

Quantum entanglement demonstrator for public engagement

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Abstract. The Networked Quantum Information Technologies (NQIT) hub was one of the quantum hubs of the first round of the United Kingdom's flagship scheme, bringing together academia, industry, and government. The Optical Engineering and Quantum Photonics Group at the University of Southampton's Optoelectronics Research Centre has developed an interactive demonstrator of a key device within NQIT to bring quantum photonics technologies to a wider audience. The system was exhibited at the 2017 UK Quantum Showcase in London to an audience of industry and government. It also featured as part of the Quantum City stand at the 2018 Cheltenham Science Festival, one of the United Kingdom's leading annual science events. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.61.8.081802](https://doi.org/10.1117/1.OE.61.8.081802)]

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1 Introduction

The Networked Quantum Information Technologies (NQIT) hub is one of the four quantum hubs from the first round of the United Kingdom's (UK's) flagship scheme, bringing together academia, industry, and government to develop the UK as a leader in quantum technology. A key part of this project involves building an optical network to support the construction of a quantum computer.

Due to the complex nature of quantum science, it is often seen as a difficult area for engagement and outreach. However, with the increasing interest in quantum technologies and their impact in the future, it is important to engage people with this science and technology. In this paper, we present a project by the lead author in developing an interactive demonstrator of a key optical component of the NQIT project to showcase it to a wider audience. The software was developed to accompany the demonstrator to show how the real-world device works on a single-photon level. This work was presented previously at SPIE Optics Education and Outreach V conference, and this paper serves to present and renew the findings.¹ The system was exhibited at 2017, 2018, and 2019 UK Quantum Showcase in London to an audience of industry representatives and government policymakers, and was also featured at the 2018 Innovation South showcase at Farnborough Conference Centre. The demonstrator was part of the Quantum City stand at the 2018 Cheltenham Science Festival—one of the UK's leading public engagement and science outreach events—and was exhibited with a handout for visitors to take away with them explaining the importance of photonics for quantum technologies. The unit has also been exhibited at the annual Southampton University Science and Engineering Festival as well as featuring on the university roadshow stand at the New Forest Show in 2019. This paper discusses the motivation behind the project, the design, and construction of the demonstrator, as well as suggestions for a more accessible “home-made” model for the education of quantum entanglement. We will also discuss the reception of the device and any feedback given, as well as lessons learned over the course of the project.

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2 Background

In this section, the context of the Quantum Technologies Programme is presented. The role of the Optical Engineering and Quantum Photonics (OEQP) Group in developing a fiber optic entangler for one of the quantum hubs is discussed. Fabrication challenges and the concept of the device are also presented.

2.1 Context

The £270 million (GBP) UK National Quantum Technologies Programme² (UKNQTP) is designed to bring together academia, industry, and government as part of a strategy to develop the UK as a future leader in quantum technology.³ Part of this is an Engineering and Physical Sciences Research Council (EPSRC) funded national network of four different quantum technology hubs, with each focusing on a different aspect of quantum science and technology. The first round of the hub ran from 2014 to 2019 and consisted of; the Sensors and Metrology hub led by Birmingham University⁴; the Communications Technologies hub led by the University of York⁵; the Quantum Enhanced Imaging hub (QuantIC) led by the University of Glasgow.⁶ The fourth hub, and the focus of the work presented here, is the NQIT hub led by the University of Oxford.⁷ This is the largest of the four hubs and is working toward building a hybrid quantum computer linking light and matter technologies for quantum information processing. These hubs have since been superseded by four new hubs that feature updated goals and directions to the research, with strong input from industry to guide the technology developed over the last seven years to commercialization. The first round of the UKNQT was summarized and reviewed by Knight and Walmsley in *Quantum Science and Technology*,⁸ which includes an outlook toward the new hubs and the commercialization of quantum technologies.

Photonics is a major part of modern quantum science, with photons being the main route for mediating quantum interactions, entanglement, and measurement.⁹ A report by the Photonics Leadership Group revealed that the UK photonics industry is worth around £12.9 billion (GBP) and employs >65,000 people.¹⁰ A report released by the Institute of Physics in May 2018 described the “health of photonics” and highlighted many of the areas that this technology feeds into.¹¹ Some of these areas include aerospace, communications, health care, food, and energy, with many set to benefit from quantum photonics technologies. Quantum entanglement is frequently mediated through the use of single photons, which immediately means that any loss in components can be catastrophic to quantum systems. Quantum entanglement is also incredibly sensitive, and any external effects can easily destroy these fragile states. Therefore, optical engineering is an important aspect for developing the low loss, quantum-compatible components and systems that are required for these advanced circuits and communication technologies.

