Coherent tunable diffractional pulse shaping and generation of the 0π-pulse in Rb vapor

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Abstract. We have experimentally studied for the first time a new operation principle of the coherent diffractional pulse shaper (Rabi shaper). In the experiment, we observed an effect of tunable pulse shaping of nanosecond semiconductor laser pulse during the resonant pumping of the D2 line (780.24 nm) of 87Rb vapor in the range of self-diffraction angles \(\phi = \pm 4^\circ\). We observed the synthesis of nanosecond 0π-pulses at the small length of the nonlinear interaction 0.1...1 mm. We propose to use the Rabi shaper as an energy efficient tunable shaper of classical and single-photon wave packets. We analyze a possibility of the Rabi shaper 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]. In [2,3], we proposed a new principle of the angular deflection of radiation wave vector during the laser pulse diffraction from the atomic resonant diffraction grating with the spatial pitch, which is time dependent – the Rabi deflector or Rabi pulse shaper.

As known, laser pulses with the shaped amplitude, frequency, phase, and wave vector \(K\) excite atoms and molecules more efficiently [4], which can be applied for the problems of all-optical signal processing and quantum technology. A review of modern linear methods of pulse shaping is given in [5].

In this report, we present the study of nonlinear transformation of the shape and pulse area during the increase of the pulse self-diffraction angle \(\phi\) in the resonant medium: positive pulse \(\rightarrow\) 0π-pulse \(\rightarrow\) negative pulse.

The 2π-pulses and 0π-pulses are classical objects of resonant optics of atoms. According to the theory of self-induced transparency, their area is preserved during the propagation in a resonant medium. After the pulse has passed, the atomic system returns to its original state. This property is very important for problems of optical signal processing, because the limiting pulse rate of processed signals is limited by their duration only.

Nevertheless, the 0π-pulses have several important properties, which the 2π-pulses do not have. In the case, where the wavefront of a 2π-pulse is different from the plane wave, it loses its stability during its propagation at long distances. The 0π-pulse can have an arbitrary wavefront and preserve its stability. In addition, 0π-pulses are stable with respect to the degeneration of a resonant transition and to the inhomogeneous broadening.
The theory of transformation of a pulse of a small area to the 0π-pulse was given in [6] and was confirmed by multiple experiments with classical fields, cf. e.g. [7]. Later, the formation of resonant 0π-pulses was observed for single-photon wave packets [8,9]. The transformation of a small area pulse to the 0π-pulse during its propagation in a resonant medium is a quasilinear phase effect and it requires the long interaction length and high density of resonant atoms $N_o$.

In this report we show a new nonlinear method of pulse shaping using the effects of nonlinear self-diffraction in resonant media [2,3].

In the experiment, the generation of a 0π-pulse took place at a small distance of a nonlinear interaction with the medium of 0.1...1 mm.

2. Experimental

The description of experimental setup and the signal processing method are presented in [3]. A cell with $^{87}$Rb vapor was pumped by a pulsed tunable laser diode with the duration of 5.15 ns at the wavelength of transition D$_2$ (780.24 nm). The density of $^{87}$Rb atoms was $N_o = 2.78 \times 10^{12}$ cm$^{-3}$. The cell was filled by buffer gas Ar at the pressure of 1 Torr. Laser pulse power did not exceed 10 mW. The transverse spatial distribution of the pump filed $E_{in}(t,x) = E_{in}(t) \cdot G(x)$ had a Gaussian shape: $G(x) = \exp\left[-(x/\sigma)^2\right]$, $\sigma = 0.017$ mm. The full pulse area was $\theta_{in} = 3\pi$.

In the experiment, we analyzed the form and pulse area of the diffraction pulse scattered from the resonant cell at different diffraction angles $\phi$. The pulse form was registered by the single-photon counting method using Single Photon Avalanche Diode with the time resolution of 27 ps. After treating the temporal histogram of detected photons, one can obtain the radiation pulse $E_{p}(t)$ of the resonant polarization of a medium in the form of a signal $S_1(t) - S_2(t) \approx 2 \cdot E_{in}(t) \cdot E_{p}(t)$ [3].

Note that the method of processing the experimental signals we used enables us separating the field of the reemission of the polarization of the medium taking into account its sign.

We performed the calculation, which models the operation of a Rabi shaper prototype. We solved numerically semiclassical Bloch equations in the model of a two-level medium for a transition with the homogeneous line broadening and given spatial profile of the pump field $E_{in}(t,x) = E_{in}(t) \cdot G(x)$.

