Single-Photon Switches for Quantum Information Processing

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Abstract: Recent work towards the realization of low-loss, high-speed, optical switches designed to accommodate single photon qubits is discussed. Preliminary results from an all-optical switch and plans for an electro-optical switch are described.

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1. Introduction

Many of the basic components required for optical quantum computing and quantum communications have recently been demonstrated, including single photon sources [1], quantum memories [2], and probabilistic logic gates [3-5]. While the results of these proof-of-concept demonstrations are encouraging, the error rates in the current devices need to be improved, including the performance of single-photon optical switches. In our approach for a single-photon source [1], pairs of photons are produced using parametric down-conversion. The detection of one member of a pair signals the presence of the other photon, which is then switched into an optical storage loop until it is needed. A prototype single-photon memory device has also been demonstrated [2] by switching a single-photon qubit into an optical storage loop. The performance of both of these devices was limited primarily by photon loss and decoherence in the optical switching elements. In addition, a scalable linear optics quantum computing architecture [6, 7] will require low-loss single-photon switches in order to dynamically switch the output of a probabilistic logic gate on to the next step of the computation when the operation is successfully completed.

The single-photon nature of optical qubits, when coupled with quantum coherence requirements, limits the feasibility of using standard telecommunications switches in these applications. The insertion losses and switching times associated with several commercial device technologies are summarized in Table 1. Although the switching time may not seem critical in a quantum computing application, the single photon qubits must be delayed to accommodate the switch, which will generally result in additional loss. For example, if a standard telecommunications fiber is used as a delay line, the qubits will experience a minimum loss of roughly 0.04dB/μsec. When this additional loss is factored in, as shown in the table, the need for high-speed and low-loss optical switches is apparent.

Table 1. Typical performance of several switching device technologies

Technology	Intrinsic Loss (dB)	Switching Time (μs)	Storage Loss (dB)	Combined Loss (dB)
Mechanical (mems)	0.5	20,000	800	800
Thermo-optical	1.5	2,000	80	82
Electro-optical	1	0.001	<.01	1
Acoustic	0.1	80	3.2	3.3
Piezoelectric	0.25	30	1.2	1.5
Integrated optics	3	0.001	<.01	3
Liquid crystal	5	3,000	120	125

We are currently investigating two approaches to make high-speed (~1 ns switching time), low-loss (~0.1dB) optical switches for use with photonic qubits. The approach described in the following section uses non-linear interactions to make an ultra-fast all-optical switch, whereas the approach described in the final section uses an evanescently coupled electro-optic modulator to make an ultra-low loss switch.

2. All-optical switch

The basic idea of the all-optical approach is to use the well-known Kerr effect to apply a non-linear phase shift to one path in a fiber-based Mach-Zehnder interferometer, as shown in figure 1. A relative phase shift of π radians is required to achieve 100% switching between the two interferometer outputs. Although this technique is well-established and has been demonstrated with many different media and many types of optical fibers [8], it has not been used in conjunction with single photon qubits. The primary difficulty with this technique is that for typical single mode fibers of limited length (<10 m), relatively strong (~10 nJ) switching pulses are required to generate the necessary phase shift.

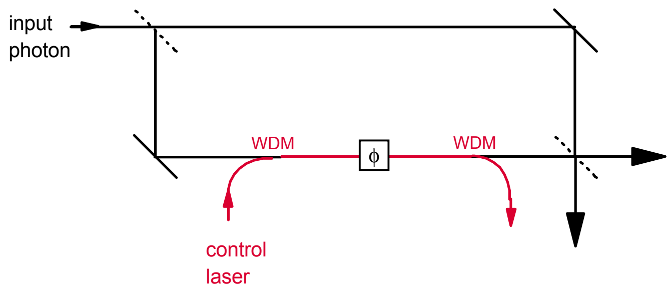

Fig. 1. Basic design of an all-optical switch using a strong control laser pulse to produce a phase shift ϕ in one arm of an interferometer.

For the current experiments we are using a strong laser pulse at 1063nm to switch our 780nm single photon qubits. While this separation in wavelength allows the use of very low loss (<.1 dB) wavelength division multiplexers (WDM) to filter out the control pulse, additional filtering in the form of dispersing prisms (not shown) is also used to provide the necessary isolation. Preliminary results from an initial test using a continuous wave (CW) laser for the signal and a high-speed photodiode receiver are shown in figure 2. The figure presents a temporal comparison of the control pulse and the switched signal, showing the nearly instantaneous nature of the switching effect. The addition of single photon counting detectors into the apparatus in the near future will allow a complete characterization of this device, including the potential generation of unwanted photons at the signal wavelength due to anti-Stokes scattering of the strong control pulse.

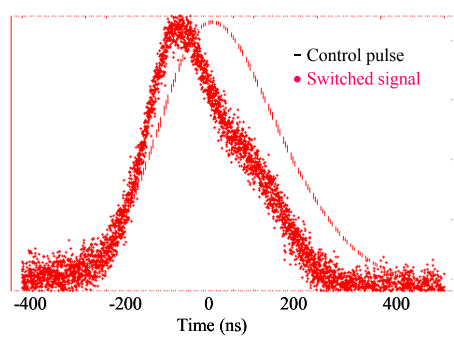

Fig. 2. Temporal comparison of the normalized control pulse and the switched signal for an initial test using a CW source for the signal and a high-speed photo-diode receiver.

3. Electro-optical switch

In our previous single photon source and memory demonstrations [1, 2], free-space electro-optic modulators (Pockels cells) were used as the switching elements. Although these devices have fast switching times (~5ns), transmission losses through the relatively long (>150mm) active medium is roughly 0.6dB. In addition, it would be desirable to replace the free-space modulators with all-fiber switches. Commercially-available fiber switches have relatively large losses due to the coupling into and out of a waveguide structure in addition to losses in the waveguide itself. The basic idea of our electro-optical switch is to avoid the coupling and transmission losses associated with the use of waveguides by making use of the evanescent field of an optical fiber that has been polished down in close proximity to the fiber core, as shown in figure 3. The evanescent field will then couple the photon into a suitable medium whose index of refraction can be controlled by applying a voltage across a set of electrodes. The main limitation on this approach is the requirement that the index of refraction of the medium be less than that of the fiber core. Fiber polishing techniques are currently being developed in order to investigate the feasibility of this approach.

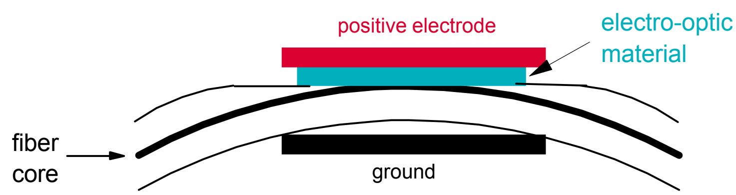

Fig. 3. Basic design of an electro-optical switch using evanescent field coupling to the core of an optical fiber.

4. References

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