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Carrier shock and frequency conversion of a few-cycle pulse laser propagating in a non-resonant two-level atom medium*

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We have studied the spectral behaviour of few-cycle soliton pulses in a non-resonant two-level atom medium by solving the full Maxwell–Bloch equations. It is demonstrated further that the carrier effects play an important role in the propagation of the few-cycle pulse laser. When the frequency detuning is not very large, both the population distribution and the refractive index of the medium follow the oscillatory carrier field instantaneously; in this case, carrier-wave compression or carrier shock occurs, and a supercontinuum broader than that in the resonant medium may be generated. When the frequency detuning is large, the carrier shock is weak and the spectrum is not continuous, only showing an odd harmonic radiation.

Keywords: supercontinuum, self-phase modulation, population distribution, carrier shock
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The propagation of the high-peak-power pulse laser in a transparent medium gives rise to strong nonlinear effects such as self-phase modulation (SPM),[1] self-focusing,[2] four-wave mixing (FWM),[3] and so on,[4] which lead to strong modification of the pulse spectrum. During the past few years, intense pulses with only two optical periods or less than 5fs have been obtained,[5,6] and some new spectral behaviours of such pulses propagating in nonlinear resonant media have been found. The intrapulse FWM, which is ignored within the rotating-wave approximation (RWA),[7] will play an important role for the intense few-cycle pulse in a dense resonant two-level atom (TLA) medium, and lead to a large spectral shift.[8] In another resonant TLA medium, the population distribution shows oscillatory features due to the time-derivative behaviour of the electric field of the input few-cycle pulse, more significant higher spectral components appear and the area theorem will break down due to the carrier-wave Rabi flopping (RF).[9]

In our previous work,[10] we have studied the spectrum evolution of the few-cycle optical pulse in a resonant TLA medium by solving the full Maxwell–Bloch (MB) equations beyond the limits of the slowly-varying-envelope approximation[11] and the RWA. It is found that the SPM and the incomplete carrier-wave RF play such an important role in the few-cycle pulse propagation that faster oscillation components appear in the forgoing separated pulses, and a supercontinuum from near ultraviolet to infrared is generated. This is a surprising spectral behaviour for the soliton pulse propagation in a resonant TLA medium. In this paper, as an extension, we study the spectral behaviour of the few-cycle soliton pulse in non-resonant TLA media with different transition frequencies. It will be demonstrated further that the carrier effects, including the carrier SPM, the oscillatory population distribution, and the intrapulse FWM, all are responsible for the spectral behaviour of the few-cycle pulse in a TLA medium.

We consider the propagation of a few-cycle pulse laser along the z-axis in vacuum to an input interface of a TLA medium at z=0, then the pulse propagates into the medium. The MBl equations take the form:[10]

$$\partial_t H_y = -\frac{1}{\mu_0}\partial_z E_x, \tag{1a}$$

$$\partial_t E_x = -\frac{1}{\varepsilon_0}\partial_z H_y - \frac{1}{\varepsilon_0}\partial_t P_x. \tag{1b}$$

$$\partial_t u = -\gamma_2 u - \omega_2 v, \tag{2a}$$

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$$\partial_t v = -\gamma_2 v + \omega_2 u + 2\Omega w, \tag{2b}$$

$$\partial_t w = -\gamma_1 (w - w_0) - 2\Omega v, \tag{2c}$$

where E_x and H_y are the electric and magnetic fields, and γ_1 and γ_2 are the population and polarization relaxation constants, respectively. ω_0 is the transition frequency of the non-resonant medium, and $\Omega = \mathrm{d}E_x/\hbar$ is the Rabi frequency. The macroscopic nonlinear polarization $P_x = N\mathrm{d}u$ is related to the off-diagonal density matrix element $\rho_{12} = (u + iv)/2$ and the population difference $w = \rho_{22} - \rho_{11}$ between the upper and lower states. N is the density of the medium, d is the dipole moment, the refractive index is determined by the real part of ρ_{12} and the gain coefficient is proportional to the imaginary part of ρ_{12}.

