Binary classification of low-resolution images using the collective modes of a nanolaser array

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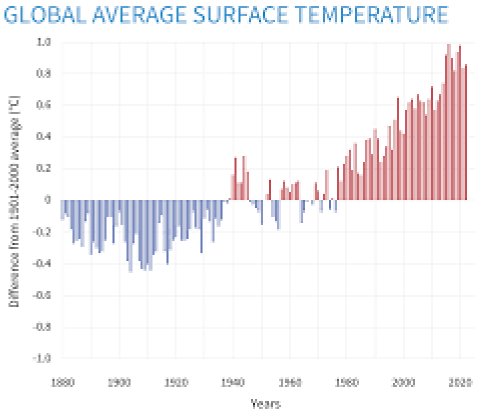
Motivation

- High performance computing systems and artificial intelligence systems consume huge amounts of energy.

- Big concern in the context of climate change.

- Photonic integrated circuits (PICs)
  - Consume much less energy
  - Faster



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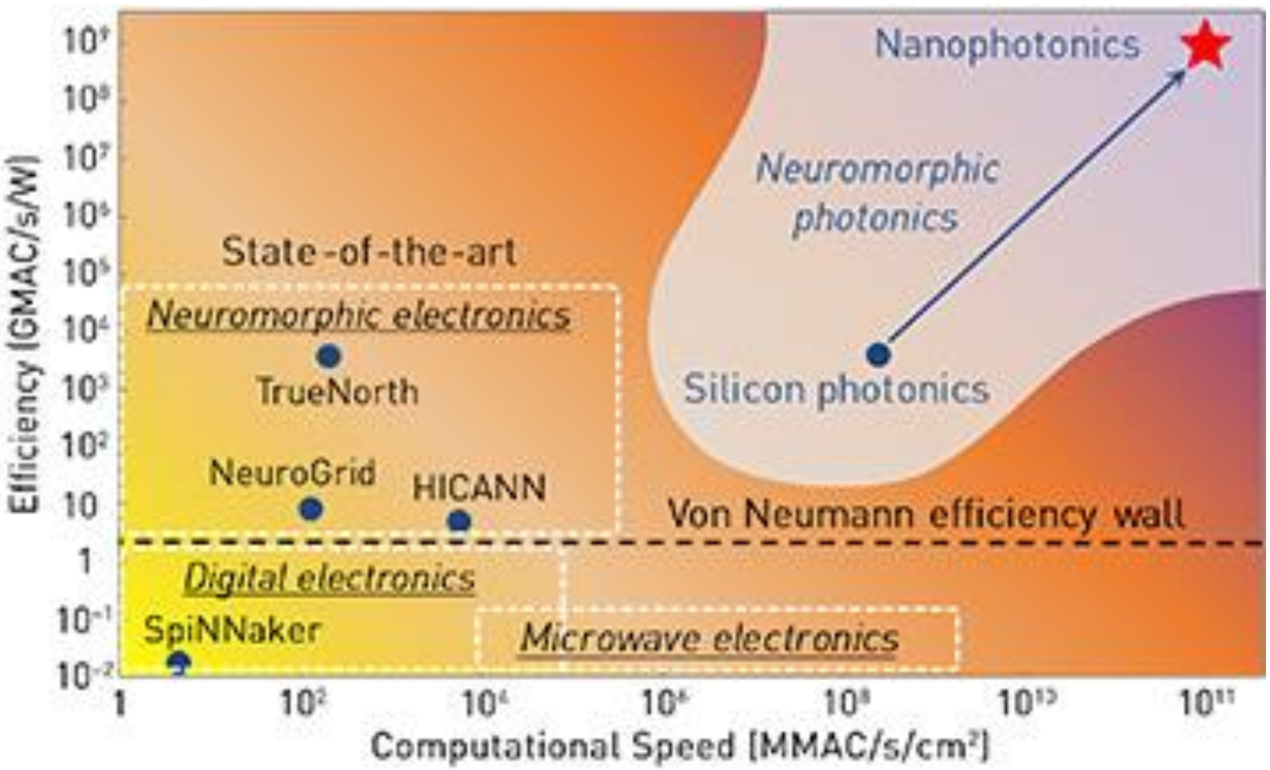
Neuromorphic photonics

Efforts are focused on developing optical systems that emulate "artificial neural networks": neuromorphic photonics



Multiply accumulate (MAC) operations

Optics and Photonics News, January 2018

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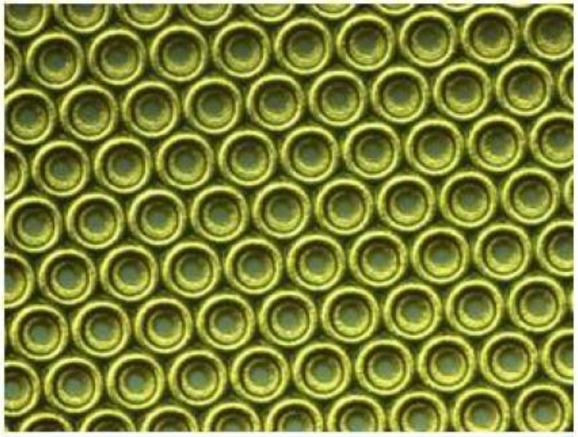
Semiconductor lasers, in particular micro and nano lasers have key advantages:

- Very low threshold
- Emit telecom wavelengths
- Fast nonlinear response
- Integration in 2D planar arrays



Chip with an array of thousands of VCSELs

VCSELs, R. Michalzik Ed. (Springer 2013)

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IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 26, NO. 1, JANUARY/FEBRUARY 2020 1500307

Photonic Computing With Single and Coupled Spiking Micropillar Lasers

Venkata Anirudh Pammi, Karin Alfaro-Bittner, Marcel G. Clerc, and Sylvain Barbay

(Invited Paper)

Review Vol. 12, No. 6 / 1 Jun 2022 / *Optical Materials Express* 2395

Optical Materials EXPRESS

Photonic neuromorphic computing using vertical cavity semiconductor lasers

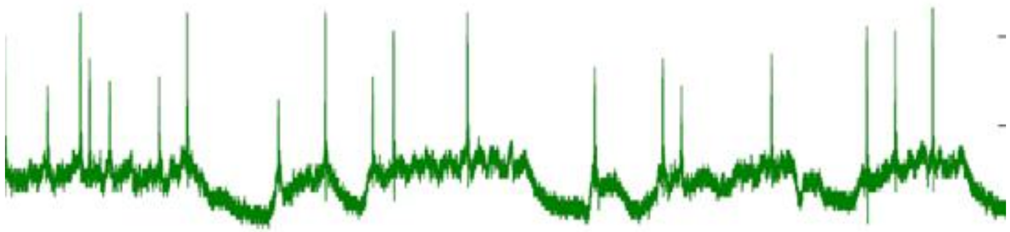
ANAS SKALLI,[1,*] JOSHUA ROBERTSON,[2] DAFYDD OWEN-NEWNS,[2] MATEJ HEJDA,[2] XAVIER PORTE,[1] STEPHAN REITZENSTEIN,[3] ANTONIO HURTADO,[2] AND DANIEL BRUNNER[1]

Side note: Research in our lab

The human brain processes huge amounts of information using only 19 Watts.

