Photonic Ising Chip

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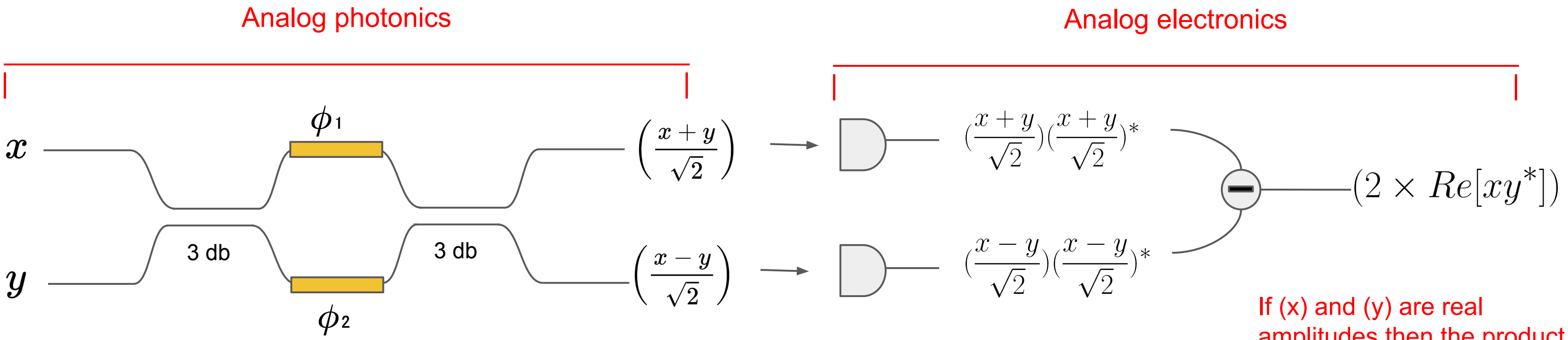
CONCEPT FOR A PHOTONIC ISING CHIP

- Matrix Multiplication Unit
- Encoding the spins
- Encoding the Coupling matrix J
- Simulation results

Matrix Multiplication Unit



x and y are field amplitudes

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

If (x) and (y) are real amplitudes then the product is = ***2xy***

$$-j \cdot e^{-j\left(\frac{\phi_1+\phi_2}{2}\right)}\begin{bmatrix}\sin\left(\frac{\phi_1-\phi_2}{2}\right) & \cos\left(\frac{\phi_1-\phi_2}{2}\right)\\ \cos\left(\frac{\phi_1-\phi_2}{2}\right) & -\sin\left(\frac{\phi_1-\phi_2}{2}\right)\end{bmatrix} \xrightarrow[\phi_2 = \frac{-3\pi}{4}]{\text{if } \phi_1 = \frac{-\pi}{4}} \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

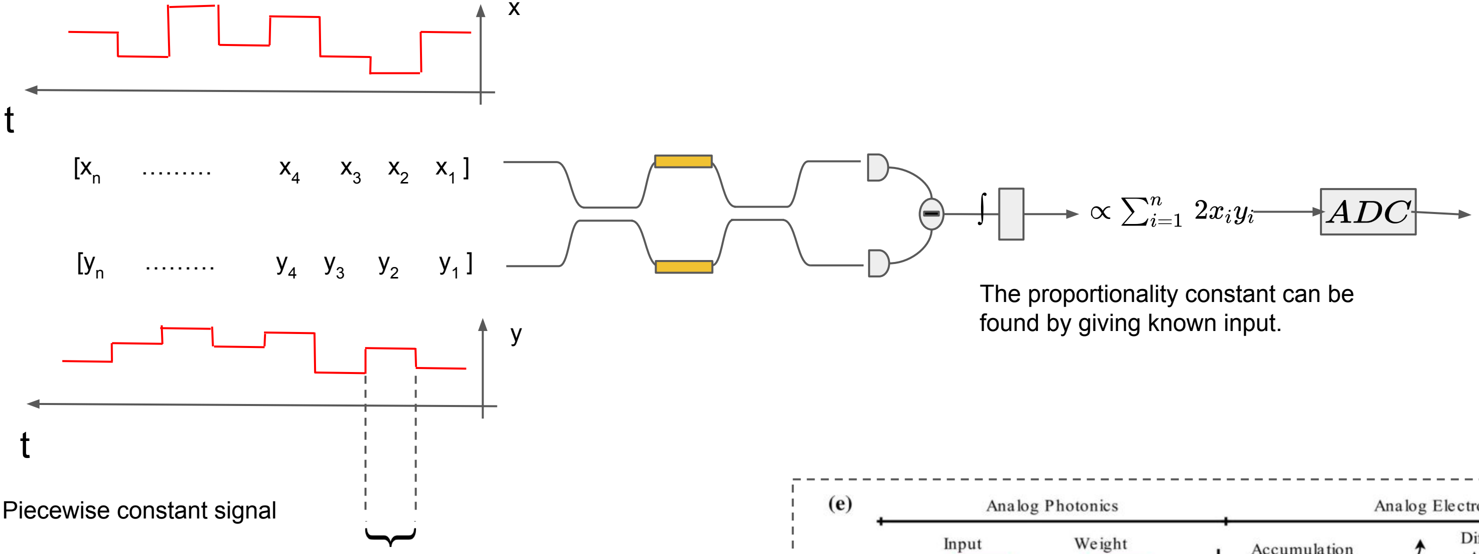
$$\begin{aligned}
&(\tfrac{x+y}{\sqrt{2}})(\tfrac{x+y}{\sqrt{2}})^* - (\tfrac{x+y}{\sqrt{2}})(\tfrac{x+y}{\sqrt{2}})^*\\
&= \tfrac{1}{2}[(|x|^2+|y|^2+x^*y+xy^*)-(|x|^2+|y|^2-x^*y-xy^*)]\\
&= x^*y + xy^*\\
&= 2Re[xy^*]
\end{aligned}$$

