Optics Communications 364 (2016) 123–128

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Abnormal enhancement against interference inhibition for few-cycle pulses propagating in dense media

Yue-Yue Chen [a,b], Xun-Li Feng [c], Zhi-Zhan Xu [a], Chengpu Liu [a,*]

[a] State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[b] University of Chinese Academy of Sciences, Beijing 100039, China
[c] Department of Physics, Shanghai Normal University, Shanghai 200234, China

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form
18 November 2015
Accepted 19 November 2015
Available online 6 December 2015

Keywords:
Few-cycle pulses propagation
Reflected spectrum
Transient

ABSTRACT

We numerically study the reflected spectrum of a few-cycle pulse propagating through an ultrathin resonant medium. According to the classical interference theory, a destructive interference dip is expected at the carrier frequency ω_p for a half-wavelength medium. In contrast, an abnormal enhanced spike appears instead. The origin of such an abnormal enhancement is attributed to the coherent transient effects. In addition, its scaling laws versus medium length, pulse area and duration are obtained, which follow simple rules.

Recent advances in ultrafast laser technology have motivated the study of the interaction between few-cycle pulses and resonance medium [1,2]. The assumptions that laser pulse only propagates in forward direction and evolves slowly over an optical wavelength are no longer appropriate in this regime [3–5], and full Maxwell–Bloch (MB) equations need to be solved for a complete and correct description of the laser-matter interaction. The implicit inclusion of the effects of counter-rotating wave components and time-derivative of the carrier field make backpropagation and energy decay arise [4], which motivates the study of the reflection of the few-cycle pulse. The reflected spectrum of a few-cycle pulse has many unique features, such as the redshift induced by intrapulse four-wave mixing [6], and low-frequency spike induced by the Doppler effect of the moving absorption front [7]. However, in the above studies, the bulk medium (medium length is much larger than a carrier wavelength, i.e., $L \gg \lambda_p$) is usually adopted. The spectral feature of an ultrathin medium ($L \sim \lambda_p$) has barely touched yet. Questions, such as, whether the redshift still exists in the reflected spectrum and whether the interference between the reflections from the front and back surfaces of an ultrathin atomic system follows the classical interference theory, remain unsolved.

In this paper, we numerically investigate the reflected spectrum of an ultrathin atomic medium. Notable redshift disappears and interference between the reflections from the front and back surfaces begins to take effects. Surprisingly, for a half-wavelength medium, an unexpected spike appears at the carrier frequency ω_p, where destructive interference is supposed to occur. Moreover, when the medium length, pulse area or duration changes, the interference behavior of the spectral amplitude at ω_p also does not follow the prediction of the classical interference theory. By analyzing the formation of the reflected field and the contribution of its each part to the reflected spectrum, the underlying physics behind the abnormal interference is obtained.

We consider the propagation of a few-cycle pulse along $+z$ in vacuum to the front surface of a dense two-level atomic (TLA) medium. Assume that the electromagnetic field is linearly polarized $E = E_x(z)$, $H = H_y(z)$. The Maxwell equations take the form [8]

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_x}{\partial z},$$
$$\frac{\partial E_x}{\partial t} = -\frac{1}{\epsilon_0}\frac{\partial H_y}{\partial z} - \frac{1}{\epsilon_0}\frac{\partial P_x}{\partial t}. \tag{1}$$

The macroscopic nonlinear polarization $P_x(z) = N\,du$, u is the real part of the off-diagonal density matrix element $\rho_{12} = (u + iv)/2$, N the density and d the dipole moment. The population difference between the excited sate 2 and the ground state 1 is denoted by $w = \rho_{22} - \rho_{11}$. u, v and w obey the following set of Bloch equations,

$$\frac{\partial u}{\partial t} = -\gamma_2 u - \omega_0 v,$$
$$\frac{\partial v}{\partial t} = -\gamma_2 v + \omega_0 u + 2\Omega w,$$
$$\frac{\partial w}{\partial t} = -\gamma_1 (w - w_0) - 2\Omega v. \tag{2}$$

* Corresponding author at: State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China.
E-mail addresses: xlfeng@siom.ac.cn (X.-L. Feng), chpliu@siom.ac.cn (C. Liu).

http://dx.doi.org/10.1016/j.optcom.2015.11.051
0030-4018/

where γ_1, γ_2 are, respectively, the population and polarization relaxation rate, ω_0 the transition frequency, $\Omega(\Omega = dE_x/\hbar)$ the Rabi frequency, and w_0 the initial population difference.