Artificial intelligent systems consume much more power.

How neurons *encode* information?



Question: can efficient neural coding mechanisms for information processing be implemented in spiking semiconductor lasers?

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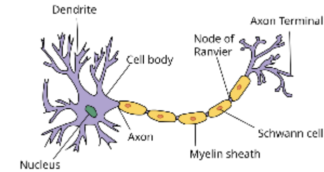
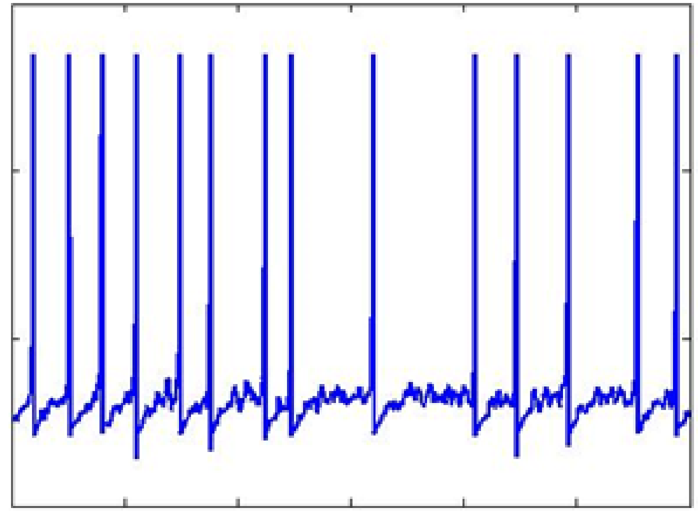
Side note: Research in our lab

Spikes simulated with a neural model





Time 10^{-9} s

Time 10^{-3} s

Statistically similar responses to time-varying external inputs?

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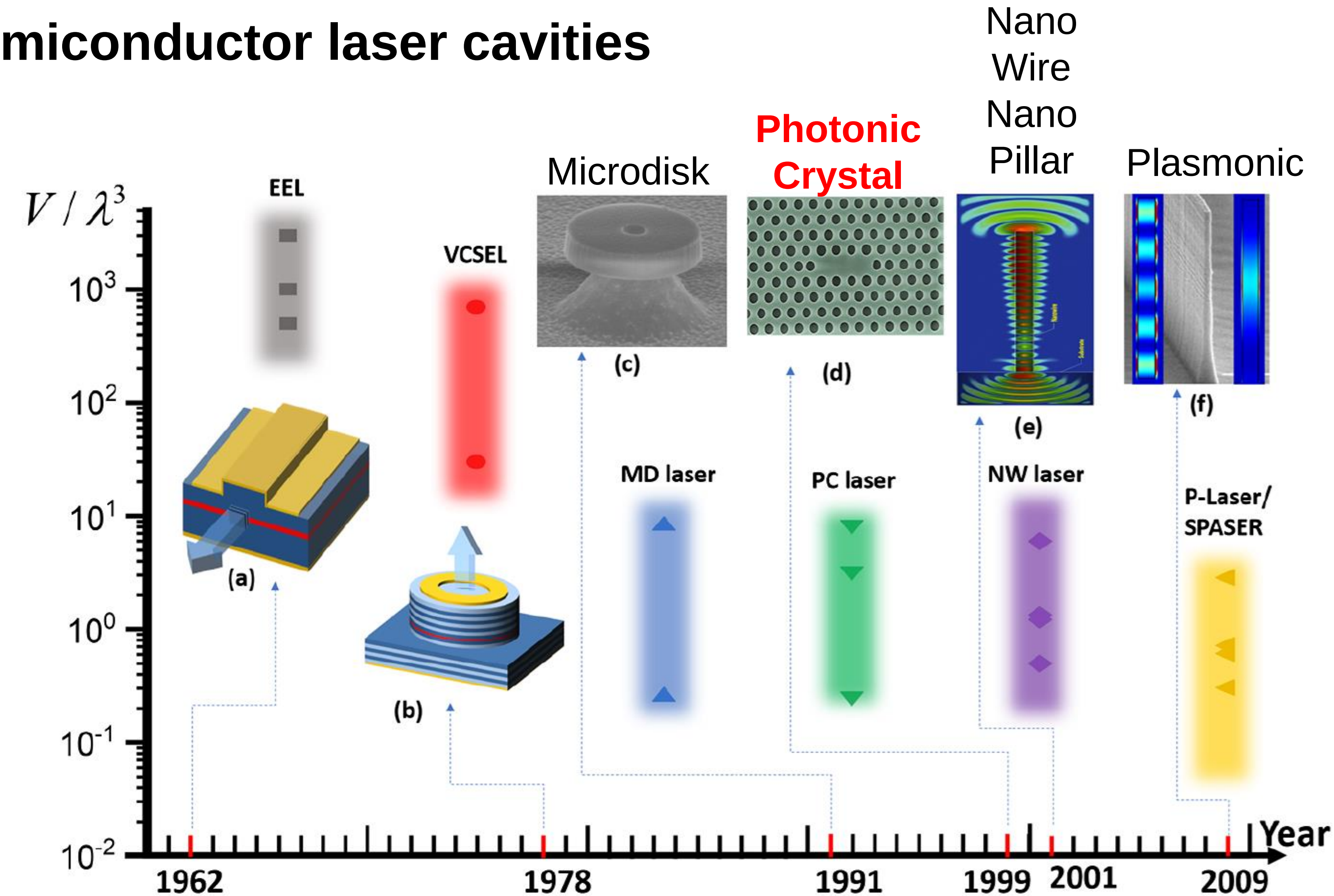
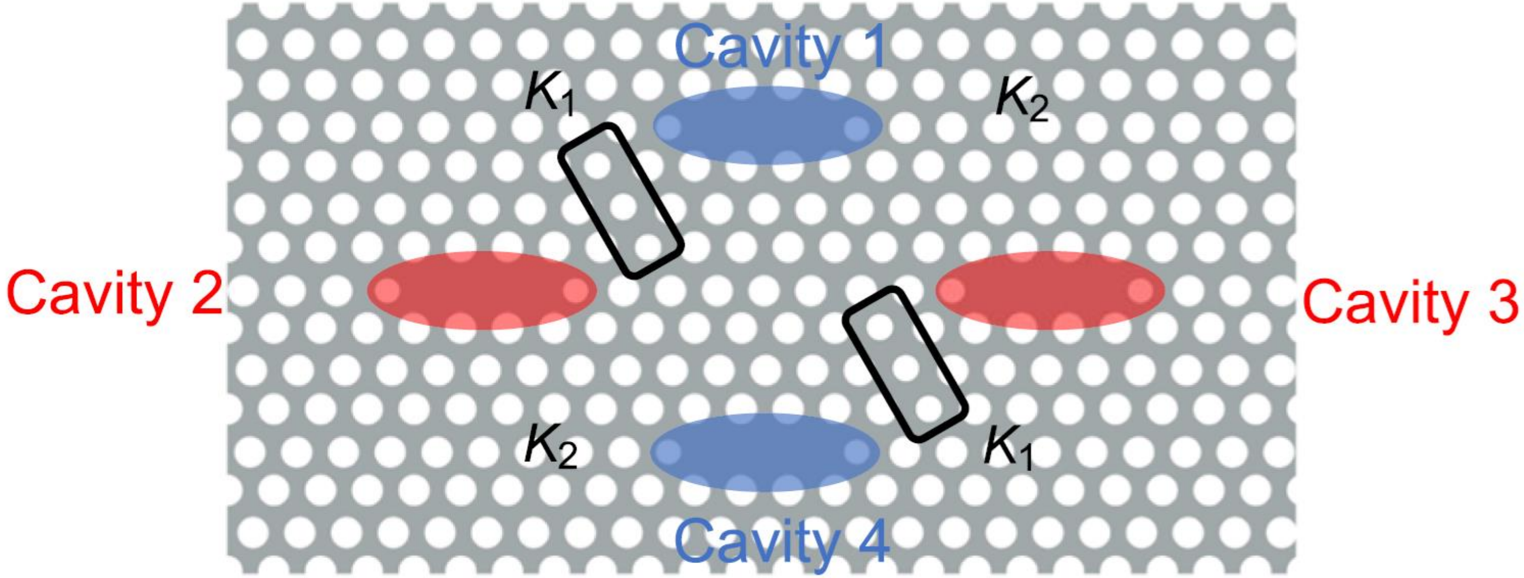
Semiconductor laser cavities



