the system :

- ***Polariton systems*: Vij =polariton-phonon interaction (phonon lifetime).**
- *Nuclear polarization*: Vij=nuclear spin polarization.
- *Optical Lithography*: Vij= optical interference (permanent).

• Operation

A set of inputs “scatters” in the desired output

$$\psi_i = -\frac{\sum_{ij} V_{ij}\psi_j}{E_0 - i\Gamma} = \frac{\sum_j V_{ij}F_j}{(E_0 - i\Gamma)^2}.$$

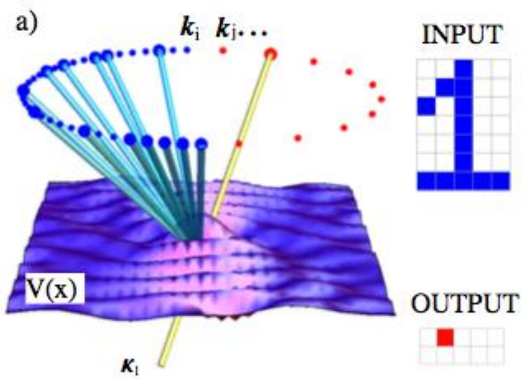
$$\xi_i^{\text{out}} = f\left(\sum_j w_{ij}\xi_j^{\text{in}}\right)$$

Perceptron

Training the neural network

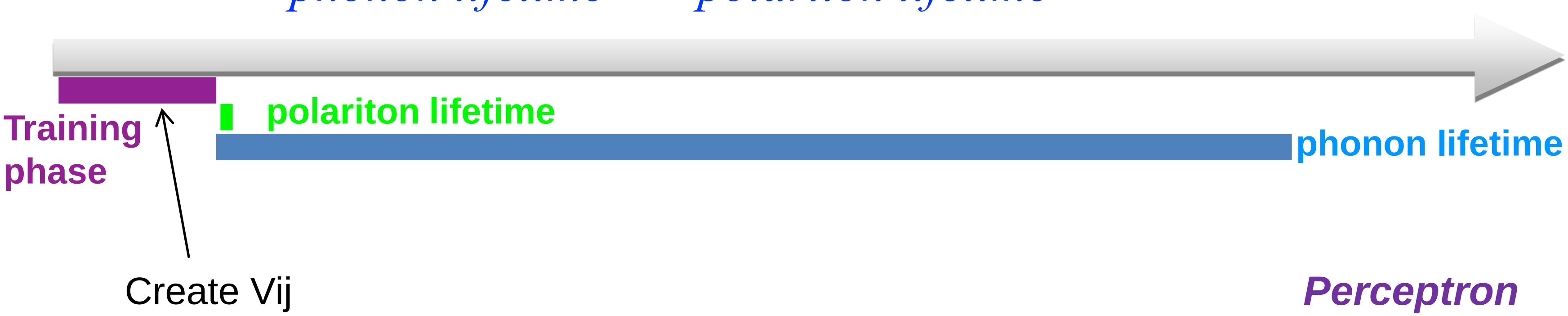
Connection weights (Vij) are increased when input and output neurons fire simultaneously. This allows training of the network where an input vector is applied and the desired output state is simultaneously activated.

Pattern recognition: each **k**i vector is associated with a pixel.



optically, the input $\{\boldsymbol{k}_j\}^{\#1}$ and the desired output $\boldsymbol{k}_{i=1}$ is sent;
this create polaritons and phonons $V_{i=1,j}$

phonon lifetime >> polariton lifetime

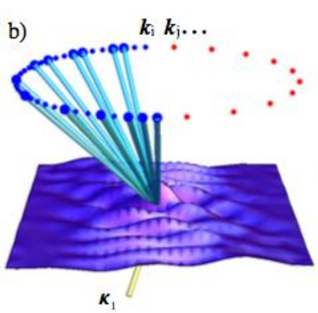


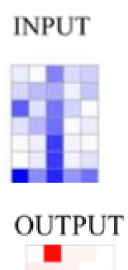
Operation phase

Polariton-phonon interaction as “weights”

- linear regime $$i\hbar\frac{\partial\psi_i}{\partial t} = (E_0 - i\Gamma_0)\psi_i + \sum_j V_{ij}\psi_j + F_i,$$
- polariton-phonon interaction $$V_{ij} = X|G_{ij}|\left(\chi_{ij} - \chi^*_{ji}\right) \qquad \chi_{ij} \propto F_i F_j$$

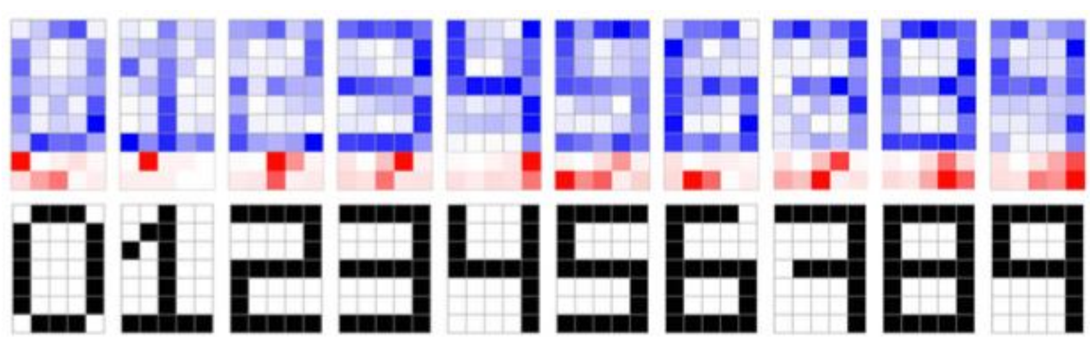
- **Operation phase: Only inputs are sent optically**





An input set $\{\boldsymbol{k}_j\}^{\#?} \sim \{\boldsymbol{k}_j\}^{\#1}$ will generate a high intensity output $\boldsymbol{k}_{i=1}$

$$\psi_i = -\frac{\sum_{ij} V_{ij}\psi_j}{E_0 - i\Gamma}$$



Summary

- A perceptron based in polariton-phonon interactions can be implemented and used in pattern recognition.

T. Espinosa-Ortega and T. C. H. Liew, Phys. Rev. Lett., 114, 118101 (2015) .


Thank you for your attention.

TERAMETANANO-3

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