The above combined Maxwell–Bloch (MB) equations (1) and (2) can be solved by adopting Yee's finite-difference time-domain discretization method for the electromagnetic fields [9–11] and the predictor–corrector method for the medium variables [3,12]. Incident pulse is $\Omega(t = 0, z) = \Omega_0 \cos[\omega_p(z - z_0)/c]\mathrm{sech}[1.76(z - z_0)/(c\tau_p)]$, where Ω_0 is the peak Rabi frequency for the input pulse, τ_p the full width at half maximum (FWHM) of the pulse intensity envelop. The medium is initialized with $u = v = 0$, and $w_0 = -1$. To study the reflection of the pulse, we adopt the following parameters to integrate the MB equations: $\omega_0 = \omega_p = 2.3\ \mathrm{fs}^{-1}$, $\lambda_p = \omega_p/c$, $d = 2 \times 10^{29}$ A s m, $\gamma_1^{-1} = 1$ ps, $\gamma_2^{-1} = 0.5$ ps, $\tau_p = 5$ fs, $\Omega_0 = 0.704\ \mathrm{fs}^{-1}$, the corresponding pulse area $A(z) = d/\hbar \int_{-\infty}^{\infty} E_0(z, t^{'})\, dt' = \Omega_0 \tau_p \pi/1.76 = 2\pi$. Define a collective frequency parameter $\omega_c = Nd^2/\epsilon_0\hbar = 0.05\ \mathrm{fs}^{-1}$ to represent the coupling strength between medium and field.

With the above parameters, the reflected field and corresponding spectrum for a half-wavelength medium ($L = \lambda_p/2$, λ_p is the carrier wavelength) are obtained, as shown in Figs. 1(a) and (b), respectively. According to the interference theory for reflection, the destructive interference takes place when the condition $2nL = m\lambda_p$ $(m = 1, 2, \ldots)$ is satisfied [13], where n is the refractive index. For a medium with $L = \lambda_p/2$, a destructive interference dip (DID) is expected to appear in the reflected spectrum positioned at $\omega_p(m = 1, n(\omega_p) \approx 1)$. However, an unexpected enhancement spike appears at ω_p (Fig. 1(b)). If investigating carefully to the time structure of the whole reflected field, and dividing them into different parts artificially, the origin of this spike can be easily clarified. Usually, when the pulse impinges on the medium, it is first reflected by the front surface, then further propagates within the medium, and finally reflected by the back surface. The two reflected fields form the leading part (red color part in Fig. 1(a)). It should be point out that this is only correct when the field is weak or large detuning is assumed. When the laser pulse is resonant with the medium, apart from the leading part of the reflected field, a long tail occurs (blue color part in Fig. 1(a)). This is because, after the pulse leaves the medium, a small part of its energy resides in the medium, which indicates itself as Re[ρ_{12}] oscillating at ω_0 with a lifetime T_2. This physical process is the so-called free induced decay (FID) [14]. By taking the Fourier transform to the leading or tail part of the reflected field, we get that the double-peak structure (dashed line) comes from the front and back surface reflections, while the abnormal enhancement spike at ω_p (dot-dashed line) comes from the tail part, as shown in Fig. 1(b). Thus, the abnormal interference for a half-wavelength medium actually results from the coherent transient process, FID. The transient effects still exist under rotating-wave approximation (RWA) and slowly varying envelope approximation (SVEA) [15], therefore the enhancement spikes obtained with full wave MB equations in Fig. 1(b) should not disappear when the RWA is used. To study the effect of RWA to the abnormal enhancement in the reflected spectrum, the complex amplitude $\tilde{\Omega}$ is obtained by solving MB equations with RWA but beyond SVEA [16]. The results are shown in Fig. 2. It can be seen that the long tail corresponding to the transient effect still exists for the envelope solution Ω_0. The reflected field with RWA shown in Fig. 2(b) is obtained with $\Omega(z, t) = \Omega_0 \cos(\omega_p t - k_p z + \varphi)$, $\Omega_0 = \sqrt{\mathrm{Re}[\tilde{\Omega}]^2 + \mathrm{Im}[\tilde{\Omega}]^2}$ and $\varphi = \arctan(\frac{\mathrm{Re}[\tilde{\Omega}]}{\mathrm{Im}[\tilde{\Omega}]})$. The reflected spectra in Fig. 2(c) show that the abnormal enhancement spike with resonance frequency does not vanish under RWA, but enhances compared with the general case. This is because RWA discards rapidly oscillating terms, leading to more energy in atoms oscillating with resonant frequency.

