High-Fidelity, Weak-Light Polarization Gate Using Room-Temperature Atomic Vapor

L. Deng, R.B. Li, C.J. Zhu, and E.W. Hagley
National Institute of Standards and Technology, Gaithersburg, Maryland 20899 USA
lu.deng@nist.gov

Abstract: Using a polarization-selective-Kerr-phase-shift technique we demonstrate an all-optical polarization gate in an atomic gain medium with the control-field intensity equivalent to 20 photons of 10 nanoseconds propagating in a 5 μm mode diameter photonic fiber.
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Efficient qubit protocols are critically important to quantum information processing, and the ability to manipulate the quantum state of light using the quantum state of another light field is the ultimate enabler of optical gates for quantum computers [1, 2]. Although various single-photon polarization gates have already been proposed [3-6], the demonstration of a fast, all-optical polarization gate using atomic media at single-control-photon levels, or even at very weak control-light levels, has proved very challenging. To date, no such weak light atomic CNOT-polarization gate has been experimentally realized.

Here, we demonstrate a fast, high-fidelity complete atomic linear polarization gating operation using a novel polarization-selective-Kerr-phase-shift (PSKPS) technique [7, 8]. We show that the polarization state of a very weak signal field (potentially at single-photon levels) can be rapidly and orthogonally changed by a free-space weak phase-control light field with an intensity of 2 mW/cm^2. This weak phase-control light intensity would be equivalent to only about 20 photons in a 10-ns pulse length confined in a typical photonic hollow fiber with a 5 μm mode diameter.

Experimentally, we use a warm ^{87}Rb vapor to demonstrate the PSKPS-based polarization gate operation. The ^{87}Rb vapor cell has a length of 7.5 cm and a diameter of 2 cm. It is shielded from ambient magnetic fields and is actively temperature stabilized to 322 K with a number density $n_0 = 6\text{x}10^{11}/\text{cm}^3$. First, we optically pump the medium using a linearly polarized light field that couples the ($5S_{1/2}$, F=2) hyperfine manifold to the $5P_{3/2}$ manifold (Fig. 1a). Immediately following the optical pumping process, we turn on a strong (15 mW/cm^2), circularly polarized pump laser coupling the ($5S_{1/2}$, F=1) to ($5P_{3/2}$, F"=2) transition with a one-photon detuning of $\delta/2\pi$ = 1.2 GHz, and a linearly polarized signal field with an intensity of < 0.3 mW/cm^2, that couples the ($5P_{3/2}$, F"=2) to ($5S_{1/2}$, F=2) transition with $\delta_{2ph}/2\pi$=700 kHz. The pump and signal fields are overlapped and combined (see Fig. 1b) using a 50-50 beam splitter (BS). Another BS splits this beam into the two arms of a Mach-Zehnder interferometer. One arm will later be overlapped with a phase-control laser, and the other arm serves as a reference for phase analysis. After exiting the cell, both arms of the Mach-Zehnder interferometer are joined together using a 50-50 BS so that the phase of the signal field can be analyzed. These beams are physically separated at a distance of about 1 m from the exit of the vapor cell. To introduce a Kerr phase shift we inject a weak (2 mW/cm^2) circularly polarized phase-control field coupling the ($5S_{1/2}$, F=2) to ($5P_{1/2}$, F'=2) transition into one arm of the Mach-Zehnder interferometer using another 50-50 BS. To put this 2 mW/cm^2 phase control-field intensity in perspective, a single 780 nm photon of 10 ns pulse length propagating in a 5 μm mode diameter photonic hollow fiber has an intensity of about 0.1 mW/cm^2. Therefore, 2 mW/cm^2 would be equivalent to about 20 phase-control photons in such a photonic fiber.