The University of Southampton has played a leading role in photonics and optical technologies research since the 1960s. The OEQP based within the Optoelectronics Research Centre (ORC) at Southampton have expertise in the design and fabrication of photonic components and devices and collaborate with many of the quantum hubs. The group also has a passion for outreach and public engagement, with its members having published several papers on engagement activities over the past few years.^{12–14} The OEQP Group was recognized in 2017 with a “Highly Commended” awarded for group public engagement by the South East Physics Network (SEPNET). The group are using their expertise in these areas to develop a fiber-optic photonic entangler system for the NQIT project and engage a wide audience with the science behind quantum technologies and how photonics plays an important role.

2.2 NQIT Entangler Concept and Fabrication

The OEQP Group works collaboratively within the NQIT hub, developing optical components for quantum applications. One key part of this collaboration is the development and testing of the optical network required for the NQIT hybrid quantum computer. This will consist of solid-state ion traps, based at Oxford, which will be used as computational nodes. Each node needs to be linked with its neighbors via a fiber-optic entangler capable of causing photons emitted by the trapped ions to undergo quantum entanglement. The process of this particular quantum

entanglement is described in detail by Olmschenk et al.¹⁵ In summary, ions used as qubits located in separate traps meters apart can be entangled through the interaction of photons. The ions are put into an excited state and prepared for entanglement using pulses of microwave radiation. The ions then each emit a photon polarized depending on the ions state, and both of these propagate to a beamsplitter (BS), where they are able to undergo quantum interference. These entangled photons are then directed through a polarizing beamsplitter (PBS) to some detectors. If the photons are of the same polarization, only one detector will fire, and we know which state both ions are in. If both detectors fire we know each ion must be in opposite states, but do not know which state either is in. By entangling the emitted photons we allow the ions themselves to become entangled. The ion traps will be linked by the entangler unit discussed here; a fiber optic unit made from off-the-shelf components used for guiding and interfering with the emitted photons. The system is designed so that it is possible to “scale up” by adding further ion traps and optical entangler systems.

The entangler itself is designed to be constructed with off-the-shelf optical fiber components currently available. This poses a technological challenge in that the majority of components are developed for the current telecommunications market, which works with infrared wavelengths of light. The ions used in the NQIT project emit light in the visible blue region, at 422 nm wavelength, for which many off-the-shelf components show a great deal of loss. With a long history of optical engineering, the OEQP Group’s role is to source and test components for operation at blue wavelengths before assembling these into an optical entangler system for use with the ion traps. These components are individually tested and assembled inside a 19” rack mount for stability, ease of use, and for system expansion through adding further units. The input fibers are attached to the ion traps and guide the photons emitted from the traps to the entangler unit. Inside, the photons are introduced to each other at a fiber beam splitter. It is here that the photons experience quantum entanglement. If the photons emitted from the ion traps become entangled this filters back to the traps, meaning that the trapped ions become entangled with each other, too. The entangled photons then propagate to a second component that splits the photons depending on their polarization. This stage is used for tuning the ion trap/entangler system, and for measurement purposes. After the measurement, it is possible to tell if the entanglement between the ions was successful.

It is clear that the function of this device, and the science behind it, can be quite challenging to explain. It was decided to produce an interactive replica of the real device for engagement purposes. The following sections describe the design and construction of the interactive demonstrator, as well as accompanying software and a handout designed to highlight the importance of photonics to quantum technology.

3 Hardware and Software Implementation

The following sections detail the construction of the demonstrator, how it was assembled, and the estimated cost of the device in terms of parts used for manufacturing the device.

3.1 Hardware

The hardware was designed to replicate the real-world entangler unit that would be used in the fundamental physical experiments of the NQIT project. Blue laser diode illuminated optical fibers were used, along with an electronic circuit to drive them and Arduino for control. The electronics were housed within a 19” rack-mountable unit with the illuminated fibers feeding through to an additional unit above. The construction of the unit and its operation are discussed in the following sections.

3.1.1 Construction

The equipment required for constructing the unit is listed as follows, with total costs displayed in GBP. The total equipment cost was approximately £685.43. The cost of staff time taken to assemble the device is not taken into account here.

