

# Polarization preserving ultra fast optical shutter for quantum information processing

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**Abstract:** We present the realization of a ultra fast shutter for optical fields, which allows to preserve a generic polarization state, based on a self-stabilized interferometer. It exhibits high (or low) transmittivity when turned on (or inactive), while the fidelity of the polarization state is high. The shutter is realized through two beam displacing prisms and a longitudinal Pockels cell. This can represent a useful tool for controlling light-atom interfaces in quantum information processing.

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In the last few years, quantum information processing (QIP) has attracted a growing interest. Its optical implementation opens new perspectives both for quantum communication and quantum computing. Quantum communication is based on the distribution of photonic entangled states [1], while quantum computing relies on optical gates in the KLM approach [2] or in measurement carried out on complex cluster entangled states [3]. The previous tasks require the fast implementation of operation conditioned on single photon measurements. The active teleportation protocol, which involves conditional fast-feedforward transformations, has been first demonstrated by Giacomini et al [4], and then by [5]. Conditional gates have been also reported by [6]. Within the context of one-way quantum computing feed-forward measurements have been implemented by [7, 8] and [9].

In quantum information framework, the ability to perform fast-switching of an optical field can have useful applications within two different contexts: for light matter interface and for measurement induced quantum operation. In the first case, single photon states are coupled to quantum memory realized through atomic system [10]. A deterministic photon-matter coupling should be activated once conditional operations on single photons have been successful, namely quantum gates realized through linear optics. Since the content of information is encoded in the polarization degree of freedom of single photon states, the switching device should be able to preserve any polarization state. More specifically, we consider a recent proposal for creating light-BEC entanglement [11]. A multiphoton quantum superposition generated by a quantum-injected optical parametric amplifier seeded by a single-photon belonging to an entangled pair is made to interact with a Mirror-BEC shaped as a Bragg interference structure. There the shutter should be adopted to stop all the light pulses generated without seed. The detection of the single photon belonging to the seed opens the shutter and turns off the optical lattice adopted to create the mirror BEC. On the other hand, in the second case conditional manipulation of quantum states of light depending on measurement carried out on part of the beam [12] or on the environment [13] can lead to interesting applications for quantum communication. In all the previous situations the switching device should be able to preserve any polarization state of the incoming radiation, as said. Hence a shutter device based on a fast-pockels cell, as the one developed by Ref.[4, 7], combined with a polarizing beamsplitter would destroy the carried information. An alternative solution based on an acousto-optic modulator requires a longer activation time and leads to an intensity of the diffracted beam between 0% and 60%, while the zero order contribution is always higher than 15%. Here we present the realization of an ultra-fast shutter for optical field, which preserves a generic polarization state and exhibits a high transmittivity. The shutter is realized through two beam displacing prisms and a longitudinal Pockels cell (PC).

Let us sketch the working details. Calcite beam displacing prism is used to separate an input beam into two orthogonally polarized output beams. Before passing through a second calcite prism these are manipulated in a PC with optical axis oriented at  $45^\circ$  (Fig. 1). When the PC is off (Fig. 1-(1)) it leaves the polarization state unperturbed and the beams are further separated in the second calcite. In this situation the shutter is off, and the output beams on modes **a** and **c** are stopped by a pin-hole. On the other hand, when the cell is on, the PC driving voltage is set to induce a  $\lambda/2$  phase shift between the ordinary and extraordinary components and it can be activated in a short time ( $t < 10ns$ ) by an external TTL signal. In this way the transformation  $\vec{\pi}_H \leftrightarrow \vec{\pi}_V$  is implemented. Then the two orthogonally beams are recombined spatially and temporally in the second calcite, Fig. 1-(2). In this situation the output field emerges on mode **b**. At

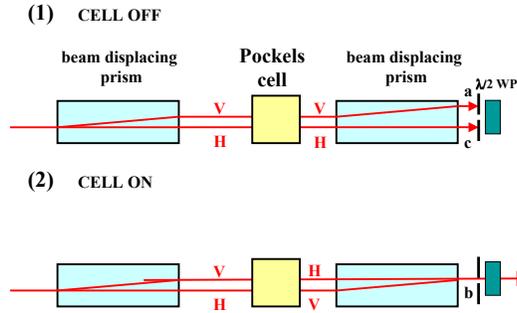


Fig. 1. Experimental scheme of the shutter: (1) when the shutter is off the two beams separated by the two calcites are stopped by the pin-hole (modes **a** and **c**). (2) On the contrary when the shutter is on the two beams are recombined on the second calcite and the resulting beam (mode **b**) passes through the pin-hole.

the end of the stage a  $\lambda/2$  waveplate at  $45^\circ$  flips the polarization of the output beam to restore its initial state. It's worth noting that the temporal overlap between the two beams is automatically ensured by the symmetry of the device: the  $\vec{\pi}_H$  polarization component of the input beam goes through the first calcite on a straight path whereas the  $\vec{\pi}_V$  component's path is deviated. At the exit of the first calcite the two orthogonal polarization components are separated by a distance  $d = 4\text{mm}$ , the PC exchanges them and in the second calcite they are recombined by virtue of the fact that they have experienced the same overall path deviation.

