Ultra high-speed all-optical coherent memory cell

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Abstract. We study the interaction of two counterpropagating unipolar video pulses of electromagnetic radiation in a dense resonant two-level medium. The pulse durations are less than one oscillation period of an atomic transition. We show that a polariton cluster (i.e. the compact long-living strongly coupled state of electromagnetic field and matter polarization) is created, when two unipolar pulses collide in a resonant medium of the frequency \(\omega_0\) (the pulses correspond to self-induced transparency solitons of the same amplitudes and opposite polarities).

We have studied for the first time the conditions of maximal excitation of a resonant polarization in the polariton cluster volume. We show that there exist optimal durations and amplitudes of the recording pulses. We studied the processes of double and multiple recording and erasing of an optical memory cell in a thin layer of a resonant medium (quantum dots). We demonstrated that the pulse rate of the recording-erasing pulses can reach 60 000 GHz and higher, which happens under the coherent regime of the interaction between the electromagnetic field and polarization of the medium.

1. Introduction

Recently, the generation, coherent propagation, and interaction in dense resonant media of ultrashort (few-cycle, one-cycle, sub-cycle) pulses of the electromagnetic field has attracted strong interest. Modern methods of generating unipolar video pulses are reviewed in [1,2], the effects of coherent interaction between counterpropagating pulses are considered in [3-6] as well.

Here we theoretically study the processes of formation and dynamics of polariton clusters, which are created during collisions between unipolar pulses of the amplitudes of opposite signs (solitons of the self-induced transparency).

The correct description of propagation and interaction of ultrashort (one-cycle, sub-cycle) solitons is possible only by eliminating the approximations imposed by the slowly varying envelope (SVEA) and rotating-wave approximations (RWA) both in time and spatial coordinate. The theory of propagation of such solitons in dense resonant media is well established, cf. for example [7-13].

Dynamics of a quantum two-level particle with the dipole moment \(d\) and transition frequency \(\omega_0\) is described by the Bloch equations [7,8] for the pseudospin vector projections \(s = (s_1, s_2, s_3)\):

\[
\dot{s}_1 = -\alpha_0 s_2 - \frac{1}{T_2} s_1
\]

\[
\dot{s}_2 = \alpha_0 s_1 + 2 \frac{d}{\hbar} E(t, z) s_3 - \frac{1}{T_2} s_2
\]
\[ \dot{s}_t = -\frac{2}{\hbar} \frac{d}{dt} E(t, z) s_t - \frac{1}{T_1} (s_t + 1) \]  
(3)

\[ P(t, z) = N_0 \cdot d \cdot s_t. \]  
(4)

Here \( E(z, t) \) is the electric filed amplitude of a pulse propagating along the coordinate \( z \), \( T_1 \) and \( T_2 \) are the longitudinal and transversal relaxation times, \( P(z, t) \) is the medium polarization, \( N_0 \) is the resonant particle density. The physical meaning of the pseudospin projection \( s_t \) is the normalized population difference of a two-level medium: \( s_t(z, t) = \frac{N(z, t)}{N_0} \).

Dynamics of the electromagnetic field propagation is described by Maxwell’s equations:

\[ \frac{1}{c} \frac{\partial H_x}{\partial t} = -\frac{\partial E_y}{\partial z} \]  
(5)

\[ \frac{1}{c} \frac{\partial E_x}{\partial t} = -\frac{\partial H_y}{\partial z} - \frac{4\pi \hat{P}}{c} \]  
(6)

or by the wave equation

\[ \frac{\partial^2 E}{\partial t^2} - c^2 \frac{\partial^2 E}{\partial z^2} = -4\pi \hat{P}. \]  
(7)

Here \( E_x \) and \( H_y \) are the projections of electric and magnetic fields of the pulse on the transverse axes \( x \) and \( y \), \( c \) is the speed of light in vacuum.

In the absence of relaxation \( (T_1 = T_2 = \infty) \), the Maxwell-Bloch equations have analytical single-soliton solutions of the self-induced transparency theory [7-13]:

\[ E = \pm \frac{\hbar}{dt} \cdot \text{sech} \left( \frac{t - zV^{-1} + l_0}{t_p} \right) \]  
(8)

\[ V = \frac{c}{\sqrt{1 + \frac{2\alpha \tau_p}{1 + \tau_p}}} \]  
(9)

\[ \alpha = \frac{4\pi}{\hbar} \cdot \frac{N_0 d^2}{\omega_0^2} = \frac{1}{t_p \omega_0}. \]  
(10)

Here \( V \) is the soliton propagation velocity along the coordinate \( z \), \( t_p \) is the soliton duration, \( t_p = \omega_0 t_p \).