In Fig. 1c and 1d, we demonstrate rapid signal-light polarization switching using a single control field pulse in Fig. 1c and multi control-field pulses by modulating the phase-control light in Fig. 1d. This latter multi-pulsed operation results in high fidelity probe-field polarization switching, proving the viability of fast CNOT-polarization switching operations using the PSKPS technique developed here. Experimentally, we routinely observe nearly 100% switching fidelity at such low phase-control light intensities. While the simplified mathematical treatment of a lifetime broadened system predicts an unwanted the nearby state contributions and far-off-the-wing effect of a Doppler broadened system reduces the actual gain in our experiments so that no amplification of the signal field is observed with a proper choice of experimental parameters.

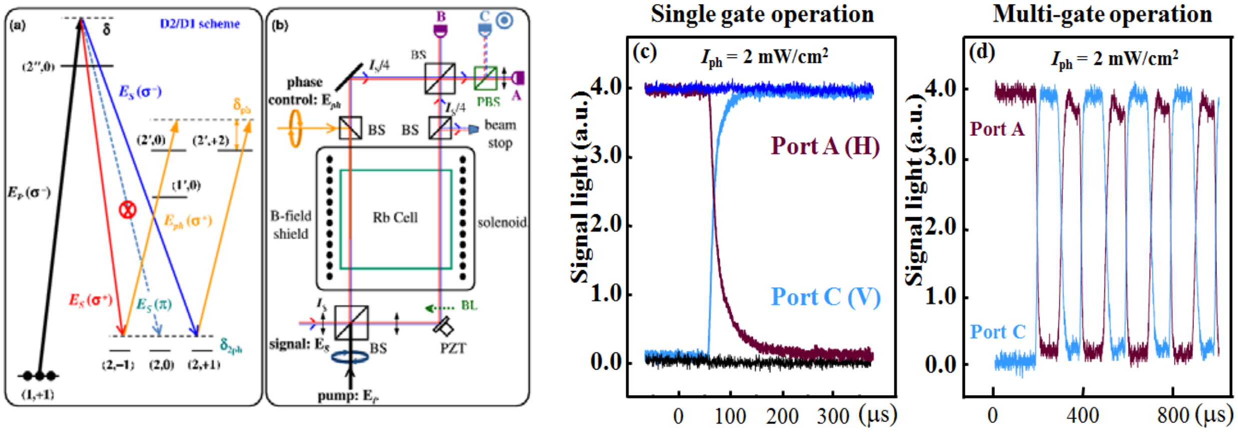

Figure 1: (a) Energy diagram and laser couplings for the photonic polarization gate. δ: one-photon pump field (E_P , thick black arrow) detuning. δ_{2ph}: two-photon detuning. δ_{ph}: the phase-control field detuning. A magic detuning $\delta_{ph} = \delta_{magic}$ is defined as the detuning that results in an orthogonal polarization rotation of the signal field (blue and red arrows) using minimal phase-control field (E_{ph}) and pump field (E_P). b) Experimental setup. BS: 50-50 beam splitter. PBS: polarization beam splitter. BL: beam block. *A*, *B*, and *C*: detectors. PZT: piezo-controlled mirror. (c) Complete horizontal linear polarization to vertical linear polarization rotation of the signal field. (e) High fidelity, multiple pulse polarization flips by modulating the phase-control light.

The experimental strategy and methods demonstrated here have significant potential for quantum information processing, and may lead to the development of critical architectural building blocks for quantum computers. Our experiment demonstrates the first high fidelity, all-optical very weak-light CNOT gate and polarization gate operations in room-temperature atomic medium. The intensity of the phase-control light, which is equivalent to 20 photons in a photonic hollow fiber, is near the single-photon level needed to achieve true control of the quantum state of one light field using the quantum state of another light field. Improvements and combinations of the method demonstrated here with electromagnetically induced transparency (EIT) [9] and other schemes may lead to further reductions in the required phase-control field intensity. It can be shown that this PSKPS technique is readily applicable in EIT-based schemes where no probe gain is present. Indeed, we have been able to show theoretically that it is possible to achieve the gated operation with only a 3 dB loss of the signal field [10]. This may lead to CNOT-polarization gate operations truly at single-signal photon levels without the need to focus the phase-control light field to the diffraction limit.

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