The present device can be adopted with ultra short pulses ( $200\text{fs}$ ). We note that this system is also stable in phase. Indeed the two orthogonally polarized beams are subjected to the same phase fluctuations since they propagate along parallel optical paths and share the same optical mounts. The phase difference between the two beams can be finally controlled by tilting the second calcite [14].

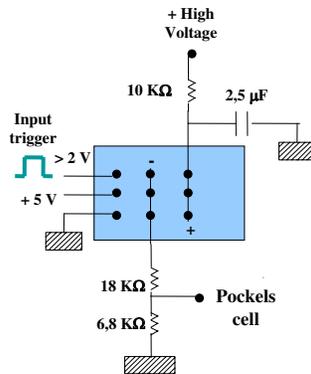


Fig. 2. Electronic driver of the Pockels cell. When the signal of the trigger is on the PC is activated.

Let us now analyze the action of the shutter on an input quantum state  $|\varphi\rangle$  with generic polarization  $\vec{\pi}_\varphi = \alpha \vec{\pi}_H + \beta \vec{\pi}_V$ , where  $(\alpha, \beta)$  are complex numbers satisfying  $|\alpha|^2 + |\beta|^2 = 1$

and  $\vec{\pi}_H$  and  $\vec{\pi}_V$  stand for horizontal and vertical polarization, respectively. The evolution of  $|\varphi\rangle$  is investigated by looking to the Heisenberg dynamic of the creation operator associated to the spatial mode  $\mathbf{c}$  with polarization  $\vec{\pi}_\varphi$ :  $\hat{c}_\varphi^\dagger = \alpha\hat{c}_H^\dagger + \beta\hat{c}_V^\dagger$ . After the first calcite the operator becomes  $(e^{i\chi_1}\alpha\hat{c}_H^\dagger + e^{i\chi_2}\beta\hat{b}_V^\dagger)$ , where  $\chi_1$  and  $\chi_2$  are the phase-shifts induced on the two orthogonal polarizations due to their different optical paths. When the Pockels cell is switched, the operator evolves into:  $(e^{i\chi_1}\alpha\hat{c}_V^\dagger + e^{i\chi_2}\beta\hat{b}_H^\dagger)$ , and the output state results after the recombination in the second calcite:  $e^{i\chi}(\alpha\hat{b}_V^\dagger + \beta\hat{b}_H^\dagger)$ , where  $\chi = \chi_1 + \chi_2$ . Finally, after the  $\frac{\lambda}{2}$ -waveplate, we obtain the same polarization state as the input one  $\alpha\hat{b}_H^\dagger + \beta\hat{b}_V^\dagger$ . On the contrary, if the cell is off, the total operator becomes  $(e^{i2\chi_1}\alpha\hat{c}_H^\dagger + e^{i2\chi_2}\beta\hat{a}_V^\dagger)$ , and, in this case, the initial polarization state is lost. We note that this scheme can be adopted in all the visible range by changing the PC voltage and by exploiting the spectral operating range (from  $350nm$  to  $2.3\mu m$ ) of the optical grade calcite of the displacers.

The adopted electro optic cell, Lasermetrics Series 1042, was composed by the series of two longitudinal PC of same length  $35mm$ , powered by a high voltage of  $3200V$  to produce a  $\lambda/2$  shift on the incident polarization and driven by the circuit reported in Fig. 2. The problem of realizing a fast electronic circuit transforming a TTL signal into a calibrated fast pulse in the kV range was solved by a solid state switch HTS 50-08-UF, characterized by a very low jitter and a lifetime typical of semiconductor devices. The switch is triggered by a positive going pulse of 2 to 10 volts amplitude and generates the signal shown in Fig. 3. The pulse remains constant

