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Compression and collisions of chirped pulses in a dense two-level medium

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ABSTRACT

Using numerical simulations, we study propagation of linearly-chirped optical pulses in a homogeneously broadened two-level medium. We pay attention to the three main topics – validity of the rotating-wave approximation (RWA), pulse compression, and collisions of counter-propagating pulses. The cases of long and single-cycle pulses are considered and compared with each other. We show that the RWA does not give a correct description of chirped pulse interaction with the medium. The compression of the chirp-free single-cycle pulse is stronger than of the chirped one, while the opposite is true for long pulses. We demonstrate that the influence of chirp on the collisions of the long pulses allows us to control the state of the transmitted radiation: the transmission of the chirp-free pulse can be dramatically changed under collision with the chirped counter-propagating one, in sharp contrast to the case when both pulses are chirped. On the other hand, the collisions of the chirped single-cycle pulses can be used for precise control of medium excitation in a narrow spatial region.

1. Introduction

Since the discovery of self-induced transparency (SIT) [1,2], light interaction with two-level quantum media attracted much attention and was discussed in a number of books [3,4] and review papers [5–8]. This interest is, to a great extent, due to the fundamental importance of the semiclassical two-level model which is one of the basic models of nonlinear optics and laser physics. Besides the SIT itself, there was a deep investigation of other nonlinear effects in two-level media, such as intrinsic (mirrorless) optical bistability [9,10], influence of local-field correction (near dipole–dipole interactions) on SIT solitons and optical switching [11–13], population control with specially constructed pulses [14], incoherent soliton generation [15], collisions of solitons [16,17], solitons in periodically modulated two-level media [18–20], etc. A more recent topic is connected with study of few-cycle and sub-cycle pulses in the two-level media when the standard rotating-wave approximation (RWA) turns out to be invalid [21–23]; see also the recent reviews [24,25] and references therein.

Additional degree of freedom is provided by chirp, i.e. temporal variation of the carrier frequency of the pulse. Influence of chirp on pulse propagation in the two-level medium is under examination, at least, from the 1980s [26]. More recent theoretical studies allowed us to find the analytical solutions for a certain class of chirped pulses [27] and investigate the validity of the RWA for the so-called ultrachirped pulses [28], showed the splitting of chirped pulses with particular spectral composition [29], demonstrated the soliton formation from a two-component chirped pulse [30] and the coherent control of spectral shifts [31], analyzed excitation of the medium with the sub-cycle and single-cycle chirped pulses and formation of sub-cycle solitons [32,23,33], etc.

In this paper, we consider some aspects of medium-light interaction in the case of linearly-chirped short pulses. We focus on the three main questions which, as far as we know, were not studied in detail previously – test of the RWA validity, pulse compression and collisions of counter-propagating pulses. We use numerical simulation technique described briefly in Section 2 to directly verify the validity of the RWA for description of linearly-chirped pulse propagation and to study the compression of such pulses and soliton formation. In Section 3, the pulses are suggested to be long enough, so that the RWA violation cannot be connected with the processes on the single-cycle scale studied previously [22]. As to collisions of counter-propagating chirped pulses inside the medium, the present study continues our previous work where interaction of chirp-free pulses in both homogeneously and inhomogeneously broadened two-level media was analyzed [17,34,35]. It was shown that, changing intensity of the first pulse, one can effectively control the transmission of the second pulse. Here we study the influence of chirp on collisions of counter-propagating pulses and the possibility to control the parameters of transmitted radiation with the chirped pulses. In Section 4, the case of single-cycle pulses is considered and compared with the results obtained for the long pulses. The paper is completed with the brief Conclusion.

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2. Main equations and parameters

We describe light propagation in the homogeneously broadened two-level medium beyond the RWA and the slowly-varying envelope approximation (SVEA) with the Maxwell–Bloch equations as given in our previous publication [34]:

$$\frac{\partial^2 \Omega}{\partial \xi^2} - \frac{\partial^2 \Omega}{\partial \tau^2} - 2i\frac{\partial \Omega}{\partial \xi} - 2i\frac{\partial \Omega}{\partial \tau} = 6\epsilon\left(\frac{\partial^2 p}{\partial \tau^2} + 2i\frac{\partial p}{\partial \tau} - p\right), \quad (1)$$

$$\frac{dp}{d\tau} = i\delta p + \frac{i}{2}(\Omega + s\Omega^* e^{-2i(\tau-\xi)})w - \gamma_2' p, \quad (2)$$

$$\frac{dw}{d\tau} = i(\Omega^* p - \Omega p^*) + is\left(\Omega p e^{2i(\tau-\xi)} - \Omega^* p^* e^{-2i(\tau-\xi)}\right) - \gamma_1'(w+1), \quad (3)$$

where $\tau = \omega t$ and $\xi = kz$ are the dimensionless time and distance; $\Omega = (\mu/\hbar\omega)A$ is the dimensionless field amplitude (normalized Rabi frequency); A and p are the complex amplitudes of the electric field and atomic polarization, respectively; w is the inversion (difference between populations of excited and ground states); $\delta = \Delta\omega/\omega = (\omega_0 - \omega)/\omega$ is the normalized frequency detuning; ω_0 is the frequency of atomic resonance; ω is the light carrier frequency; μ is the dipole moment of the quantum transition; $\gamma_{1,2}' = \gamma_{1,2}/\omega$ are the normalized relaxation rates of population and polarization, respectively; $\epsilon = \omega_L/\omega = 4\pi\mu^2 C/3\hbar\omega$ is the dimensionless parameter of interaction between light and matter (normalized Lorentz frequency); C is the concentration (density) of two-level atoms; $k = \omega/c$ is the wavenumber; c is the speed of light, and $\hbar$ is the Planck constant. Asterisk stands for complex conjugation. We introduced here the auxiliary two-valued coefficient s, so that $s=0$ corresponds to the RWA (absence of "rapidly rotating" terms), while $s=1$ is used in the general case.

