MICROCAVITIES AND PHOTONIC TIME CRYSTALS FORMED BY COLLISION OF HALF-CYCLE LIGHT PULSES IN A RESONANT MEDIUM

© 2025 R. M. Arkhipov[a,b,*], M. V. Arkhipov[a,b], A. V. Pakhomov[a,b], O. O. Diachkova[a,b], N. N. Rosanov[a,b]

[a]*St. Petersburg State University, Saint-Petersburg, Russia*

[b]*Ioffe Institute, Saint-Petersburg, Russia*

**e-mail: arkhipovrostislav@gmail.com*

Received September 06, 2024

Revised September 16, 2024

Accepted September 30, 2024

Abstract. We discussed the authors' recent research into the generation and ultrafast control of light-induced dynamic microcavities and photonic time crystals created by the collision of half-cycle pulses in a medium. The possibility of guiding microcavities during the collision of self-induced transparency half-cycle pulses of the same polarity has been demonstrated.

Keywords: *unipolar pulses, half-cycle pulses, dynamic microcavities, photonic time crystals, population density gratings, coherent effects*

DOI: 10.31857/S03676765250112e5

INTRODUCTION

Unipolar, half-cycle, limit short pulses (LSPs) are the limit of shortening the duration of electromagnetic pulses in a given spectral range [1]. They contain a half-wave field of one polarity and can have a non-zero electric area defined as the integral of the electric field strength$\vec{E}(t)$ over time$t$ at a given point of space [2-4]:

$$\vec{S}_E = \int \vec{E}(t)dt. \qquad (1)$$

The interest in obtaining such pulses has increased recently in connection with their possible numerous applications for ultrafast control of properties of quantum systems, holography with ultrahigh temporal resolution and other applications, see reviews [1,5-8] and monograph [9]. Thus, semi-cyclic quasiunipolar pulses of attosecond duration (of the order of hundreds of attoseconds) in the optical range can be obtained by coherent addition of monochromatic components of broadband pumping [10], as well as by fast braking of a beam of relativistic electrons in thin targets [11,12]. In the terahertz range, unipolar pulses can be produced by various nonlinear processes in plasma [13-16], superradiation of stopped polarization [17], and other methods, see reviews [1, 5-9].

For single-cycle and half-cycle PKI pulses of such a short duration, the features of coherent propagation and interaction with resonant media look differently, in contrast to the case of long multicycle pulses [10,18-22]. The study of the interaction of PKI with matter has led to the prediction of a number of new phenomena in optics, such as self-compression of the pulse [23], splitting of half-waves of opposite polarity [24], self-stopping of light [25], etc. The use of a sequence of PKIs coherently propagating in a resonant medium when the pulse duration is shorter than the polarization relaxation time of the medium T_2 , leads to the creation and ultrafast control of population difference gratings and polarization waves of the medium at times of the order of the pulse duration [26-42].

It is also possible to create so-called dynamical microresonators when a pair of extremely short pulses collide in the medium [43-45]. In this case, the population difference in the overlap region of the pulses has an almost constant value, and a lattice of the population difference appears at its edges. It is also possible that the population difference has another constant value different from the value in the pulse overlap region. Thus, a microresonator with a size on the order of the wavelength of the resonance transition arises. The interest in such structures is related to the active study recently of the so-called temporal and spatiotemporal photonic crystals, i.e., media whose refractive index changes rapidly in time or in space and time, respectively [46-49].

This paper gives an overview of the authors' recent research in the field of creation and control of population gratings and dynamic microresonators by means of a sequence of extremely short pulses coherently interacting with the medium and colliding in the medium. We present an analysis of the dynamics of microresonators when colliding 2π such self-induced transparency (SIT) pulses. In this case, in contrast to earlier studies in which it was shown that dynamical resonators do not arise when pulses of the same polarity collide, it is shown in this work that this limitation is removed when a trailing edge of opposite polarity is added to the pulse.

CREATION OF POPULATION LATTICES AT COHERENT INTERACTION OF EXTREMELY SHORT PULSES WITH THE MEDIUM

The possibility of creating atomic population lattices in the coherent interaction of light pulses with the medium was discovered quite a long time ago in the first photon echo experiments [26-27]. However, these studies used long multicycle pulses of light of nanosecond duration, which did not overlap in the medium at one time [28,29]. Obviously, the use of long multi-cycle pulses does not allow for ultrafast control of the population difference gratings. The gratings created in this way were used in echo holography [30,31] and for measuring the relaxation time of the medium polarizationT_2 [32].

Another alternative, more common method of grating creation is based on the interference of long monochromatic laser fields overlapping in the medium [50]. In this method it is obviously also impossible to realize ultrafast control of gratings, for example, their erasure or spatial frequency multiplication.

Creation and ultrafast control of lattices can be realized by extremely short pulses - one-cycle and half-cycle pulses coherently interacting with the medium. This possibility was first shown theoretically in the works of the authors [33-40], when the pulses do not overlap in the medium [33-36] and overlap in the medium [37,39-40], see also reviews [41-42]. The creation of such lattices occurs due to the interference of the polarization waves of the medium induced by the previous pulse with the subsequent pulse.

An alternative explanation for the creation of such lattices, which is valid at small amplitudes of excitation pulses and in a sparse medium when the medium is weakly excited, is based on the interference of the pulse areas or the interference of the amplitudes of the bound states of the medium [51]. A review of recent results of these studies is given in [41,42], and we will not dwell on it.