C. Z. Ning, "*Semiconductor nanolasers and the size-energy efficiency challenge: a review*", Advanced Photonics 2019

Photonic crystal nanolasers

Four Photonic Crystal cavities in an Indium Phosphide (InP) membrane, with four embedded InGaAsP quantum wells



The strength of the couplings (K_1, K_2) can be tuned by adjusting the fabrication parameters

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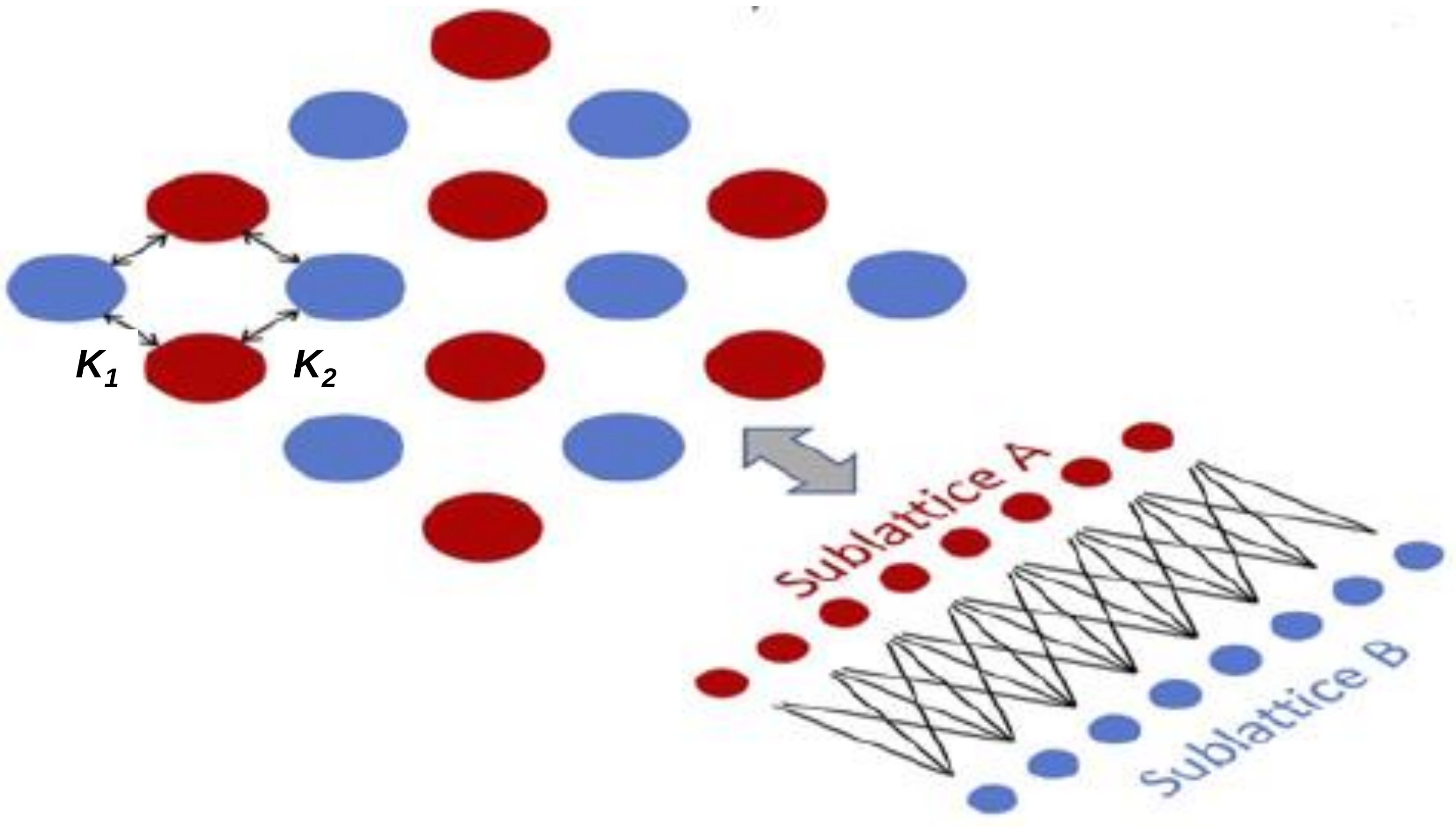
Schematic representation of a 4 x 4 array of photonic crystal cavities