R. Hamerly, L. Bernstein, A. Sludds, M. Soljacic and D. Englund, "**Large-scale optical neural networks based on photoelectric multiplication**", Phys. Rev. X, vol. 9, no. 2, May 2019

[The Future of Deep Learning Is Photonic - IEEE Spectrum]

- For vector- vector dot product, the inputs are time-multiplexed
- It detector basically keeps accumulating the charges until the readout is performed which would then discharge the detector and prepare it for the next rout of dot product.

the integrating front-end accumulates in the analog domain the results of several operations before sampling, hence relaxing the ADC bandwidth specifications, In particular, sampling every N+1 operations allows the ADC rate to be N+1 times lower than the MAC rate. This is a critical aspect to reduce the ADC power consumption

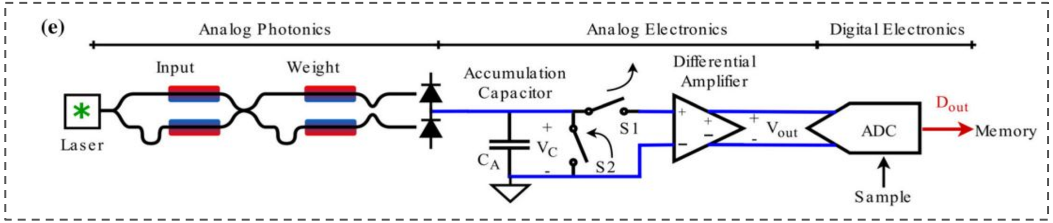


The proportionality constant can be found by giving known input.

Piecewise constant signal

$$\left(\frac{1}{f_{modulation}}\right)$$

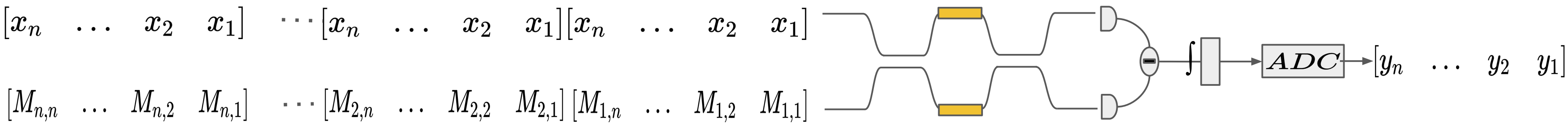
$$f_{modulation} = modulation\ frequency\ of\ the\ signal$$

