Universal self-Correcting Computing with Disordered Exciton-Polariton Neural Networks

Theoretical and Mathematical Physics
Cergy-Singapore-Warwick

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Outline

1. Artificial Neural Networks
   1) Feedforward neural networks
   2) Recurrent neural networks and reservoir computing

2. Exciton-polariton Networks
   1) Polariton networks in real space
   2) Polariton networks in reciprocal space

3. Universal self-correcting computing
   1) Toffoli gates realization
   2) Composite circuits

4. Conclusions
1. Artificial neural networks (ANN)

- Artificial neurons
- Connections (weights)
- Synapses in biological brain
- Neurons in biological brain
1. Artificial neural networks (ANN)

What is the point of ANN?

Von Neumann bottleneck

ANN computational architecture
1.1 Feedforward neural networks

Feedforward neural networks

Recurrent neural networks & Reservoir computing

$I_n, H_n, O_n$: Neurons (nodes)

$w_n$: Connection weights

$H_1 = I_1w_1 + I_2w_2$

Activation of $H_1 = f(H_1)$

$O_1 = f(H_1)w_5 + f(H_2)w_6$

Activation of $O_1 = f(O_1)$
1.2 Recurrent neural networks

Temporal dynamical behavior

Capability of processing time-dependent information, like speech recognition or nonlinear time series prediction
1.2 Reservoir computing

Obtained output from the reservoir $y = [y_1; y_2; y_3 \ldots y_n]$

Desired output $= Y$

$Y = W^{out} y$

Superconducting chips. (F. Schürmann, et al., NIPS17(2005))

Optoelectronics. (L. Larger et al., PRX(2017))

Optical systems (F. Duport et al., Optical Express (2012))

Memristor arrays (C. Du et al., Nat. Com. (2017))
2. Exciton-polariton Networks

Electron-hole pair: exciton

Exciton-polariton (polariton)

Polariton:
1. Low effective mass (in the order of $10^{-4}$ mass of an electron)
2. Capacity to interact with each other. (orders of magnitude stronger than in other photonic systems)
3. Ultrafast response (in picosecond time scale)
2.1 Polariton Networks in real space

\[ W_{nm} u_m - i \sum_{m=nn} W_{nm} \psi_m + \left( \gamma - \Gamma|\psi_n|^2 - ig|\psi_n|^2 \right) \psi_n, \]

95% success rate


2.2 Polariton Networks in reciprocal space

\[ i\hbar \frac{\partial \psi}{\partial t} = \left( -\frac{\hbar^2 \nabla^2}{2m} + V(r) - ig + \alpha |\varphi|^2 \right) \varphi + F e^{-i\omega t} \]

\[ \varphi = \frac{-F}{\frac{\hbar^2 k^2}{2m} - \hbar\omega - ig + \alpha |\varphi|^2} \]

3. Universal self-correcting computing

Truth table

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Reversible and universal

\[ F = \frac{W_{in}^{in} u_m e}{\delta_k^2} \]

\[ u_1 = [0; 0; 0] \]
\[ u_8 = [1; 1; 1] \]

output_1 = [0; 0; 0]
output_8 = [1; 1; 0]
output_8 = [1.1; 0.95; 0.02]

Logic level = 0.5

3.1 Toffoli gates realization

\[ F = W_{nm}^i u_m e^{-\frac{(k-k_n)^2}{\delta_k^2}} \]

\[ W_{in} \sim [0 - W_{max}^i] \]

3.1 Toffoli gates realization

Influence of disorder

Dependence of the maximum output error on the correlation length and strength of disorder in the system.

3.1 Toffoli gates realization

Noisy data

\[ u_1 = [0.2 + 0.1i; 0.11i; 0.2] \]

\[ u_8 = [1.2 + 0.01i; 0.99 + 0.1i; 1.1 - 0.1i] \]

- a) Input noise randomly distributed from -0.1 to 0.1 for both real and imaginary part.
- b), c) and d) output noise distribution for 10, 14, 18 polariton-node reservoir

3.2 Composite circuits (full adder)

Conclusions

• 1. Artificial Neural Networks (definition; usage; working principles; kinds)
• 2. Reservoir computing
• 3. Hardware implementation platform: exciton-polariton networks
• 4. Polariton networks in reciprocal space
• 5. Realization of Toffoli gates and full adder with noise correction

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