Experimental new ultra-high-speed all-optical coherent streak-camera

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Abstract. We have experimentally studied for the first time a new operation principle of the all-optical coherent streak-camera (Rabi deflector). In the experiment, we observed an effect of significant dynamical angular deflection of a pulse of semiconductor laser during the resonant pumping of the D₂ line (780.24 nm) of ⁸⁷Rb vapor in the range of diffraction angles \( \varphi = \pm 5.45^\circ \). We propose to use the Rabi deflector as an energy efficient shaper of classical and single-photon wave packets. We analyze a possibility of the Rabi deflector operation in quantum systems with feedback.

1. Introduction

A problem of the angular deflection of laser radiation is the most difficult problem of the laser radiation control [1,2]. In [2-4], we proposed a new principle of the angular deflection of radiation wave vector during the laser pulse diffraction of the atomic resonant diffraction grating with the spatial pitch, which is time dependent – the Rabi deflector.

For this, the pump-field transversal profile \( E(t,x) \) should have a form of \( E(t,x) = \varepsilon(t) \cdot \text{saw}(x) \) for the discrete angular deflection [2-4], or \( E(t,x) = \varepsilon(t) \cdot \text{ramp}(x) \) for the continuous in time angular deflection (cf. Figure 1). In this case, the polarization of a two-level resonant medium \( P(x,t) \) in the far field radiates only two moving diffraction orders (-1, +1). Limiting angles \( \alpha \) and \( \alpha \) are determined by the total area of the pump pulse \( \theta(x',t), t = \infty \), where \( x' \) is the coordinate of the extremum \( E(t,x) \) [2-4]. In the experiment we used a simpler case of the pump spatial distribution as S-shaped ramp(x) (cf. Figure 2).

2. Experimental

The setup is shown in Figure 3. A cell with ⁸⁷Rb vapor was pumped by a pulsed tunable laser diode with the duration of 5.15 ns at the wavelength of transition D₂ (780.24 nm). The cell was filled by buffer gas Ar at the pressure of 1 Torr. The cell diameter is 25 mm, its length is 75 mm.

The pump laser consisted of a continuous single-frequency laser diode (1) with the line bandwidth of 100 kHz and pulsed semiconductor laser amplifier (5), which was excited by a current pulse of the generator (4) with the duration of 4-7 ns and current amplitude in the range of 1-3 A. Laser pulse power did not exceed 10-40 mW. The pulse rating was equal to 200 kHz. The tuning of the laser frequency to the Rb atomic resonance was controlled by the Fabry-Perot interferometer (11) with the base of 1 mm, 5 mm or 10 mm.
The interferometer rings were focused by an objective (12) on the CCD camera (16) with the resolution of 2592х1944 pixels. The fine-tuning to the line $D_2$ $^{87}$Rb was performed using the registration of linear absorption in the reference cell with $^{87}$Rb (14) and the photodiode module (17).

Figure 1. Upper panel: angular distribution of radiation of the polarization $P(x,t)$ in the form of two single diffraction orders (-1,+1). Short bold arrows points to the directions of the angular deflection of the diffraction orders, 2 – thin resonant atomic layer, 3 – pump pulse direction. Lower panel: the ideal spatial distribution of the pump field $E(t,x) = \varepsilon(t) \cdot \text{ramp}(x)$ (bold line) and normalized polarization $P(x,t)$ for the current value of the pulse area $\theta(x',t) = 4.5 \pi$ (thin line).

Figure 2. Upper panel: angular distribution of radiation of the polarization $P(x,t)$ in the form of two groups of diffraction orders (-1,+1). Lower panel: the real S-shaped spatial distribution of the pump field $E(t,x) = \varepsilon(t) \cdot \text{ramp}(x)$ (bold line) and normalized polarization $P(x,t)$ for the current value of the pulse area $\theta(x',t) = 4.5 \pi$ (thin line).