Further, we solve Eqs. (1)–(3) numerically choosing the appropriate value of s. The numerical approach is the same as in our previous publication [34], more details on it can be found in [36]. We perform calculations for the following parameters of the medium and light: the relaxation rates $\gamma_1 = 1$ and $\gamma_2 = 10$ ns^{-1} are large enough, so that we are in the regime of coherent light-matter interaction; the detuning $\delta=0$ (exact resonance, $\omega = \omega_0$); the central light wavelength $\lambda = 2\pi c/\omega_0 = 0.83$ μm; and the strength of light-matter coupling $\omega_L = 10^{11}$ s$^{-1} \ll \omega$. For this choice of parameters, the inequality $\Omega\omega \gg \omega_L$ is valid, so that we can neglect here the so-called local field effects [37]. The medium is supposed to be initially in the ground state ($w = -1$).

In this paper, we consider the pulses of Gaussian shape with linear chirp, so that for the incident normalized Rabi frequency (electric field amplitude) we have $\Omega = \Omega_p \exp(-(t-t_0)^2/2t_p^2 + i\beta\omega_0^2 t^2)$, where β is the dimensionless chirp parameter (chirp normalized by $\omega_0{}^2$), i.e. the instantaneous carrier frequency changes linearly with time as $\omega_i(t) = \omega_0 + 2\beta\omega_0^2 t$. The duration of the pulse t_p is defined through the number of cycles N as $t_p = NT/2\sqrt{\ln 2}$, where $T = \lambda/c$ is the period of electric field oscillations. The parameter t_0 governs the instant of maximum of the pulse intensity (the peak offset). It is important to note that the instantaneous frequency is not equal to ω_0 at the pulse peak: $\omega_i(t)$ grows linearly from ω_0 at $t=0$ and, at $t = t_0$, differs from this initial frequency more or less significantly. The peak Rabi frequency Ω_p is measured in the units of $\Omega_0 = \lambda/\sqrt{2\pi}ct_p$ corresponding to the chirp-free pulse area 2π.

3. Long pulses

In this section, we consider the long pulses with the number of cycles $N=50$ and the peak offset $t_0 = 3t_p$. We start with the dynamics of a single chirped pulse in the two-level medium focusing on pulse transmission through layers of different thicknesses. One of our main intentions is to test the applicability of the RWA for description of pulse dynamics. Fig. 1 shows the comparison of the intensity profiles and inversions calculated with and without the RWA for the chirp-free pulse and for the pulse with the chirp

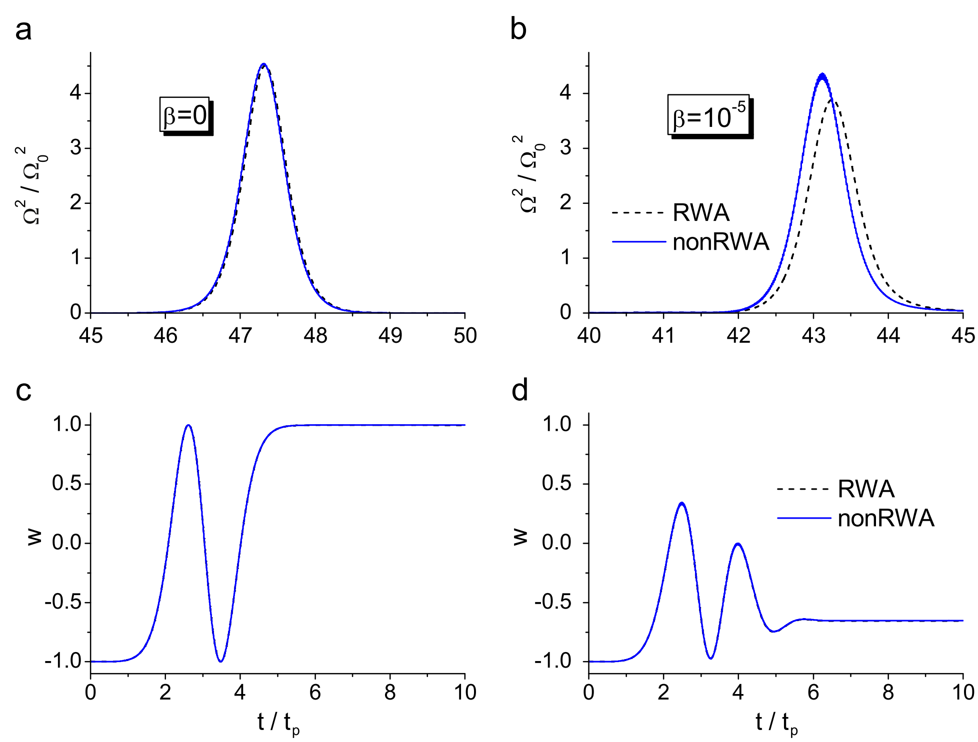

Fig. 1. (a, b) The profiles of transmitted radiation and (c, d) inversion dynamics (at the medium entrance) for the incident pulse (a, c) without chirp and (b, d) with the chirp $\beta = 10^{-5}$. The layer thickness is $L = 1000\lambda$, the pulse amplitude is $\Omega_p = 1.5\Omega_0$.