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Creation of dynamic microcavities by collision of extremely short pulses in a dense three-level medium

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Dynamic microcavities may arise when extremely short light pulses collide in a resonant medium. Such structures are of interest for the creation of ultrafast optical switches and optical memory cells. In early studies, it was shown that the particle concentration strongly affects the shape of dynamic microresonators; with increasing particle density, the shape of such structures is distorted. In this paper, based on the numerical solution of the Maxwell-Bloch equations, the possibility of creating non-blurred dynamic microresonators in a dense three-level medium is shown.

Keywords: extremely short pulses, attosecond pulses, dynamic microresonators, optical switching, optical memory.

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Introduction

Obtaining electromagnetic pulses of attosecond duration is an important task of modern physics, as they make it possible to study and control the dynamics of electrons in matter [1–3]. The 2023 Nobel Prize in Physics [4] proves the relevance of this area of modern physics. The pulses received to date contain several half-waves of field strength. Extremely short light pulses are needed to study faster processes occurring at times shorter than the period of electron rotation in the Bohr orbit.

Extremely short duration in a given spectral range are unidirectional semi-cyclic pulses consisting of a single half-wave of electric field strength and having a nonzero electric area, defined as the integral of the electric field strength over time $\mathbf{E}(\mathbf{r}, t)$ at a given point in space [5]:

$$\mathbf{S}_E = \int \mathbf{E}(\mathbf{r}, t)dt. \quad (1)$$

Unipolar pulses, unlike conventional multicycle pulses, can excite quantum systems (atoms, molecules, nanoscale structures, etc.) superfast and, therefore, have many interesting applications in modern ultrafast optics. The latest results in the field of obtaining and applying semi-cyclic pulses are summarized in the reviews in Ref. [5,6] and the chapter of the monograph in Ref. [7].

The study of the interaction of extremely short pulses with matter has led to the prediction of a number of new and unusual phenomena that cannot be observed using conventional multi-cycle pulses [5–7]. One of these phenomena is the possibility of creating dynamic microresonators (DM) in the collision of semi-cyclic attosecond pulses in a resonant medium that we predicted and actively studied (see, for example, [8,9] and the review in Ref. [10]). Such structures are formed in case of the coherent interaction of pulses with the medium, when the duration of the exciting pulse field and the intervals between them are less than the time of the phase memory of the medium T_2 [9].

When the pulses collide in the area of their overlap, the difference in the population of atomic levels has an almost constant value. And outside of this area, either a Bragg lattice of population differences appears, or the population jumps to another value. Such structures are DM, the parameters of which can be easily changed by the subsequent collision of pulses in the medium when selecting the intervals between them [9, 10]. Such resonators can lead to self-stop in the environment of even the pulse that created them [11]. The theory of such structures, including their analytical description, has been sufficiently developed to date [8,9]. The results of theoretical studies show the possibility of formation of such structures at each resonant transition of a multilevel medium, which provides ample opportunities for controlling the shape of such DM. They are of interest for the creation of optical memory systems based on atomic coherence and the creation of ultrafast optical switches [10, 12].

The Q factor is an important characteristic of such DM. A high particle density is required, of the order of $N_0 \sim 10^{20}\,\text{cm}^{-3}$ for achieving a high Q factor of the order of 1000 and above [9]. The results of early studies in

Ref. [9,13] showed that the structures of DM are blurred with the increase of particle concentration which leads to a loss of their quality. The possibility of creating and ultrafast control of indistinct DM in the collision of semi-cyclic attosecond pulses in a dense three-level environment is shown in this paper, based on numerical calculations with selected parameters. The parameters of the medium are chosen to be the same as in atomic hydrogen gas, which makes any atomic gas with pronounced discrete energy levels an attractive medium for creating and ultrafast DM control using semi-cyclic attosecond pulses.

