All-optical switching of pulse transmission in disordered resonant media

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Abstract. Using numerical calculations of Maxwell-Bloch equations, we propose a scheme for all-optical transmission switching based on interaction between ultrashort copropagating pulses in disordered resonant media. The physical mechanism of this nonlinear effect is revealed as well as its dependence on the amplitudes of pulses and the interval between them.

Switching and modulation of optical response are the basic effects needed for controlling light signals and construction of tunable optical devices. A number of mechanisms and materials are proposed to realize ultrafast switching. For example, photonic crystals can be used as all-optical modulators based on the band-gap shift effect. Such shift can be reached due to nonlinear response of solid materials (usually semiconductors, such as GaAs [1] or doped metal oxides [2]) and is characterized by picosecond relaxation times. Semiconductors are also proposed as a key element for compact tunable metasurfaces where switching is a result of shifting the Mie-type resonances [3]. Another class of perspective materials is the transparent conductive oxides, which claim to replace metals in tunable and switchable plasmonic devices [4].

In this paper, we propose a new mechanism for all-optical transmission switching based on disorder-induced interaction of copropagating coherent pulses in resonant media. It is known that in the uniform resonant medium (disorder parameter \( r = 0 \)), such pulses eventually transform into standard \( 2\pi \) solitons and interact elastically, i.e., they do not lose any energy as a result of collision [5]. We show that the presence of random variations of active particles density (\( r \neq 0 \)) results in effective inelastic interaction between the pulses when portion of light energy gets absorbed by the medium. This light trapping depends on the strength of disorder, which is a necessary ingredient for the effect to occur. Launching either one or two pulses inside disordered resonant medium, one will obtain strongly different levels of transmission having a means for realizing all-optical switching.

The system considered in this paper consists of a background dielectric doped with active (two-level) atoms, which initially are in the ground state. Light propagation in such media is described with the semiclassical Maxwell-Bloch equations for the dimensionless electric-field amplitude \( \Omega = (\mu/\hbar\omega)E \) (normalized Rabi frequency), complex amplitude of the atomic polarization \( \rho \), and difference between populations of ground and excited states \( w \) [5]:

\[
\frac{d\rho}{d\tau} = i\Omega w + i\rho \delta - \gamma_2 \rho,
\]  

(1)
\[
\frac{dw}{d\tau} = 2i(l^* \Omega^* \rho - \rho^* l \Omega) - \gamma_1(w - 1), \tag{2}
\]
\[
\frac{\partial^2 \Omega}{\partial \xi^2} - n_d^2 \frac{\partial^2 \Omega}{\partial \xi^2} + 2i \frac{\partial \Omega}{\partial \xi} + 2i n_d^2 \frac{\partial \Omega}{\partial \tau} + (n_d^2 - 1) \Omega
\]
\[
= 3\epsilon l \left( \frac{\partial^2 \rho}{\partial \xi^2} - 2i \frac{\partial \rho}{\partial \xi} - \rho \right), \tag{3}
\]
where \(\tau = \omega t\) and \(\xi = k z\) are the dimensionless time and distance, \(\mu\) is the dipole moment of the quantum transition, \(\hbar\) is the reduced Planck constant, \(\delta = \Delta \omega / \omega = (\omega_0 - \omega) / \omega\) is the normalized frequency detuning, \(\omega\) is the carrier frequency, \(\omega_0\) is the frequency of the atomic resonance, \(\gamma_1 = 1/\omega T_1\) and \(\gamma_2 = 1/\omega T_2\) are the normalized relaxation rates of population and polarization respectively, and \(T_1 (T_2)\) is the longitudinal (transverse) relaxation time. The dimensionless parameter \(\epsilon = \omega_L / \omega = 4 \pi \mu^2 C / 3 \hbar c\) is responsible for the light-matter coupling, where \(C\) is the density of two-level atoms and \(\omega_L\) is the normalized Lorentz frequency. Quantity \(l = (n_d^2 + 2) / 3\) is the local-field enhancement factor due to the polarization of the background dielectric with refractive index \(n_d\) by the embedded active particles. Further we numerically solve Eqs. (1)–(3) using the finite-difference time-domain (FDTD) approach adapted to this particular problem [6, 7].

We consider the system in which the density of active particles experiences periodical random variations along the light propagation direction, so that the strength of light-matter coupling at some point \(z\) of the medium is given by [7]
\[
\omega_L(z) = \omega_L^0 [1 + 2r(\zeta(z) - 0.5)], \tag{4}
\]
where \(\omega_L^0\) is the constant determined by the average density of two-level particles, \(\zeta(z)\) is the random number uniformly distributed in the range \([0; 1]\), and \(r\) is the parameter of disorder strength. Such disordered resonant medium can be considered as a multilayer (total thickness \(L\)) consisting of slabs (thickness \(\delta L\)) with different density of active atoms. The transition to light localization in such structures was studied in [7].

