



AFRL-AFOSR-UK-TR-2021-0019

Towards deterministic photonic entanglement using time-frequency control

Walmsley, Ian
THE UNIVERSITY OF OXFORD
UNIVERSITY OFFICES
OXFORD, ,
GB

06/29/2021
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 29-06-2021	2. REPORT TYPE Final	3. DATES COVERED (From - To) 01 Dec 2016 - 30 Nov 2019
--	--------------------------------	--

4. TITLE AND SUBTITLE Towards deterministic photonic entanglement using time-frequency control	5a. CONTRACT NUMBER
	5b. GRANT NUMBER FA9550-17-1-0064
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Ian Walmsley	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) THE UNIVERSITY OF OXFORD UNIVERSITY OFFICES OXFORD, GB	8. PERFORMING ORGANIZATION REPORT NUMBER
--	---

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD UNIT 4515 APO AE 09421-4515	10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOE
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-UK-TR-2021-0019

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Made good progress and produced a Physical Review Letter, "Optical Coherent Filtering for Single Noisy Photons," Vol 123, article 213604, 2019. Synopsis from report: The project objectives were: first, to set up and operate a single-photon source based on a semiconductor microcavity quantum dot emitter, and to interface the emitted photons with a fiber-optic cavity network. Second, to interface the quantum dot source with a novel room temperature quantum memory with a broad spectral acceptance tailored to match the GHz-bandwidth photons characteristic of quantum dot emission. We made significant progress towards both of these objectives, although the move of the group to Imperial in 2018-19 and the COVID pandemic 2020 slowed work considerably without time to recover before the end of the project. Nevertheless, the outcomes are very promising, and we hope to be able to continue the work in the future.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON JASON FOLEY
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 555-555-5555
U	U	U	SAR	5	

Towards deterministic photonic entanglement using time-frequency control

*I. A. Walmsley,
Imperial College London*

Final report for Project FA9550-17-1-0064

I. Project Aims and Approach

This project aimed to harness the transformative capabilities of photonic quantum networks by facilitating the creation of multiphoton entangled states. These are difficult to generate using current technologies. The most realizable schemes are based on probabilistic quantum operations using linear optical circuits and photon-counting detectors, but the success probability for concatenated operations falls exponentially without a multiplexing strategy to actively pick out successful events.

Our proposal was to investigate the time-frequency degrees of freedom of photons for enhancing multiplexing schemes. This approach is well suited to guided-wave and fibre integrated networks, which may support just one spatial and polarisation mode but can support thousands of temporal/spectral modes. Crucially, temporal encoding exploits the high degree of indistinguishability between sequentially emitted photons from a single quantum dot source. Additionally it can be added onto any spatial multiplexing scheme to provide a dramatic increase in the number of modes available, without requiring additional components.

The project objectives were: first, to set up and operate a single-photon source based on a semiconductor microcavity quantum dot emitter, and to interface the emitted photons with a fiber-optic cavity network. Second, to interface the quantum dot source with a novel room temperature quantum memory with a broad spectral acceptance tailored to match the GHz-bandwidth photons characteristic of quantum dot emission.

We made significant progress towards both of these objectives, although the move of the group to Imperial in 2018-19 and the COVID pandemic 2020 slowed work considerably without time to recover before the end of the project. Nevertheless, the outcomes are very promising, and we hope to be able to continue the work in the future.

II. Research

We followed two work streams to develop deterministic methods to generate entangled resources for photonic networks. The first work stream addressed the creation of multipartite entanglement using quantum dot light sources by injecting time-bin-coded multiphoton sequences into a network of fiber-optic cavities.

Task 1: Multi-photon quantum networks from a quantum dot.

We adopted the approach of time-bin coding to demonstrate the opportunity for large scale entangled state preparation using a single quantum light source – the better to ensure identical quantum emission on each trial. By moving from the spatial to the temporal domain, this architecture has the potential to alleviate the hardware requirements in terms of interferometric components, number of single-photon sources and number of detectors.

Besides these features, its scalability, robustness and allow easy upgrade of the configuration to a higher complexity using current state of the art fiber-optical hardware.

Milestone 1.1 (month 12): Build cryogenic apparatus for operation an efficient quantum dot microcavity source.

We developed an apparatus to generate single photons emitted by quantum dots in collaboration with with Pascale Senelart (CNRS-C2N, Paris), a world leader in the production of nanopillar microcavity-coupled quantum dot single photon sources, and with Robert Taylor, an expert in quantum dot spectroscopy at the University of Oxford.