DYNAMIC MICRORESONATORS AND TEMPORARY PHOTONIC CRYSTALS AT COLLISION OF EXTREMELY SHORT PULSES IN THE MEDIUM

In [43], the possibility of forming so-called dynamic microresonators arising from the collision of$\pi/2$ similar unipolar pulses of rectangular shape in a two-level resonant medium was shown for the first time. In this case, as numerical calculations have shown, in the region of pulse overlap the population difference has a constant value - the "light-induced channel", and outside this region it changes by a jump and has another value. In this sense we can talk about the formation of a dynamic microresonator in the medium. The size of such a structure is of the order of the spatial size of the pulse (wavelength of the resonance transition).

In the subsequent work [44], the dynamics of such a microresonator was considered in the collision of already2π similar CIP pulses of rectangular shape and duration of the order of 1 fs. Numerical calculations showed the possibility of formation and control of dynamic microresonators at increasing number of pulse collisions in the medium. Detailed studies in [45] showed that the shape and parameters of the resonator depend significantly on the shape of the colliding pulses and on the steepness of the fronts - the steeper the fronts, the greater the modulation depth of the microresonator. These studies were carried out when the medium was modeled in the two-level approximation. Numerical calculations carried out in [52] showed the possibility of guiding microresonators at collision of unipolar pulses of rectangular and triangular shape in a three-level medium.

In the mentioned studies, the colliding pulses were unipolar. The possibility of creating microresonators with Bragg mirrors was shown in [53]. In this work, a pair of single-cycle attosecond pulses consisting of two half-waves of opposite polarity collided in the center of the medium. The parameters of the pulses were chosen so that the pulses acted similarly to4π CIP pulses. Numerical calculations showed that in the center of the medium, where the pulses collide, the medium remains practically unexcited. At the edges of this region, quasiperiodic lattices of populations with a length of only a few periods and localized in the vicinity of the pulse overlap region are formed.

The spatial frequency of these structures increased with increasing number of collisions of pulses. Thus, a local microresonator with Bragg-like mirrors appeared in the medium. Estimates showed that the reflection coefficient of such structures at the wavelength corresponding to the maximum of Bragg reflection was about 30%.

A detailed analysis of the dynamics of such microresonators arising from the collision of half-cycle attosecond pulses was carried out on the basis of the numerical solution of the system of Maxwell-Bloch equations in two- and three-level medium in [54]. In [55], the possibility of creating temporary photonic crystals in the collision of a pair of semi-cyclic attosecond pulses in a three-level medium was shown. Practical realization of such media with rapidly changing refractive index is difficult to realize in practice due to conventional nonlinear optical mechanisms because they are very slow [56]. A number of exotic materials with unusual properties have been developed for this purpose [56,57]. However, our studies show that it is possible to realize spatiotemporal photonic crystals in two- and multilevel resonant media by means of a sequence of extremely short pulses, since this creates lattices of populations, i.e., changes the refractive index of the medium in space and time.

The mentioned studies of the dynamics of such structures were carried out by numerical solution of the system of equations for the density matrix together with the wave equation for the electric field strength. Any analytical description was absent. In [58], a simple analytical approach was proposed to show the feasibility of such microresonators. It is based on an approximate solution of the time-dependent Schrödinger equation in the approximation of sudden perturbations, when the pulse duration was considered small compared to the period of the resonance transition of the medium. The amplitude of the excitation pulse field was also considered small. In this approach, the medium was considered to be sparse and weakly excited, and the dynamics of polarization waves was not taken into account.

A more detailed approach outside the framework of the sudden perturbation approximation was described in [59]. In the case of a two-level medium, it allows one to take into account dynamics of the medium polarization. This approach was also generalized to the case of a multilevel medium by approximate solution of the time-dependent Schrödinger equation with the help of ordinary perturbation theory outside the framework of the sudden perturbation approximation. The results of this analysis show the possibility of creating microresonators with Bragg-like mirrors (the population difference varies in space according to the harmonic law to the left and right of the pulse overlap region) at each resonance transition of the medium allowed in the dipole approximation. In the case of unipolar pulses of unusual shape (rectangular) in [52] the possibility of guiding microresonators was also shown.

A detailed analytical approach showing the creation of such microresonators, based on an approximate solution of the Schrödinger equation using perturbation theory, is presented in [60]. The results of calculations of the populations (microresonator goodness of fit) performed using this approach agree with the results of the numerical solution of the system of equations for the density matrix of the medium when the amplitude of the excitation pulses is small.

Let us briefly discuss the main idea of this approach. It is based on an approximate solution of the Schrödinger equation in the weak field approximation, when perturbation theory is applicable. The medium is considered sparse, and the influence of neighboring atoms on each other and the change in the shape of incident pulses during propagation in the medium can be neglected. Also in the above approximations, as it has been shown earlier [36,41], the problem about interaction of sequence of extremely short pulses with extended medium can be reduced to the problem about interaction of these pulses with a single quantum system at change of delay between pulses. In the first order of perturbation theory the expression for the population of bound states with number *k* after passage of the pulse has the form [61]

$$w_k = \frac{d_{1k}^2}{\hbar^2} \left| \int E(t) e^{i\omega_{1k} t} dt \right|^2.$$

In this expression, d_{1k} is the dipole moment of the transition, ω_{1k} is the frequency of the resonant transition of the medium. For simplicity, we consider that the medium is affected by a pair of half-cycle pulses (the trailing edge of the opposite polarity is neglected), following with a delay :$\Delta E(t) = E_{01}\exp[-t^2/\tau_1^2] + E_{02}\exp[-(t-\Delta)^2/\tau_2^2]$. Then the expression for the population in the above approximations can be written in the form (provided: $\omega_{1k}\tau_{1,2} \ll 1$) [36,41,58-60]:

$$w_k = \frac{d_{1k}^2 S_{E,1}^2}{\hbar^2} + \frac{d_{1k}^2 S_{E,2}^2}{\hbar^2} + 2\frac{d_{1k}^2}{\hbar^2} S_{E,1} S_{E,2} \cos\omega_{1k}\Delta, \qquad (2)$$

in which $S_{E,1,2} = E_{01,2}\tau_{1,2}\sqrt{\pi}$ are the electrical areas of the pulses.

