The Enabling Role of Optics and Photonics in the National Quantum Initiative

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Abstract: Optics and photonics play key roles in integrating university, industry and government research to move quantum information science and technology from theory into practice, including the central areas of quantum sensors, communication systems and computers.

The National Quantum Initiative

This paper reviews aspects of the US National Quantum Initiative and the roles optics and photonics play, including an example of the manipulation of optical temporal modes for quantum information research.

Optics and photonics are widely viewed as enabling technologies, and play key roles in the nascent revolution in quantum information science and technology (QIST). From the first experimental observations of quantum-state entanglement across macroscopic distances [fre72, etc.], to the recent demonstration of a quantum-repeater-enhanced entanglement-distribution channel [ngu19], optics and photonics have led the way toward understanding the unique aspects of quantum systems and exploiting these for potential new information technologies. It is anticipated that QIST is now laying the groundwork for a new industry, with parallels to the early days of the semiconductor electronics revolution in the 1950s and 60s.

For the above reasons, an alliance of professional societies focused on optics and photonics (called the NPI [npi19]) started and shepherded the federal lobbying effort that led ultimately to the passage of the National Quantum Initiative Act (H. R. 6227) in the US Congress and its signing by the President. The history of this successful effort was recounted in [mon19a].

Questions we should be asking ourselves: What do we expect to come out as a consequence of the National Quantum Initiative or NQI, and on what time scales? Which technologies will be impacted promptly or on longer time frames? What are the "hot topics" and the opportunities for optics and photonics? How will the quantum-industry ecosystem evolve? What are some of the risks that might be encountered? How will countries cooperate across borders?

To quote from a paper describing the goals and challenges of the NQI, [mon19b] "The NQI looks to follow a science-first approach that will stimulate development and use of new technologies spanning academia, government laboratories, and industry. … A fully functioning quantum computer would radically enhance our capabilities in simulating nuclear and high-energy physics; designing new chemicals, materials, and drugs; breaking common cryptographic codes; and performing more speculative tasks such as modeling, machine learning, pattern recognition, and optimizing hard logistical problems such as controlling the electric energy grid or traffic control systems." And, "Using qubits instead of conventional bits makes it possible to create shared randomness between parties while knowing whether the communication channel has been compromised by an eavesdropper. This enables sending information securely. … Quantum communication can also allow secure communication between multiple parties, and for interconnecting large-scale quantum computers via a quantum internet."

A good case can be made that optics and photonics, spanning from microwaves to ultraviolet, are essential in virtually all the leading-candidate platforms for implementing quantum technologies Obviously, quantum states of light will be used for communicating across optical fibers or free-space links. And laser or microwave-based techniques are used in most quantum sensing schemes. Less obvious is that most likely all practical quantum computers will require photonic interconnects between memory units and processing units. As a conjectured example, long-lived memory might be provided by trapped-ion qubits while rapid processing might be performed in a superconductor-based chip. In such a scenario, the quantum "data bus" would involve interconversion between the microwaves that interact with the superconductor and the visible photons that interact with the trapped-ion qubits [zho19] Another example is a modular quantum computer consisting of a collection of ion traps, each containing about 50 ions, all inter-connected by photonic links. Finally, there are all-optical schemes being developed for quantum computing using quantum-state squeezers and photon-number-resolving detectors [e.g., bou19].

A challenge for the optics and photonics community is to create practical implementations of a variety of high-quality, low-loss interconnects between a wide range of physical degrees of freedom and electromagnetic frequency ranges that make up the sub-systems comprising a diverse quantum information network. Such interconnects must preserve the quantum state with high fidelity during interconversion.

Quantum Frequency Conversion and Temporal Mode Manipulation – a Case Study

Many implementations of quantum information technology use single-photon light pulses, a state that does not exist in classical electromagnetic theory. Single-photon states have the property that under illumination by such a state, only one photodetector among several can register a detection event. While the detection of a photon is probabilistic, in the absence of random environmental influences the temporal and spatial evolution of a single-photon state is *deterministic*. Such a state undergoes 'unitary' quantum evolution; in fact, the equation of motion for the state is the same as the classical Maxwell equations [smi07]. A simple way to view the situation is to consider a set of orthogonal 'classical' wave packets, or spatial-temporal modes, of the EM field, and that each mode may be 'occupied' by a state – be it a single-photon state, a coherent state, or a squeezed state, etc. The orthogonal 'classical' wave packets are called temporal modes (TMs) [bre15, ray19].

Given the importance of quantum states of light propagating as pulses in free space or in waveguides for quantum technologies, it is necessary to devise techniques for creating, manipulating, and detecting such states and the temporal modes that contain them [ray12]. Recently progress has been made toward these goals using a variety of optical techniques: tailored spontaneous parametric downconversion, pulsed nonlinear-optical frequency conversion, cavity parameter modulation, and phase-only manipulations.

Quantum frequency conversion (QFC) is a good example of a quantum interconnect. It may be designed to be TM selective [red13]. QFC uses nonlinear optical techniques, either three-wave mixing in crystals or four-wave mixing in amorphous materials such as optical fibers or crystalline waveguides to convert or 'translate' a quantum state of light from an initial frequency band to another band.

QFC is, in principle, a background-free process – if there is no input signal then there is no output signal and no added "noise." In this way it is distinct from parametric amplification, which always creates a background of spontaneously emitted photons.

When dealing with short optical pulses, such as those used in communication systems, it was found that the efficiency of QFC depends on the similarity of the input signal pulse to the strong laser pulses driving the nonlinearity – that is, the coherent overlap between the temporal wave packets (TMs) describing the signal and the control laser pulses. This realization led to the invention of the quantum pulse gate (QPG) – a device that frequency converts a targeted temporal mode while leaving all temporally orthogonal modes unaffected [eck11]. Thus a QPG ideally acts as a noise-free demultiplexer for TMs, a useful function in communication networks.

Because the process adds no noise, it is mathematically analogous to a beam splitter – a special type of linear mode transformer. Any state of light in a targeted input TM can be fully or partially transformed into a different TM in a different frequency band. The beam-splitter analogy implies that TMs and QPGs together create a sufficient platform to carry out any all-optical implementation of quantum information processing (e.g., cluster-state quantum computing) [bre15]. The engineering challenge is to implement QPGs with high efficiency and wide optical bandwidth so they can process (demultiplex or linearly mix) many orthogonal TMs.

Such capabilities will enable flexible manipulation of temporal modes of light that will have applications in quantum information technology.

MR was supported in part by the U.S. National Science Foundation (grants PHY-1820789 and PHY-1839216).

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