The initial conditions are taken to be the same as those in Ref.[10] for solving the MB equations. The input soliton pulse is $\Omega(t = 0, z) = \Psi(t = 0, z) = \Omega_m \cos[\omega_p(z+z_0)/c]\mathrm{sech}[1.76(z/c+z_0/c)/\tau_p]$ where ω_p is the carrier frequency, Ω_m is the maximum Rabi frequency and τ_p is the FWHM of the pulse intensity envelope. The values of the following parameters are also the same as those in Ref.[10]: τ_p=5fs, ω_p=1.5fs^{-1} (λ=1256 nm), z_0=15μm, $d = 2 \times 10^{-29}$ A s m, N=0.8$\times$10^{26}m^{-3}, $\gamma_1^{-1} = \gamma_2^{-1}$=1ns. The corresponding pulse area is $A = \Omega_m \tau_p \pi/1.76$, and Ω_m=1fs^{-1} corresponds to the electric field of E_x=5$\times$10^{9}V/m or an intensity of $I = 6.6 \times 10^{12}$W/cm^2.

We first model the propagation of an 8π pulse (Ω_m=2.816fs^{-1}, τ_p=5fs) in the non-resonant TLA medium with a transition frequency $\omega_0 = 2\omega_p$=3fs^{-1}. Figure 1(a) shows the Rabi frequency (solid line) of the propagating 8π pulse, the population difference (dashed line), and u (dotted line) at the propagation distance of z=12μm. As is known, a strong pulse laser propagating in a medium may cause an intensity-dependent refractive index change of the medium, the medium then reacts back and inflicts a phase change on the incoming pulse, resulting in a SPM. We can see that, for the few-cycle pulse laser propagating in a TLA medium, u, which determines the refractive index of the medium, follows the carrier field instantaneously, and the peak of u appears when the carrier field varies rapidly. Hence, in turn, the carrier field will be modulated instantaneously, i.e. a type of carrier SPM occurs. On the other hand, the population distribution is also closely connected with the oscillation of the carrier field although the population cannot be inversed completely in the non-resonant medium, and the maximum inversion occurs at the maximum of the carrier field.

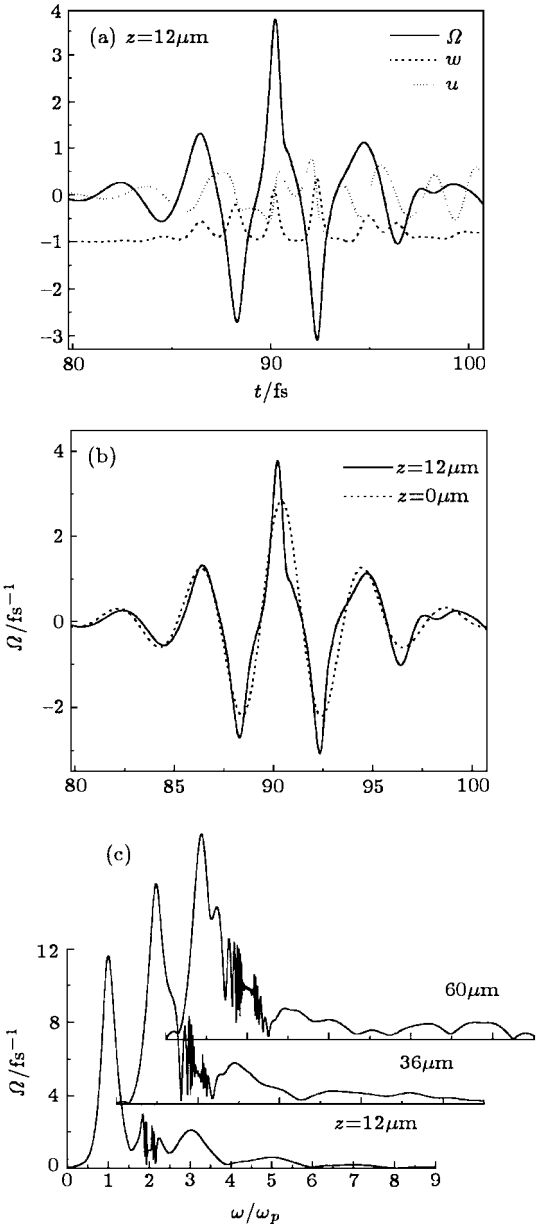


Fig.1. (a) The carrier field of the 8π pulse Ω(fs^{-1}) (solid line), the population difference w (dashed line), u (dotted line) at the propagation distance of z=12μm. (b) The carrier fields of the 8π pulse at z=12μm (solid line) and z=0μm (dashed line). (c) The corresponding spectra of the carrier fields at z=12, 36 and 60μm, respectively. The transition frequency of the non-resonant medium is ω_0=3fs^{-1}.

