Upskilling Photonics Technicians to Meet Challenges of the Quantum 2.0 Revolution

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ABSTRACT

As there is no sizable, trained workforce to support product commercialization, recent advances in quantum research have created a significant mismatch between quantum science and the emerging quantum industry. Part of this new workforce will be developed through the upskilling of incumbent photonics technicians whose current qualifications present a solid foundation for the new quantum-related competencies. In order to provide the greatest access to these new skills, curriculum requirements need to be delivered largely through flexible distance-learning platforms. In this paper, we describe our efforts to produce an open-access educational curriculum and introduce new quantum-related competencies to the new and incumbent skilled technical workforce. A detailed list of the competencies sought by the quantum industry is given and then followed by the results of a survey through which the proposed competencies were assessed. This project introduces the complex subject of quantum science to advanced technological education. An open-access educational platform will reduce geographical barriers between colleges, students, and industry and help academic institutions with recruitment, retention, and completion. This high-tech workforce will see an increase in diversity, thus removing social barriers and fostering equal economic growth across our nation. The proposed curriculum is expected to help the US maintain the world lead in quantum technologies. This project is funded by the NSF Advanced Technological Education grant (NSF DUE 2055061). This grant focuses on the education of technicians for advanced technologies that drive the nation's economy.

Keywords: photonics, quantum, NQI, EdQuantum, superposition, entanglement, spectroscopy, cryogenic

1. INTRODUCTION

With the recent scientific breakthroughs in quantum computing, quantum sensing, and quantum networks, the quantum technologies are emerging as one of the most important technologies of the twenty-first century. These technologies have a potential to radically transform the way we live, communicate, and sense the world around us. The strategic importance of this technology and its impact on the US economy and national security over the next few decades have been recognized by the US Congress; the National Quantum Initiative (NQI) Act[1] was passed by the US Congress in December 2018 with the goal of accelerating American leadership in quantum information science and technology. In the Second Annual Report on the progress of the NQI (which also acts as the supplement to the President's FY 2022 budget[2]), the core efforts over a dozen federal agencies have been acknowledged and a few policy areas identified including the development of the workforce capacity needed to support the commercialization of the quantum-research-enabled products and applications. Rapid changes in the nature of work, education, workforce demographics, and international competition have led the National Science Board (NSB) to conclude that our national competitiveness and security depend on the skilled technical workforce (STW)—individuals possessing advanced technical skills with significant levels of science and engineering expertise and whose educational attainment is less than a bachelor's degree[3]. A shortfall of nearly thirty-four million skilled technical workers by 2022 has been identified as a near-term urgency and a national strategy was requested for training workers across "high-demand industries" including quantum technologies. The transition from quantum research to usable quantum technology in the marketplace is impeded by a mismatch between the quantum research community, which does not engineer or manufacture products, and the industrial engineering community, which does not have a sizable workforce with training in the quantum sciences.

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As much as it is of national interest to foster quantum research through Quantum Innovation Labs, it is of utmost importance to prepare the STW to support Phase II of the National Photonics Initiative (NPI). This is going to result in a new workforce with quantum skills and competencies that will support emerging quantum industry through the twenty-first century and assure that the US maintains a leadership role in quantum technologies. It is widely believed that the seed of this new quantum workforce lies in the existing photonics workforce since optics and photonics are widely viewed as enabling technologies that play key roles in the nascent revolution of quantum information science and technology[4]. Therefore, the most natural way to reach the goal of increasing the highly-skilled quantum workforce is in upskilling the incumbent photonics workforce. This workforce has already been developed through a few two-year laser and photonics educational programs across the US as well as the efforts by OPTEC, LASER-TEC, and other regional educational centers. An overwhelming consensus in the evolving quantum community is that universities and colleges need to create educational tracks to advance both theoretical skills and hands-on laboratory skills and that the industrial stakeholders need to incentivize the future quantum STEM technical workforce.

In this paper, we propose quantum technician skills and competencies needed to support Quantum 2.0 revolution. The proposed skills and competencies were established with the support and advice of our industrial and academic partners and were assessed through a quantum industry survey[5]. The feedback by the quantum industry was positive and encouraging. The outcome of the survey and its impact on the larger effort of developing quantum technician curriculum is included in the paper.