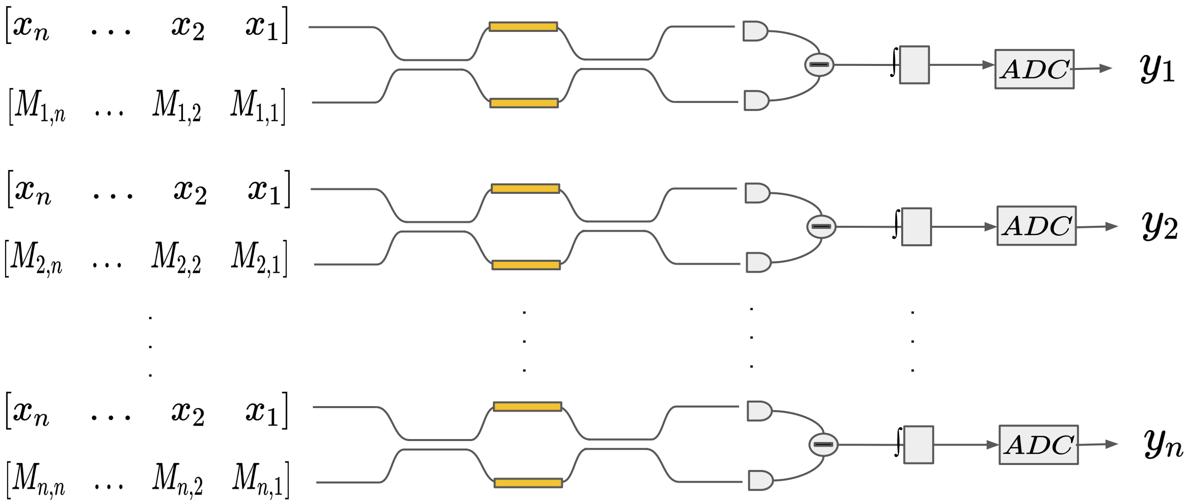


L. De Marinis et al., "**A Codesigned Integrated Photonic Electronic Neuron**," in IEEE Journal of Quantum Electronics, vol. 58, no. 5, pp. 1-10, Oct. 2022, Art no. 8100210, doi: 10.1109/JQE.2022.3177793.

For matrix vector multiplication:

$$\begin{bmatrix} M_{1,1} & M_{1,2} & \dots & M_{1,n} \\ M_{2,1} & M_{2,2} & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ M_{n,1} & \dots & \dots & M_{n,n} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

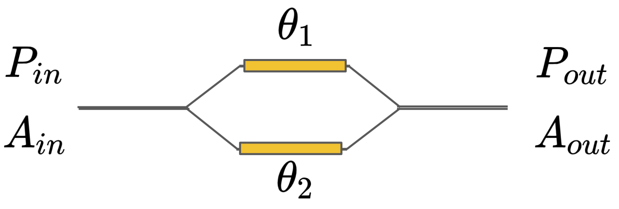




Encoding the Spins

For the Poor man's CIM:

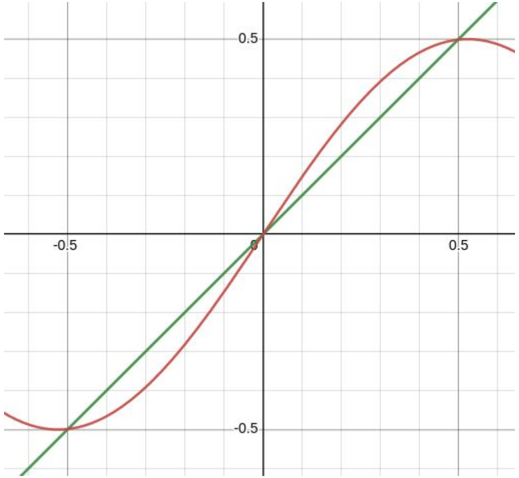
- The spins were encoded in the intensity of the output light from the MZM.
- Bistable state can be achieved from the intensities of the MZM.
- But the multiplication unit discussed in the previous slide only multiplies amplitudes.
- Basically you have to encode the spins in the amplitudes……which is quite simple..



$if\, \theta_1 = \theta,\ and\, \theta_2 = -\theta$

$$P_{out} = P_{in} \cos^2 \theta$$

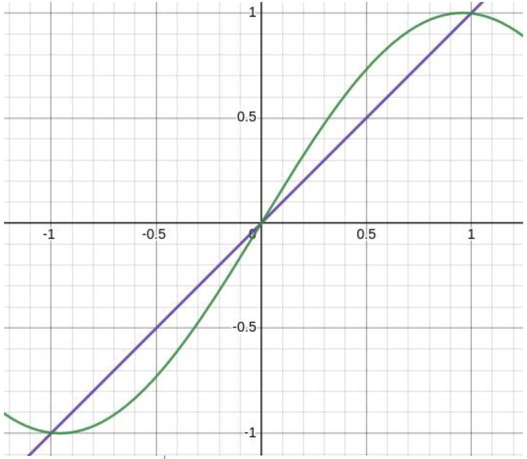
$$A_{out} = A_{in} \cos \theta$$



α=1.5

$$y = \cos^2\left(\alpha \cdot x - \frac{\pi}{4}\right) - 0.5$$

$$x_{t+1} = \cos^2\left(\alpha \cdot x_t - \frac{\pi}{4}\right) - 0.5$$



$$y = \cos\left(\alpha \cdot x - \frac{\pi}{2}\right)$$

$$x_{t+1} = \cos\left(\alpha \cdot x_t - \frac{\pi}{2}\right)$$

Derivation of the Aout

$$A_{out} = \frac{1}{\sqrt{2}} \ \frac{A_{in}}{\sqrt{2}} e^{j\theta_1} + \frac{1}{\sqrt{2}} \ \frac{A_{in}}{\sqrt{2}} e^{j\theta_2}$$