### 2. Recording and erasing polariton clusters. All-optical coherent memory cell.

In this work we have studied the process of inelastic collision between two self-induced transparency solitons (8) in a resonant medium. We theoretically considered a problem of two identical counterpropagating unipolar solitons of either the same or different polarities. We solved numerically the Maxwell-Bloch equations (1)-(3) and (5)-(6) without using the slow amplitude approximations (SVEA, RWA) both in time and spatial coordinate. We took into account the finite relaxation times of a medium \( T_1 \) and \( T_2 \). The details of the simulation methods are described in [4].

We studied theoretically for the first time the optimal conditions for creation of polariton clusters, which appear in the process of collision between unipolar pulses of opposite signs. In particular, we considered a case, where in a thick layer \( (\approx 5\lambda, 3 \text{ mkm}) \) of resonant medium, two pulses of the duration \( t_p \) equal to 1/3 of the atomic transition period \( (t_p = 0.67 \text{ fs}) \), collide (cf. Figures 1 and 2). The light-induced stationary polariton cluster appears in the pulse collision point and it has a size of \( \approx \lambda/5 \) (120 nm). Within the cluster, the medium polarization \( P(z, t) \) oscillates with the amplitude close to the maximal one \( (s_t \approx 1) \) at the atomic transition frequency \( \omega_0 \), but its emission is forbidden in the far field (cf. Figure 1). The maximal lifetime of polariton cluster (optical memory time) is determined by
the time $T_2$. The repeated action of two pulses of opposite polarities on the polariton cluster leads to its destruction (cf. Figures 1 and 2).

![Figure 1](image1.png)

**Figure 1.** Dynamics of the polarization $P(z,t)$ in the polariton cluster during its recording and erasing. The horizontal axis represents the unitless propagation coordinate $K_z$, the vertical axis represents the unitless time $\omega_0 t$. $K = 2\pi/\lambda$ is the wave vector, $\lambda = 600$ nm. The pulse rate is 60 000 GHz (60 THz). The pulse duration is $\tau_p = 0.67$ fs ($\omega_0 \tau_p = 2$), $T_1 = T_2 = 1$ ps.

![Figure 2](image2.png)

**Figure 2.** Dynamics of the population difference $N(z,t)$ in the polariton cluster during its recording and erasing.

Therefore, the polariton cluster has all necessary properties of the RAM memory cell: properties of the recording and erasing, enough information storage time. From a practical point of view, a convenient method to obtain two counterpropagating unipolar pulses of opposite polarities is based on the pulse reflection from a mirror [6].

The problem under consideration has two aspects. The first aspect is the study of physical processes leading to the suppression of the radiation of a polariton cluster in the far field in a dense medium. This question was discussed in details in [4] for the case of few-cycle pulses and in [6] for the case of the one-cycle pulses.

The second aspect is the study of such conditions of the cluster recording that simultaneously realize the radiationless regime of the cluster existence and the oscillation amplitude of the resonant polarization reaches the limiting value of $s_1 = 1$. 
In Figure 2, we show dynamics of the normalized population difference $s_3 = N(z,t)/N_0$ during the collision of two unipolar solitons. One can see that the long-living polariton cluster is formed during the inelastic collision between the solitons of the opposite polarity near the collision point $z_o$ ($Kz_o = 15$). The cluster has a double spatial structure. By varying the soliton duration $t_p$, we have shown that the quantity $<N(z)>/N_0$ averaged over the cluster existence area $Kz = [14...16]$ and the temporal range of $\omega ot = [37...40]$ has a well-defined maximum at the soliton duration $\omega ot_p = 0.755$ (cf. Figure 3).

![Figure 3](image)

Figure 3. The dependence of $<s_3> = <N(z,t)>/N_0$ on the duration of colliding solitons $t_p$.

At the optimal soliton duration ($\omega ot_p = 0.755$), the oscillation amplitude of the resonant polarization in polariton cluster reaches its maximal value of $s_3 = 1$.

As we see in Figure 2, the cluster has a double spatial structure with maxima of $N(z,t)$ at the points $z'$ and $z''$. Figure 4 shows the dynamics of resonant polarization of a medium at the points $z'$ and $z''$. One can see that the polariton cluster represents a very compact coupled structure of the resonant medium polarization and electromagnetic field: $z'' - z' \approx \lambda/20$.

