The Role of Optics and Photonics in a National Initiative in Quantum Science and Technology (QST)

Executive Summary

Whether or not you realize it, technologies that run our modern world are in large part enabled by optics and photonics – the science and application of light. Optics- and photonics-enabled technologies enhance our quality of life by safeguarding our health, safety and security; and driving economic growth, job creation and global competitiveness.

A global quantum revolution is currently underway, and optical sciences and technologies will play in a large role in the US initiative to advance quantum science and technology (QST). This revolution is driven by recent discoveries in the new area of quantum information science, which is based on the recognition that the subtler aspects of quantum physics, such as quantum superposition and entanglement, are far from being merely intriguing curiosities and can be transitioned into valuable, real-world technologies.

Quantum science and technology will revolutionize many aspects of our lives, including improved security and privacy in the digital communications systems that connect our world; enhanced navigation in demanding environments; advanced sensors for geological resource exploration; and superior computational capabilities for complex simulations and modeling of new pharmaceutical drugs and solar-energy-harvesting materials. Quantum information science will continue to yield some of the deepest insights into the fundamental workings of the universe, including the behaviors of black holes, complex network systems (such as living systems), and individual atoms and molecules that will form the basis of new electronics and other emerging technologies.

Recognizing the potential of QST, governments in Europe and Asia are committing billions of dollars to major research and development (R&D) initiatives for technological, scientific and economic benefits. For example, Asia has committed $415 million USD; the European Commission is committed to investing €1 billion in a flagship initiative in quantum technologies in 2018; the United Kingdom is currently investing £385 million[1] on a national quantum technologies program; and Australia is investing $65 million AUD on two quantum centers of excellence focused on computation and communications technology and engineered systems. Most recently, China launched the world's first quantum satellite on August 16, 2016 – a $100 million USD collaboration between the Chinese Academy of Sciences and the Austrian Academy of Sciences.

In the United States, the quantum revolution is commanding attention at the highest levels. The White House's interagency National Science and Technology Council (NSTC) produced a report in June 2016, entitled, "Advancing Quantum Information Science: National Challenges and Opportunities." Per the White House, quantum information science has "significant synergy" with its National Strategic Computing Initiative. The National Science Foundation and US Department of Energy are also setting quantum information science agendas.

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[1] Corrected on 10 March 2017 to reflect updated numbers on the size of the U.K. investment in quantum technologies, reported as "over £200 million" in an earlier version

Missing from the top-level policy discussions in the United States is the recognition of the importance of optical sciences and technologies in QST. The promise of QST rests on new and unique capabilities in three core areas: 1) computation and simulation; 2) advanced sensors; and 3) communications. In all of these areas, optical sciences and technologies play key roles.

This brief white paper expresses the vital importance of *optical sciences and technologies* in the quantum revolution, and focuses on areas that have the biggest impact on job creation, homeland security, industrial competitiveness and scientific leadership. By developing the essential quantum capabilities of optical sciences and technologies, the US will:

- Protect its IT infrastructure through secure quantum communication;
- Maintain its IT leadership position by employing quantum devices to enable the most energy-efficient, fastest and highest capacity data centers;
- Enhance homeland security with nuclear and biological threat detection through quantum-based sensors;
- Create a new generation of compact, ultrasensitive devices for biomedical diagnostics;
- Improve its ability to design and simulate new pharmaceutical drugs through quantum-enhanced probing and computational simulation of protein structure and interactions;
- Enhance efforts to generate energy from solar and other means more efficiently to increase economic growth and reduce risks of climate change;
- Improve navigation in demanding environments and build better sensors for geological resource exploration;
- Maintain its optics industry capabilities in product design, manufacture and delivery; and
- Enhance our understanding of the universe through advanced gravitational wave detection and other breakthrough areas using quantum technologies.

Through this white paper, the National Photonics Initiative (NPI) recommends that the federal government incorporate quantum-enabled optical sciences and technologies into its plans to advance this area most efficiently and productively. In the event that a separate national initiative is created in the broader subject of QST, which would include technologies beyond optical ones, we recommend that optical sciences and technologies be closely integrated. The rationale and specific recommendations are expanded in the following.