$\Rightarrow$Two-layer photonic artificial neural network

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Steps for using a nanolaser array for binary classification tasks (e.g., 0/1 images)

1. The input data (e.g. the pixel values) is written as an "input vector", **I**, with D elements.
2. **I** is encoded into the "pump pattern" **P** through a "transformation matrix" **M**: P = | M I | (absolute value to ensure non-negative values).
3. **P** is projected onto the nanolaser array via a spatial light modulator (SLM).
4. Detect response: if the optical spectrum shows lasing of a particular mode (a symmetry protected "zero-mode" of the array), the output is a positive response (e.g., the image of digit "1" was encoded in the pump pattern).

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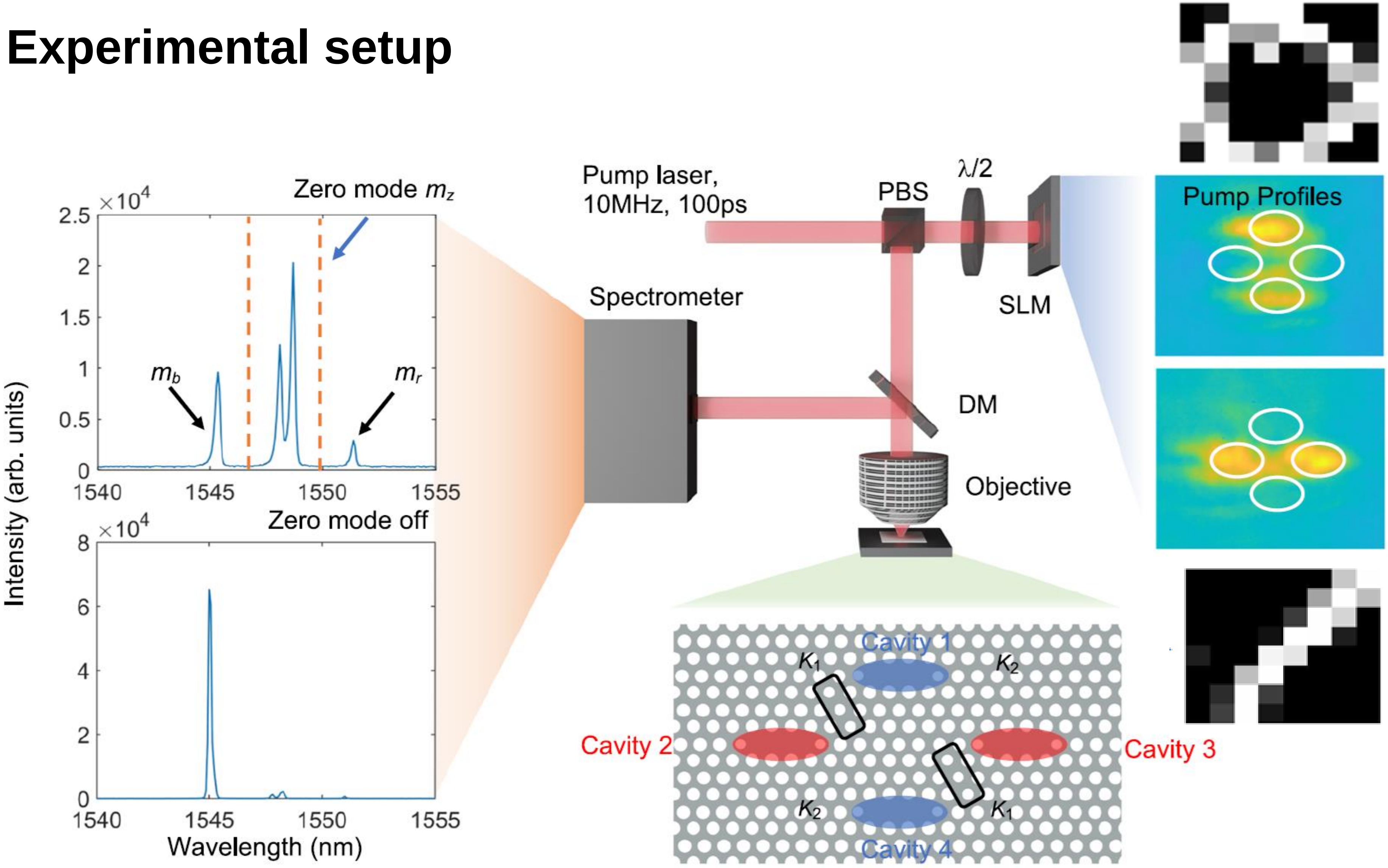
Experimental setup



We classify pump patterns that excite the central two modes as positive inputs, those that excite side-modes: negative inputs