![Figure 4](image)

Figure 4. Temporal behaviour of the resonant polarization in two points of the polariton cluster $z'$ and $z''$ near the point of the pulse collision $z_o$ ($Kz_o = 15$). Left panel: $Kz' = Kz_o - 0.16$, right panel: $Kz'' = Kz_o + 0.16$.

At the change of the soliton duration $t_p$, its amplitude $E_o$ changes as well self-consistently (cf. (8)). In this part of the work, we studied the dependence of the time of life of the polariton cluster and the polarization oscillation amplitude on the amplitude of the colliding pulses $E_{op}$, when the soliton duration is optimal and is fixed ($\omega ot_p = 0.755$).
Figure 5 shows the amplitude dependence of the medium excitation in the polariton cluster on the ratio between the amplitude of the colliding pulses \( E_{op} \) and the amplitude of the solitons of self-induced transparency \( E_o \) (8).

![Figure 5](image)

**Figure 5.** Dependence of \( \langle N(z,t) \rangle/N_o \) on the pulse duration \( E_{op} \).

\( T_1 = 1 \) psec, \( T_2 = 1 \) psec, \( d = 5D \), \( \omega_p = 1\cdot10^{15} \) rad/sec, \( \omega_p \rho = 0.755 \).

The study of the radiative decay time of the polariton cluster also showed that it is maximal at \( E_{op}/E_o \approx 1 \) and \( E_{op}/E_o \approx 2 \).

Therefore, we demonstrated that the use of self-induced transparency solitons (2π-pulses) with the optimal duration (\( \omega_p \rho = 0.755 \)) for recording information in the optical memory cell is optimal for three reasons. The colliding solitons are stable during the propagation in a resonant medium, they induce in the polariton cluster resonant polarization with the maximal amplitude, and they create the polariton cluster with the maximal lifetime.

3. Conclusion

In conclusion, we have systematically studied an effect of creation of polariton cluster (i.e. a compact long-living strongly coupled state of the electromagnetic field and medium polarization). We performed numerical solution of the problem of inelastic collision between two counterpropagating solitons of the self-induced transparency effect.

We show that there exist three conditions for the efficient creation of polariton clusters (memory cells).

First, the colliding pulses should have the opposite signs. In this case, near the collision point of the unipolar pulses, the field \( E(t) \) has a form of oscillating one-cycle pulses.

Second, the duration of colliding pulses \( \tau_p \) should satisfy the condition of the resonance between the one-cycle pulse and atom frequency \( \omega_o \).

Third, the amplitude of unipolar pulses should be equal to the amplitude of solitons in the self-induced transparency theory (2π-pulses of the duration \( \tau_p \)).

We demonstrated that the self-induced transparency solitons (2π-pulses) with the optimal duration (\( \omega_p \rho = 0.755 \)) are the optimal pulses for recording information in an optical memory cell.

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References

[1] Frantzeskakis D J, Leblond H, Mihalache D 2014 Rom. J. Phys. 59 (7-8) 767-784
[2] Arkhipov R M, Pakhomov A V, Arkhipov M V, Babushkin I, Tolmachev Yu A, Rosanov N N 2017 JETP Lett. 105 (6) 408-418
[3] Rosanov N N, Semenov V E, Vyssotina N V 2007 Laser Physics 17 (11) 1311–1316
[4] Bagaev S N, Egorov V S, Nikolaev V G, Chekhonin I A, Chekhonin M A 2015 Russian Journal of Physical Chemistry B 9 (4) 582-586
[5] Novitsky D V 2012 Phys. Rev. A 85 (4) 043813-1 - 043813-7
[6] Bagaev S N, Egorov V S, Nikolaev V G, Mekhov I B, Chekhonin I A, Chekhonin M A 2018 J. Phys.: Conf. Ser. 1124 051018
[7] Allen L, Eberly J H, Optical resonance and two-level atoms (Wiley, New York, 1975)
[8] Bullough R K, Caudrey P J, Eilbek J C, Gibbon J D 1974 Opto-electronics 6 121-140
[9] Eilbeck J C, Gibbon J D, Caudrey P J, Bullough R K 1973 J. Phys. A 6 1337-1347
[10] Bullough R K, Jack P M, Kitchenside P W, Saunders R 1979 Phys. Scripta 20 364-381
[11] Maimistov A I, Caputo J G Optics and Spectroscopy 2003 94 (2) 245–250
[12] Kalosha V P, Herrmann J Phys. Rev. Lett. 1999 83 544-547
[13] Bullough R K, Ahmad F 1971 Phys. Rev. Lett. 27 (6) 330-333