$$if\, \theta_1 = \theta, \ and\, \theta_2 = -\theta$$

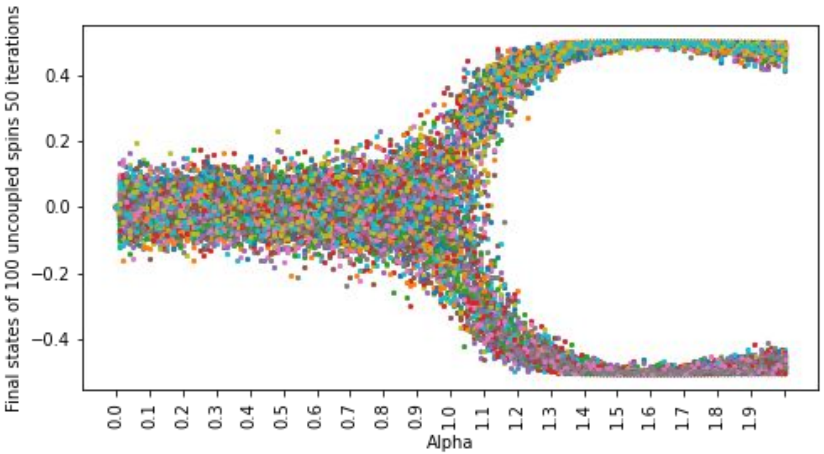
$$A_{out} = \frac{1}{\sqrt{2}} \ \frac{A_{in}}{\sqrt{2}} e^{j\theta} + \frac{1}{\sqrt{2}} \ \frac{A_{in}}{\sqrt{2}} e^{-j\theta}$$

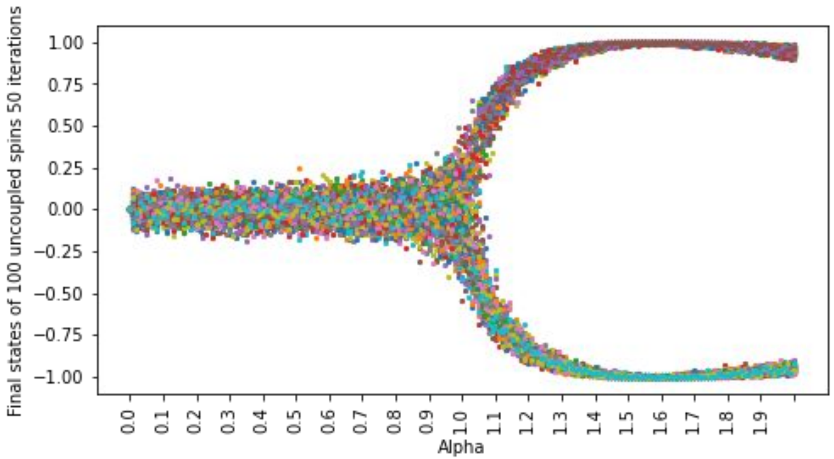
$$A_{out} = A_{in} \left(\frac{e^{j\theta} + e^{-j\theta}}{2} \right)$$