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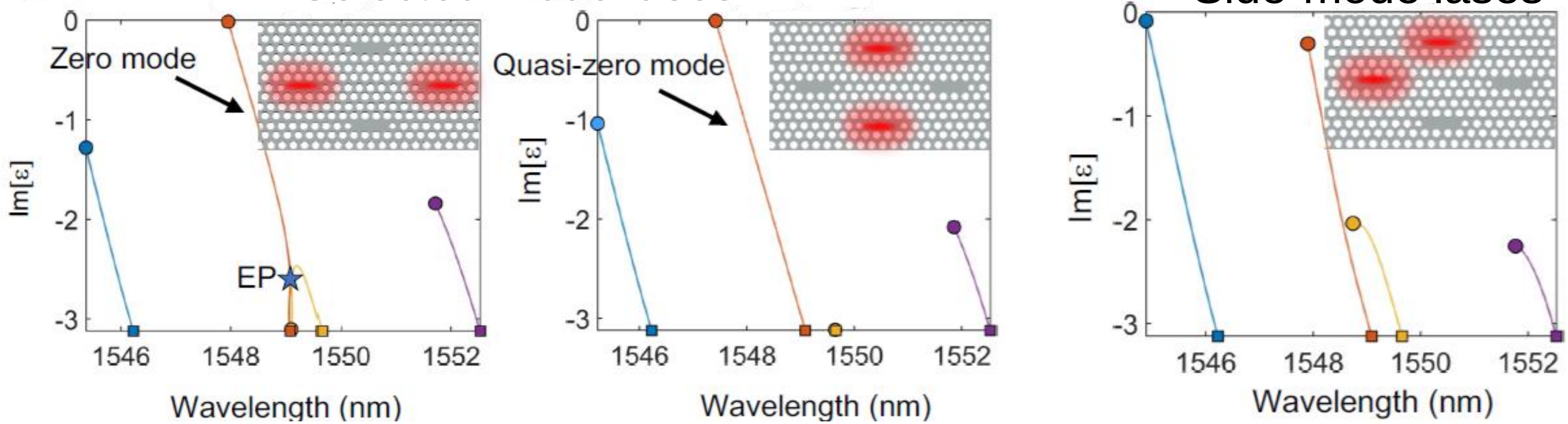
Key problem: We need good "spectral gap" to separate the selected modes from other modes.

Solution: Model simulations & machine learning optimization of the elements of the transformation matrix M that determines the pump pattern (P = |M I|).

Selected mode lases

Side-mode lases



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Numerical demonstration

- Simulate **8x8** diffusively coupled nanocavities.

$$i\frac{da_{m,n}}{dt} = \kappa_x(a_{m-1,n} + a_{m+1,n}) + \kappa_y(a_{m,n-1} + a_{m,n+1}) + i(g_{m,n} - \gamma)a_{m,n}$$

Spatial pump pattern: $P = \{g_{m,n}\}$

- 64 rate equations for the complex amplitudes a_{mn}.
- Images to be classified re-sized to 8x8.
- Goal: find the elements of the transformation matrix M that optimize the classification performance.

$$P^{(k)} = |\, M\, I^{(k)} \,|$$

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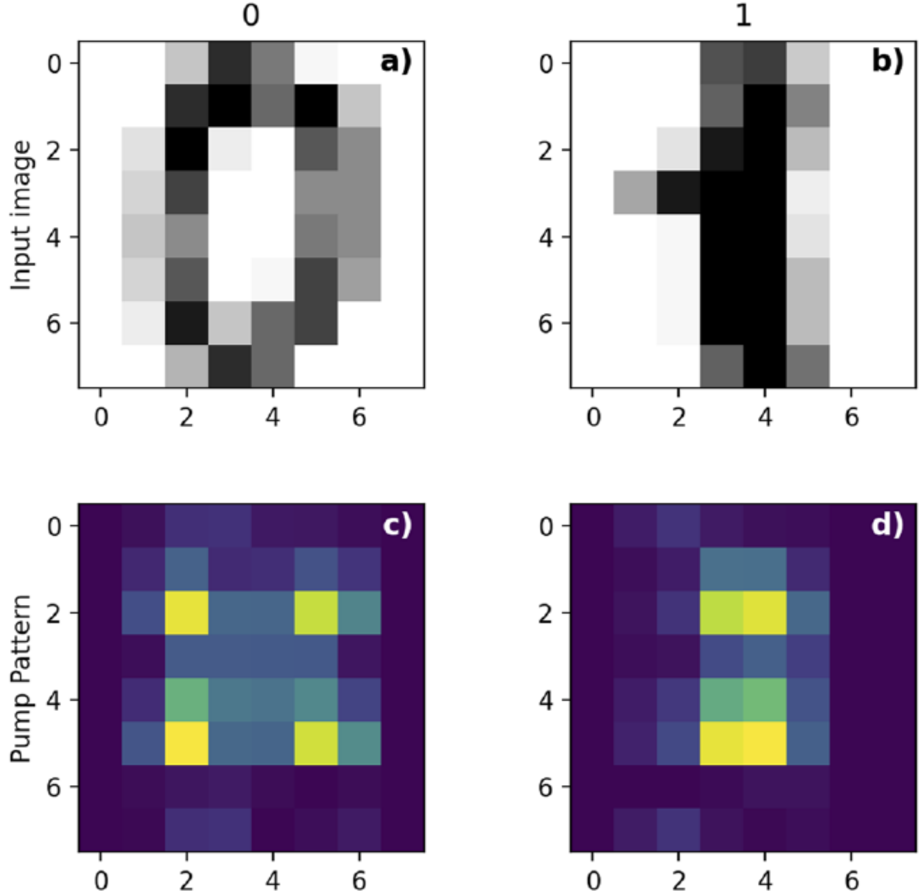
Data

- Hand-written digit dataset ML repository.
- 360 images: 270 training + 90 testing.
- 8x8 image resolution.



