Joint SU-NTU PhD Proposal: Quantum Neural Networks of Excitons-polaritons

Abstract: This project aims at exploring a novel approach for sensing and generating quantum states of light. The project is at the frontier between quantum physics and applied artificial intelligence, targeting the realization of a novel device based on strongly interacting photons (exciton-polaritons) that, using principles of neuromorphic computing, is able to recognize, characterize, and generate a variety of quantum states.

Context: Photons are the best particles to use for quantum application giving their robustness to decoherence and for their relatively easy generation of quantum states. However, one of the major drawbacks is the very small nonlinearities that photons can feel in standard nonlinear media. In this project we will make use of a hybrid state of light and matter, the exciton-polariton, that keeps the long coherence time while possessing strong nonlinearity, reaching more than 3 orders of magnitude with respect to what is usually obtainable in standard photonic nonlinear crystals. This advantage has led to the observation of an interesting phenomenology, spanning from superfluidity to ultra-efficient four-wave mixing and they have been proposed for optical switching, transistors and ultra-low threshold lasers. More recently polaritons have also entered the quantum regime, demonstrating entanglement and quantum coherence.

Objectives: In this project, we propose to exploit the properties of a quantum neural networks (QNN) of polariton nonlinear nodes, using state-of-the-art interactions, to identify and generate quantum states: this strongly innovative idea relies on the resonant injection of states as excitations of the QNN, which physically realizes–rather than simulates–a massively parallel computing task. Indeed, based on recent theoretical advancements, prompting the feasibility of quantum neural networks with presently achieved polariton interactions and modal volumes, we propose to implement a polariton platform to solve one of the most interesting problems of quantum mechanics: the recognition of quantum states of photons, like Fock states or entangled pairs, without the need of correlation measurements (like those in quantum tomography). Moreover, we will explore the idea of converting classical light from a classical source into a quantum state.

Impact: this proposal will have a huge impact both in the field of artificial neural networks and quantum information. Apart from offering a new way of recognizing and eventually also generating complex quantum states, this idea could revolutionize the way a quantum state is measured, leading to a clear technological advance with a useful quantum device.

Indeed, one of the main needs in Quantum Optics and Quantum Information field is the ability to fully characterize and manipulate arbitrary quantum states generated both in discrete and continuous variable domains. These non-classical states are then exploited as quantum resources for a large variety of applications, ranging from quantum computing to quantum sensing and quantum communications.

This proposal goes beyond the present mainstream approaches for the characterization–or else sensing–and the generation of quantum states. This can be summarized as follow:

1) The full characterization of an arbitrary quantum state is based on a quantum tomography measurement, which requires the implementation of sophisticated interferometric set-ups very demanding in terms of stability and locking of the laser sources. Moreover, for detecting quantum light, specific systems are necessary to perform the measurement (APD, TCSPC, homodyne detection) depending if experiments are performed in continuous variable (CV) or discrete variable (DV) regimes.

2) As for the case of detection also the generation of a given class of non-classical states requires the implementation of specific set-ups which is only able to perform the task for which it has been designed and is hardly reconfigurable. For instance, to create DV entangled states, one needs to implement indistinguishable single photon sources; while to generate CV entangled states, the main conventional approach relies on the realization of optical parametric oscillators. This leads to a proliferation of several, independent platforms hardly interchangeable.

Our proposal has a radically different approach able to solve the bottlenecks mentioned above:

1) Concerning the measurement of an arbitrary quantum state, the QNN proposed here, once a quantum state is fed to the network, has the ability to fully characterize all the properties of this state, including the entanglement

witness, which is one of the most challenging tasks to perform. It is achieved by simply measuring the output intensity of each non-linear node, with no need of phase dependent measurements. This will constitute a major simplification of the current protocols with an enormous impact on the applications exploiting quantum states.

2) The very same system, namely the QNN of non-linear polariton nodes exhibits even more striking properties: it can generate an arbitrary quantum state, in DV domains (indistinguishable single photons, two photon entangled states) as well as in CV domain (squeezed states, entangles states, Schrödinger cat states). Remarkably this is achieved by simply optimizing the linear superposition of the outputs of the non-linear nodes. The system is fully reconfigurable and can switch easily from discrete to continuous variable operation. A unique platform, compatible with both the operation regimes, is needed.

3) This quantum platform has the ability to be reversible: by injecting a quantum state in the QNN, the time integrated output gives access to the full characterization of the input quantum state; conversely, by feeding the QNN with a classical state of light (a coherent state, emitted by a laser), an arbitrary quantum state can be generated on demand at the output. This is all realized in a single device.

To summarize our novel approach will enable the realization of a completely new, fully reconfigurable and reversible universal quantum platform which will significantly advance the state of the art in the field of Quantum Technologies.

PhD program: During the PhD, the candidate will implement a quantum neural network using a planar semiconductor microcavity, where polaritons are arising from the strong coupling between exciton and photons.
In the first year the candidate will use advanced numerical simulations, in closed collaboration with the supervisor at NTU, Tim Liew, expert in the field, to identify the optimal parameters and the optimal sample characteristics for the implementation of the polariton network. In parallel (month 6 – month 12), the candidate will develop different sets of states to be injected into the polariton network, for the training procedure. Interestingly it has been demonstrated in recent theoretical papers [1, 2] that the training can be performed using a set of classical states with anisotropic noise, the so-called thermal squeezed states. These states can be realized modulating a coherent state emitted by a laser with an electro-optical modulator: intensity modulation will provide a state with increased noise on the amplitude quadrature of the electromagnetic field; on the other hand, phase modulation will increase the noise of the phase quadrature (see fig. 1). An engineered mix of phase-intensity modulation will then allow to modify in a controlled way the noise of an arbitrary quadrature of the electromagnetic field [3]. Remarkably, the numerical simulations show that, when trained with such a set of training states the Quantum neural polariton network is able to recognize a large variety of quantum states, including single photon states, two-mode entangled states and Schrodinger cat states.
In the central part of the PhD (month 12- month 24), the candidate will proceed to the generation of continuous variable vacuum squeezed states with controllable squeezed quadratures and bright entangled states. The implementation of such states will be done by using custom made Optical Parametric Oscillators (OPO); a typical setup is shown in fig. 2. The wavelength of operation of the OPOs will be chosen to have quantum states resonant with the polariton QNN. Standard detection techniques will also be implemented to characterize the states and benchmark the performances of the QNN in identifying unknown quantum states.

In third years, the objective will be to fully characterize the polariton neural network. The device will be trained and benchmarked for the task of the characterization of quantum states with known properties, measured independently using standard tomographic techniques. The theoretical analysis performed in collaboration with the NTU partner will be crucial to guide the experiments while the constant feedback theory-experiment will allow to optimize the performance of the device.
Finally, the Polariton neural network will be tested against classical signals to obtain non-conventional quantum states at its output (see fig. 3 for an illustration of the operating principle).

References

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[3] J. W. Wu, P. K. Lam, M. B. Gray and H.-A. Bachor, Optical homodyne tomography of information carrying laser beams. Optics Express, 3, 154 (1998)