Applications of Photonic Integrated Circuits to Quantum Computation

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Contents

1 Abstract

We aim to understand how near-term advances in microphotonic and microphonic systems may facilitate the scaling of trapped ion and photonic noisy intermediate scale quantum (NISQ) computers. By capitalizing on the same principles that spawned a revolution in classical integrated circuits, quantum engineers hope to implement high fidelity photonic integrated circuits (PICs) into their NISQ computers. We will analyze the state of the art of each microsystem component needed for this transition: optical cable interfaces, tunable waveplates, electromagnetically induced transparency (EIT), waveguides, beamsplitters and gratings. Of these, only tunable waveplates and beamsplitters are not at high enough fidelity to implement these PICs.

2 Introduction

2.1 PICs shrink bulk macroscopic optical components to the microscopic range. PICs also confine photons to narrow pathways, which can be used to route and manipulate photons in a confined space. By shrinking optical components, denser photonic operations can be carried out and higher fidelities can be ensured due to the controlled and repeatable nature of confined optics. In macroscopic optics, even with our best efforts to preserve rigidity and noise isolation, single photon interactions cannot be predictably reproduced or scaled.

2.2 PICs use the advantages of traditional electrical integrated circuits to scale photonic systems. Some of the main reasons integrated circuits were first developed are the scalability, affordability, energy efficiency, and gigahertz clockspeed computation that they offer [1]. These advancements are responsible for the massive increase in computational power of traditional computers. In addition to these benefits, PICs can scale even more densely than electrical integrated circuits because photons rarely interact with each other, meaning their paths can overlap [1]. Commercial telecommunications equipment operates in the near visible spectrum and thus at a terahertz frequency. This means that PICs can operate roughly three orders of magnitude faster than traditional integrated circuits [1].

2.3 The three main applications of PICs to quantum technologies are optical switches, photonic quantum computers, and trapped ion quantum computer control infrastructure [1-4]. Optical switches are useful for photon linking as well as for telecommunication routing optical signals directly to optical outputs [2]. In current iterations of this technology, optical signals must be converted to electrical signals, with gigahertz clockspeed, routed, and returned to optical signals. Direct optical switching using PICs can offer a three order of magnitude speedup. Photonic quantum computers take advantage of the limited nature of photon-photon interactions to scale at a much higher density and to interact each qubit with every other qubit [1]. However, current generations use macroscopic optical modulators, which limits their scalability. Switching to PICs would allow these photonic quantum computers to scale far faster than other quantum computing technologies [3]. An example of current generation layered programmable PIC photonic quantum computer is shown in Fig. 1e [4]. While photonic quantum computers are still in their infancy, trapped ion quantum computers have the most direct path to scaling. Trapped ion quantum computers come in ~20 ion chains, which all can interact with each other. Beyond this ~20 ion limit ions begin to fall out of the ends of the trap [5]. In order to further scale trapped ion quantum computers, photon linking between a number of ion chains must be implemented. An ion trap may also serve as an optical resonator, which can funnel photons to different traps through an optical switch [5]. This would facilitate fast scaling and far higher connectivity and fidelity than superconducting quantum computers. Additionally, current generations of trapped ion quantum computers rely on macroscopic optics which cannot scale without PICs [5]. Future trapped ion quantum computers will likely use PICs underneath ion traps to route photonic cooling, control, and measurement channels to and from the ions, as shown in

Fig. 1a-d. This will facilitate the miniaturization and thus, the scalability of trapped ion quantum computers.