P=|MI|

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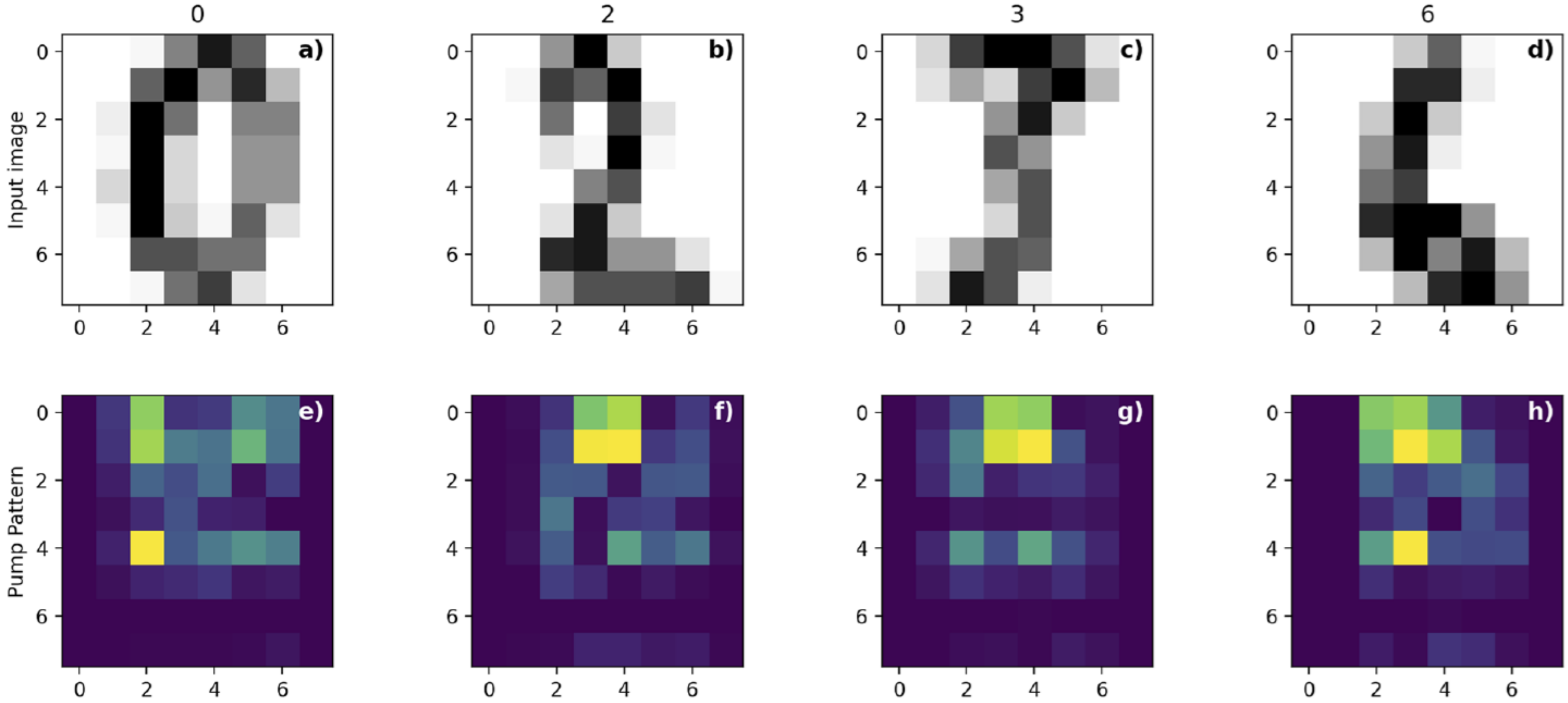

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Machine learning optimization

Minimization of the cost function using images of the training set.

$$C = -\sum_{k\in\{+\}} \tanh\left(\eta\Delta\varepsilon^{(k)}\right) + \sum_{k\in\{-\}} \tanh\left(\eta\Delta\varepsilon^{(k)}\right)$$

{+} and {−} denote the two sets of images for which the "spectral gap" of k*th* image $\Delta\varepsilon^{(k)}$ is expected to be + or -.

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Results

- Once the cost function was minimized using the images in the training set (about 24 hs on a 40 core cluster), the transformation matrix M was used to classify the images in the testing set.
- Tasks: distinguish 0s and 1s (one-vs-one classifier) and distinguish 0s and any other digit (one-vs-all classifier).

			One-vs-one		One-vs-all
	Resolution	δ	10^{-3}	10^{-1}	10^{-1}
(TP+TN)/total	Accuracy (%)	*Train*	100	98.9	97.8
		Test	98.9	97.8	96.7
TP/predicted yes	Precision (%)	*Train*	100	100	97.7
		Test	100	100	97.9
TP/actual yes (fraction of 0s correctly identified)	Recall (%)	*Train*	100	97.6	97.7
		Test	98	96.1	95.8

G. Tirabassi, J. Kaiwen, C. Masoller, A. M. Yacomotti, "*Binary image classification using collective optical modes of an array of nanolasers*", APL Photonics 7, 090801 (2022).

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Effect of noise in the input image

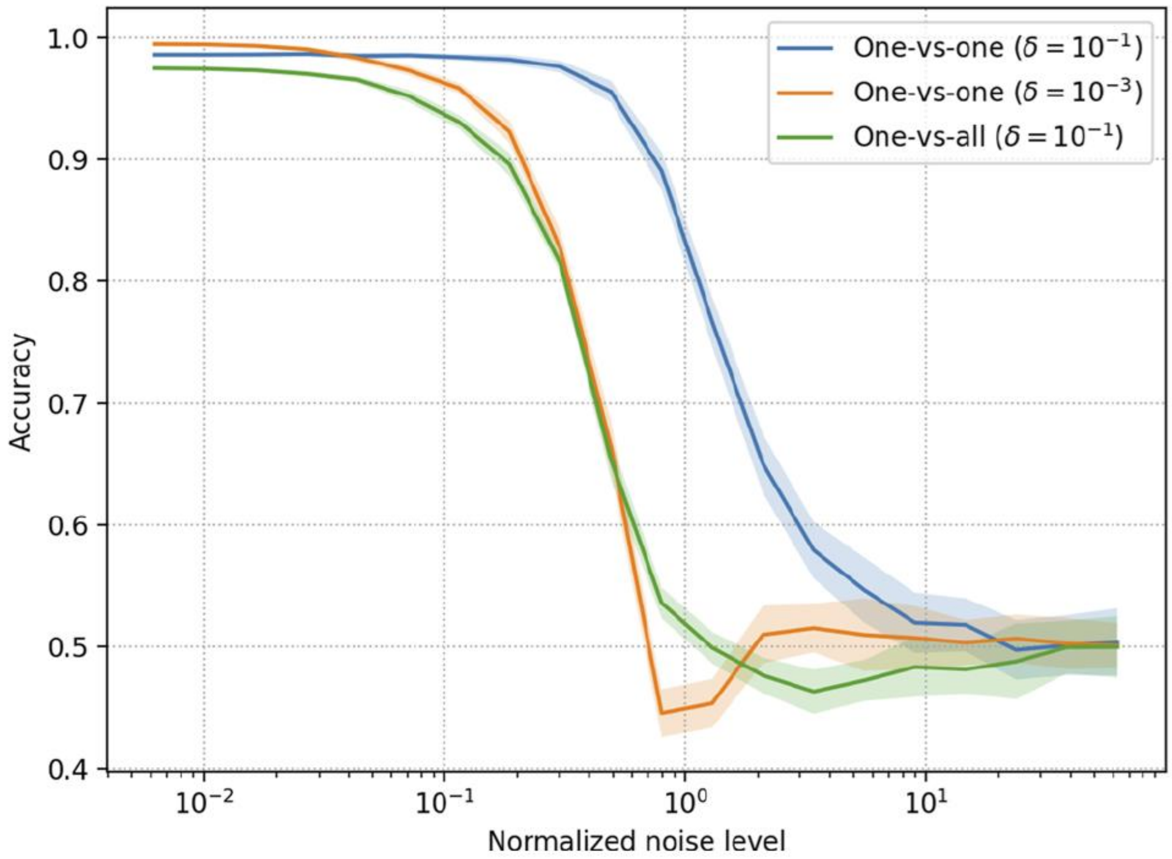

FIG. 6. Accuracy of the classifiers as a function of the noise level in the input images. The noise intensity is normalized by the maximum pixel value in the original. The shaded area represents the standard deviation of the accuracy values over 20 independent realizations.