The parameters used for calculations agree with both rare-earth atoms and semiconductor quantum dots as the active particles. In particular, we take the relaxation times \(T_1 = 1\) ns and \(T_2 = 0.1\) ns, the Lorentz frequency \(\omega_L^0 = 10^{12}\) s\(^{-1}\), the frequency detuning \(\delta = 0\), the full thickness of the medium \(L = 1000\) \(\mu\)m, the period of random density variations \(\delta L = \lambda / 4\), and the background refractive index \(n_d = 1\). Incident light pulses have the central wavelength \(\lambda = 0.8\) \(\mu\)m and the Gaussian envelope \(\Omega = \Omega_p \exp(-t^2 / 2\tau_p^2)\), where the pulse duration is \(\tau_p = 50\) fs. The peak Rabi frequency \(\Omega_p\) is measured in the units of \(\Omega_0 = \lambda / \sqrt{2\pi} \tau_p d_p\) corresponding to the pulse area of \(2\pi\).

Let us consider two pulses copropagating in the disordered resonant medium. Interactions of copropagating pulses can be realized due to the fact that pulse speed depends on its intensity: more powerful pulses move faster. So, if the first pulse has lower amplitude than the second one, they can collide and interact after a certain propagation length. The main result of this paper is shown in Fig. 1, where the dependencies of transmission, reflection and their sum on disorder strength \(r\) are shown for the copropagating pulses with amplitudes \(\Omega_p1 = \Omega_0\) and \(\Omega_p2 = 1.5\Omega_0\) and the interval \(\Delta t = 10\tau_p\) between peaks at the entrance. We compare the case of two simultaneously propagating pulses with the case of single pulses. This latter case is used to calculate transmission and reflection for the situation with \textit{a priori} no interaction between pulses; namely, transmitted or reflected energy of two non-interacting pulses can be calculated as \(E_{12} = (E_1\Omega_{p1}^2 + E_2\Omega_{p2}^2) / (\Omega_{p1}^2 + \Omega_{p2}^2)\), where \(E_1\) and \(E_2\) are the data from the single pulse propagation calculations.

It is clearly seen from Fig. 1 that the resulting transmission and reflection for the pulses with and without interaction are the same in the uniform medium \((r = 0)\) and are sharply different in
Figure 1. Average transmitted, reflected and total energy of pulses as a function of the disorder parameter $r$. The cases of interacting co-propagating pulses and single pulses with the amplitudes propagating without interaction are shown. The amplitudes of the pulses are $\Omega_{p1} = \Omega_0$ and $\Omega_{p2} = 1.5\Omega_0$; the interval between pulses is $\Delta t = 10t_p$. Energy averaged over 100 realizations was calculated for the time interval $700t_p$ and was normalized on the input energy. The error bars show the unbiased standard deviations for the corresponding average values.

The presence of disorder ($r > 0$). In other words, disorder induces effective interaction between copropagating pulses, which now collide inelastically and lose a portion of their energy due to interaction, in sharp contrast to the ordered case. The reason is that the medium is not uniform anymore, so that even relatively weak reflections due to varying densities of active particles can give rise to the coupling between the pulses.

This additional loss can be used to control transmission of light through the system. Indeed, after the collision, the pulses have lower intensity and, hence, move slower. They become more vulnerable to trapping inside the disordered medium. As a result, transmission and total output demonstrate a drop at rather low disorder, i.e., the threshold of localization is shifted to lower $r$: this threshold occurs at $r > 0.2$ for the interaction-free propagation, whereas light is localized already at $r > 0.1$ for the interacting copropagating pulses. The situation considered can be treated as a peculiar scheme of all-optical transmission switching based on disorder-induced pulse-pulse interactions: launching the second (control) pulse significantly modifies transmission of light through the medium in comparison to the case of single (signal) pulse.

We have also analyzed the influence of pulse amplitude, interval between pulses, and background dielectric on the efficiency of transmission switching. Calculations show that as
we decrease the amplitude of the second pulse from $\Omega_{p2} = 1.5\Omega_0$ down to $1.1\Omega_0$, transmission drops from 0.5 to almost 0.3, so that the ratio of transmission for the pulses without and with interaction grows from approximately 1.5 up to 2. This means that the pulses with close amplitudes (e.g., $\Omega_{p1} = \Omega_0$ and $\Omega_{p2} = 1.1\Omega_0$) are better suited for transmission switching. The reason is that these pulses move with closer velocities and therefore have more time to interact than colliding pulses with strongly differing velocities.

As to the interval $\Delta t$ between pulses, according to our calculations, transmission increases as the interval decreases, i.e., pulses collide too soon after launching and lose smaller portion of energy. On the contrary, increase in $\Delta t$ first lowers transmission, which at $\Delta t \geq 20t_p$ keeps practically the same value. Thus, efficiency of transmission modulation is high in the wide range of intervals between pulses.

Finally, to examine the possibility of transmission switching in a more realistic set-up, we have simulated propagation of pulses in the disordered resonant medium with the background refractive index $n_d = 1.5$. The distinction of this situation is that there is additional reflection at the entrance and exit interfaces due to refractive index discontinuity. This reflection can strongly influence the results even in the ordered case, since a reflected portion of the faster (control) pulse can interact with the slower (signal) one. This situation resembles the well-known case of counterpropagating pulses which interact inelastically and lose large portion of energy due to collision [5]. In order to suppress this possibility and save the copropagating geometry, the system can be supplemented with the caps of pure background material of proper thickness (40\diameter) from both sides of the medium. This is enough to obtain almost interaction-free propagation of pulses at $r = 0$, so that the curves obtained in this case are generally similar to those shown in Fig. 1 and corroborate the presence of the transmission switching effect for non-vacuum background.

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