- 2 × 1U 19" rack-mountable units (RS components PF-19), used for housing the optics and electronics and for the operation of the demonstrations (£95.74).
- 5 × Toggle switches for activating the device and controlling the circuit (£5.28).
- 5 × Blue laser diode–illuminated fibers (World Star Tech ML5-20G-450-2M), which relate directly to the optical fiber component of the real entangler. These illuminate to show the paths that photons would take in the device (£450.00).
- 1 × Arduino Uno microcontroller for control of the electronics to allow the fibers to light up under certain combinations of switches (£20.70).
- 1 × Buck voltage/current converter, for electronically driving the illuminated fibers and light-emitting diodes (LEDs) on the unit (£1.20).
- 5 × Transistors (FETs), used for gating the illuminated fibers with the Arduino (£4.50).
- 1 × Piece of clear polycarbonate for the lid of the unit, so that the fibers can be viewed but are also protected (£38.16).
- 1 × universal serial bus (USB) port and cable for reprogramming Arduino without having to dismantle the box (£8.11).
- 2 × Die cast boxes to represent the BS components (£11.74).
- Other components such as resistors, cables, electronic connectors, cable glands, electronic prototype board, LEDs, foam, etc. (~£50).

The electronic components were assembled as shown by the circuit diagram in Fig. 1. The entire circuit was driven through a DC adapter, which converted the 240 V AC mains supply to a 9 V DC supply of <math><1.2\text{ A}</math>, through a switch to control power to the entire device. The five illuminated fibers are driven by blue laser diodes, which are directly coupled and provided as a complete unit from World Star Tech. These were connected electrically in parallel through separate FETs to a buck voltage/current converter, which scaled the input current to that accepted by the fibers. The Arduino was powered directly from the input 9 V supply and was programmed to accept four input signals (four switches) and respond accordingly. Five outputs from the Arduino were used to gate the FETs, allowing the fibers to illuminate with respect to the input signals. The Arduino outputs were also programmed to give the fibers a pulsing effect when illuminated.

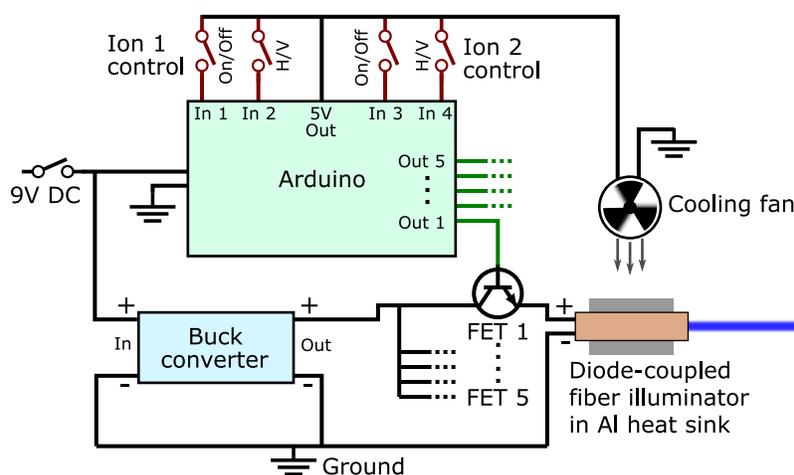


Fig. 1 A simplified diagram showing the layout of the circuit for operating the demonstrator. The system is driven by a 9 V DC, 1 A power supply that powers the Arduino Uno microcontroller and Buck voltage/current converter. The Arduino is controlled by switches connected to its digital input ports, which are fed from a 5 V output on the Arduino board itself. The switches turn each channel on and off, and also simulate H or V polarization of light. This also powers the fan used to cool the laser diodes. The Buck converter converts the input supply to provide up to 2.5 A of current to drive the laser diodes. The output from this is connected in parallel with the five laser diodes through five transistors (FETs). The FETs are gated by the digital outputs from the Arduino.