The pump laser duration was equal to 5.15 ns, the phase memory time is $T_2 = 52.48$ ns for the homogeneously broadened line, and $T_2 = 13.39$ ns for the line broadened by the collisions with the
buffer gas atoms of Ar at the pressure of 1 Torr. Therefore, the light-matter interaction can be considered as the coherent one.

The rubidium vapor density was \( N_0 = 2.9 \times 10^{11} \, \text{cm}^{-3} \). For the Rabi deflector operation, we created the transverse pump-field profile \( E(t,x) = \varepsilon(t) \cdot \text{ramp}(x) \) (S-shaped) of the size of 800 x 20 \( \mu \text{m} \) using the diffractive profile shaper (9) (cf. Figure 2).

![Figure 3](image_url)

**Figure 3.** Experimental setup. 1 – CW tunable laser diode TLD-799.8-14BF, 2 – single-mode fibers of 1 m length, 3 – optical splitter 1x4, 4 – pulsed nanosecond current generator, 5 – optical amplifier SOA-780-14BF, 6 – collimators, 7 – plate, 8 – cylindrical lenses, 9 – shaper of the pump field \( E(x) \), 10 – rotating disk, 11 – Fabry–Perot interferometer, 12 – objective, 13 – attenuating plate, 14 – cell with Rb vapor, 15 – neutral attenuating filters, 16 – CCD camera DCMC 510, 17 – Photodiode Module IPL10530DAL, 18 – Avalanche Photodiode Module APM-400, 19 – Single Photon Avalanche Diode MPD PD-050-CTD-FC, 20 – multichannel temporal analyzer of single-photon pulses BH SPC130, 21 – oscilloscope Tektronix TDS1012B, 22 – computer.

In the experiment, we analyzed the form of the diffraction pulse scattered from the resonant cell at different diffraction angles \( \phi \). For this, the collimator (6d) was moved at the circle with the radius of 550 mm. The pulse form was registered by the single-photon counting method using Single Photon Avalanche Diode (SPAD) MPD PD-050-CTD-FC (19) with the time resolution of 27 ps and the multichannel time analyzer of single-photon pulses BH SPC130 with the time resolution of 0.8 ps.
To synchronize the analyzer operation, we used the pulse of the Avalanche Photodiode Module (18) with the signal increase time of 200 ps. The radiation of Rabi-deflector was attenuated by neutral filters (15) so that the probability to record a single photon by the SPAD (19) would not exceed the range of 1/4-1/5 per a single laser pulse.

For certain observation angles, we first recorded an oscillogram (more precisely a temporal histogram of detected photons) $S_1(t)$, under the condition that the pump frequency is tuned to the resonance of $D_2 \ ^{87}\text{Rb}$. This is the signal oscillogram $S_1(t)$. Then, the laser diode (1) was detuned in frequency from the line $D_2 \ ^{87}\text{Rb}$ by 2 GHz, and the second oscillogram $S_2(t)$ was recorded, which served as a reference oscillogram. During the post-processing of recorded files, we calculated the normalized difference between the two oscillograms: $(S_1(t)-S_2(t))/\max S_2(t)$.

![Figure 4](image1)

**Figure 4.** The result of numerical solution of the Maxwell-Bloch equations. The dashed line is the pump pulse; the solid line is the beats between pump pulse and dynamical diffraction maxima. The angle of the pulse diffraction observation is $\phi = -0.05^\circ$.

![Figure 5](image2)

**Figure 5.** Temporal beats between the pump pulse and dynamical diffraction maxima in the experiment. The angle of the pulse diffraction observation is $\phi = -0.05^\circ$. 
Figure 6. The result of numerical solution of the Maxwell-Bloch equations. The dashed line is the pump pulse; the solid line is the beats between pump pulse and dynamical diffraction maxima. The angle of the pulse diffraction observation is $\phi = 1.82^\circ$.