In Figures 1-6, we show the results of numerical simulations for a realistic pulse shape and the results of the observation of nonlinear transformation of the pulse shape for different angles of self-diffraction in a resonant medium.

The generation of a positive pulse.

![Figure 1](image.png)

Figure 1. (a) a realistic pump pulse $E_{in}(t)$; $E_{in}(t) \sim (N_{ph/channel})^{1/2}$. (b) calculated normalized quantity $2 \cdot E_{in}(t) \cdot E_{p}(t)$ at the diffraction angle of $\phi = 0.78^\circ$. 
The generation of a $0\pi$-pulse.

Figure 3. (a) a realistic pump pulse $E_{in}(t); E_{in}(t) \sim (N_{ph/channel})^{1/2}$. (b) calculated normalized quantity $2 \cdot E_{in}(t) \cdot E_p(t)$ at the diffraction angle of $\phi = 1.82^\circ$.

Figure 4. The measured value of $2 \cdot E_{in}(t) \cdot E_p(t)$ at the diffraction angle of $\phi = 1.82^\circ$. 
The generation of a negative pulse.

Figure 5. (a) a realistic pump pulse $E_{\text{in}}(t)$; $E_{\text{in}}(t) \sim (N_{\text{ph/channel}})^{1/2}$.
(b) calculated normalized quantity $2E_{\text{in}}(t)E_p(t)$ at the diffraction angle of $\phi = 2.86^\circ$.

Figure 6. The measured value of $2E_{\text{in}}(t)E_p(t)$ at the diffraction angle of $\phi = 2.86^\circ$.

3. Conclusion

In this report, we analyze a possibility to use the tunable Rabi shaper of classical and single-photon wave packets. Note that the studied Rabi shaper can perform shaping of nanosecond pulses at the small distances of nonlinear interactions of 0.1 ... 1 mm.

We showed that the nonlinear coherent tunable Rabi shaper has the following degrees of freedom for shaping the classical and single-photon wave packets in a broad range:
- the amplitude of a pump pulse, its spatial shape $E_{\text{in}}(x)$;
- the temporal (amplitude and phase) profile of the pump pulse $E_{\text{in}}(t)$;
- the diffraction angle $\phi$.

The coherent tunable Rabi shaper can be used as a prototype of perspective quantum systems with a feedback loop [10,11]. Being based on the coherent and collective [12,13] light scattering, it can serve as a prototype for testing theories in atomic [14,15] and molecular [16] media, which are yet difficult to realize.

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References

[1] Sarantos C H and Heebner J E 2010 Opt. Lett. 35 (9) 1389
[2] Arkhipov R M, Arkhipov M V, Egorov V S, Chekhonin I A, Chekhonin M A and Bagayev S N 2015 J. Phys.: Conf. Ser. 643 012029
[3] Bagayev S N, Averchenko V A, Chekhonin I A, Chekhonin M A, Balmaev I M and Mekhov I B 2020 J. Phys.: Conf. Ser. 1695 012129
[4] Dudovich N, Oron D and Silberberg Y 2002 Phys. Rev. Lett. 88 (12) 123004-1
[5] Monmayrant A, Weber S and Chatel B 2010 J. Phys. B: At. Mol. Opt. Phys. 43 103001
[6] Crisp M D 1970 Phys. Rev. A 1, 1604
[7] Rothenberg J E, Grischkowsky D and Balant A C 1984 Phys. Rev. Lett. 53 (6) 552
[8] Costanzo L S et al. 2016 Phys. Rev. Lett. 116 023602
[9] Specht H P, Bochmann J, Mücke M, Weber B, Figueroa E, Moehring D L and Rempe G 2009 Nature Photon 3 469
[10] Ivanov D A, Ivanova T Yu, Caballero–Benitez S F and Mekhov I B 2020 Phys. Rev. Lett. 124 010603
[11] Mazzucchi G, Caballero–Benitez S F, Ivanov D A and Mekhov I B 2016 Optica 3 1213
[12] Mekhov I B and Ritsch H 2011 Laser Phys. 21 1486
[13] Kozlowski W, Caballero–Benitez S F and Mekhov I B 2015 Phys. Rev. A 92 013613
[14] Kozlowski W, Caballero–Benitez S F and Mekhov I B 2016 Phys. Rev. A 94 012123
[15] Caballero–Benitez S F and Mekhov I B 2015 New J. Phys. 17 123023
[16] Mekhov I B 2013 Laser Phys. 23 015501