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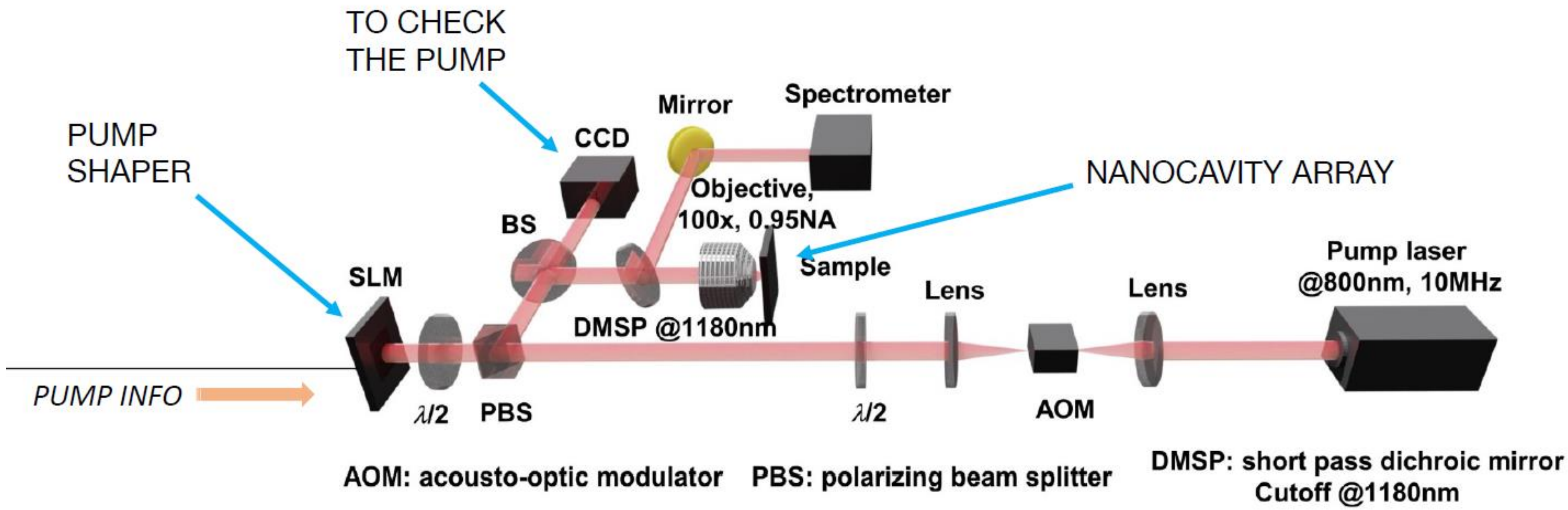
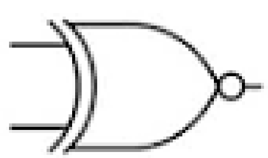
Experimental demonstration, first example: XNOR logic gate



XNOR



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

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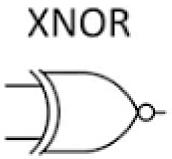
First experimental demonstration: XNOR logic gate



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

The pump powers in cavities 1 and 4 encode A and B

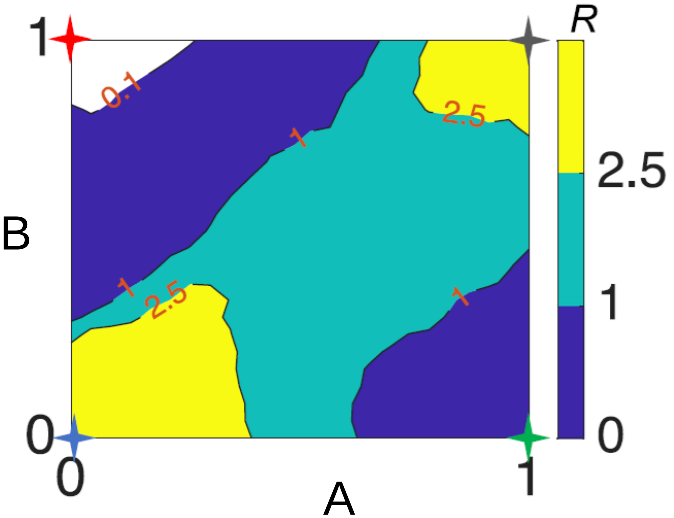
$A = B \Rightarrow O=1 \quad P_1 = P_4 = 4.1\ \mu W$

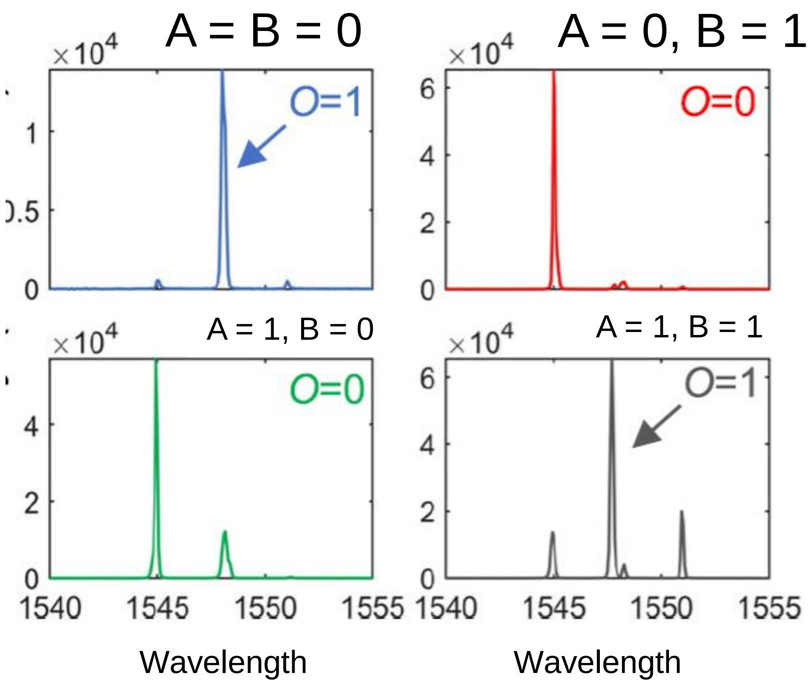
$A \neq B \Rightarrow O=0 \quad P_1 = P_4 = 8.2\ \mu W$