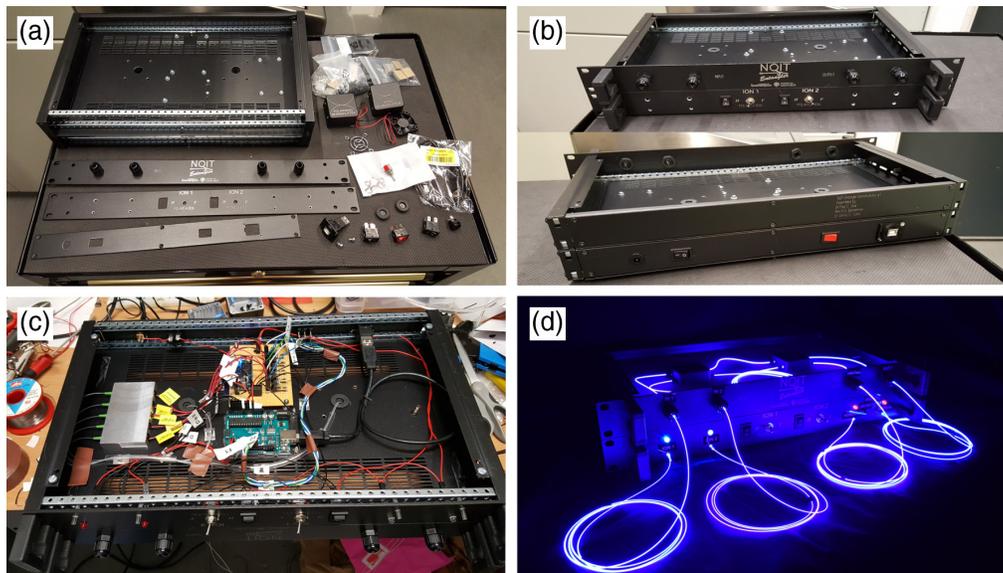


Fig. 2 Collection of images showing the construction of the demonstrator. (a) The parts layed out prior to assembly. (b) The front (top) and back (bottom) of the assembled unit prior to electronics installation. (c) The installation of the electronics in the lower rack unit, with diode-coupled illuminated fibers on the left, Arduino at the center bottom, and the FETs and Buck converter center top. (d) The completed demonstrator unit in operation ([Video 1](#), 8780 KB, MOV [URL: <https://doi.org/10.1117/1.OE.61.8.081802.1>]).

The two rack mount units were assembled and attached together [Figs. 2(a) and 2(b)]. The electrical components were installed in the lower of the two units, shown in Fig. 2(c). An electrical port and a switch were installed on the rear of the unit for connection to the 9 V DC power supply. A USB port was also installed and connected internally to the Arduino to allow reprogramming without requiring disassembly of the unit. The four switches for control of the device were installed on the front panel of the lower unit. LEDs were also installed on this front panel to indicate when the circuit was activated and wired into the switches. The front and back panels are shown in Fig. 2(b).

The parts of the illuminated fibers that housed the laser diodes were also installed in the lower unit. A block of aluminum was machined to hold these five components and to act as a heat sink. A small fan was fixed inside the casing next to this block to ensure constant airflow and cooling of the diodes when under operation. The illuminated fibers were then fed through holes into the unit above.

The front panel of the top unit was machined to hold four cable glands, which the illuminated fibers can pass out of for demonstrations. The top unit was also filled with soft black foam to protect the fibers that lay on top of it. The holes that the fibers pass-through from the lower unit were covered with small die-cast boxes, which were patterned and labeled as “BS” and “PBS” to indicate the two fiber components used in the real entangler device. The fibers then fed out of small holes drilled in the sides of these boxes. The top unit was capped with a piece of Perspex cut to size, to protect the fibers within and allow viewing. Both front panels of the top and bottom unit were engraved with a CO₂ laser, labeling the function of the switches, inputs and outputs, and including the NQIT logo. Figures 2(a)–2(c) show the assembly of the unit and Fig. 2(d) shows the completed device in operation.

3.1.2 Operation

The demonstrator was designed to mimic the real-world entangler unit that accepts photons from two separate ion traps. Figure 3 shows a schematic of the device operation. The switches to control the channels “ion 1” and “ion 2” are designed to mimic inputs from two ion traps that are individually controlled. These switches primarily control the illumination of fibers 1, 2, and

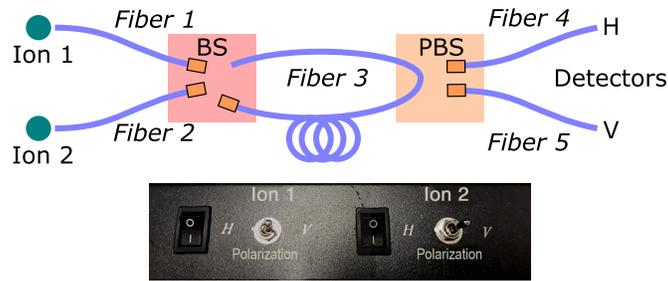


Fig. 3 Schematic of the demonstrator operation. This shows how the illuminated fibers are routed out of the BS and PBS, and the way in which they will light up depending on the switches. The lower image is of the switches on the front panel.