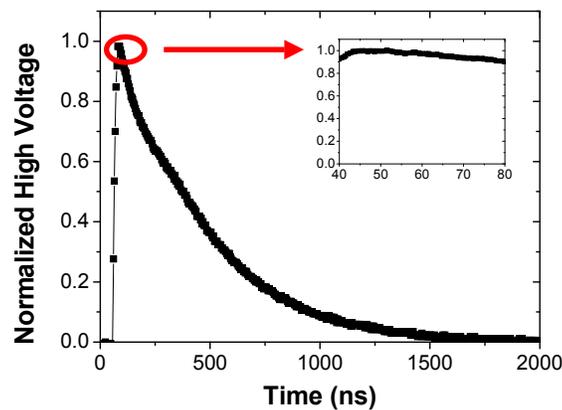


Fig. 3. Trend of the high voltage signal as function of time. Inset: the trigger signal remain constant for almost  $10ns$ .

for a time window of almost  $10ns$  and decays exponentially within  $500ns$ . The time duration of the driver pulse has been chosen to satisfy two criteria: (a) reduced low-frequency components and (b) suitable activation time window. (a) The KD\*P crystal suffers the piezoelectric effect: when excited by a long high voltage pulse an effective coupling is introduced between the corresponding low frequency spectral components and the acoustic phononic modes of the crystal. The corresponding strain causes a mechanical damped oscillation of the crystal for a time duration longer than the ultra fast activation time of the shutter. This effect due to the polarizability of the Pockels cell is harmonically modulated. Hence, the shutter is periodically reactivated and several subsequent pulses are partially transmitted. In order to eliminate this effect an ultra-short activation pulse is required [15]. (b) The electronic jitter of the driver

circuit, almost  $1 - 2ns$ , gives a lower limit to the time activation window.

We describe now the experimental characterization of the shutter device. We used a pulsed laser source centered at  $800nm$  with a repetition rate of  $250kHz$  and a bandwidth of  $1.5nm$ , selected before the shutter by two interferential filters. A  $\lambda/2$  waveplate (WP) and a polarizing beam splitter (PBS) allowed to vary the polarization of the input beam on the first calcite (fig. 4). A second  $\lambda/2$ -WP and a PBS realized the polarization analysis of the output beam, which was detected by a photodiode (PD).

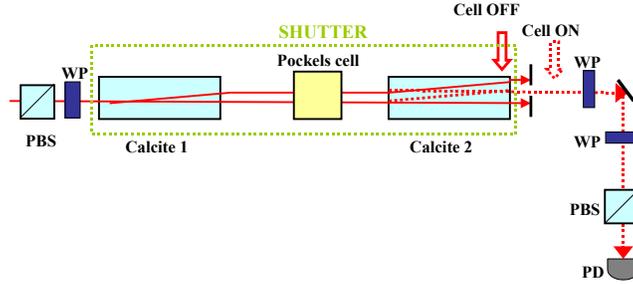


Fig. 4. Experimental setup. A PBS and a  $\lambda/2$  waveplate allow to vary the polarization of the input beam. A second PBS and  $\lambda/2$  waveplate analyze the polarization state of the output beam **b**. The signal is detected by a photodiode (PD).

The PC was activated via the circuit above described (fig. 2). For different values of the frequency of the TTL trigger signal, we measured the fidelity  $\mathcal{F}_{ON}$  of the polarization state when the PC was on, the transmittivity  $\mathcal{T}_{ON}$  and the transmittivity  $\mathcal{T}_{OFF}$  when the shutter was on and off respectively:

$$\mathcal{F}_{ON} = \frac{I_i^{ON}}{I_i^{ON} + I_{i\perp}^{ON}} \quad (1)$$

$$\mathcal{T}_{ON} = \frac{I_i^{ON} + I_{i\perp}^{ON}}{I_{IN}} \quad (2)$$

$$\mathcal{T}_{OFF} = \frac{I_i^{OFF} + I_{i\perp}^{OFF}}{I_{IN}} \quad (3)$$

where  $I_i^{ON}$  ( $I_i^{OFF}$ ) stands for the measured intensity on spatial mode **b** with polarization state  $\vec{\pi}_i$  equal to the input one when the PC is (is not) activated.  $I_{i\perp}^{ON}$  ( $I_{i\perp}^{OFF}$ ) stands for the measured intensity of the analyzed polarization state  $\vec{\pi}_i^\perp$  perpendicular to the input one  $\vec{\pi}_i$ .  $I_{IN}$  stands for the incident intensity on the shutter. For a trigger signal frequency equal to  $1kHz$  we found the following results:

Polarization	$\mathcal{F}_{ON}$ ( $\pm 0.001$ )	$\mathcal{T}_{ON}$ ( $\pm 0.001$ )	$\mathcal{T}_{OFF}$ ( $\pm 0.001$ )
$\vec{\pi}_\perp$	0.956	0.991	0.0025
$\vec{\pi}_\parallel$	0.956	0.991	0.0025
$\vec{\pi}_H$	0.998	0.991	0.0050
$\vec{\pi}_V$	0.998	0.991	0.0020