In the case of an extended medium, the delay $\Delta \sim z/c$ (c - speed of light) is proportional to the moment of time when the second pulse arrives at the point of the medium having the coordinate z [36,41]. If the pulses collide at some point of the medium, then to calculate the populations at this point (and near it) we must put the delay $\Delta = 0$ in expression (2), which leads to the relation $w_k = \frac{d_{1k}^2}{\hbar^2}\left(S_{E,1} + S_{E,2}\right)^2$. It shows that in this region the populations are determined by the square of the total electric area of the pulses.

Outside the pulse overlap region, the general relation (2) should be used to calculate the populations. It shows that the expression for the population w_k is the sum of squares of the electrical areas of the pulses and contains an "interference term", i.e., it periodically depends on the delay between the pulses . $2\frac{d_{1k}^2}{\hbar^2} S_{E,1} S_{E,2} \cos\omega_{1k}\Delta$ i.e., periodically depends on the delay between pulses Δ . In this sense, as shown in [36], we can say that the effect of a pair of unipolar pulses in the weak field approximation is determined by the interference of the electric areas of the pulses.

Also, this expression shows the appearance of a periodic lattice of harmonic-shaped populations outside the pulse overlap region. Despite its simplicity, the results of this approach have heuristic power, since they predict the possibility of forming a microresonator with Bragg-like mirrors in the form of lattices of population harmonic form (2) at each resonance transition of a multilevel medium. The modulation depth of these lattices is determined by the square of the electrical area of the pulses. Physically, the appearance of these lattices is related to the interference of the electric areas of pulses in the weak field approximation.

In strong fields and dense media, when the above approximations become inapplicable, it is necessary to consider more complex models based on the material equations for a multilevel medium together with the wave equation for the electric field strength. In this case, the two-level approximation is usually used to describe the medium, which may not be suitable in the case of extremely short pulses. This issue was discussed in [62-64]. Numerical calculations carried out in these works showed that the effect of the appearance of lattices whose shape is close to harmonic, as predicted by the results obtained in the framework of perturbation theory, persists in a three-level medium. In numerical calculations, the parameters of the three-level medium corresponded to Rb87 atoms [63], as well as to atomic hydrogen [54,64], which shows that the effect can be observed in real systems. Also, the results of the numerical solution of the time-dependent Schrödinger equation for a one-dimensional quantum well taking into account ionization showed lattice conservation [65].

From the practical point of view, the appearance of lattices of good quality (e.g., in the form close to harmonic) is possible when the ground state of the medium is not strongly emptied, i.e., the medium is not strongly excited and ionization is not significant. In this case the medium should not be strongly excited under the action of pulses. Such a criterion is easily established in the case when the duration of the half-cycle pulse τ is shorter than the characteristic time T_g associated with the ground state energy $E_1, \tau < T_g = 2\pi\hbar/E_1$. The medium will not be strongly excited and ionization is negligible if the electrical area of the incident pulse S_E is smaller than the characteristic atomic area measure $S_E < S_{at} = \hbar/er$, where e is the electron charge, r is the characteristic size of the quantum system [22]. In numerical calculations carried out in [64] for parameters corresponding to the hydrogen atom, this condition was fulfilled.

Physically, the preservation of the effect of lattices and microresonators in a multilevel medium is easy to understand if we recall the physical mechanism of their formation [34-36,41]. An extremely short pulse passing through the medium leaves the medium in a superposition quantum state in which the medium coherence (medium polarization), i.e. non-diagonal elements of the density matrix oscillate at each resonance transition of the medium. This leads to the appearance of polarization waves of the medium, which exist during the relaxation time T_2 . These polarization oscillations always exist no matter how many levels of the medium two or more are considered. A subsequent pulse will coherently drive these dipole moment oscillations, resulting in a population difference lattice at each resonance transition of the medium, as noted above. Therefore, the two-level medium approximation seems justified in such problems. Therefore, below we will use the two-level approximation for simplicity.

In the case of a large field amplitude, the dynamics of microresonators was studied by numerically solving the system of Maxwell-Bloch equations for a two-level medium [60]. Fully unipolar pulses of Gaussian form with a duration of hundreds of attoseconds were used in the calculations. The pulses acted similarly to2π CIP pulses. The results of numerical calculations showed the impossibility of creating microresonators when the colliding pulses had the same polarity. When the pulses had opposite polarity, a local microresonator appeared in the overlapping region of the pulses. The spatial period of the induced gratings increased with increasing number of collisions. More complicated dynamics of microresonators arose when4π pulses collided.

The results of these studies [60] show that the formation of microresonators is possible when the colliding pulses have different polarity. These limitations can be removed if one uses not a fully unipolar pulse, as in [60], but a quasiunipolar subcycle pulse containing a powerful half-wave of the field and trailing edges of opposite polarity. The above is illustrated by the results of the numerical calculation presented in the next section.