Figure 7. Temporal beats between the pump pulse and dynamical diffraction maxima in the experiment. The angle of the pulse diffraction observation is $\phi = 1.82^\circ$.

During recording of the reference oscillogram $S_2(t)$, we measured the power of input pump pulse $E_{\text{in}}(t)$: $S_2(t) = |E_{\text{in}}(t)|^2$. During recording of the signal oscillogram $S_1(t)$, we measured the power of the superposition of two fields: the pump field $E_{\text{in}}(t)$ and the reemission field of resonant polarization $E_p(t)$: $S_1(t) = |E_{\text{in}}(t) + E_p(t)|^2$. Consequently, $S_1(t) - S_2(t) = 2E_{\text{in}}(t)E_p(t) + |E_p(t)|^2$. Usually, in the experiment, the pump field $E_{\text{in}}(t)$ significantly exceeded $E_p(t)$. Therefore, $2|E_{\text{in}}(t)E_p(t)| \gg |E_p(t)|^2$ and $S_1(t) - S_2(t) \approx 2E_{\text{in}}(t)E_p(t)$. Thus, we measured the temporal beats of the fields $E_{\text{in}}(t)$ and $E_p(t)$.

Note, that from the experimental point of view, the appearance of the term $2E_{\text{in}}(t)E_p(t)$ is very useful for recording very weak optical signals, because the radiation power of the atomic polarization $|E_p(t)|^2$ can be very small for small densities of resonant atoms. In addition, in an experiment, one records the signal proportional to the amplitude $E_p(t)$, rather than to the intensity $|E_p(t)|^2$, which enables getting information about the sign of $E_p(t)$.
We performed the calculation, which models the operation of a Rabi-deflector prototype. We solved numerically semiclassical Bloch equations in the model of a two-level medium for a transition with homogeneous line broadening and given spatial profile of the pump field $E_{\text{in}}(t,x)$ (cf. Figure 2). For calculating the temporal beats, we took into account both terms: $2E_{\text{in}}(t)\cdot E_{\text{p}}(t) + |E_{\text{p}}(t)|^2$.

We measured the signal forms of the temporal beats for 34 observation angles $\phi$. The temporal beat signal was observed in the angle range of $\phi = \pm 5.45^\circ$. The recording of the form of diffraction pulses was done using temporal beats between the pump pulse and moving diffraction maxima of the field of resonant medium radiation (cf. Figures 4-7).

The best agreement between simulated and experimental oscillograms of temporal beats was observed for the total pulse area $\theta=10\pi$ (5 full rotations of the Bloch vector) during the pump pulse $E_{\text{in}}(t)$. This value agrees well with the experimental value of the pump amplitude $E_{\text{in}}(t)$.

3. Conclusion
We have experimentally studied for the first time a new operation principle of the all-optical coherent streak-camera (Rabi deflector). In the experiment, we observed an effect of significant dynamical angular deflection of a pulse of semiconductor laser during the resonant pumping of the $D_2$ line (780.24 nm) of $^{87}$Rb vapour in the range of diffraction angles $\phi = \pm 5.45^\circ$.

In this report, we analyze a possibility to use the Rabi deflector as an energy efficient shaper of classical and single-photon wave packets. As our experiments show, in addition to a special case of deflection of a single diffraction maximum (cf. Figure 1, i.e., using the Rabi-deflector as all-optical streak camera), there exist broad opportunities for controlling the probability of photon creation in time, as well as by the angle. Such a simple device based on the resonant light-atom interaction can operate as an energy efficient pulse shaper. There exist three degrees of freedom for controlling the profile of the single-photon wave packets in a broad range: (i) spatial profile $E(x)$, (ii) temporal shape of pump pulses $E(t)$ and its amplitude, and (iii) the pulse diffraction angle.

The Rabi deflector can be used as a prototype of perspective quantum systems with a feedback loop [5-7], which can be applied to many-body systems [8].

Acknowledgements
This work was supported by Russian Science Foundation (project № 17-19-01097-P).

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