Now if we change the medium length to other parameters,

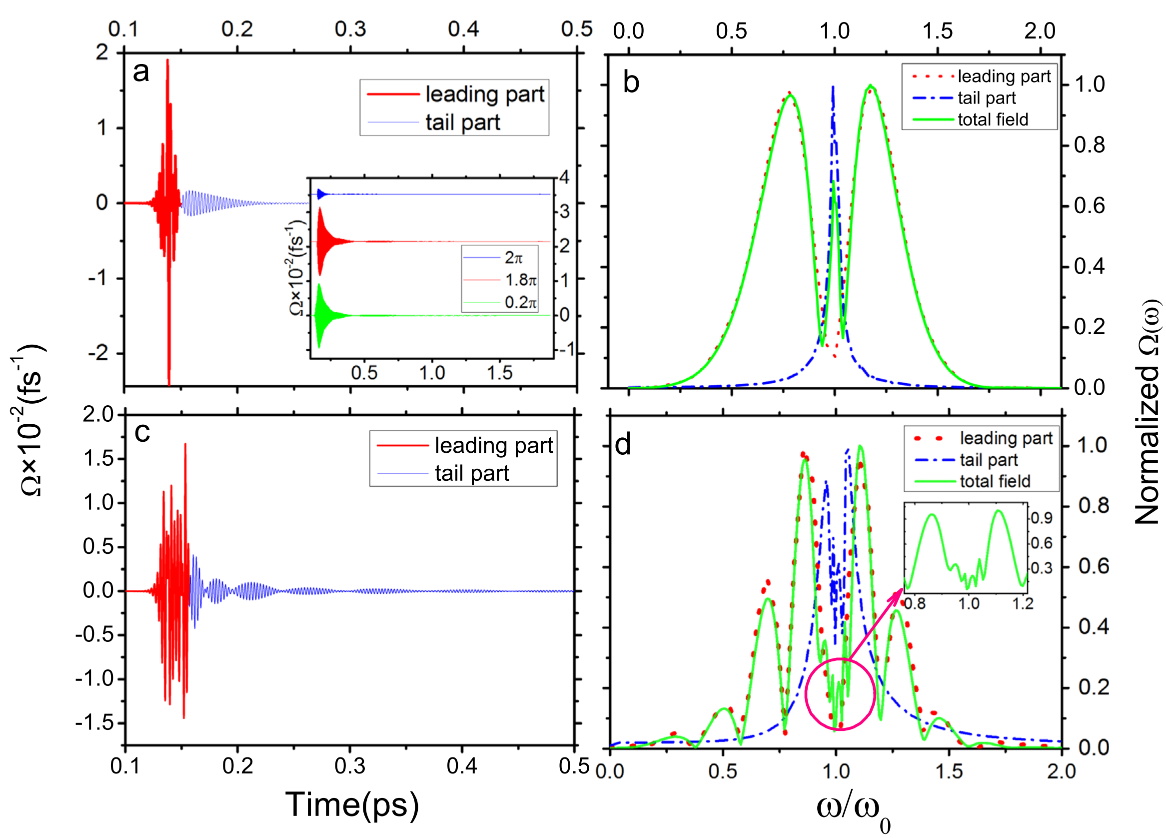

Fig. 1. (left) The reflected fields consist of a leading (thick line) and tail (thin line) parts. (right) The corresponding reflected spectra. The top and bottom are corresponding to $L = \lambda_0/2$ and $2\lambda_0$, respectively. The insert in (a) is the tail parts of the reflected field for 2π (top), 1.8π (middle), and 0.2π (bottom) pulses. The insert in (d) is the enlarged view of the spectral component around ω_0. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)