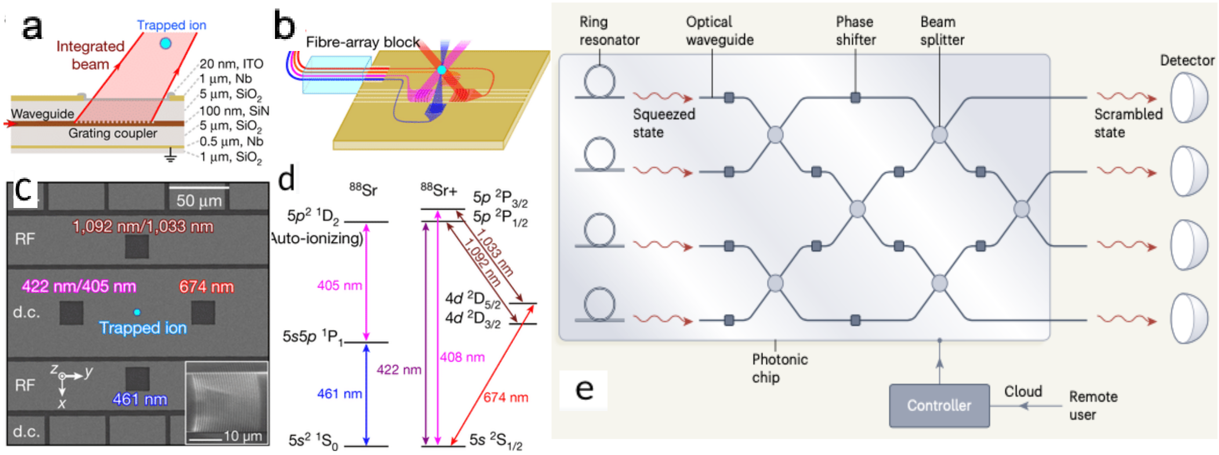

Figure 1 a) Diagram showing how waveguides and waveguide gratings inside a PIC below an ion trap can be used to control trapped ions [5]. b) Diagram shows how fiber optics can be routed into PIC and individually manipulated before being sent up to or down from the trapped ion [5]. c) This shows the number of different optical sources needed to control and receive photons from trapped ions [5]. d) This shows why one needs 4 different optical pathways for trapped ion control [5]. e) Diagram of a multilayered photonic quantum computer on a PIC. Photonic quantum computers rely on the entanglement produced by interacting differently phased light through a 50/50 beamsplitter [4].

2.4 A PIC is designed to take optical signals in from external sources, manipulate those signals, and route them into an external detector. For this, one must develop high fidelity: optical fiber PIC interfaces, waveguides, tunable waveplates, beamsplitters, and EIT. Optical fiber PIC interfaces are the sub-wavelength waveguide gratings used to transfer incoming photons into and out of waveguides [6]. Once photons are on the PIC, they must be routed to a desired location with minimal signal and intensity modification [6]. In some instances, the routes through PICs are predetermined; in other cases, they may be modulated through the use of an EIT, which can selectively modulate reflectance, allowing for a choice of optical route [7]. Tunable waveplates are designed to modulate the phase of light within a waveguide [8-10]. Phase is the predominant metric by which photonic quantum computers store entangled information [4]. Beamsplitters are typically 50/50 meaning that half of the photons are reflected with a pi phase shift and half are transmitted [4,12]. As a result, photon-photon interactions can be seen by sending signals on each side of the beamsplitter simultaneously, interfering signals and generating a superposition [4].

3 Results & Discussion

3.1 Waveguides come in three main forms: strip, slot and photonic crystal waveguides [6]. Strip waveguides are the simplest implementation in which a rectangular prism of SiO_2 or Lithium-Niobate serves as a conduit for photon routing, as shown in Fig. 2 [6]. Strip waveguides are the most common and cheapest implementation; they are responsible for an ~.2 dB/cm drop [4]. This means that they are sufficiently low loss for current generations of PIC implementation. There has also been additional study into further confined waveguides such as slot waveguides, which have an air core as seen in Fig. 2 [4]. Future generations of PICs may need higher density and even lower loss, which may be offered by photonic crystal waveguides. They use Si_3N_4 cores to route photons at even higher fidelity, but with higher cost manufacturing complexity [13]. As a result, strip waveguides are the only commercially viable implementation, except in the case wherein extremely minimal loss or higher channel density is needed. These advanced waveguides will likely take higher prominence in future scaled implementations of PIC technology.

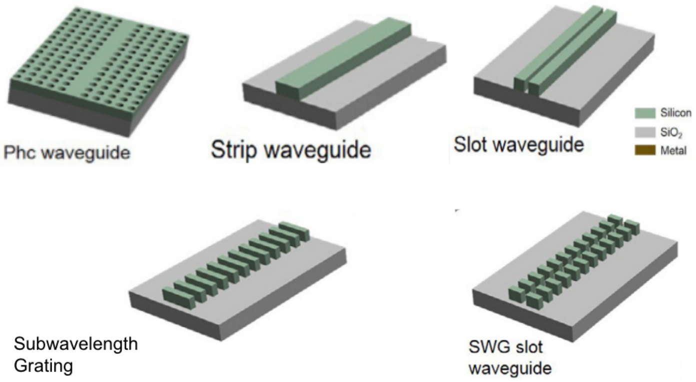

Figure 2 Phc waveguide is a photonic crystal with a regularly spaced geometry confining photons. Strip waveguide uses sub-critical angle reflection to confine light. Slot waveguides use hollow cores to further confine photons. Subwavelength gratings use low index of refraction materials spaced on the order of nanometers apart to to turn, absorb and emit photons from waveguides [6].