NUMERICAL SIMULATION RESULTS

To study the dynamics of the population difference lattice at collision of a sequence of 2π-like CIP pulses in a resonant medium, we numerically solved the system of Maxwell-Bloch equations including material equations for the non-diagonal element of the density matrixρ_{12} , the population difference of the medium (inversion) $n = \rho_{11} - \rho_{22}$ of the two-level medium, its polarization P , and the electric field strength E [66,67]:

$$\frac{\partial \rho_{12}(z,t)}{\partial t} = -\frac{\rho_{12}(z,t)}{T_2} + i\omega_0 \rho_{12}(z,t) - \frac{i}{\hbar} d_{12} E(z,t) n(z,t) \,, \tag{3}$$

$$\frac{\partial n(z,t)}{\partial t} = -\frac{n(z,t) - n_0(z)}{T_1} + \frac{4}{\hbar} d_{12} E(z,t) \mathrm{Im}\rho_{12}(z,t), \tag{4}$$

$$P(z,t) = 2N_0 d_{12} Re\rho_{12}(z,t), \tag{5}$$

$$\frac{\partial^2 E(z,t)}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E(z,t)}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P(z,t)}{\partial t^2} \,. \tag{6}$$

This system of equations (3)-(6) contains the following parameters (values of some of them are given in the table below): z - longitudinal coordinate, c - speed of light in vacuum, t - time, N_0- concentration of two-level atoms, $\hbar$ - reduced Planck's constant, ω_0 - frequency of the resonance transition of the medium ($\lambda_0 = 2\pi c/\omega_0$ - wavelength of the resonance transition), d_{12} - matrix element of the dipole moment of the resonance transition of the medium, n_0 - population difference of the medium in the absence of electric field, and $n_0 = 1$ for the absorbing medium. The possibility of applying the two-level approximation in such problems was discussed above and in [36,41,52-55,58-60, 62-65].

To create the pulse sequence, zero boundary conditions were used at the ends of the integration domain, which had a length of $L = 12\lambda_0$. The two-level medium was placed in the center of the integration region between the points with coordinates $z_1 = 4\lambda_0$ and $z_2 = 8\lambda_0$. At the initial moment of time, a pair of subcyclic impulses was launched into the medium from left to right and right to left from vacuum, the expression for which has the form:

$$E(0,t) = E_{01}e^{-\frac{(t-\tau_1)^2}{\tau^2}}\cos(\omega_0[t-\tau_1]), \quad (7)$$

$$E(L,t) = E_{02}e^{-\frac{(t-\tau_2)^2}{\tau^2}}\cos(\omega_0[t-\tau_2]). \quad (8)$$

Here$\tau_{1,2}$ are delays that regulate the moment when the pulses meet. The pulses acted similarly to 2π CIP pulses and had the same polarity but contained trailing edges of opposite polarity. One-dimensional propagation of half-cycle pulses over long distances can be realized in coaxial waveguides [68].

In this case, the impulses collided in the center of the medium and then left it. Ideal mirrors were placed on the boundaries of the integration region. The impulses were reflected from them and returned to the medium again. The system of equations (2)-(5) was numerically solved at the parameters given in the table below with initial conditions in the form of impulses (6)-(7). The spatial and temporal dependences of the polarization and population difference of the medium were constructed and analyzed. The parameters of the numerical simulation are given in the table. Transition wavelengths of hundreds of nanometers can be realized, for example, in atomic pairs or quantum dots. However, the results of the theoretical consideration based on the Schrödinger equation above show the possibility of lattice and resonator formation and are general in nature. The concentration of particles affects the reflectivity of lattices, and their shape can be distorted at its large values [53,54,60].

Figure 1 shows the spatiotemporal dynamics of the population difference and polarization. After the first collision of the pulse near time instant of the order of 23 fs, the medium remains in a weakly excited state. The microresonator begins to form after the 2nd collision, which occurred near the time instant of 50 fs, the population difference in the center is almost constant, while at the edges it changes by a jump. Outside the pulse overlap region, the medium remains in the unexcited state with the inversion value$n = 1$. After subsequent collisions at time moments 75, 100, 125 fs, etc., the shape of the microresonator becomes more pronounced. Of particular interest is the formation of complex polarization structures formed in the region of the microresonator, see Fig. 1b. Such polarization structures exist during the timeT_2 and can emit light waves in different directions.

The results of calculations when the pulses had opposite polarity,$E_{01} = -E_{02}$, are presented in Fig. 2. The other parameters are the same as in Fig. 1. It can be seen that the change of polarity of one of the pulses affects the dynamics of the system. In this case, the microresonator is formed immediately after the first collision of pulses. In the center of the medium, at the point $z=6\lambda_0$, the system is in the unexcited state, while at the edges of the medium the population difference changes by a jump. With increasing number of collisions, the spatial frequency of the lattice increases. In this case, complex polarization structures in the form of standing waves are formed in the region of microresonator localization. The interaction of incident excitation pulses with these polarization fluctuations is the reason for the increase in the spatial frequency of the population lattices [34,35]. A similar behavior of the population difference was observed in [60] at collision of fully unipolar pulses of opposite polarity.