Numerical model and calculation results

As in the early studies in Ref. [10], a system of equations for the density matrix of a three-level medium was used in numerical calculations to study the dynamics of DM, which was numerically solved together with a wave equation describing the evolution of the electric field strength in the medium:

$$\frac{\partial}{\partial t}\rho_{21} = -\rho_{21}/T_{21} - i\omega_{12}\rho_{21} - i\frac{d_{12}}{\hbar}E(\rho_{22}-\rho_{11}) - i\frac{d_{13}}{\hbar}E\rho_{23} + i\frac{d_{23}}{\hbar}E\rho_{31}, \quad (2)$$

$$\frac{\partial}{\partial t}\rho_{32} = -\rho_{32}/T_{32} - i\omega_{32}\rho_{32} - i\frac{d_{23}}{\hbar}E(\rho_{33}-\rho_{22}) - i\frac{d_{12}}{\hbar}E\rho_{31} + i\frac{d_{13}}{\hbar}E\rho_{21}, \quad (3)$$

$$\frac{\partial}{\partial t}\rho_{31} = -\rho_{31}/T_{31} - i\omega_{31}\rho_{31} - i\frac{d_{13}}{\hbar}E(\rho_{33}-\rho_{11}) - i\frac{d_{12}}{\hbar}E(\rho_{32} + i\frac{d_{23}}{\hbar}E\rho_{21}, \quad (4)$$

$$\frac{\partial}{\partial t}\rho_{11} = \frac{\rho_{22}}{T_{22}} + \frac{\rho_{33}}{T_{33}} + i\frac{d_{12}}{\hbar}E(\rho_{21}-\rho_{21}^{*}) - i\frac{d_{13}}{\hbar}E(\rho_{13}-\rho_{13}^{*}), \quad (5)$$

$$\frac{\partial}{\partial t}\rho_{22} = -\rho_{22}/T_{22} - i\frac{d_{12}}{\hbar}E(\rho_{21}-\rho_{21}^{*}) - i\frac{d_{23}}{\hbar}E(\rho_{23}-\rho_{23}^{*}), \quad (6)$$

$$\frac{\partial}{\partial t}\rho_{33} = -\frac{\rho_{33}}{T_{33}} + i\frac{d_{13}}{\hbar}E(\rho_{13}-\rho_{13}^{*}) + i\frac{d_{23}}{\hbar}E(\rho_{23}-\rho_{23}^{*}), \quad (7)$$

$$P(z,t) = 2N_0 d_{12}\mathrm{Re}\rho_{12}(z,t) + 2N_0 d_{13}\mathrm{Re}\rho_{13}(z,t) + 2N_0 d_{23}\mathrm{Re}\rho_{23}(z,t), \quad (8)$$

$$\frac{\partial^2 E(z,t)}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E(z,t)}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P(z,t)}{\partial t^2}. \quad (9)$$

This system of equations contains the following parameters: d_{12}, d_{13}, d_{23} are the transition dipole moments, $\hbar$ is the reduced Planck constant, N_0 is the particle concentration, P is the polarization of the medium, $\omega_{12}, \omega_{32}, \omega_{31}$ are the resonant transition frequencies, variables ρ_{11}, ρ_{22}, ρ_{33} are the occupancies of the 1st, 2nd and 3rd states of the medium, respectively, ρ_{21}, ρ_{32}, ρ_{31} are the off-diagonal elements of the density matrix determining the dynamics of the polarization of the medium, T_{ik} are the relaxation times. The relaxation times are tens and hundreds of nanoseconds in gaseous media and cooled quantum dots, which is much longer than the duration of the processes discussed below, and therefore they are insignificant.

Parameters used in numerical calculations

Frequency (wavelength λ_0) transition $1 \to 2$	$\omega_{12} = 1.55 \cdot 10^{16}$ rad/s ($\lambda_{12} = \lambda_0 = 121.6$ nm)
Dipole moment of the transition $1 \to 2$	$d_{12} = 3.27$ D
Frequency (wavelength) transition $1 \to 3$	$\omega_{13} = 1.84 \cdot 10^{16}$ rad/s ($\lambda_{13} = 102.6$ nm)
Dipole moment of the transition $1 \to 3$	$d_{13} = 1.31$ D
Frequency (wavelength) transition $2 \to 3$	$\omega_{23} = 2.87 \cdot 10^{15}$ rad/s ($\lambda_{23} = 656.6$ nm)
Dipole moment of the transition $2 \to 3$	$d_{23} = 12.6$ D
Atomic concentration	$N_0 = 10^{20}$ cm^{-3}
Field amplitude	$E_0 = 10^6$ ESU
Pulse duration τ	$\tau = 80$ as