3.2 Optical cable interfaces take the form of subwavelength gratings [6]. These gratings are periodically arranged regions of low and high refractive index within the path of a waveguide [6]. Gratings are useful for both tuning waveguides and to add and remove photons from the PIC [12]. This process of photon entrance and egress from the PICs has been completed reliably with current models from Xanadu inserting squeezed state light at ~12 dB and in current implementations receiving ~9.8 dB after ~8 dB of losses through several layers of optical components [4].

3.3 There are a number of tunable waveplate technologies that could be implemented into PICs. The first major type of tunable waveplate is thermo-optic phase shifters [8,9]. Thermo-optic phase shifters are very consistent compared to competitive technologies. Current generations of this technology correspond to ~3 dB intensity drop per phase shifter and respond to stimulus over a number of microseconds, as shown in Fig. 3b [8,9]. This ~3 dB intensity drop is too large for many layer implementations of PICs [9]. Additionally, microsecond reaction speed is far too slow to take advantage of the terahertz potential clockspeed offered by near visible optics [4]. Thermo-optic phase shifters are made by heating SiO_2 waveguides with a tungsten alloy heating element, as seen in Fig. 3a [8]. Finally, thermo-optic phase shifters have to be spaced significantly and cooled to prevent thermal crosstalk [8]. This all means that although thermo-optic phase shifters are easy to produce, they are quite undesirable. Thermo-optic phase shifters are thus only viable for a large number of cycles through a low layer system. The dominant technology for tunable waveplates is electro-optic phase shifting [10]. These are made of Lithium-Niobate crystals or Aluminum Nitrides and are responsible for a ~.45 dB intensity drop per layer [10]. The key advantage of electro-optic phase shifters is their gigahertz reaction speed [10]. Although this doesn't make full use of the terahertz frequency of the near visible spectrum, it does come much closer than thermo-optic phase shifters. With a relatively mild drop in stability and affordability compared to thermo-optic, electro-optic phase shifters are clearly the most commercially viable tunable waveplate.

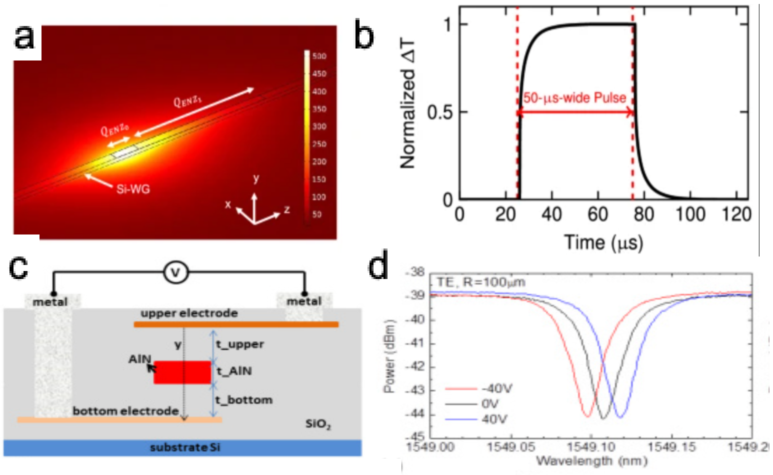

Figure 3 a) Thermo-optic phase shifter made from a SiO_2 waveguide heated with tungsten element to modify phase [8]. b) Thermo-optic phase shift has a delayed response on the order of megahertz [8]. c) Electro-optic phase shift is an Aluminum Nitride waveguide inside a capacitor. d) Precise phase shifting with gigahertz response.

3.4 EIT uses radio signals to modulate the state of a magneto-optical material with a terahertz reaction time. This induces what's known as fano resonance [7]. This modulation as previously mentioned can induce transparency in an otherwise reflective material, as shown in Fig. 4a. Significant research has gone into minimizing the range of possible radio frequencies and energies, which can activate EITs, as shown in Fig. 4b [7]. Current generation EIT technology corresponds to an ~1 dB intensity loss per layer if activated and very nearly ~0 dB loss per layer if not activated [7]. This is sufficiently low to allow for current generations of high density optical switching up to ~100 by ~100 channels; however, this is not yet sufficient for telecommunications scale optical switching [2].