CONCLUSION

The study of the interaction of half-cycle pulses with resonant media has led to the prediction and detailed investigation of a new phenomenon - the possibility of formation and ultrafast control of dynamic microresonators arising from the collision of extremely short pulses in the medium. With increasing number of collisions of pulses the parameters of this microresonator can be controlled. It is shown that a microresonator can arise when colliding2π similar subcyclic CIP pulses have both the same and opposite polarity, in contrast to the results of earlier studies [60].

The investigated effect is of interest for stopping and storing light pulses in the medium [25], creation of ultrafast attosecond optical switches [69], holography with ultrahigh temporal resolution [70], creation of space-time photonic crystals of a new type with controllable parameters [46-49], and in the physics of photonic crystals [71-73]. The obtained results open new directions of research in attosecond physics and optics of extremely short pulses and show the possibility of ultrafast control of the medium state on ultra-short time scales by means of subcyclic light pulses.

FUNDING

The research was supported by the grant of the Russian Science Foundation under the project№ 23-12-00012 (creation of dynamic resonators) and by the State assignment of the A.F. Ioffe Institute of Physics and Technology, topic 0040-2019-0017 (creation of population difference gratings).

REFERENCES

1. *Arkhipov R.M., Arkhipov M.V., Rosanov N.N.* // Quantum Electron. 2020. V. 50. No. 9. P. 801.
2. *Jackson J.D.* Classical Electrodynamics. N.Y.: Wiley, 1997.
3. *Bessonov E.G.* // ZhETF. 1981. T. 80. C. 852; *Bessonov E.G.* // Sov. Phys. JETP. 1981. V. 53. P. 433.
4. *Rozanov N.N.* // Opt. and Spectrosc. 2009. T. 107. № 5. C. 761; *Rosanov N.N.* // Opt. Spectrosc. 2009. V. 107. No. 5. P. 768.
5. *Sazonov S.V.* // Opt. and Spectrosc. 2022. T. 130. № 12. C. 1846; *Sazonov S.V.* // Opt. Spectrosc. 2022. V. 130. No. 12. P. 1573.
6. *Rosanov N.N., Arkhipov R.M., Arkhipov M.V.* // Phys. Usp. 2018. V. 61. P. 1227.
7. *Arkhipov R.M., Arkhipov M.V., Pakhomov A.V. et al.* // JETP Lett. 2023. V. 117. No. 1. P. 8.
8. *Rozanov N.N.* // UVN. 2023. T. 193. C. 1127; *Rosanov N.N.* // Phys. Usp. 2023. V. 66. P. 1059.
9. *Rozanov N.N., Arkhipov M.V., Arkhipov R.M. et al.* Terahertz photonics. MOSCOW: RAS, 2023. C. 360.
10. *Hassan M.T., Luu T.T., Moulet A. et al.* // Nature. 2016. V. 530. P. 66.
11. *Wu H.-C., Meyer-ter Vehn J.* // Nature Photon. 2012. V. 6. P. 304.
12. *Xu J., Shen B., Zhang X. et al.* // Sci. Reports. 2018. V. 8. P. 2669.
13. *Bogatskaya A.V., Volkova E.A., Popov A.M.* // Phys. Rev. E. 2021. V. 104. Art. No. 025202.
14. *Bogatskaya A.V., Volkova E.A., Popov A.M.* // Bull. Russ. Acad. Sci. Phys. 2024. V. 88. No. 1. P. 61.
15. *Ilyakov E., Shishkin B.V., Efimenko E.S. et al.* // Opt. Express. 2022. V. 30. P. 14978.
16. *Sazonov S.V.* // Izv. RAS. Ser. phys. 2022. T. 86. № 6. C. 766; *Sazonov S.V.* // Bull. Russ. Acad. Sci. Phys. 2024. V. 88. No. 1. P. 643.
17. *Pakhomov A., Arkhipov M., Rosanov N. et al.* // Phys. Rev. A. 2022. V. 106. No. 5. Art. No. 053506.

18. *Bucksbaum P.H.* // AIP Conf. Proc. 1994. V. 323. No. 1. P. 416.
19. *Dimitrovski D., Solov'ev E.A., Briggs J.S.* // Phys. Rev. A. 2005. V. 72. Art. No. 043411.
20. *Moskalenko A.S., Zhu Z.-G., Berakdar J.* // Phys. Reports. 2017. V. 672. P. 1.
21. *Arkhipov R., Arkhipov M., Babushkin I. et al.* // J. Opt. Opt. Soc. Amer. B. 2021. V. 38. P. 2004.
22. *Rosanov N., Tumakov D., Arkhipov M. et al.* // Phys. Rev. A. 2021. V. 104. No. 6. Art. No. 063101.
23. *Arkhipov R., Arkhipov M., Demircan A. et al.* // Opt. Express. 2021. V. 29. P. 10134.
24. *Arkhipov R.M., Arkhipov M.V., Fedorov S.V. et al.* // Opt. Spectrosc. 2021.
25. *Arkhipov M., Arkhipov R., Babushkin I. et al.* // Phys. Rev. Lett. 2022. V. 128. Art. No. 203901.
26. *Abella I.D., Kurnit N.A., Hartmann S.R.* // Phys. Rev. 1966. V. 141. P. 391.
27. *Shtyrkov E.I., Lobkov V.S., Yarmukhametov N.G.* // JETP Lett. 1978. V. 27. No. 12. P. 648.
28. *Moiseev S.A., Shtyrkov E.I.* // Quant. electron. 1991. T. 18. № 4. C. 447; *Moiseev S.A., Shtyrkov E.I.* // Sov. J. Quant. Electron. 1991. V. 21. no. 4. P. 403.
29. *Shtyrkov E.I., Samartsev V.V.* // Opt. and Spectrosc. 1976. T. 40. № 3. C. 392.
30. *Shtyrkov E.I., Samartsev V.V.* // Phys. Stat. Sol. A. 1978. V. 45. P. 647.
31. *Shtyrkov E.I.* // Opt. and Spectrosc. 2013. T. 114. № 1. C. 105; *Shtyrkov E.I.* // Opt. Spectrosc. 2013. V. 114. No. 1. P. 96.
32. *Szczurek M., Kusnierz M.* // Opt. Commun. 1989. V. 74. P. 121.
33. *Arkhipov R.M., Arkhipov M.V., Babushkin I. et al.* // Opt. Spectrosc. 2016. V. 121. P. 758.
34. *Arkhipov R.M., Arkhipov M.V., Babushkin I. et al.* // Opt. Letters. 2016. V. 41. P. 4983.
35. *Arkhipov R.M., Arkhipov M.V., Babushkin I. et al.* // Sci. Reports. 2017. V. 7. Art. No. 12467.
36. *Arkhipov R., Pakhomov A., Arkhipov M. et al.* // Sci. Reports. 2021. V. 11. Art. No. 1961.