2. QUANTUM TECHNICIAN TOP-LEVEL COMPETENCIES

In this section, we present the top-level competencies that a future quantum technician should possess in order to effectively serve their specific support roles in the quantum industry. This competency list is a result of an effort that involved multiple industrial and academic partners with professional experience and engagement in quantum education, quantum scientific research, and quantum industry. The EdQuantum team conducted a survey of the quantum industry and collected the feedback on what skills and competencies should the future quantum technician possess to meet the demands of this emerging industrial sector. For each question, the survey participants were given four choices ranging from “definitely needed” to “definitely not needed” as well as an open-ended section for the participants to provide descriptive comments or recommendations. The survey was conducted over a two-month period with the help of internal and external collaborators: Quantum Economic Development Consortium (QED-C), Quantum Industry Coalition, LASER-TEC, Optics and Photonics College Network (OPCN), and a few regional photonics industrial clusters. The survey consisted of thirty-one multiple-choice questions, took about fifteen to twenty minutes to complete, and was anonymous. The random participants who responded to the survey were asked to categorize themselves into one of the following categories—industry, academia, legislator, or other. A total of twenty-four professionals responded to the survey and provided their valuable feedback.

The following top-level competencies have been defined as required by a quantum technician to successfully support the quantum industry:

- Have basic theoretical understanding of the language and main concepts of quantum mechanics necessary to actively support quantum research and quantum industry in the role of a technician.
- Illustrate and contrast in fundamental terms the postulates of the classical Newtonian physics and those of quantum theory and their effect on the perception of the macroworld versus microworld.
- Demonstrate proficiency in the operation, maintenance, and troubleshooting of various optical components and optical systems applied in typical quantum laboratory settings.
- Demonstrate a fundamental understanding of operation, troubleshooting, and maintenance of cryogenic systems, vacuum chambers, and other cold-fluid apparatus.
- Model, analyze, and troubleshoot a simple two-qubit quantum computing circuit and elaborate on its advantages over the classical approach.
- Apply different techniques and instrumentation of high-precision spectroscopy used in forensics, chemistry, medicine, and other fields of interest.

3. SPECIFIC QUANTUM TECHNICIAN SKILLS

To develop the competencies outlined in Section 2, the future quantum technician should have prior knowledge or be formally trained in the following six categories: (1) prerequisite knowledge of math, (2) prerequisite knowledge of optics and photonics, (3) fundamentals of quantum mechanics, (4) quantum hardware, (5) quantum information theory, and (6) fundamentals of spectroscopy. Specific learning outcomes for each of these six categories are shown below:

3.1 Prerequisite knowledge of math

To develop a basic understanding of quantum technology, a quantum technician needs new math knowledge that goes beyond that acquired in traditional photonics programs. Quantum technology is probabilistic by nature; therefore, the knowledge of random events and variables and statistics in general is required. There are also other concepts that need to be introduced such as complex numbers, vector algebra, and basic matrix operations. Here are the specific objectives:

1) Convert imperial units into metric units and vice versa.
2) Perform algebraic operations with fractions, decimals, powers, scientific notation, and unit conversion.
3) Calculate perimeter, area, and volume of simpler and symmetric 2D and 3D figures and objects.
4) Conduct linear and angular measurements using different units and tools.
5) Perform basic operations with vectors such as addition, subtraction, scalar product, and vector product.
6) Determine probability of an independent or a dependent random event in a random experiment space.
7) Demonstrate basic knowledge of statistics such as mean, median, variance, and Gaussian distribution.
8) Be familiar with the concept of a complex number and how it relates to the amplitude and phase of a signal.
9) Conduct basic 2x2 matrix operations such as addition, subtraction, scalar multiplication, and transpose.

3.2 Prerequisite knowledge of optics and photonics

Understanding theories and having practical, hands-on experiences with classical wave optics and the wave particle nature of light are critical to successfully understand quantum technologies. These skills and competencies are taught in the existing laser technology programs and can form the basis of future quantum technician knowledge. The basic topics in optics include reflection, refraction, polarization, absorption, and scattering of light. The main topics from physical optics identified in the survey include interference, diffraction, and wave superposition.

1) Apply the classical wave theory of light to describe reflection, refraction, polarization, and scattering.
2) Explain constructive and destructive interference and diffraction of light using wave superposition.
3) Employ the particle theory of light to describe photon, absorption, emission, and blackbody radiation.
4) Compare and contrast the classical concept of photon versus wave in the context of the dual nature of light.
5) Set up Young’s double slit experiment and interpret the results using the classical wave theory of light.
6) Illustrate main stages in laser operation such as pumping, population inversion, photon seeding, and lasing.
7) Exhibit a solid knowledge and application of optical components (mirrors, lenses, beam splitters, optical filters, and diffraction gratings) and various stationary, translational, rotational, and other optical mounts.
8) Demonstrate ability to perform high-precision laser alignment using different techniques and tools.
9) Identify the main properties of PIN and avalanche photodiodes, IR and pyroelectric detectors, and photomultipliers.
10) Measure output characteristics of a laser beam using power meters, beam profilers, and spectrometers.
11) Exhibit practical skills in fiber-optic connector installation, fusion splicing, and fiber-to-fiber and fiber-to-device alignment.
12) Perform fiber-optic test measurements including fiberscope, OLTS, and OTDR.