The transmittivity obtained with the shutter off gives an estimation of the extinction power of the shutter. The mean transmittivity in this case was  $\mathcal{T}_{OFF} = 0.003$ . In order to verify the

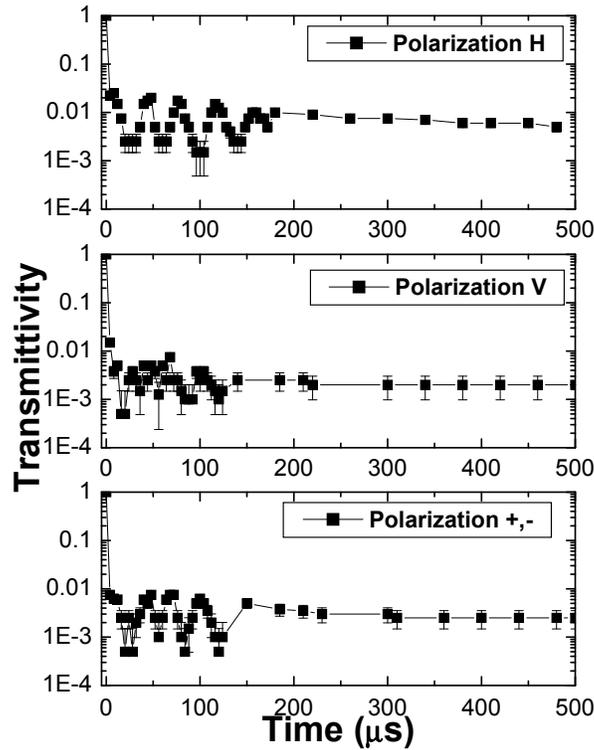


Fig. 5. Transmittivity for an input state with polarization  $\{\pi_+, \pi_-\}$  and  $\{\pi_H, \pi_V\}$  measured with a frequency of the trigger equal to 1 kHz.

absence of the piezoelectric ringing effect we report in Fig. 5 the transmittivity of the shutter as a function of time. After few  $\mu s$  the transmitted signal is reduced by a factor of 100, leading to the transmission of one pulse once activated and the extinction of the subsequent pulses. When the shutter was on we obtained a mean fidelity  $\mathcal{F}_{ON} = 0.998$  for  $\vec{\pi}_H$  and  $\vec{\pi}_V$  polarizations, and  $\mathcal{F}_{ON} = 0.956$  for  $\vec{\pi}_+$  and  $\vec{\pi}_-$  polarizations.

We observe at last that the increase of the repetition rate causes an increase of transmittivity  $\mathcal{T}_{OFF}$  and a decrease of fidelity  $\mathcal{F}_{ON}$  (fig. 6). Indeed for high repetition rate values, the time interval between two following trigger signals is shorter than the PC recovery time. By varying the frequency of the trigger signal, we have at last studied the fidelity in the two polarization basis:  $\{\vec{\pi}_H, \vec{\pi}_V\}$  and  $\{\vec{\pi}_+, \vec{\pi}_-\}$ . We report the experimental results in fig. 6. The fidelity values for the states  $(\vec{\pi}_+, \vec{\pi}_-)$  are lower due to the interferometric feature of the device, however an average fidelity value as high as 97% has been observed with the present scheme.

In conclusion, we reported the experimental realization and characterization of a ultra fast shutter for optical field, based on a self-stabilized interferometer, which preserves a generic polarization state with high fidelity and exhibits a high contrast operation. This device can have direct applications in the context of measurement induced quantum operations.

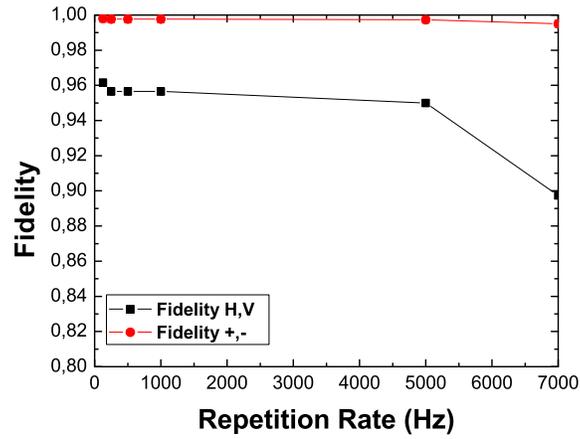


Fig. 6. Fidelity of the polarization state in the  $\{ \pi_+, \pi_- \}$  and the  $\{ \pi_H, \pi_V \}$  basis versus the frequency of the trigger signal.

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