

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

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**Abstract:** Using a polarization-selective-Kerr-phase-shift technique we demonstrate a fast, all-optical, high-fidelity polarization gate in a room-temperature atomic medium. By writing a  $\pi$ -phase shift to one selected circularly-polarized component of a linearly-polarized input signal field and by equalizing the gain of both circularly-polarized components we can maintain the original strength of the signal field and yet achieve a perfect  $90^\circ$  rotation of its linear polarization., demonstrating a fast, high-fidelity, dynamically-controlled polarization gate operation. The orthogonal linear polarization switching field intensity can be as low as  $2 \text{ mW/cm}^2$  using a warm rubidium vapor, which is equivalent to a 100-nanosecond pulse containing about 200 photons and confined in a typical commercial photonic hollow-core fiber with a  $5\text{-}\mu\text{m}$  mode diameter.

## 1. Introduction

Efficient optical-field gating operations with very low gating control light intensities are critically important to next-generation advanced telecommunication technology. One of such devices is the optical polarization phase gate where a polarization-encoded optical signal field is controlled by a weak light field via nonlinear Kerr effect. Although various weak-light and low power consumption optical phase gate operation schemes have already been proposed [1-4] and a continuously controlled optical phase gate has been recently demonstrated [5], to date no weak-light, dynamic polarization gate has been experimentally demonstrated in room-temperature media. Here, we describe the concept and principles of Polarization-Selective-Kerr-Phase-Shift (PSKPS) based polarization gate operation and we show experimental results of a fast, high fidelity, all-optical polarization gate operation based on this PSKPS protocol. The work presented here opens the door for possible potential applications and implementations of extremely low control light optical logic operations in advanced telecommunication protocols and networks.

## 2. The concept and principle of PSKPS

The concept of the PSKPS protocol and the all-optical polarization gate operations are based on the principle of “selective and differential Kerr phase engineering of different polarization components of the single linearly polarized signal field”. This process can be understood with a lifetime broadened atomic system shown in Fig. 1a. Here, the phase engineering process involves a three-photon transition where the core of the process is a three-state  $\Lambda$ -type Raman gain scheme. A strong pump field couples the fully occupied ground state to an upper electronic state with a large one-photon detuning to suppress spontaneous emission. A linearly polarized signal field is forced, by the atomic transition selection principle, to address two separate channels involving the two circularly polarized components of the linearly polarized input signal field. To complete the three-photon process a circularly-polarized phase-control field writes different nonlinear Kerr phase shifts  $\phi^{(\pm)}$  to the different signal polarization branches. Because of the Raman gain in the core  $\Lambda$ -scheme, the different polarization components of the signal field will



acquire different nonlinear gain and nonlinear Kerr phase shift. If the differential nonlinear gain  $\Delta G = G^{(+)} - G^{(-)}$  can be made negligibly small while simultaneously achieving  $\phi^{(+)} = 0$  and  $\phi^{(-)} = \pi$ , then at the exit of the medium the linear polarization of the signal field will have undergone a perfect  $90^\circ$  rotation. With this perfect polarization gate operation, a CNOT gate and a host of other fast, all-optical logic gates [6] can be easily constructed.

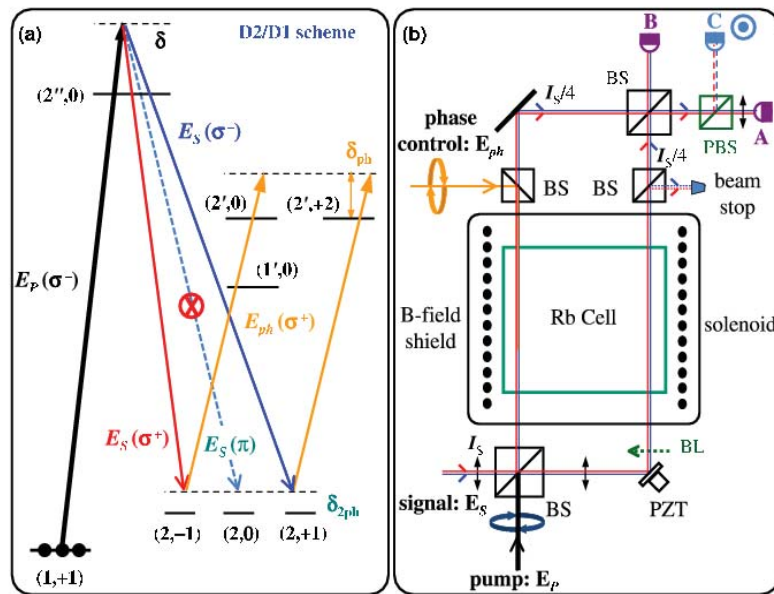


Figure 1: (a) Energy diagram and laser couplings for the photonic polarization gate.  $\delta$ : one-photon pump field ( $E_P$ , thick black arrow) detuning.  $\delta_{2ph}$ : two-photon detuning.  $\delta_{ph}$ : the phase-control field detuning. A magic detuning  $\delta_{ph} = \delta_{magic}$  is 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.