Advancing QST in the United States: *Quantum Optics and Photonics*

The promise of QST rests on new and unique capabilities in three core areas: 1) computing and simulation; 2) advanced sensors; and 3) communications. In all of these areas, optical science and technology play key roles. Working together, the three aspects of QST may ultimately comprise a globally distributed network. Optical quantum communications systems will be the means by which a *Quantum Internet* will carry quantum information between distant locations, enabling distributed quantum sensing and distributed quantum computing.

Computing and Simulation

A computer is a machine that receives and stores information input; processes that information according to a programmable sequence of steps; and, creates a resulting information output. A quantum computer is one that performs these operations while storing and representing each piece (or quantum bit – typically referred to as a qubit) of information using a single quantum object such as an electron, a photon or a superconducting electric current. While the "race to the bottom" is partially motivated by the desire to further miniaturize electronic components, a far greater motivation is that, as American theoretical physicist Richard Feynman first pointed out, a computer operating by quantum principles such as superposition and entanglement could perform certain kinds of computations exponentially faster than any supercomputer based on current designs. A quantum computer would have superiority in breaking standard encryption codes; design and understanding of new materials; determining the optimal molecular structures of pharmaceutical drugs; monitoring activity in information networks; searching databases; and other yet-to-be discovered applications.

While there are a number of promising implementations for a quantum computer, several leading candidates rely crucially on optical techniques. Examples include a chain of atomic ions held in a vacuum chamber; an array of superconducting microwave cavities; ultracold trapped atoms and atom-like impurities in the solid state excited by light; and all-optical approaches for small-scale processors. Moreover, as with classical computers, quantum computers need to move their information around to enable communication between their different parts. *Flying qubits* in the form of photons are one of the easiest means to achieve such communication.

Advanced Sensors

A 'sensor' is any physical or chemical process that generates a measurable signal informing of a physical stimulus or condition. Quantum-based sensing technologies are those whose functions rely on quantum-physics principles, and can lead to orders-of-magnitude improvements in performance. Devices that can better sense the strength of gravity will be used to map the variation of the earth's density over a geographical area, thus revealing mineral deposits and underground features of interest. Devices that can better sense acceleration will be used for absolute navigation – that is, for determining the precise location and orientation of a vehicle in remote environments where the GPS system is not available. Such technologies are needed to navigate vehicles that move underground, underwater or through locations where electronic interference – accidental or intentional – hinders the accuracy of GPS.

Quantum optical sensors can outperform current technologies in several areas. Atomic interferometer-based gravity sensors and accelerometers are applicable to geo-exploration and navigation; nanoscale diamond magnetic field sensors can be used in biological and medical research, such as nanoscale magnetic resonance imaging of individual molecules and in biomedical diagnostic technology; and quantum techniques can enhance the sensitivity and robustness of various types of optical measurements, from spectroscopy to imaging technologies.

Furthermore, synchronization of the processes on the Internet is required for near-future technologies, including remotely controlled surgical procedures (tele-surgery), driverless cars, operation of the electrical power grid, and financial transactions. Such synchronization requires improved clocks, the state of the art of which relies on quantum optical techniques.

Communications

The Internet transmits the bulk of the world's communications using short pulses of laser light traveling through optical fibers, illustrating just two of the optical inventions that have been recognized by Nobel prizes. In quantum information networks, information will be transmitted by extremely dim light pulses containing the minimum amount of energy allowed by quantum physics – a single photon. Communication technologies based on single photons allow near-perfect, unbreakable encryption of messages. Quantum communications systems may also provide the breakthroughs needed to overcome the current slowing down of Moore's Law – the expectation that our systems' information capacities will double every eighteen months.

Recommendations

QST will open new scientific, technological and economic avenues to bettering and advancing society. R&D in optical science continues to develop new enabling technologies for a wide range of basic studies and applications in quantum science. The furthering of such supporting technologies is crucial for the success of QST. In particular, many quantum innovations rely on precision photonics, for example compact lasers, optical frequency 'combs,' ultra-stable optical references, nonlinear optical materials, advanced optical mirrors, integrated photonics, advanced photon detectors, and optical communications technologies. Support for such enabling technologies has a two-way benefit, as these commercial products will drive the development of quantum technologies, and the developing quantum arena will provide market space for these products.