$(P_2 = P_3 = 5.7\ \mu W$ fixed)

Ratio between selected mode and other modes

White: R=0





K. Ji, G. Tirabassi, C. Masoller, G. Li, A. M. Yacomotti, "*Photonic neuromorphic computing using symmetry-protected zero modes in coupled nanolaser arrays*", Nature Comm. 16, 9203 (2025).

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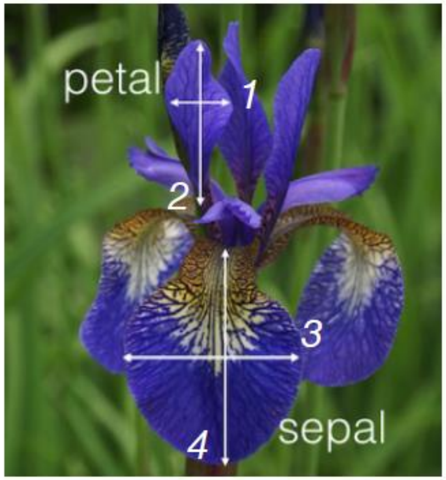
Second experimental demonstration: classification of the iris dataset

4 features
150 measurements



Iris Versicolor

Iris Setosa

Iris Virginica

		Setosa	*Versicolor*	*Virginica*
Accuracy	Test	100%	92%	92%
	Total	100%	97%	97%
F1	Test	100%	90%	86%
	Total	100%	95%	95%

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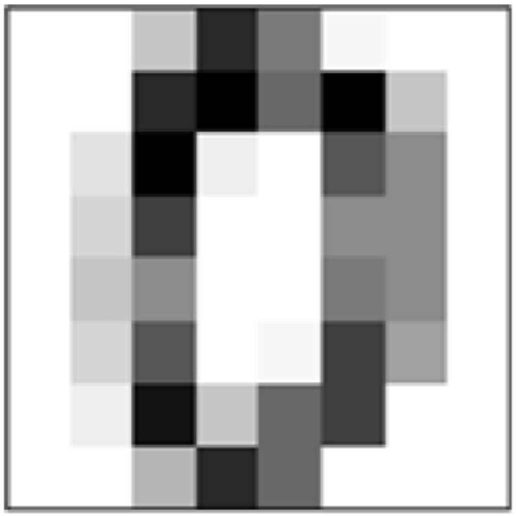
Third experimental demonstration: classification of the hand written digits

$$P^{(k)} = | M \, I^{(k)} |$$

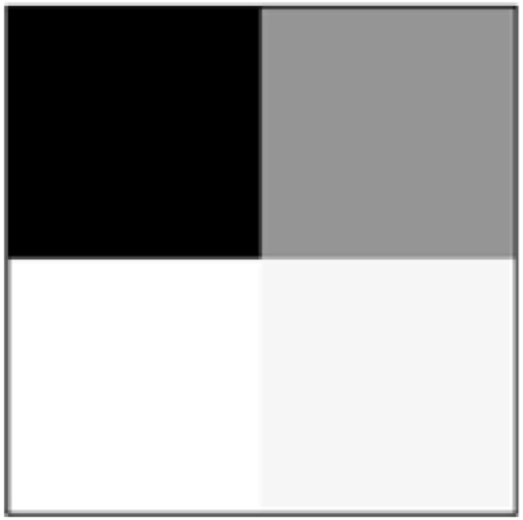
Pump Vector with 4 elements **Input Vector with D elements**

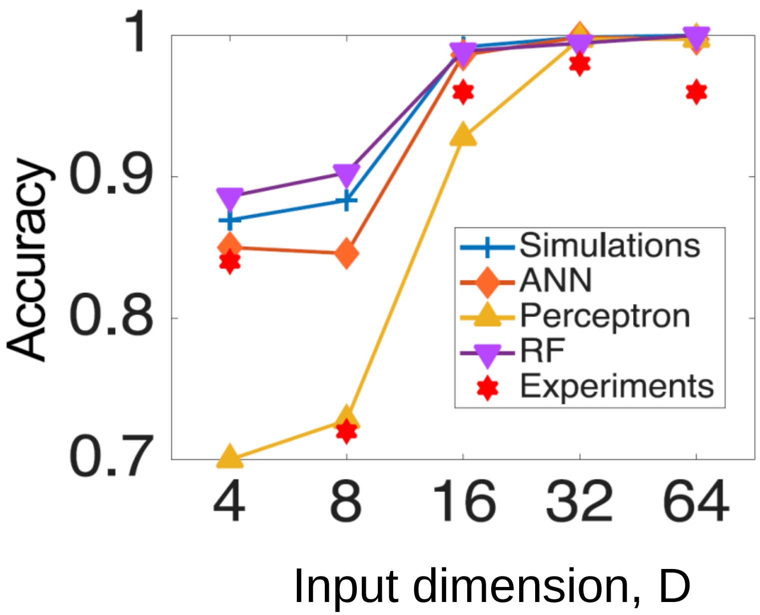
M: Transformation Matrix with D x 4 elements

Input dimension=64



Input dimension=4





K. Ji, G. Tirabassi, C. Masoller, G. Li, A. M. Yacomotti, "*Photonic neuromorphic computing using symmetry-protected zero modes in coupled nanolaser arrays*", Nature Comm. 16, 9203 (2025).

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Conclusions

- We have shown that a nanolaser array can be used to implement a photonic two-layer artificial neural network for binary classification of *low-dimensional* data.
- Data input via the spatial pump pattern; output read from the optical spectrum.
- Performance is competitive with the state of the art.

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Thank you for your attention!

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