3. They also control the illumination of fibers 4 and 5; however, which of these fibers illuminates is controlled by the other switches with positions labeled “H” and “V” to denote the polarization of the photons as either horizontal or vertical.

The best way of understanding how the demonstrator works is by considering one channel at a time. For instance, with the “ion 1” switch activated fiber 1 will be illuminated. This passes into the first black box, which is presented as a BS. A BS would take the light from input and split the light 50/50 into two outputs. As both outputs of the BS would be illuminated whether “ion 1” or “ion 2” is activated, we use only fiber 3 in a loop between the two black boxes to give the impression of two output fibers. The second black box is presented as a PBS. This directs the light into an output depending on what polarization it is, horizontal or vertical. The polarization of the light is controlled by the “H” and “V” switch. For instance, if the switch is set to “H” then fiber 4 will illuminate. If the switch is set to “V” then fiber 5 illuminates.

This is similar to the outcome when the “ion 2” switch is activated, with fiber 2 instead of fiber 1 illuminated. With both “ions” activated fibers 1, 2, and 3 will illuminate and fibers 4 and 5 are controlled by the two “H” and “V” switches. The Arduino handles all of these switch inputs and activates the fibers accordingly.

3.2 Supporting Software

The demonstrator works well to show the function of the device in terms of how different inputs affect the outputs; however, the real entangler operates at the single-photon level. To describe the function of the demonstrator in terms of single photons some supporting software was developed using National Instruments LabVIEW. The resulting GUI is shown in Fig. 4.

The software was designed to mirror the demonstrator design, with different cases for H and V entanglement for the different ions, and a graphic representation of the fibers and BSs. When one of the buttons at the bottom is pressed, two “photons” labeled “H” or “V” travel from the “ion traps” at the far left of the image toward the first “BS.” Here, they interact depending on the button selected before propagating to the “PBS” to interact again. They then move onward to the “detectors,” which flash depending on how many “photons” are detected. While supporting the demonstrator, the software is targeted at explaining the function of the entangler to a technical audience. This means that it may not be suitable for all engagement audiences and there are some scenarios when the demonstrator alone would be most suitable.

4 Engagement with the Demonstrator

The demonstrator was first exhibited along with the accompanying software at the Quantum Technologies Showcase on the November 22, 2017, held at the Queen Elizabeth II Conference Centre in Westminster, London, UK. The annual showcase is designed to demonstrate the technological progress arising from the UKNQTP, its relevance to commercial sectors, and the collaborative nature of the program involving academia, industry, and government partners. As such, the audience at this event mainly consisted of academics, company representatives, and policymakers. The demonstrator was exhibited as part of the OEQP Group stand and featured

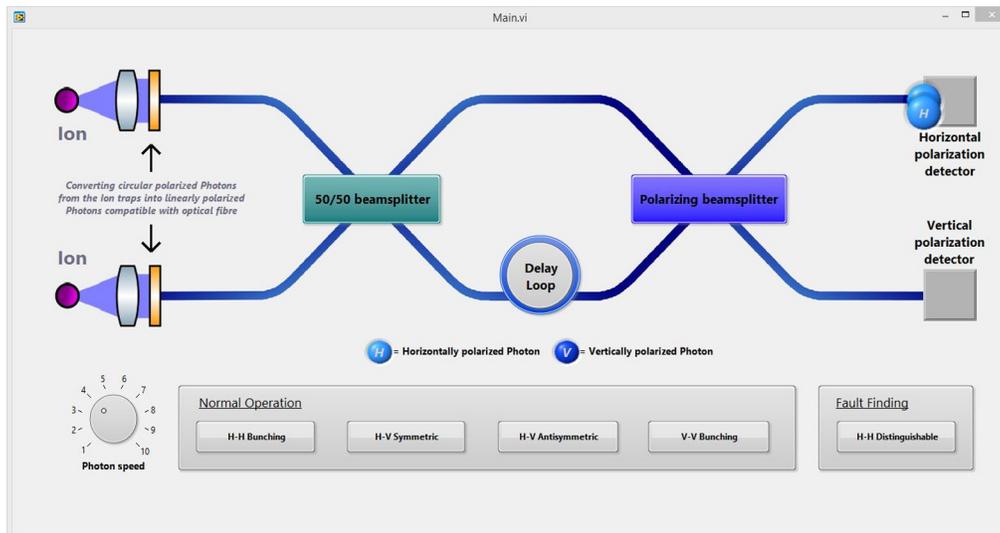


Fig. 4 The LabVIEW developed software to support the demonstrator. The design mimics the experimental setup, with two ion traps emitting photons that enter the fiber optic circuit. The buttons at the bottom of the image select different entanglement scenarios, which are then played out by the blue circular “photons” over the diagram (Video 2, 468 KB, MOV [URL: <https://doi.org/10.1117/1.OE.61.8.081802.2>]).