CNRS provided us with a custom chip containing a 200x200 array of quantum dot containing nanopillars (Fig. 1) with a small frequency gradient around 917nm across the array for us to be able to choose a quantum dot suitable for the memory. To investigate this sample and to extract photons from the quantum dot we built our own cryogenic confocal microscope as well as using a system in Prof. Taylor's laboratory. Both confocal microscopes consisted of liquid helium flow cryostats capable of cooling the sample to 4K. Long-working distance objective lenses were used to excite and collect light from individual nanopillars through the top window of the cryostats. For a first set of experiments, a small portion of the pulsed 852nm control laser for the memory was used to off-resonantly excite the quantum dots. As each nanopillar contains a large number of dots, this leads to the observation of ensemble fluorescence and is not suitable for the production of single photons. A typical spectrum is shown in Fig 1b.

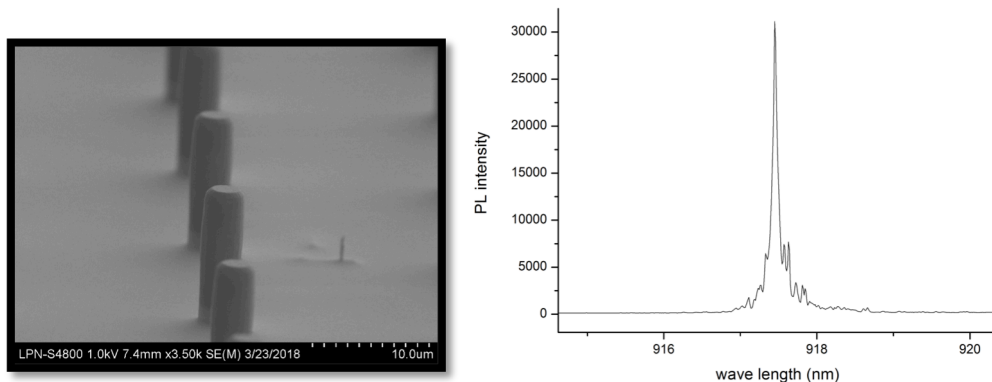


Figure 1: Left: Micrograph of the CNRS nano-pillar quantum dot cavity light sources. Right: typical fluorescence spectrum from a single nano-pillar containing multiple quantum dots under off-resonant excitation at 852nm.

To interface single photons with the ORCA memory it is necessary to move to p-shell excitation between 870nm and 905nm of individual dots within a nanopillar. To accomplish this we built a tunable external cavity diode laser operating in this regime. As single dots are considerably dimmer and narrower as ensembles it is necessary to first identify a dot with a center frequency within the signal window of the memory and then to temperature-tune the nanopillar cavity to this frequency using an electric heater inside the cryostat to couple it to the dot and enhance its emission. Unfortunately, the temperature stability of the flow cryostats available to us at the time of the experiments, even with active temperature stabilization, was not sufficient to keep a nanocavity coupled to a specific dot. Moreover, the daily cool down-warm up cycles necessary with this type of cryostat make realignments and re-identification of quantum dots necessary, taking up several hours per day and

severely limiting time for experiments and optimization. This technical limitation prevented us from demonstrating coupling of a single quantum dot to the memory and ultimately to study multi-photon quantum interference.

To address this in the future we have recently purchased a state-of-the-art closed cycle helium cryostat with cryogenic confocal microscope (Attocube attoDRY800) through funding provided by the UK Quantum Computing & Simulation Hub. The system will be installed in spring 2021 and provide considerably greater temperature stability. Moreover it provides much better light extraction efficiency through a cryogenic high-numerical aperture objective lens and will enable stable operation of a single quantum dot source for months at a time, allowing us to overcome previous limitations outlined above and to progress with the project

Milestone 1.2 (month 24): Study multi-particle, multidimensional time-encoded quantum walk.

In parallel with developing the quantum-dot light source, we developed the time-bin interferometer based on fiber-loops to demonstrate that it was a suitable platform for manipulating quantum light. The outcome of this experiment showed that it was possible to undertake multi-photon interference experiments in fibres using time-bin coding.