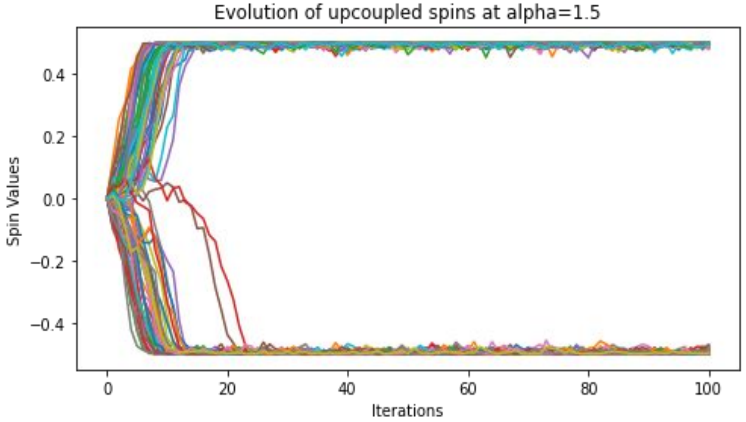
$$A_{out} = A_{in} \cos\theta$$

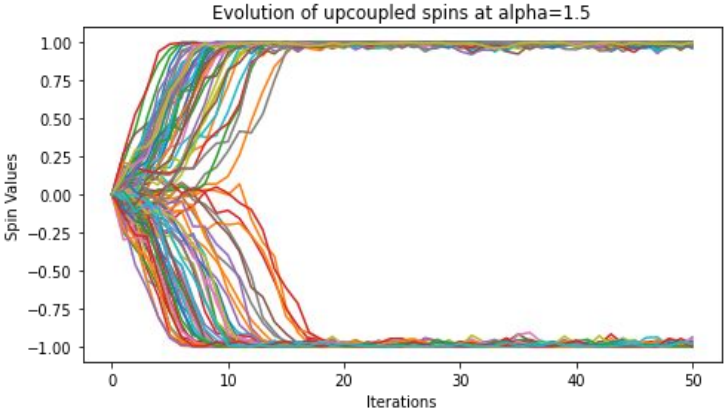
$$x_{t+1} = \cos^2\left(\alpha \cdot x_t - \frac{\pi}{4}\right) - 0.5$$