Since the carrier wave is modulated by both the carrier SPM and the oscillatory population distribution, it is strongly reshaped. In Fig.1(b), we can see clearly that the carrier field at z=12μm (solid line) is quite different from the input electric field (dashed line). The top of the carrier wave is compressed and becomes more intense, i.e. a type of carrier compression occurs. The corresponding spectrum in Fig.1(c)

is broadened and shows distinct peaks at odd harmonics. This is similar to that of the carrier shock.[12] However, the odd harmonics are not phase-matched in the nonlinear medium, then the spectral peaks at z=36μm are no longer clear and a spectral plateau from 5ω_p (λ=251nm) to 9ω_p (λ=140nm) appears. Because the 8π soliton pulse is difficult to split in a non-resonant medium, more energy of the pulse is transferred to the higher spectral components due to the carrier reshaping. The spectrum thus spans a broader range (from ultraviolet to infrared) than that in a resonant medium (from near-ultraviolet to infrared)[10] and the spectral components from 6ω_p to 8ω_p increase at z=48μm. In such a broadband frequency conversion and such an interesting spectral evolution, we should expect that the intrapulse FWM, which is ignored in the framework of RWA, may play an important role.

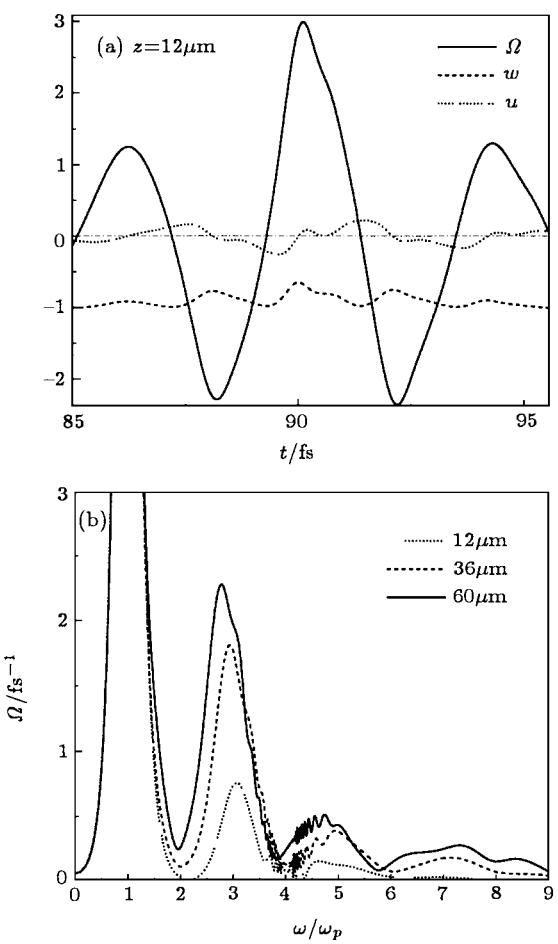


Fig.2. (a) The carrier field of the 8π pulse Ω(fs^{-1}) (solid line), the population difference w (dashed line) and u (dotted line) at the propagation distance of z=12μm. (b) The corresponding spectra of the carrier fields at z=12, 36 and 60μm, respectively. The transition frequency of the non-resonant medium is ω_0=6fs^{-1}.