37. *Rosanov N.N., Semenov V.E., Vysotina N.V.* // Laser Phys. 2007. V. 17. P. 1311.
38. *Pusch A., Hamm J.M., Hess O.* // Phys. Rev. A. 2010. V. 82. No. 2. Art. No. 023805.
39. *Arkhipov R.M., Arkhipov M.V., Pakhomov A.V. et al.* // Opt. Spectrosc. 2017. V. 123. P. 610.
40. *Arkhipov R.M., Arkhipov M.V., Pakhomov A.V. et al.* // Opt. Spectrosc. 2018. V. 124. P. 541.
41. *Arkhipov R.M.* // Letters in ZhETF. 2021. T. 113. C. 636; *Arkhipov R.M.* // JETP Lett. 2021. V. 113. P. 611.
42. *Arkhipov R.M., Arkhipov M.V., Pakhomov A.V. et al.* // Radiophys. Quantum Electron. 2024. V. 66. No. 4. P. 286.
43. *Arkhipov R.M., Arkhipov M.V., Pakhomov A.V. et al.* // Opt. Spectrosc. 2022. V. 130. No. 11. P. 1443.
44. *Diachkova O.O., Arkhipov R.M., Arkhipov M.V. et al.* // Opt. Commun. 2023. V. 538. Art. No. 129475.
45. *Arkhipov R.M., Diachkova O.O., Arkhipov M.V. et al.* // Appl. Phys. Phys. B. 2024. V. 130. P. 52.
46. *Lustig E., Sharabi Y., Segev M.* // Optica. 2018. V. 5. No. 11. P. 1390.
47. *Galiffi E., Tirole R., Yin S. et al.* // Adv. Photonics. 2022. V. 4. No. 1. Art. No. 014002.
48. *Sharabi Y., Dikopoltsev A., Lustig E. et al.* // Optica. 2022. V. 9. No. 6. P. 585.
49. *Boltasseva A., Shalaev V.M., Segev M.* // Opt. Mater. Expr. 2024. V. 14. No. 3. P. 592.
50. *Eichler H.J., Günter P., Pohl D.W.*. Laser-induced dynamic gratings. Berlin, Heidelberg, New York, Tokyo: Springer-Verlag, 1981.
51. *Arkhipov R., Arkhipov M., Pakhomov A. et al.* // Laser Phys. 2022. V. 32. No. 6. Art. No. 066002.
52. *Arkhipov R.M.* // Quant. electron. 2024. T. 54. № 2. C. 77.
53. *Arkhipov R., Pakhomov A., Diachkova O. et al.* // Opt. Letters. 2024. V. 49. No.10. P. 2549.

54. *Diachkova O., Arkhipov R., Pakhomov A. et al.* // Opt. Commun. 2024. V 565. P. 130666/.
55. *Arkhipov R.* // arXiv:2402.16122. 2024.
56. *Lustig E., Segal O., Saha S. et al.* // Nanophotonics. 2023. V. 12. P. 1.
57. *Saha S., Segal O., Fruhling C. et al.* // Opt. Express. 2023. V. 31. No. 5. P. 8267.
58. *Arkhipov R.M., Rozanov N.N.* // Opt. and Spectrosc. 2024. T. 132. № 5. C. 532.
59. *Rozanov N.N., Arkhipov M.V., Arkhipov R.M.* // UVN. 2024. T. 194. № ... C. ...
60. *Arkhipov R., Pakhomov A., Diachkova O. et al.* // JOSA B. 2024. V. ... P. ...
61. *Landau L.D., Lifshitz E.M.* Quantum mechanics: non-relativistic theory. V. 3. Elsevier, 2013.
62. *Arkhipov R.* // Laser Phys. 2024. V. 34. 36. Art. No. 065301.
63. *Arkhipov R.M., Arkhipov M.V., Rozanov N.N.* // Opt. and Spectrosc. 2024. T. 132. № 4. C. 434.
64. *Arkhipov R., Arkhipov M., Pakhomov A. et al.* // Phys. Rev. A. 2024. V. 109. Art. No. 063113.
65. *Arkhipov R.M., Dyachkova O.O., Belov P.A.,* et al. // ZHETF. 2024. T. 166. № 2(8) C. 1.
66. *Allen L., Eberly J.H..* Optical resonance and two-level atoms. N.Y., Wiley, 1975.
67. *Yariv A.* Quantum Electronics. Moscow: Soviet Radio, 1980. 488 p; *Yariv A.* Quantum Electronics. N.Y.: Wiley, 1975.
68. *Rozanov N.N.* // Opt. and Spectrosc. 2019. T. 127. C. 960; *Rosanov N.N.* // Opt. Spectrosc. 2019. V. 127. P. 1050.
69. *Hassan M.T.* // ACS Photonics. 2024. V. 11. No. 2. P. 334.
70. *Arkhipov R.M., Arkhipov M.V., Rosanov N.N.* // JETP Lett. 2020. V. 111. P. 484.
71. *Mantsyzov B.* Coherent and nonlinear optics of photonic crystals. Moscow: Fizmatlit, 2013. 149 c.
72. *Dvuzhilova Yu.V., Dvuzhilov I.S., Shilov T.B. et al.* // Bull. Russ. Acad. Sci. Phys. 2022. V. 86. No. 12. P. 1454.
73. *Dvuzhilova Yu.V., Dvuzhilov I.S., Belonenko M.B.* // Bull. Russ. Acad. Sci. Phys. 2024. V. 88. No. 1. P. 66.