3.3 Fundamentals of quantum mechanics

The concepts of blackbody radiation, the photoelectric effect, the Compton effect, Heisenberg's Uncertainty Principle, Bell's inequality, photon entanglement, and quantum mechanical measurement accuracy limitations at the fundamental level represent the essential knowledge of the quantum theory. Understanding and experiencing these will form the foundation needed to build on in various quantum-based applications. Deep-level mastery of the above subjects with the ability to provide theoretical proofs are not required.

1) Explain blackbody radiation, the photoelectric effect, and the Compton effect in the context of the collapse of the classical theory of light.
2) Interpret Young's double slit experiment using the quantum behavior of light.
3) Employ the harmonic oscillator model to explain the quantum behavior of an atom.
4) State the de Broglie hypothesis and its effect on the relationship between matter and waves.
5) Recognize the impact of the Heisenberg principle of uncertainty on the quantum measurement accuracy.
6) Illustrate the concept of superposition utilizing light propagation through an interferometer.
7) Utilize the photon polarization state to describe the idea of the photon entanglement.
8) Formulate the Bell inequality and argue how it proved the existence of the "spooky action at distance."

3.4 Quantum hardware

The key role of quantum technicians is to be able to set up and run various practical experiments necessary to move quantum projects forward. This includes setting up and running an apparatus for photon down conversion, methods of optical fiber coupling to lasers and resonating cavities, use of cryogenic and vacuum systems, and precision microscopy and surface profilometry. Here are the specific objectives:

1) Categorize and contrast properties and application of quantum-specific detectors such as single-photon avalanche diodes, superconducting nanowire single-photon detectors, and similar.
2) Set up and operate an apparatus for down conversion of photons using a given crystal.
3) Align a Mach Zehnder interferometer and perform a superposition experiment and a quantum eraser experiment.
4) Outline methods of superconducting qubit fabrication—coherence and couplings.
5) Recognize the importance of lasers to cool down the atoms in cold-atom quantum experimentation.
6) Outline the basics of photonic integrated circuits such as the photonic waveguide, ring resonator, and Mach Zehnder interferometer as well as their application in quantum circuitry.
7) Summarize the steps in photonic-circuit fabrication and list the relevant photonic integrated foundries.
8) Execute various methods of optical-fiber mode matching such as laser-to-fiber coupling, laser-to-resonator coupling, and laser-to-laser injection coupling.
9) Demonstrate understanding and laboratory experience with cryogenic refrigeration systems and vacuum chambers.
10) Have a full grasp of tools and techniques for precision microscopy such as scopes or surface profilometers, micrometers, calipers, and similar.

3.5 Quantum information theory

This section focuses on the theoretical and practical aspects of quantum computing, quantum networking, and quantum cryptography. A quantum technician needs to be exposed concepts such as quantum states, qubits, superposition, Bloch sphere, spin qubits, superconducting qubits, quantum-memory devices, and QKD protocols. Quantum computing programming is also specifically identified as a subject of interest to be introduced at the most fundamental level. The following objectives are identified in this section:

1) Define the fundamental terms of quantum computation such as quantum computer, quantum states, qubits, superposition, and Bloch sphere.
2) Manipulate states of a single qubit or two qubits using unary and binary quantum gates and Dirac notation.
3) Compare and contrast quantum gates and classical gates.
4) Briefly describe current quantum computer architectures and technologies such as a neutral atom, the silicon-based approach, spin qubits in semiconductors, superconducting qubits, trapped ion, and others.
5) Explain in the most fundamental terms the concept of quantum teleportation and its role in quantum encryption and quantum key distribution.
6) Demonstrate a basic knowledge of QKD protocols such as BB-84, DIM, or TOSHIBA.
7) Demonstrate familiarity with the techniques of qubit state measurement including microwave and optical manipulation.
8) Demonstrate basic knowledge of quantum memory devices and quantum sensing.
9) Analyze a basic two-qubit quantum circuit realized in Qiskit, Cirq, or an alternative quantum software package.
10) Write a simple program in the Python programming language.