To achieve national economic and security objectives through the development of quantum science and technology, the NPI recommends to the federal government the following:

- Work with professional science societies and the federal agencies represented in the NSTC report to develop a major initiative in QST defined broadly, while recognizing the key and central role played by optical technologies and sciences.

- Establish R&D centers of excellence in QST, with close integration of academia, industry and government, across both optical and non-optical approaches, working together.

- Find means to provide sustainable support for companies developing enabling technologies for QST or developing products based directly on QST.

- Work with universities to develop education and training programs in QST.

- Encourage coordination or integration of the efforts of federal agencies having interest in supporting QST.

- Find opportunities for cooperation with select nations in areas where expertise, person-power, trainees, materials or special products will have to cross national boundaries and national initiatives, while ensuring a competitive edge in the US.

The NPI has extensive reach to top experts in both academia and industry, and across all fields from quantum physics to defense to health and medicine, energy and IT and communications, and has served as a trusted resource to the federal government on high-level technology policy solutions. The NPI is committed to working with the new administration on a national quantum initiative and incorporate optical sciences and technologies to advance critical quantum science and technology in the United States.

About the NPI

Established in May 2013, the NPI was formed to increase collaboration and coordination among US industry, government and academia to identify and further advance areas of photonics critical to regaining US competitiveness and maintaining national security. The initiative is led by top scientific societies including the American Physical Society (APS), the IEEE Photonics Society (IPS), the Laser Institute of America (LIA), The Optical Society (OSA) and SPIE, the International Society for Optics and Photonics (SPIE). The NPI has focused its efforts on identifying areas where US public and private interests intersect, and where joint collaboration can achieve breakthroughs in research commercialization and technology innovation.

For more information on the NPI, please visit www.lightourfuture.org.

Appendix I

What is Quantum Information?

US computer scientist and IBM physicist Rolf Landauer explained that:

"Information is not a disembodied abstract entity; it is always tied to a physical representation. It is represented by engraving on a stone tablet, a [magnetic] spin, [an electric] charge, a hole in a punched card, a mark on paper, or some other equivalent. This ties the handling of information to all the possibilities and restrictions of our real physical world, its laws of physics and its storehouse of available parts."

Computers store and manipulate information using a *binary* language with an alphabet that consists of only two symbols: 0 and 1. Each 0 or 1 symbol is a *bit*, short for binary digit. As the components in computers shrink to ever-smaller sizes, the piece of material storing a single bit is fast-approaching the size of a single quantum object, such as an atom. At this level, the behavior of the objects storing and processing information is subject to the laws of quantum physics. Such information is called quantum information and objects storing these bits are called qubits.

Communication is carried out using pulses of light. When single photons of light are used to represent and transmit information, it becomes quantum information, which can be represented by various characteristics of photons: their direction of vibration (polarization), their color (frequency), their spatial shape, or their temporal shape.

The key feature of quantum information that is not present in classical information is quantum entanglement, which is a characteristic of special quantum states describing two or more quantum entities, such as photons or electrons. It describes correlations that can be stronger than any allowed by classical physics, and can be put to use in quantum technologies. An *entangled state* of a composite entity is a state that provides a complete quantum description of the whole entity, but nevertheless cannot be divided into separate complete quantum descriptions of its constituent parts. Applications of entanglement are quantum-state teleportation, quantum cryptography and quantum computing.

Appendix II

How can quantum physics be harnessed to create perfectly secure Internet communication?

For financial, industrial, military, or personal reasons, people often want to send messages so that only the sender and intended recipient can know their contents. An already developed application of QST is quantum cryptography, which uses single photons to represent information bits in a manner that is nearly impervious to eavesdropping. According to the famous Heisenberg Uncertainty Principle, if a quantum object is disturbed (as necessarily happens if an eavesdropper tampers with the object) the state of the object is altered. Such tampering can be detected by the legitimate persons who are attempting to establish a secure communication link. Not only can an eavesdropper be detected, but also can be thwarted in that quantum techniques can encode information in ways that permit secure data transmission even in the presence of eavesdropping. Developing practical means to implement such techniques in the commonly used channels of the Internet would change the landscape in positive ways.