FIGURE CAPTIONS

Fig. 1. Dynamics of the population difference *n(z,t)* (*a*); dynamics of the polarization *P(z,t)* at the collision of a pair of subcyclic CIP pulses of the same polarity (*b*), $E_{01} = E_{02}$, in the center of the medium at the point $z=6\lambda_0$. The calculation parameters are given in Table 1.

Fig. 2. Dynamics of the population difference *n(z,t)* (*a*); dynamics of the polarization *P(z,t)* at the collision of a pair of subcyclic CIP pulses of opposite polarity (*b*), $E_{01} = -E_{02}$, in the center of the medium at the point $z=6\lambda_0$. The calculation parameters are given in Table 1.

Table 1. Problem parameters used in numerical modeling.

Wavelength of the resonance transition of the medium	$\lambda_0 = 700$ nm
Dipole moment of the transition	$d_{12} = 20$ Д
Relaxation time of the population difference	$T_1 = 10$ ps
Polarization relaxation time	$T_2 = 5$ ps
Concentration of atoms	$N_0 = 10^{18}$ cm^{-3}
Field amplitude	$E_{01} = E_{02} = 259\,000$ units. GHS
Excitation pulse duration τ	$\tau = 580$ ace
Delay parameters	$\tau_1 = \tau_2 = 3\tau$

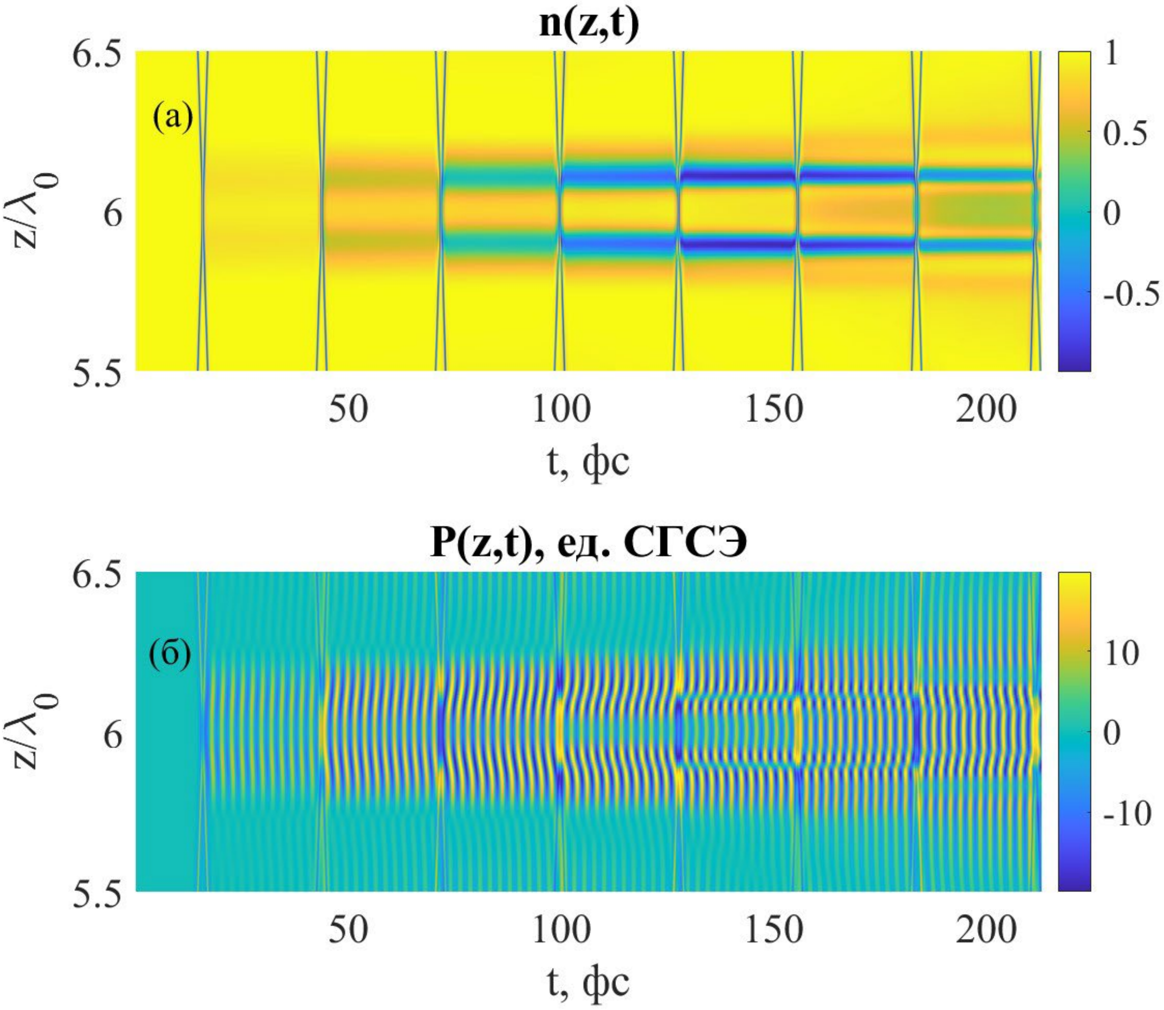
n(z,t)
(a)
6.5
6
5.5
z/λ0
50
100
150
200
t, фс
1
0.5
0
-0.5
P(z,t), ед. СГСЭ
(б)
6.5
6
5.5
z/λ0
50
100
150
200
t, фс
10
0
-10