Figure 2 shows a simplified schematic of the setup we built to perform the multi-photon interference experiments. To generate the input state, we employ a heralded single-photon source based on spontaneous-parametric down-conversion in a periodically-poled KTP crystal pumped by an fs-pulsed laser. Operating this source with low pump power allows us to approximate the performance of a deterministic single-photon source. The source produces a train of time-bin modes that encode the quantum information in the temporal domain. The heralding arm is then used to identify which of these time-bins are occupied. The single-loop structure is employed to perform quantum interference by matching its length to the time-bin mode spacing. A variable fibre coupler allows us to tune the interference and, thus, modify the range of the correlations along the 1D time-bin train. Finally, we use a spatially multiplexed array of superconducting nanowire single-photon detectors to perform pseudo-photon-number-resolving detection.

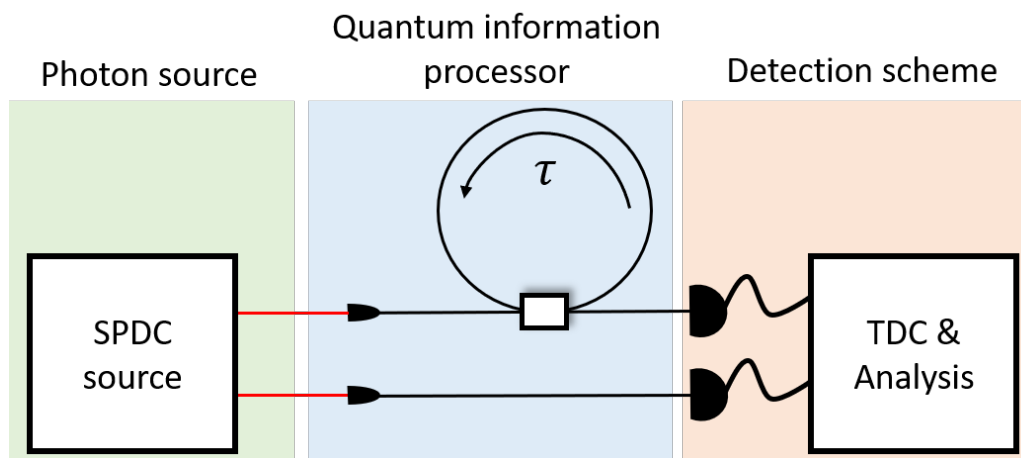


Figure 2: Schematic representation of the setup we are employ in which we differentiate three blocks, the single-photon source based on SPDC, the time-bin quantum information processor and the photon detection apparatus.

Figure 3 shows the probability distribution measured at the output of the fibre loop for

several splitting ratios. The x-axis, $\vec{d}(\vec{s})$, represents the output detection time-bins, e.g. [1; 2] is the case in which we detect a photon in the first time-bin and another photon in the following time-bin. Signatures of quantum interference can be seen in the increase of the probability of states in which the photons are bunched together, e.g. the output states [2; 2]; [3; 3], for instance. This proof-of-principle experiment shows how we can carry out multi-photon interference experiments in the time-domain, and paves the way for fibre-optical loops to be scaled up.

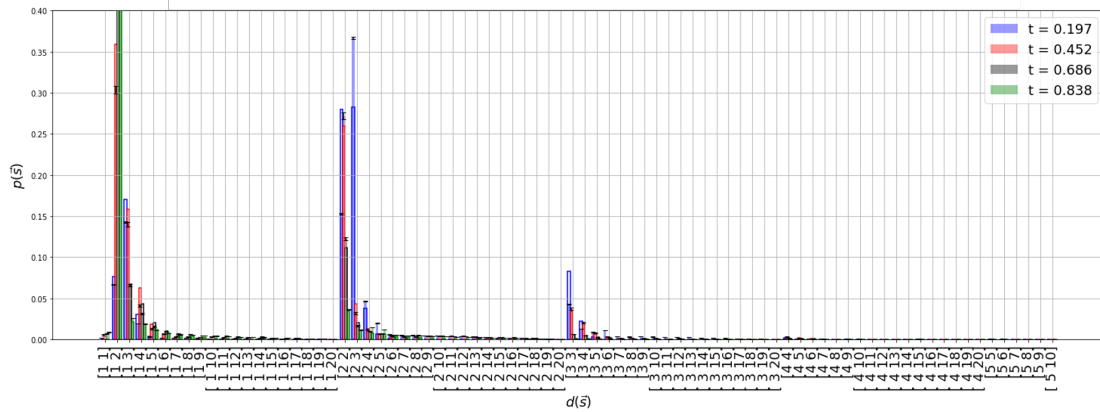


Figure 3: Probability of obtaining detections at time-bins defined by $\vec{d}(\vec{s})$ after the loop for a heralded input state $\vec{d}(\vec{r}) = [1; 2]$, meaning a photon was detected in the first time-bin and another in the second one, for different splitting ratios t .