As initial conditions, at the initial moment of time, a pair of semi-cyclic pulses with a Gaussian shape were sent from the edges of the integration region having a length of $L = 12\lambda_0$ to the medium from the left and right:

$$E(z=0,t) = E_0 e^{-t^2/\tau^2}, \quad (10)$$

$$E(z=L,t) = E_0 e^{-t^2/\tau^2}. \quad (11)$$

The studied three-level medium located between points $z_1 = 2\lambda_0$ and $z_2 = 10\lambda_0$. The pulses collided in the center of the medium, at point $z_c = 6\lambda_0$, exited the medium, reflected off the boundaries of the integration region, and moved back into the medium, and so on for the entire duration of the count. A three-level medium modeled after the first three levels of the hydrogen atom was considered. The parameters used in the numerical calculation are given in the table and taken from Ref. [14]. The concentration value $N_0 = 10^{20}$ cm^{-3} was used in numerical calculations. High densities of atomic hydrogen can be obtained, for example, in a matrix at low temperatures [15].

The results of numerical calculation of the population differences are shown in Fig. 1.

Discussion of the results and conclusion

The first pulse collision occurs at time $t = 2.56$ fs, the second pulse collision occurs at time $t = 7.40$ fs, etc. The instantaneous values of the distribution of the population difference after the first ($t \sim 5$ fs) and the third ($t \sim 14.2$ fs) pulse passage are shown in Fig. 2, *a* and *b*, respectively.

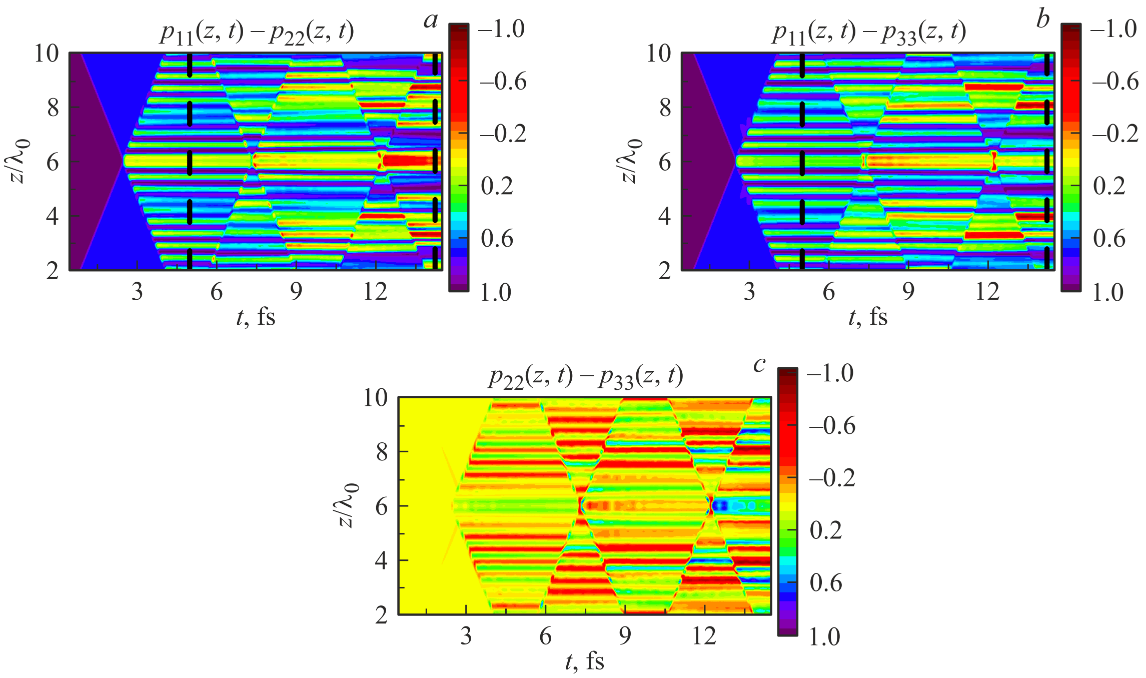

Figure 1. Spatial and temporal dynamics of population differences in a three-level medium: $\rho_{11} - \rho_{22}$ (a), $\rho_{11} - \rho_{33}$ (b) and $\rho_{22} - \rho_{33}$ (c).