Fig. 1.

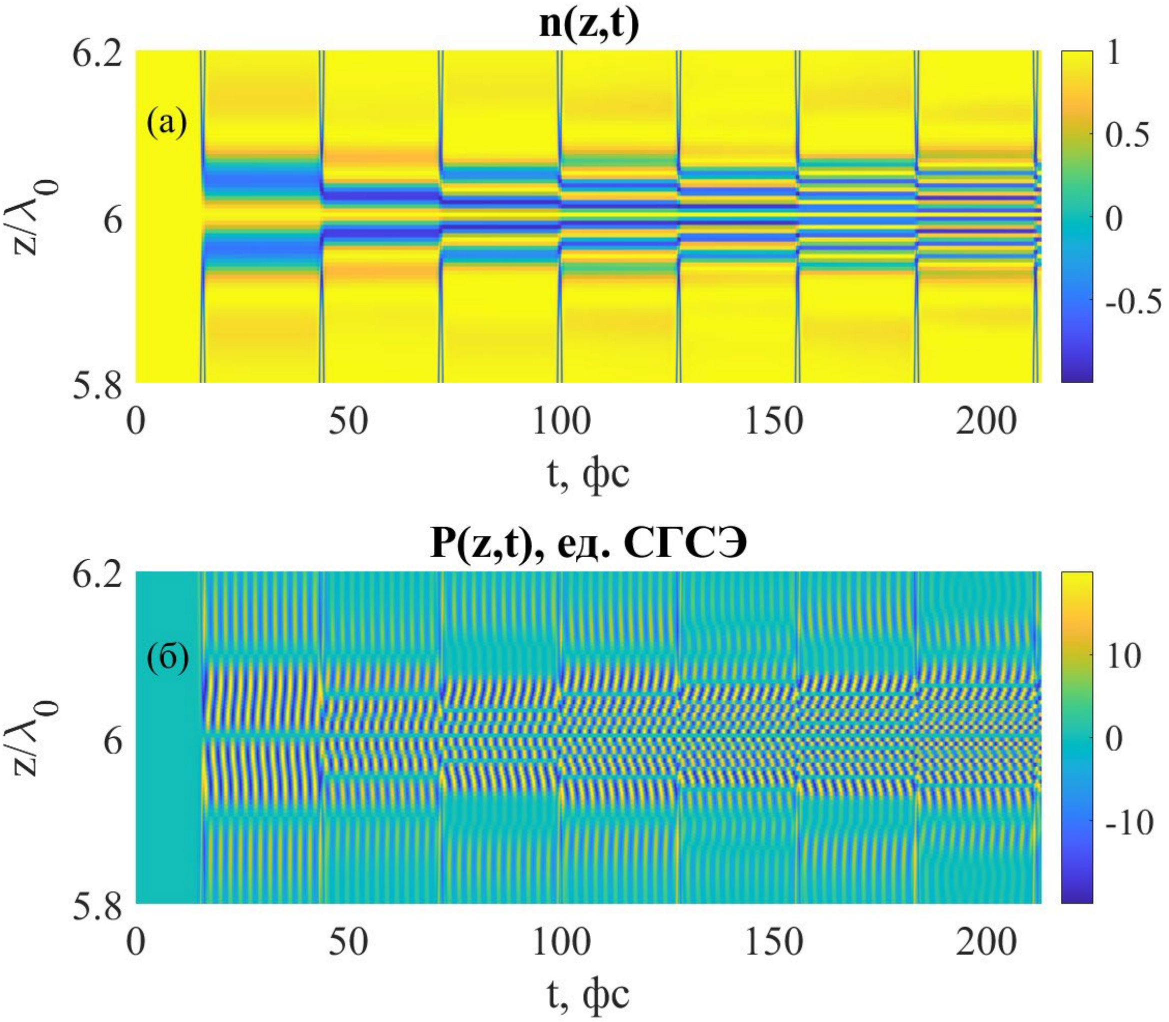
n(z,t)
(a)
z/λ0
6.2
6
5.8
0
50
100
150
200
t, фс
1
0.5
0
-0.5
P(z,t), ед. СГСЭ
(б)
z/λ0
6.2
6
5.8
0
50
100
150
200
t, фс
10
0
-10

Fig. 2.