Task 2: Photonic networking with quantum memory.

In the second work stream, we addressed the probabilistic nature of photon entanglement generation by interfacing a quantum dot with robust, efficient quantum memories. Quantum memories are devices that can store, manipulate and release quantum light on demand. To date no memory has been shown to introduce zero noise and be compatible with light from quantum dots.

We also explored the possibility of improving the quality of the quantum dot photons using the memory as a coherent temporal filter.

Milestone 2.1 (month 18): Interface a quantum dot photon source with a coherent ladder quantum memory.

Recently we introduced a new memory protocol, off-resonant two-photon absorption: ORCA. We were able to interface this fluorescence with an ORCA memory based on Cs (see Fig. 4 for schematic of atomic energy levels). Using the 917nm transition plus a suitable control field derived from the same laser pumping the quantum dots, were able to synchronise the memory and light source operation.

We observed control-field dependent absorption by the memory (memory read-in) on the order of 15%, as shown in Fig. 4. The small read-in efficiency is likely due to the large number of photons emitted by the ensemble. Moreover, non-ideal pulse overlap between signal and control cannot be ruled out, which was difficult to optimize in this experiment. Consequently, no read out could be observed due to the small read-in efficiency.

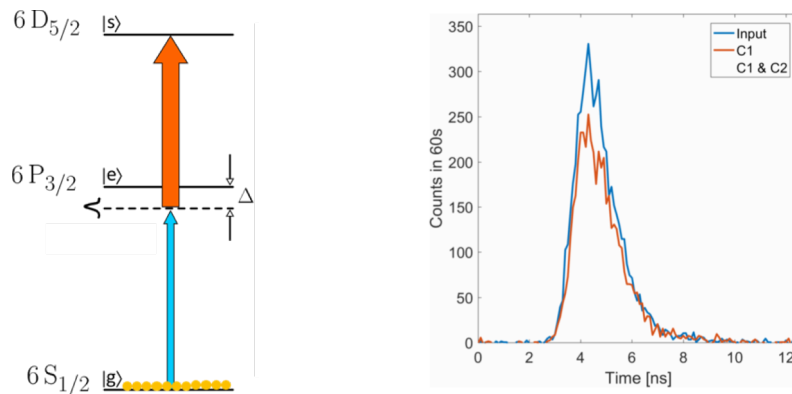


Figure 4: Left: ORCA quantum memory scheme. Right: Control-field dependent absorption of ensemble fluorescence by the ORCA memory, showing some 15% absorption efficiency.

Milestone 2.2 (month 30): Benchmark the storage of non-classical states.

Although we were not able to store and retrieve single photons from a quantum dot, we did come up with an important application for the memory in making these light sources more scalable.

A quantum memory, when appropriately designed, can select a particular temporal shape out of a pulse that is a mixture of multiple, temporally and spectrally overlapping pulses. This unique feature, which is not shared by ordinary passive filters, will allow us to use the memory to purify the quantum light from the quantum dots to remove the environmental noise from the artificial atoms. This will remove the last remaining roadblock to making quantum dots technology ready.

As a proof of principle,¹ we showed that ORCA could perform as a noise-free quantum buffer with large optical bandwidth with the capability both to filter temporal-spectral modes, as well as inter-convert them and change their frequency. We theoretically showed that such quantum buffers optimally filter out temporal-spectral noise; producing identical single-photons from many distinguishable noisy single-photon sources with the minimum required reduction in brightness. We experimentally demonstrated a noise-free quantum buffer in a warm atomic system that is well matched to quantum dots and can outperform all intensity (incoherent) filtering schemes for increasing indistinguishability of individual photons from successive quantum dot emissions, or from different quantum dots.

We expect that the improved single-photon quality from the quantum dot pulse ORCA combination will be an ideal light source for the cavity quantum walks. Further, the memory itself can work as an active element in quantum walks, acting as both a reconfigurable switch and a delay at the same time.

¹ arXiv:1704.00013; *Optimal Coherent Filtering for Single Noisy Photons*, S. Gao, O. Lazo-Arjona, B.