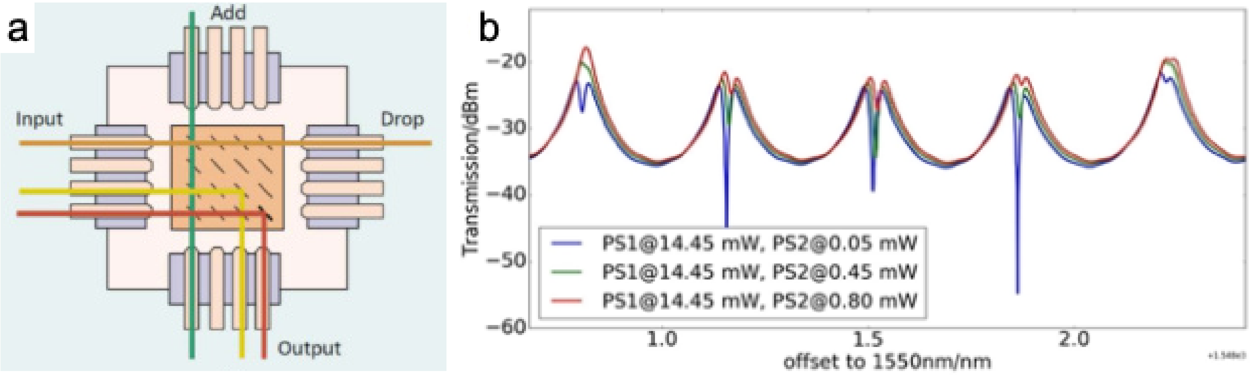

Figure 4 a) Optical switch shows how EIT can be used to add and drop signals from 2 series of optical cables [2]. b) Demonstration of how advanced material science can narrow the range of acceptable radiowaves to trigger EIT transparency [7].

3.5 50/50 beamsplitters reflect half and transmit the remaining photons. In bulk optics these components are simply half silvered mirrors. In PICs, beamplitters work on an entirely different principle known as a multimodal Fabry-Perot cavity as seen in Fig. 5 [12]. In integrated photonics, beamsplitters are referred to as multimode interference waveguides, but they serve the same purpose as beamsplitters do in macroscopic optics [12].

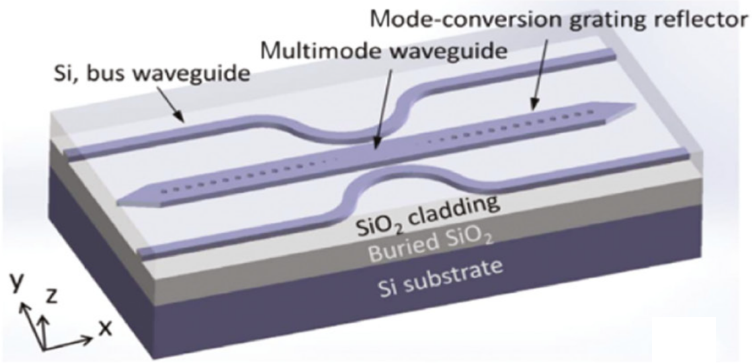

Figure 5 Using a multimodal Fabry-Perot cavity to build a multimodal interference device. This device reflects half of the incoming photons back onto the first waveguide and transmits the remaining half to the other waveguide [12].

4 Conclusions

4.1 Current limitations of PIC are the intensity drop and the low fidelity optical components [4]. Major materials improvements must be attained in order for PICs to reach maturity and commercialization.

4.2 In the near future EIT material science may improve allowing for commercialization of optical switching technology [7]. In the near future, Xanadu projects that it will be able to create a multilayer programmable photonic quantum computer with ~3 dB of loss [4]. The most novel near term advance may come from trapped ion quantum computer photonic linking. Photonic linking has been achieved with several other types of particles, however combining the difficulty of trapping ions, controlling ions and receiving data has so far been too much to complete simultaneously [14]. A major concern is controlling the ions without the data being sent in a non-data capturing direction. Using a mirror on the trap surface and a concave optical fiber, researchers hope to soon build optical resonators around the ion to capture and funnel these photons into an optical fiber [14]. Once these photons are in an optical fiber, they can be routed through an EIT to an ion on another chain. By doing so, one would link ion chains together and thus solve the limitations on the near term scalability of trapped ion systems. This photon linking is expected to be demonstrated and implemented in the near future.

5 References

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