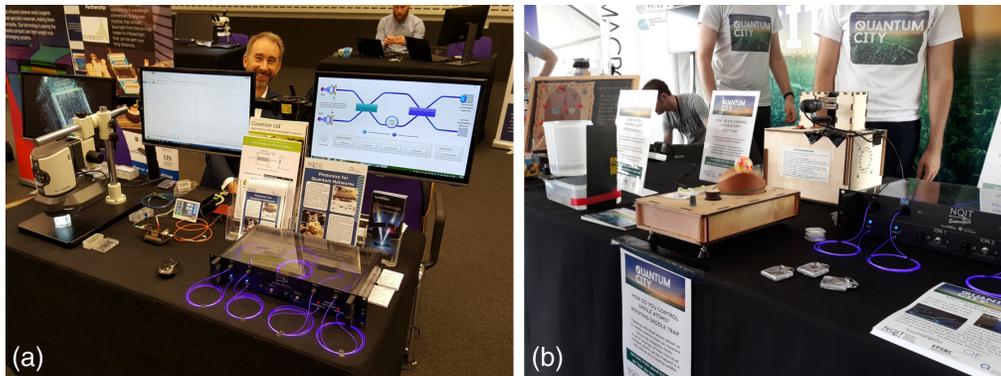


Fig. 5 (a) Images of the demonstrator on exhibition at the National Quantum Technologies Showcase and (b) on the Quantum City stand at the Cheltenham Science Festival.

alongside other examples of engineering and photonic components developed by the group [Fig. 5(a)]. For this event, an estimated 70 people were engaged on the stand. The demonstrator was also exhibited for the following two Quantum Showcases in 2018 and 2019 without the accompanying software.

The second event to exhibit the demonstrator was the Innovation South showcase event hosted by Innovate UK on March 27, 2018, at the Farnborough Conference Centre. There were ~20 stands from companies, universities, and funding bodies there. Around 400 people registered for the day, with an estimated 40 people engaged on the entangler demonstrator alone during the course of the day. In this instance, the hardware unit was displayed alone without the accompanying software. The demonstrator mainly sparked conversation on what a photon was and the “strange” aspects of quantum science. Most comments were focused around what quantum would be useful for building blocks for quantum computers to enable faster parallel processing, drug design, and security.

The demonstrator also featured as part of the “Quantum City” stand at the Cheltenham Science Festival, which ran from June 5, 2018, to June 10, 2018. A public dialogue commissioned by EPSRC indicated that the public would better relate to quantum research if it was presented through familiar applications and situations.¹⁶ The idea of a “Quantum City” stand