$$x_{t+1} = \cos\left(\alpha \cdot x_t - \frac{\pi}{4}\right)$$

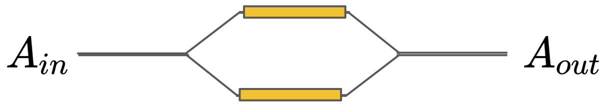






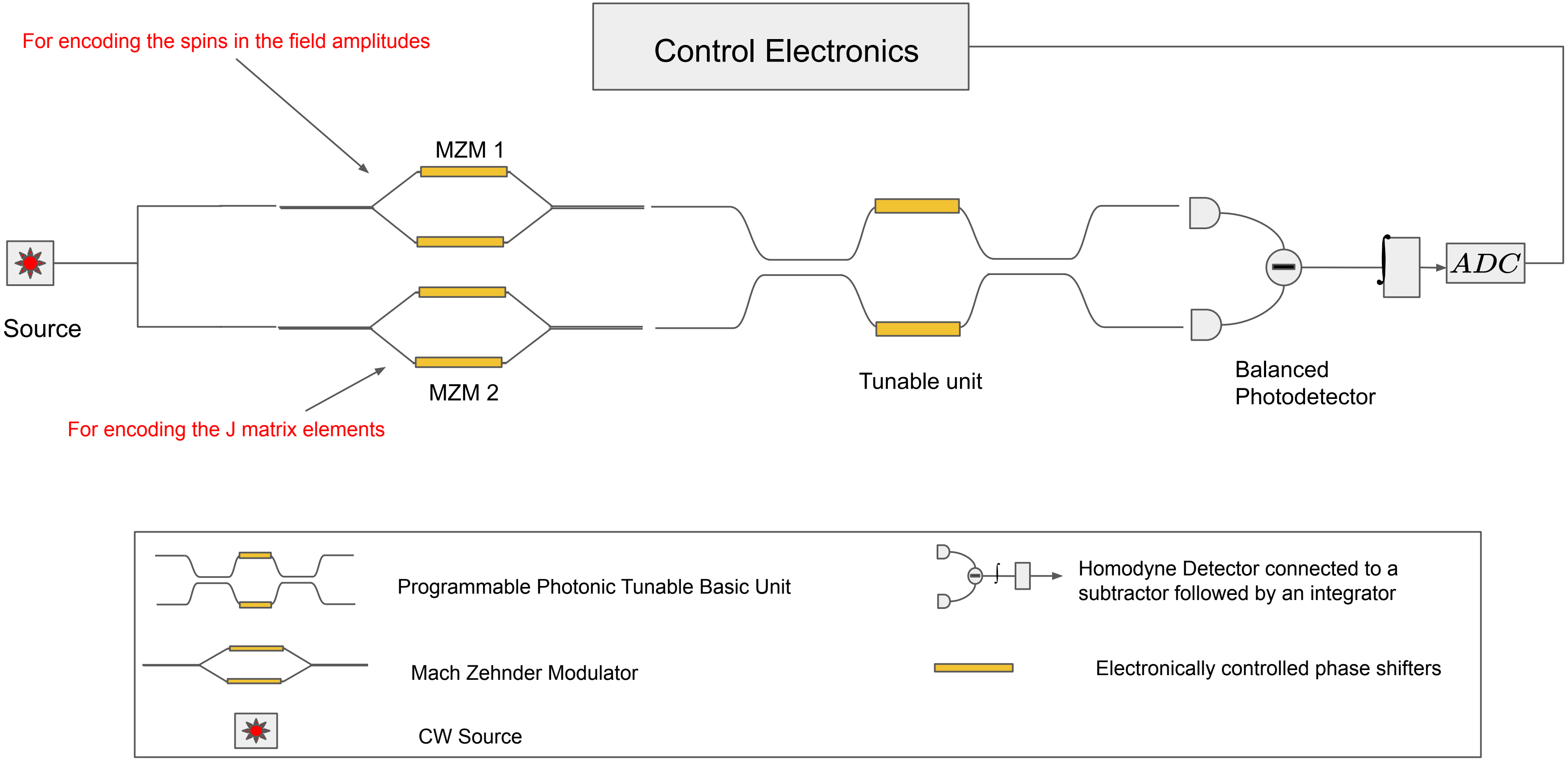


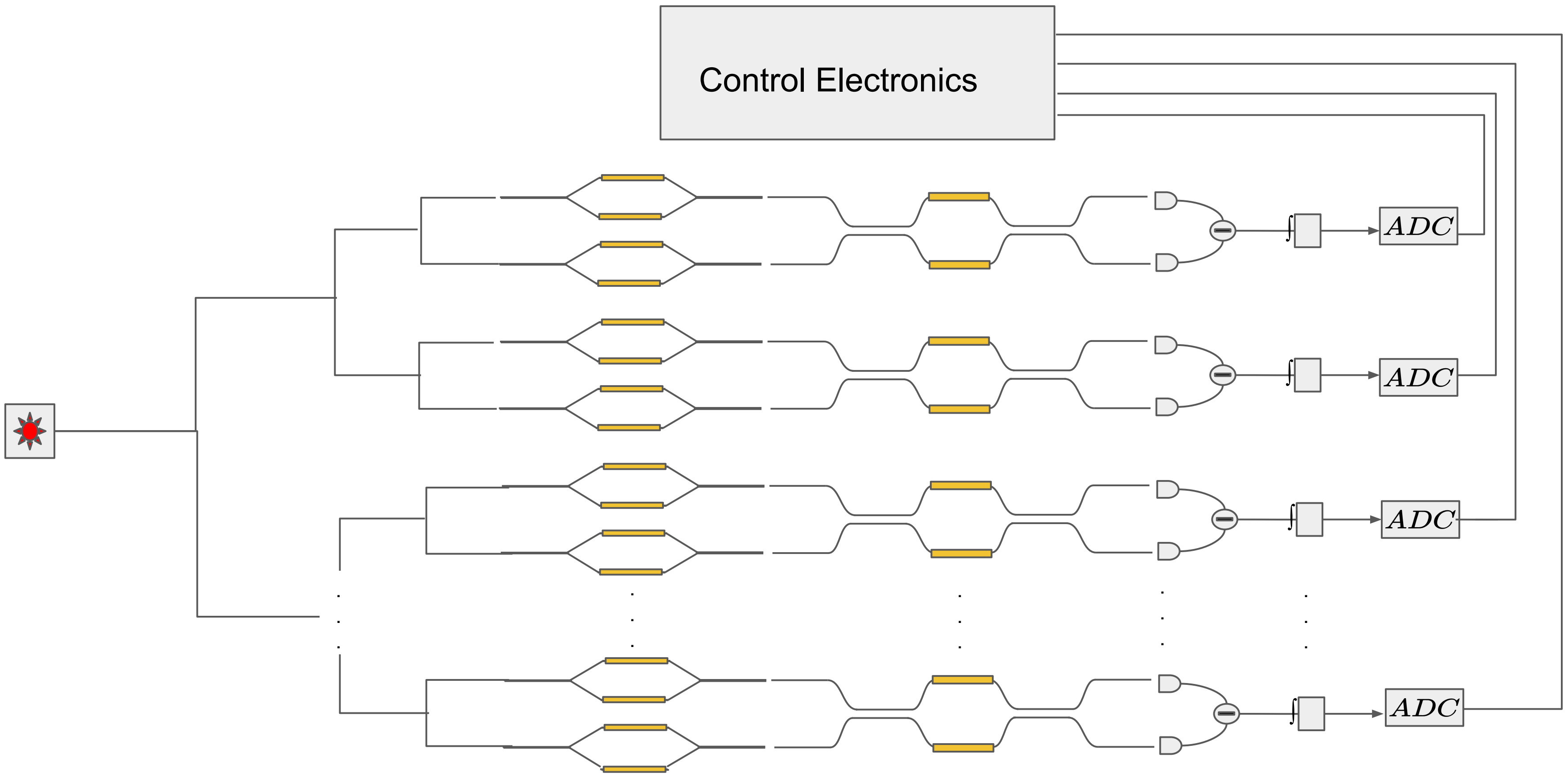
Encoding the J matrix



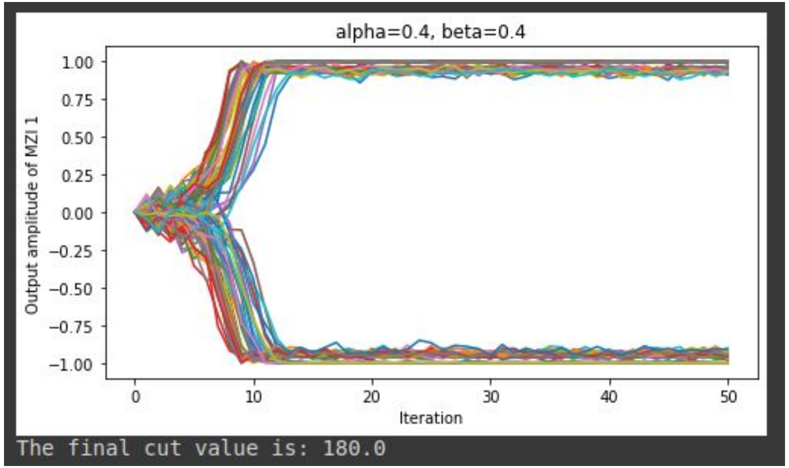
- The elements of J matrix can be simply modulated using a MZM.
- Since the output amplitudes of the MZM is a cosine function, $A_{out} = A_{in}\cos\theta$ The values must be normalized and the normlization factor can be multiplied electronically, which is easy since it will be a constant throughout the iterations.