3.6 Fundamentals of spectroscopy

Spectroscopy plays a large role in many areas of quantum technology, and it is the least-developed field for the laser technician education. At the same time, this industrial sector is relatively mature and has an ongoing need for technician skills and knowledge. To perform the responsibilities of a spectroscopy technician, a solid understanding of real-world spectroscopy applications and different types of spectroscopy techniques (absorption, transmission, fluorescence, reflectance, irradiance, and Raman) is vital. The technicians should also be familiar with various types of spectrometer designs and instrumentation such as FTIR, single and double monochromators, polychromators, MEMS, Bragg sensors, spectrophotometers, filter wheels, and photonic integrated circuits. Finally, a balanced mix of hands-on and virtual inquiries including best practices in the optics spectroscopy laboratory, standard spectrometer operations, and opto-mechanical assembly techniques should be included in the training. Specific objectives in this section are:

1) Name the most common techniques of optical spectroscopy with a few examples or case studies of real-world spectroscopy applications.
2) Differentiate between major optical spectroscopy techniques such as absorbance, transmission, fluorescence, reflectance, irradiance, and Raman.
3) Explain the basics of various spectrometers and their operation such as signal-to-noise ratio, dynamic range, signal averaging, thermal or temporal drift, dark current, and similar.
4) Describe in the most fundamental terms spectroscopy instrumentation such as FTIR, monochromators and polychromators, MEMS, Bragg sensors, spectrophotometers, filter wheels, and photonic integrated circuits.
5) Demonstrate best practices of a spectroscopy lab such as handling and cleaning of cuvettes, use of calibration lamps, safety procedures, working with chemicals, etc.
6) Be skilled with various methods of spectrometer operation such as choice of reference, alignment with respect to ray traces, stray-light stopping, peak identification, intensity interpretation, etc.
7) Be familiar with various types of filters and filtering techniques used in spectroscopy such as notch, pass, dichroic filters and alignment, and differences in interference versus absorption filters.
8) Perform spectral analysis using ray-tracing software such as Zemax, 3DOptix, or an alternative.
9) Describe the concept of a Fabry Perot interferometer and its use in high-precision spectroscopy.
10) Perform basic opto-mechanical assembly including, but not limited to, specific optical adhesive and epoxy application, various curing techniques, and basic procedures.
11) Perform material analysis and matching using a standard COTS Raman spectrometer

4. NEXT STEP: EDQUANTUM EDUCATIONAL CURRICULUM

To formally introduce the skills and competencies presented above, we propose a three-course curriculum through which a photonics technician will acquire this new quantum knowledge. To the best of our knowledge, this is going to be for the first time ever that a curriculum in quantum technologies at a technician level is methodically structured and proposed to community colleges across the nation. The proposed quantum technician curriculum will be a cohesive sequence of lectures, analytical exercises, experiments, simulations, and examinations following all pedagogical standards in an effective and inclusive learning environment. Each course will be taught in a hybrid format consisting of theory presentation in an online, open-access environment and the hands-on practice (capstone) offered through short workshops at the host institution or at an industrial site.

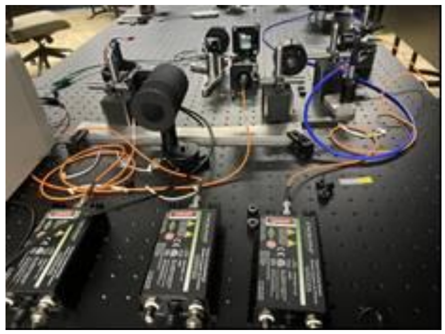

Figure 1. Equipment used to set a quantum entanglement experiment at the quantum technician lab at Indian River State College.

Remote access will be developed to the established laboratories that would enable hands-on training at a distance. For example, the quantum lab will provide motorized equipment controlled through a remote access to perform experiments such as parametric down conversion of photons, the Stern-Gerlach experiment, interference using a Mach-Zehnder interferometer, quantum eraser through polarization, delayed choice, and photon entanglement (Figure 1). In addition to the fundamental quantum experiments presented above, the students will also be exposed to the applications of the quantum concepts such as optical tweezers, an atomic force microscope, LiDAR, laser gyroscopes, and laser Doppler anemometers. The curriculum content and delivery model will be tested and validated through courses offered in real time to the targeted audience and promoted through collaboration with academic partners and the local industry. We hope that with the proposed curriculum for future quantum technologists, we will provide an important first step in quantum education at a community-college level that results in the development of a strong and skilled technical workforce to support the quantum 2.0 revolution and emerging quantum industry.

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