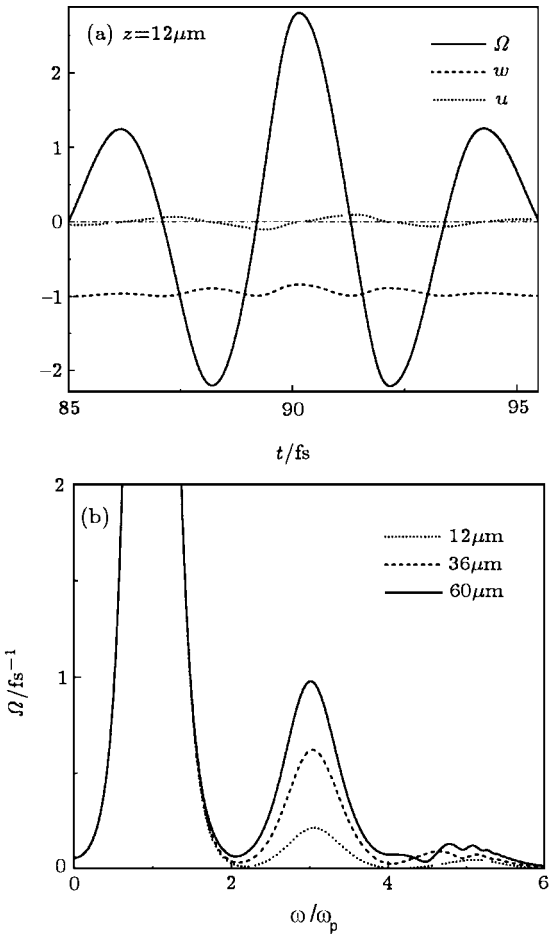


Fig.3. (a) The carrier field of the 8π pulse Ω(fs^{-1}) (solid line), the population difference w (dashed line) and u (dotted line) at the propagation distance of z=12μm. (b) The corresponding spectra of the carrier fields at z=12, 36 and 60μm, respectively. The transition frequency of the non-resonant medium is ω_0=9fs^{-1}.

Figure 2 presents the corresponding profiles of the 8π pulse in the non-resonant medium with ω_0=6fs^{-1}, which is four times that of the carrier frequency. In Fig.2(a), although both u (dotted line) and the population difference (dashed line) follow the electric field instantaneously, they vary within a small range, so the carrier wave reshaping (solid line) is not as evident as that in Fig.1(a). However, Fig.2(a) shows that u is negative at the leading side of the carrier wave and is positive at the trailing side, and the absolute value of u is small near the maximum of the electric field. In this case, the wave with higher values of E_x propagates faster than that with lower E_x. Then a nonlinear distortion occurs towards the leading side of the carrier wave and the so-called carrier shock appears. The spectra in Fig.2(b) show a strong third-harmonic radiation, while higher harmonics are weak and not phase-matched. With further propagation of the car-

rier wave, evident spectral shift occurs to the third harmonic, and the spectral components between the first and the third harmonics increase. In addition, we stress that the carrier shock is also discussed theoretically in triple-resonance Lorentz dielectric media with subfemtosecond nonlinear electronic Debye relaxation, wherein the full Maxwell equations are employed.[13] And again, because a femtosecond pulse propagates in a weak dispersive medium with linear Lorentz response and a Kerr nonlinearity, the carrier distortion occurs towards the trailing side.[12]

To make a further comparison, we consider also the propagation of the 8π pulse in the medium with $\omega_0 = 6\omega_p$=9fs^{-1} in Fig.3. When the frequency detuning is large, the effect of the carrier field on u and the population distribution is weak, so the carrier shock is too trivial to discover and the corresponding spectra show a weak third harmonics. But in this case, the third harmonics are nicely phase-matched and the spectral shift at further distances is not evident; thus they look like those in a dispersionless medium. With this comparison, it can be inferred that it is the carrier SPM, the oscillatory population distribution of the medium, as well as the intrapulse FWM (with further propagation) that affect the propagation of the few-cycle pulse laser in a TLA medium.

In conclusion, by comparing the spectrum behaviours of the propagating few-cycle pulse in a nonresonant TLA medium with different transition frequencies, we have demonstrated further that the carrier effects play an important role in the propagation of the few-cycle pulse laser. When the frequency detuning is not very large, the carrier wave is reshaped strongly and a supercontinuum from ultraviolet to infrared is generated. When the frequency detuning is large, the carrier effects are weak and the carrier shock only shows a weak odd harmonic radiation.

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