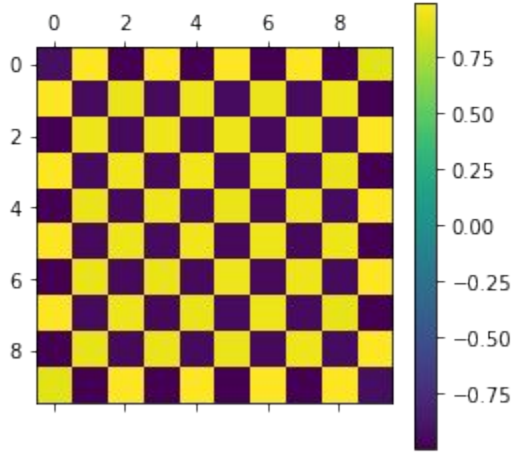
Complete unit

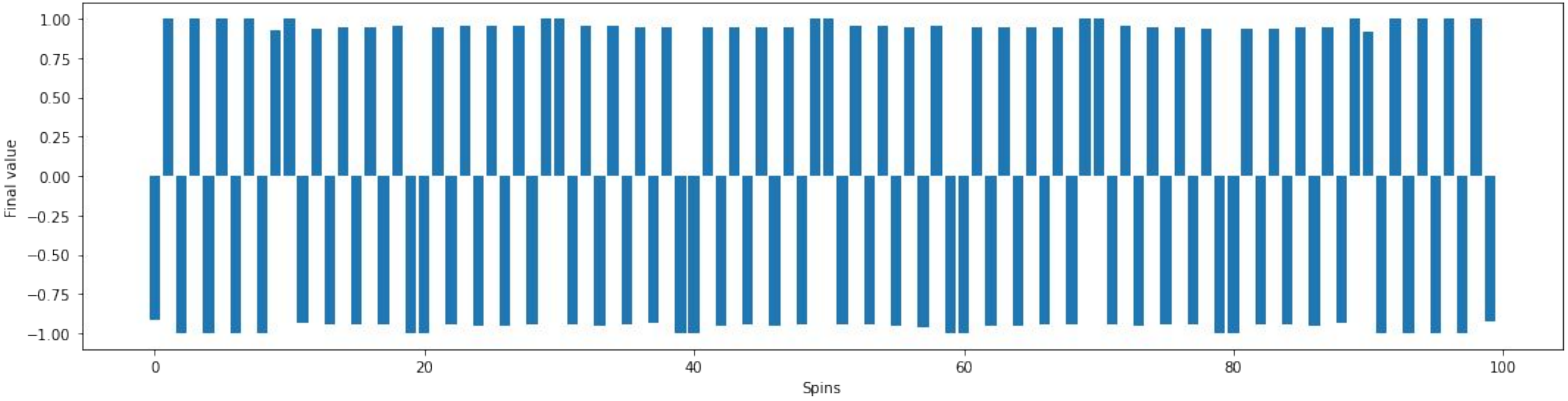



Control Electronics
ADC
ADC
ADC
ADC

Simulation of a square grid lattice of 100 spins

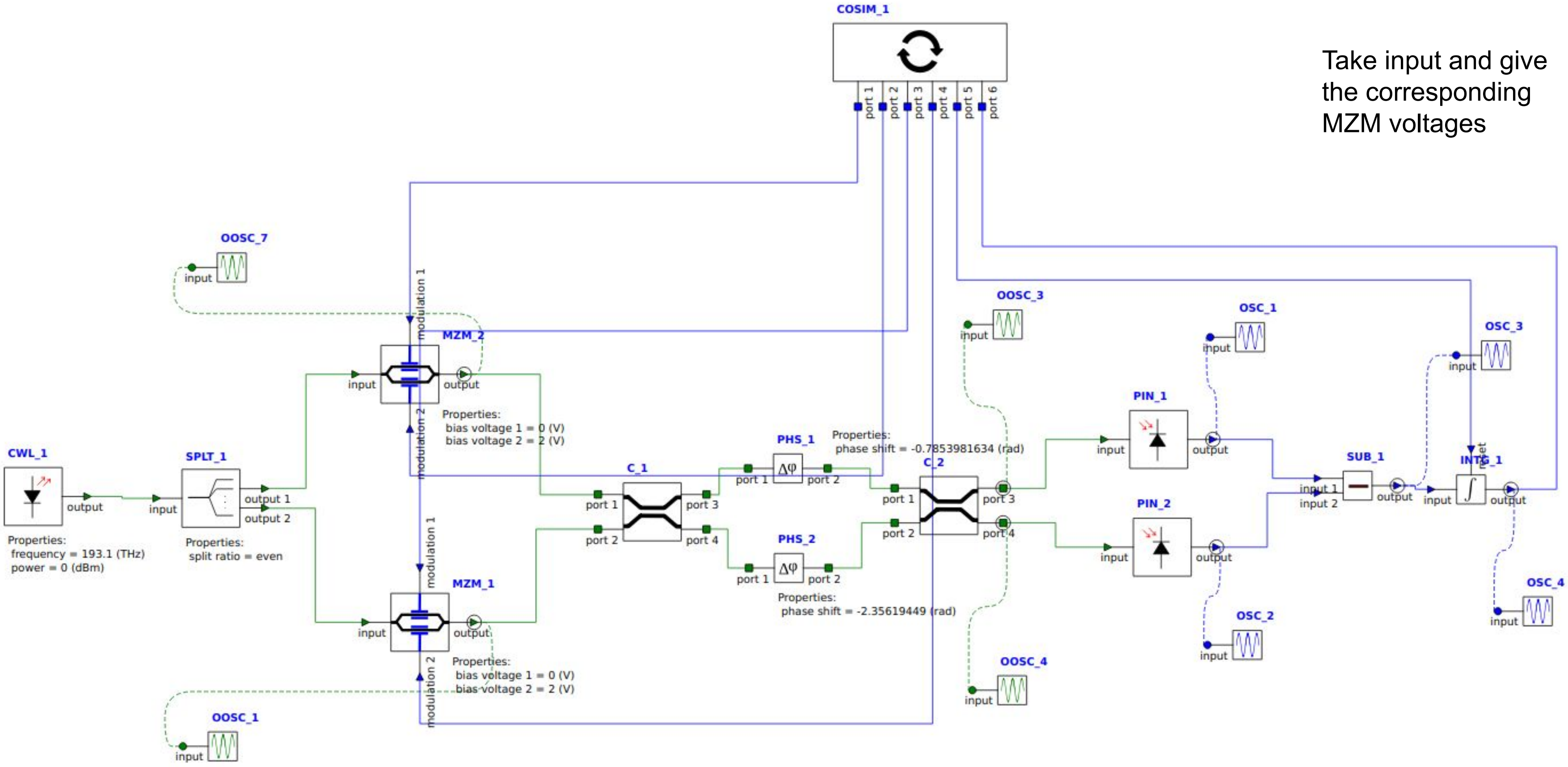






Currently working on simulation the circuit on Lumerical INTERCONNECT

Take input and give the corresponding MZM voltages



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