An ultra-fast optical switch for quantum networking

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A new in-fiber switching device is capable of routing entangled single photons with minimal noise, loss, and decoherence.

Quantum communications hold the promise of classically impossible communication tasks, such as the physically secure transmission of secret cryptographic keys (i.e., quantum key distribution) or transfer of the complete quantum state of an object to a distant location without moving the object through the intervening space (i.e., quantum teleportation). A key requirement for most quantum communication protocols is the successful distribution of entangled photons. To date, most demonstrations of quantum communications have established point-to-point links between two locations. To enable many-to-many—i.e., networked—quantum communications, a new type of switch capable of routing entangled single photons is needed. Here, we describe our progress in developing an ultra-fast switch for quantum communications.

Classical communications is the study of sending signals over long distances, such as electrical signals transferred over copper wires (e.g., phone lines) or optical signals transmitted through fiber-optic cables (e.g., the Internet). Although many advanced encoding and decoding techniques have been developed, at a basic level each bit of classical information is encoded as a binary choice: 0 or 1, yes or no. In contrast, a bit of quantum information can exist as a ‘yes’, ‘no’, or many flavors of ‘maybe’. Interestingly, when quantum information is measured, the bit ceases to exist as ‘maybe’ and immediately takes on a state of ‘yes’ or ‘no’. Entangled bits can exist in a correlated state of ‘maybe’, where each will be random when measured. However, when the answers to these two measurements are compared, they will always match perfectly, i.e., both ‘yes’ or both ‘no’. The consequence of this behavior is that any material interacting with the photons runs the risk of destroying or degrading their fragile correlations. Since entangled correlations are exquisitely sensitive to measurement, any useful entangled photon switch must exhibit low loss and noise as well as high contrast and speed. Most importantly, it must not alter the

switched photon’s quantum state. We have recently constructed and characterized an all-optical, single-photon switch that fulfills each of these exacting requirements and whose aggregate

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Figure 2. (a) A basic switch, like a rail switch, either transmits an input to output T, or reflects an input to output R. (b) The quantum switch transmits input photons to port T if a pump pulse is present, or reflects them to port R (via a circulator) if a control pulse is absent. The longer the Sagnac loop, the wider the switching window.

performance—in terms of speed, loss, and noise—exceeds those of all available alternatives by three orders of magnitude.

All previously demonstrated switching technologies are either too slow or generate too much single photon noise and loss to be useful for quantum networks that use polarization-entangled photons (see Figure 1). In contrast, our new device is based on a nonlinear-optical-loop mirror (NOLM) switch (see Figure 2). It uses bright, 1550nm pump pulses to switch 1310nm signal photons, which leads to a negligible probability of Raman scattering at the signal wavelength. As a result, the pump pulses generate an insignificant amount of signal noise. The NOLM is a fiber-optic Sagnac interferometer, i.e., a two-input, two-output 50/50 fiber coupler with both outputs connected to each other by a long fiber loop. We can configure the NOLM to either reflect or transmit all incoming light by changing the geometry of the Sagnac fiber loop. This property is a consequence of the constructive and destructive interference of light between the clockwise and counterclockwise optical paths inside the Sagnac loop. We can induce a relative phase difference between the two paths using an optical pump pulse, multiplexed into the clock-wise path of the interferometer. The pump pulse imparts a phase shift on any signal pulse with which it co-propagates. For a pump pulse of the right energy, this causes an input signal to be transmitted instead of reflected. That is, the input signal can be switched from its initial path.

To quantify the performance of our new switch, we subjected it to a full battery of tests using both classical input pulses and entangled single photons. Our switch exhibited high contrast (150:1), low loss (~1.5dB), and generated negligible noise photons in the signal band. When we tested the switch with polarization-entangled photons, it induced no detectible decoherence or degradation. Moreover, the switching window (i.e., the temporal extent of the switching effect) was found to be controlled not by the intensity of the pump pulse, but by the length of fiber in the main Sagnac loop (~2ps/m). Using a few meters of fiber, therefore, we can create an ultrashort (~10ps) switching duration, which in principle is capable of operating on 100GHz repetition-rate signals, that is, faster than the fastest commercial telecommunications networks.

The most promising property of our new switch is that its operation is completely coherent. This allows the switch to not only place an input signal into a superposition of two possible output signals, but also to coherently couple the temporal (i.e., time) and spatial (i.e., signal path) degrees of freedom. To demonstrate this capability, we used the switch to demultiplex a single high-fidelity entangled channel from a highly mixed, dual-channel entangled photon stream.

In summary, we have developed an entangled photon switch that can enable a number of intriguing applications for quantum information processing and quantum communications, taking us one step closer to, for example, a fiber-optic ‘quantum Internet.’ Our device design is flexible enough to permit further improvements to its function. For example, the switching window duration can be altered because the speed of the device is limited only by the pump-pulse profile and fiber-loop length. Since loss is limited by the coupling efficiency of simple devices, it should be possible to dramatically reduce the device’s loss to less than 0.1dB. Furthermore, by adding a second circulator, 5

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the one-input, two-output device can be converted into a more familiar two-input, two-output crossbar design. Two switches in series can even be used to generate a selectable delay line, trapping an input entangled photon into a fiber cavity before releasing it on demand. These variations constitute our ongoing work.

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References


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