### 3. Experiment

Experimentally, we use a warm  $^{87}\text{Rb}$  vapor to demonstrate the PSKPS-based polarization gate operation (Fig. 1b). The  $^{87}\text{Rb}$  vapor cell has a length of 7.5 cm and a diameter of 2 cm. It is filled with about 933 Pascal Neon buffer gas and it is also shielded from ambient magnetic fields under three layers of  $\mu$ -metal. During the operation the cell is actively temperature stabilized to 322 K with a number density  $n_0 = 6 \times 10^{11}/\text{cm}^3$ .

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, resulting in all atoms initially are in the ground state manifold ( $5S_{1/2}$ ,  $F=1$ ). Immediately following the optical pumping process, we turn on a strong ( $8 - 15 \text{ mW/cm}^2$ ), circularly polarized pump laser coupling the ( $5S_{1/2}$ ,  $F=1$ ) to ( $5P_{3/2}$ ,  $F''=2$ ) transition with a one-photon detuning of  $\delta/2\pi = 1.2 \text{ GHz}$  (Fig. 1a). A linearly polarized signal field which is derived from the same laser that provides the pump power is also injected into the medium. It has an intensity of  $< 30 \mu\text{W/cm}^2$  and it couples the ( $5P_{3/2}$ ,  $F''=2$ ) to ( $5S_{1/2}$ ,  $F=2$ ) transition with a similar large one-photon detuning  $\delta/2\pi = 1.2 \text{ GHz}$ . The pump and the signal field form the usual two-photon Raman gain configuration with a typical two-photon detuning of  $\delta_{2ph}/2\pi = 700 \text{ kHz}$ . The pump and signal fields are overlapped and combined using a 50-50 beam splitter (BS).

We further split this dual-beam into the two arms of a Mach-Zehnder interferometer using a separate beam splitter (Fig. 1b). 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. The output from this Mach-Zehnder interferometer is then further analyzed with a high precision polarization beam splitter (PBS). The signals simultaneously detected at two polarization ports of the PBS yield an assessment of how effective, complete and efficient of the polarization

switching process. Because of the frequency proximity of the pump and signal fields these beams must be physically separated at the signal detectors. This is because that even these two fields have orthogonal linear polarizations an extremely small nonlinear-polarization residual in the strong pump could pass the analyzing PBS and enters the detector for the signal field polarization analysis, and therefore dominates the detector response. In our experiment we set up two special filters at a distance of about 1 m from the exit of the vapor cell to improve the signal/leakage-pump discrimination and this proved very effective.

The Kerr phase shift is introduced with a weak circularly polarized phase-control field coupling the ( $5S_{1/2}$ ,  $F=2$ ) to ( $5P_{1/2}$ ,  $F'=2$ ) transition. This phase-control field is injected into one arm of the Mach-Zehnder interferometer using another 50-50 BS and it propagates in the opposite direction in comparison with the signal field (Fig. 1b). We first scan the Mach-Zehnder interferometer to make sure that a  $\pi$ -phase shift is written to the arm of the interferometer where the signal and phase control field propagate anti-co-linearly. By adjusting the intensity of the phase control field we can switch the output light field from one polarization port of a polarization beam splitting cube (PBS) to the orthogonal output port of this PBS, demonstrating the fast orthogonal polarization rotation. With the warm rubidium vapor at about 322 K we routinely execute such polarization rotation with a phase control light field of  $2 \text{ mW/cm}^2$ . To put this phase control-field intensity in perspective, a single 780 nm photon of 100 ns pulse length propagating in a  $5 \mu\text{m}$  mode diameter photonic hollow fiber has an intensity of about  $10 \mu\text{W/cm}^2$ . Therefore,  $2 \text{ mW/cm}^2$  would be equivalent to about 200 phase-control photons in such a photonic fiber.