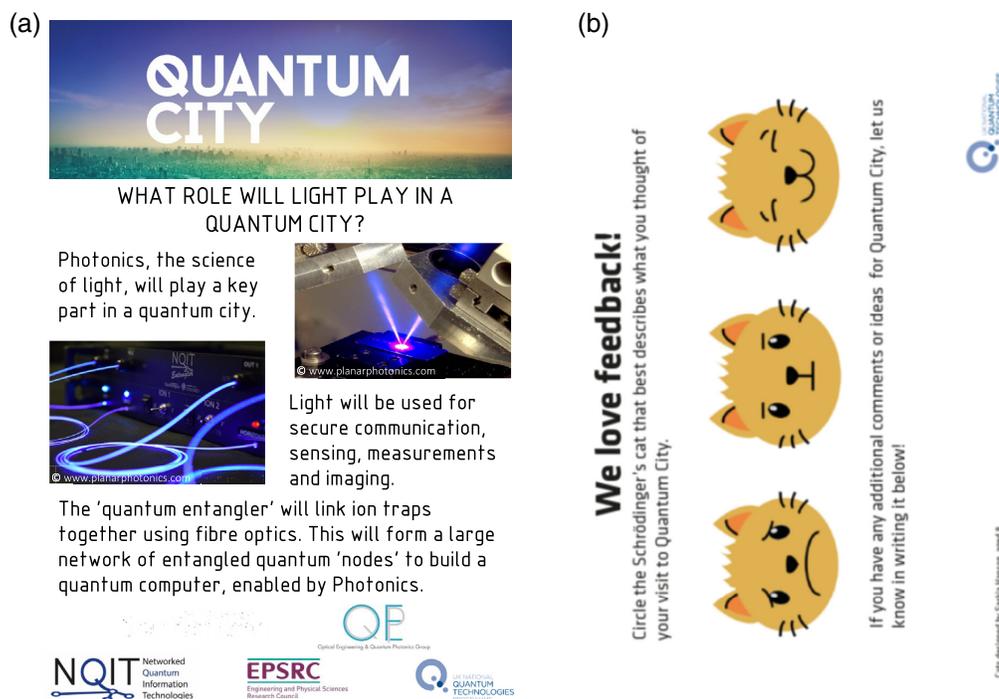


Fig. 6 Examples of the handouts used for the Quantum City stand. (a) The flyer developed to show how photonics and the entangler are important for the NQIT project. (b) An example of the feedback form used for the Quantum City stand. People engaged at the stand are encouraged to provide feedback by circling either the happy, neutral or sad cat to indicate their experience. There was space below for any additional comments to be filled in.

was developed for this purpose and will continue to exhibit at many science-related festivals and events. At the Cheltenham Science Festival, the stand exhibited different demonstrations from the various partners of the UKNTQP on each day of the festival between 10 am and 5 pm, with June 10, 2018 focusing on the NQIT hub. The demonstrator was exhibited alongside other demonstrations of ion traps and interactive games design to educate about quantum science and what makes quantum computers unique [Fig. 5(b)]. The number of people engaged at the stand was measured with a finger-clicker over the course of an hour between 11:30 am and 12:30 pm. During this time, 62 people were engaged at the stand, therefore giving an estimated 430 interactions during the day. The handout shown in Fig. 6(a) was produced as something for people to take away with them that explained the importance of photonics, light, and the entangler to a Quantum City of the future. People interacting with the stand were encouraged to fill out a “Schrödinger’s Cat” feedback postcard with space for optional comments [Fig. 6(b)], and 95% of responses highlighted the happy cat symbol.

The demonstrator was also exhibited at other Southampton University events. Including the Southampton Science and Engineering Festival in 2018 and 2019, where it was part of an interactive stand demonstrating the OEQP Group work and that of the wider ORC and had a large audience age range. It was also featured for one day as part of the University Roadshow stand at the New Forest show. This is an annual agricultural show focused on farming and country life, which gave a unique opportunity to access people who would not usually be exposed to quantum science.

5 Perspectives and Outlook

This section highlights some of the lessons learned during the construction and exhibition of the demonstrator and looks ahead to further opportunities for engagement in the near future. A way of achieving an alternative demonstration for the education of entanglement at a fraction of the cost is also discussed.

5.1 Lessons Learned

The initial concept of the demonstrator was to construct a replica of the entangler that would be used in experiments in the NQIT hub. This replica was to be used to explain the function of the real-world device and help to explain the importance of photonics to quantum research and the NQIT hub. Upon construction, it was realized that, while the demonstrator showed the general concept of the device, it did not do well explaining the science on the single-photon level at which the real world entangler would be operating. For this reason, some software was developed to be exhibited alongside the demonstrator, which would show the different means of operation for single photons. However, the combination of the demonstrator and software make this quite a complicated engagement tool. This worked well for the UK Quantum Technologies Showcase, which was targeted at company representatives, academics, and government officials; however, this did not work well as an engagement tool for the general public. Therefore, a hand-out was developed for the Quantum City stand to inform about the use of the entangler and the importance of photonics for quantum technology. Therefore, the software was subsequently disregarded for the majority of exhibitions. The demonstrator was also intended to be interactive, with people encouraged to try out the switches and use the software to explore the device operation. However, it often resulted in the person exhibiting the device operating both switches and software whilst explaining the function. Due to the delicate nature of the illuminated fibers, this was also exhibited as a “hands-off” device to the public, which was not the original intention. An alternative suggestion for a “hands-on” demonstration is discussed in the following section. The construction of the device, while not costing a large amount, could prove costly to replicate on a minimal budget. The demonstrator was also time-consuming to construct and therefore could be inaccessible for many people to replicate. The following section discusses an alternative option for demonstrating quantum entanglement in a “hands-on” way that would prove cheap and quick to implement. In general, this demonstrator proved a valuable asset to most exhibitions. The highly visual nature of the unit worked to draw people in and initiate conversation. The demonstrator proved not only a good route for talking about quantum technologies, but also fiber optics, lasers, and telecommunications.