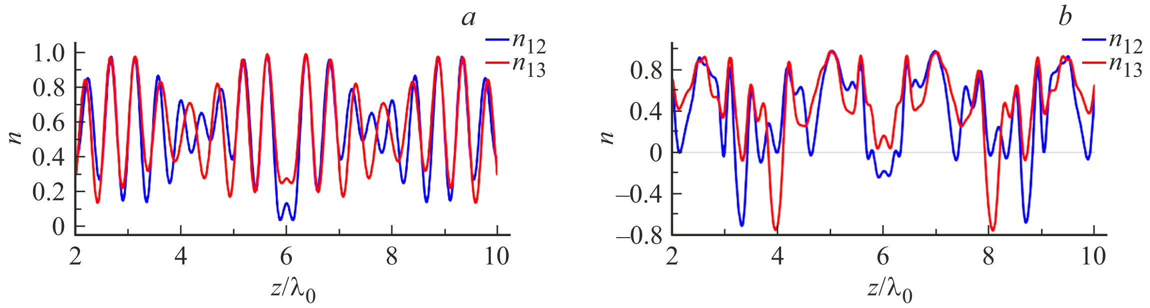

Figure 2. Instantaneous distribution of population differences after the first (a) and the third (b) passage of pulses; sections are marked with a black line in Fig. 1, a and b. Blue: $\rho_{11} - \rho_{22}$, red: $\rho_{11} - \rho_{33}$. The calculation parameters are listed in the table.

Fig. 1 and 2 show that the population difference at each transition has an almost constant value in the region of pulse overlap, and a Bragg-like population grid appears outside it. In this sense, such DM is formed in the medium, the parameters of which change with each subsequent collision of impulses in the medium. The shape of Bragg-like lattices, as seen in Fig. 2, a, has the form of beats, rather than an ideal harmonic sinusoid, as in the case of a two-level medium. This behavior is similar to the one previously discussed behavior when the pulses did not overlap in the medium [16]. Physically, it is explained by the fact that, in addition to the main transition of the medium 1−2, off-diagonal elements of the density matrix, oscillating at other transition frequencies according to expression (8), contribute to the overall polarization (coherence of the medium).

As can be seen in Fig. 1, the microresonator is still present in the pulse overlap region after repeated passage of pulses, however, as can be seen in Fig. 2, b, the shape of the lattices on the sides becomes more „chaotic“.

It is also interesting to note that the value of the pulse field amplitude used in the calculations $E_0 = 10^6$ ESU is not a strong excitation. To characterize the effect of semi-cyclic pulses on quantum objects (when the pulse duration is shorter than the period of electron rotation along the first Bohr orbit), it is necessary to compare the electric area of this pulse (S_E) with its atomic measure (S_a), introduced in Ref. [17] and defined as $S_a = 2\hbar/ea_B$ ($a_B = 0.053$ nm is the -Bohr radius). The ratio is $S_E/S_a \sim 0.16$ for the task parameters used ($S_a = 2.48 \cdot 10^{-7}$ V·s/cm). This means that only low levels in the atom will be populated with the selected parameters, which also indicates the high quality of the induced DM.

The calculations used pulses with a duration of 80 as. An experimental paper has appeared when this article was written [18], which shows the possibility of obtaining pulses with a duration of about 50 as, having a shape close to unidirectional — in the form of a characteristic half-wave of the field.

Thus, the paper shows the possibility of DM guidance in a dense gaseous medium when semi-cyclic attosecond pulses collide in it. At the same time, the shape of the structures is not blurred. The use of dense media makes it possible to achieve high quality of such DM, which is important for their practical use in various tasks of ultrafast optics, the creation of ultrafast optical switches and the creation of optical memory based on atomic coherence in the simplest atomic media using semi-cyclic attosecond pulses, which are already practically available today [18].

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Conflict of interest

The authors declare that they have no conflict of interest.

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