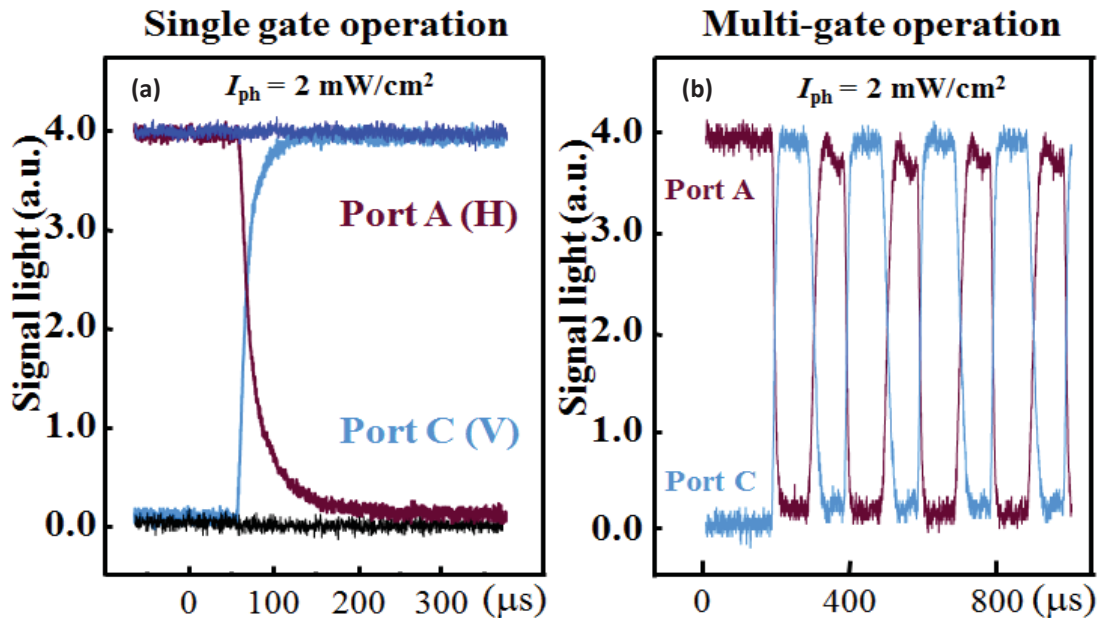


Figure 2: (a) Polarization gate operation. A signal field with horizontal linear polarization is rapidly switched to a signal field with vertical linear polarization by using a phase-control field of  $2 \text{ mW/cm}^2$ . The signal field switching fidelity is typically better than 96%. The switching time can be reduced to  $2 \mu\text{s}$  which is the limit of our system. (b) High fidelity, multiple pulse polarization flips by modulating the phase-control light. The polarization switching can be as fast as MHz which is the limit of our system.

In Fig. 2a we demonstrate signal-light linear polarization switching using a single control field pulse of intensity  $2 \text{ mW/cm}^2$ . Slight optimization of signal, pump and phase-control light fields timing resulted in a polarization switching at about  $2 \mu\text{s}$  which is roughly the performance limit of our frequency-intensity modulators. Due to the broad Doppler profile of room-temperature atomic medium nearby parasitic transitions, even are very far from resonance, and still contribute to some degree to the loss of the signal and this explains why the signal intensity has not exceeded 100% in this Raman gain scheme. That is, the small gain in this Raman gain configuration is compensated partially by the background absorption of the signal field. In Fig. 2b we show multiple phase-control

field pulses by modulating the phase-control light source. This multi-pulsed operation results in high fidelity probe-field polarization switching that can be achieved on the order of MHz (again the limit rate of our control devices). This demonstration proves the viability of fast polarization switching operations using the PSKPS technique developed here.

#### 4. Conclusion

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 polarization gate operations in room-temperature atomic medium. The intensity of the phase-control light can be significantly reduced by using a high density atomic vapor trapped in a photonic hollow fiber. In addition, using of short pulsed phase control field can also reduce the complication of fast relaxation rate resulted from the transverse motion of atoms in the hollow fiber. Further improvements and combinations of the PSKPS protocol and technique demonstrated here with schemes such as electromagnetically induced transparency (EIT) [7, 8] may lead to further reductions in the required phase-control field intensity. Indeed, fully second quantization theoretical calculation has shown that the PSKPS technique is readily applicable in EIT-based schemes at single photon levels where no probe gain is present. This raises an interesting possibility of polarization gate operations at single-signal photon levels without the need to focus the phase-control light field to the diffraction limit.

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