5.2 Hands-On Entanglement

A concept for an interactive, hands-on method for describing photon entanglement that could be exhibited on its own or alongside the demonstrator is introduced here and shown in Fig. 7. The general principle behind the real-world entangler is that photons emitted by two different ions are brought together at a BS to achieve entanglement. An important aspect of entanglement is that observers must not know which photon came from which ion, otherwise they will know which

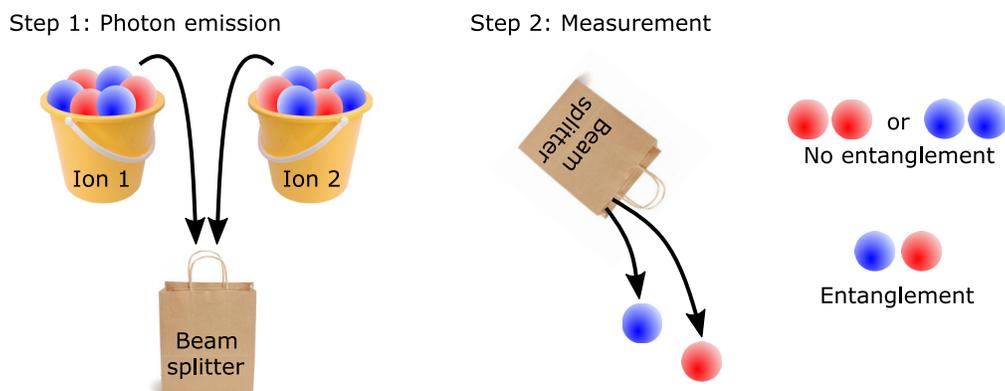


Fig. 7 Example of a simple scheme for demonstrating entanglement. In step 1, a “photon” from each “ion” is selected blindly and at random, and placed into the “BS.” In step 2, the “photons” are measured. If the “photons” match, we know the state of the “ions” and do not achieve entanglement. If they do not match, we cannot tell from which “ion” each “photon” came and entanglement is achieved.

state each ion is in, thus breaking the quantum entanglement. The simplest way to demonstrate this concept would be through the use of colored or numbered tokens being selected from two separate containers, or even dispensed by two “bingo ball” machines. For instance, assuming the use of red and blue balls to signify the different photon states, two buckets to hold a mixture of the balls representing the ions, and an opaque bag to represent the BS, the following could be a demonstration of entanglement:

- First a “photon” ball is selected blindly from one “ion” bucket and placed into the “BS” bag.
- Next a “photon” ball is selected blindly from the other “ion” bucket and placed into the “BS” bag.
- The “BS” bag is opened and the “photons” are compared.

If the balls are both red (blue) we know that both buckets produced a red (blue) ball, therefore, we know which state each ion is in and so they are not entangled. If one ball is red and the other is blue, then we know that each bucket must have produced a red or blue ball, but we do not know which bucket produced which ball. In this case, we can say that the buckets are in a state of entanglement. This method is hands-on, simple to explain, and easy to implement for a low cost.

6 Conclusion

A replica of the entangler to be used in experiments in the NQIT hub was constructed to explain the function of the real-world device and help to explain the importance of photonics to quantum research and the NQIT hub. The software was developed to be exhibited alongside the device to show the different means of operation for single photons. The demonstrator was exhibited to members from academia, industry, and government at the UK Quantum Technologies Showcase 2017, 2018, and 2019, and the Innovation South Showcase 2018. It was also exhibited to the general public at the Cheltenham Science Festival 2018 as part of the Quantum City stand, an initiative by the UKNQIT hubs to engage people in quantum science and find out what a “Quantum City” of the future might look like. It was also shown at the Southampton Science and Engineering Festival (2018, 2019) and on the Roadshow stand at the New Forest Show 2019. The total number of people engaged with the demonstrator so far number ~1200. The demonstrator proved to be successful in highlighting the importance of photonics and fiber optics for quantum technology and the growing quantum sector as a whole. The device proved to be “hands-off” during demonstrations and could prove inaccessible for many people to replicate, therefore a supplementary option for demonstrating quantum entanglement in a “hands-on” and cost-effective way was discussed.

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