Generation of high-intensity individual attosecond pulses

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ABSTRACT

The generation of individual high-intensity attosecond pulses by stimulated electronic Raman self-scattering of femtosecond optical pulses is investigated through numerical simulation. The shortest and most intense attosecond pulses are found to occur for 4π-pulses, which are associated with previously predicted self-induced transparency in the stimulated Raman self-scattering of fs-pulses. The simulations show that an initial 10 fs laser pulse (4 optical cycles at the full width at half maximum with 780 nm wavelength) is transformed into a pulse of width 0.33 fs having a peak intensity significantly greater than the initial pulse.

Keywords: Individual attosecond pulses, rare gases, supercontinuum, electronic Raman scattering

1. INTRODUCTION

At present the interest to generate subfemtosecond pulses is quickly rising (see, for example, [1-11] and references cited therein). A method to obtain 980-attosecond beats by way of transient four-wave mixing on Na D doublet lines was proposed in Ref. [1]. However, this method don't permits to obtain a following decrease in the pulse duration nor a dramatic increase in the peak intensity of the pulse. Another way to generate attosecond pulses, which has been discussed in many works (see, for example, [2,3,8-11] and references cited therein), is based on high harmonic generation (HHG). But the achieved efficiency of conversion of energy from driving pulse into HHG is below 10^{-5} [12]. Recently a method for generating attosecond pulses at a possibly much higher conversion efficiency was proposed [4,5,7]. It is predicted the method can be realized by means of multiple simulated Raman scattering (SRS) at vibrational as well as rotational transitions in molecular gases. All above mentioned methods expect the four-wave mixing on Na are based on a Fourier synthesis of discrete equidistant frequencies of spectra (HHG or multiple SRS), generating only periodic subfemtosecond pulse trains with the pulses separeted, for example, under vibrational SRS, by about 8 fs [4,5], and under rotational SRS, by 57-94 fs [4,7]. Therefore, those methods do not permit to generate individual attosecond pulses having extreme intensities since the energy is destributed into a number of individual peaks. The formation of individual 10 - 0.1 femtosecond pulses consisting of a half-cycle electromagnetic field was investigated in Ref. [6] relying on the two-level (Bloch) equations as well as on a classical nonlinear (Duffing) equation to approximate the interaction with noble atoms. It is necesary to stress that the idea of generating half-cycle pulsed elecromagnetic fields with two-level system is not new. The exact soliton-like solution for propagation of half-cycle pulses in strongly driven two-level systems described by the full Maxwell-Bloch equations, had been found long ago [13-15]. These solutions, being soliton-like pulses of one-quantum self-induced transparency (SIT) for real elecromagnetic field, have strict correspondence $E \sim h/(d \cdot \tau)$ between the duration τ and amplitude E of each pulse and the dipole moment d of the one-quantum transition [6,15]. Therefore, as was estimated in [15], even at τ=1 fs the intensity I of such a pulse must be about $10^{15} W/cm^2$. Because of the necessity of such high intensity, the idea was rejected in [15]. As was estimated in [6], the 0.2-fs half-cycle pulsed solitons must have an intensity of about $10^{16} W/cm^2$, an amplitude approaching the atomic field strength and a continuous power spectrum from zero frequency to 144 nm wavelength (i.e. in the far ultraviolet). In addition to the problems connected with ionization, since, for example, at the intensity of $3 \times 10^{14} W/cm^2$ approximately half the atoms of Ar, and at the intensity about $2 \times 10^{15} W/cm^2$ approximately half the atoms of He are ionized [16], the idea has difficulties stemming from the two-level approximation. Since in [6] the one-quantum transition from the ground energy state to the excited state is considered for strongly driven noble atoms (i.e., one-quantum Rabi frequency is much more than $1/\tau$) and since the subfemtosecond solitons (see, for example the 0.2-fs half-cycle pulse soliton mentioned above) have very broad

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and continuous spectra, then the other states of these excited atoms are resonantly stimulated by spectra of such solitons; that is other stimulated one-quantum transitions must be taken into account.

New way to generate intense individual attosecond pulses based on stimulated Raman self-scattering (SRSS) [17-20] of femtosecond pulses was proposed recently [21,22]. SRSS is resonant coherent SRS when the frequency of Raman transition is contained by the spectrum of initial pulse [23]. The continuous Stokes frequency shift associated with the spectral broadening of femtosecond pulses under SRSS in vibrational transitions was experimentally investigated in different media [24]. In [17-20] it was shown theoretically that under SRSS the spectral broadening in the Stokes direction takes place when the two-photon Rabi frequency that correspond to this stimulated Raman process is less than π/τ. For pulses with higher intensity, when the two-photon Rabi frequency is greater than π/τ (especially $\sim 2\pi/\tau$), the superbroadening in both the anti-Stokes and Stokes direction and the generation of a spectral supercontinuum occur [18-20]. For the first time, supercontinuum generation in noble gases by fs-pulses was demonstrated in [25]. It is known that SRS can be realized not only in vibrational or rotational modes but also in purely electronic states (electronic SRS) [26-28], states connected with the spin flip and others [28,29]. For example, electronic SRS was observed with transition frequency $\Omega/2\pi c = 58\ cm^{-1}$ in K atoms [26,27], and $\Omega/2\pi c = 882.5\ cm^{-1}$ in Cl atoms between $^2P_{3/2}$ and $^2P_{1/2}$ states [30], and in noble gases [31]. Therefore, as soon as the condition for SRSS be realized (i.e. a transition frequency of SRS be contained in spectrum of pulse) a electronic SRSS can also be realized for these transitions. In [21,22] a scheme was proposed based on self-indued transparency (SIT) in SRSS [18-20] of 5- and 7-fs pulses for a Raman transition in the fine structure $^2P_{3/2}$-$^2P_{1/2}$ levels of the Ne^+, Ar^+, Kr^+, Xe^+ ions to generate attosecond pulses. The ground $^2P_{3/2}$ and the nearest excited $^2P_{1/2}$ states of these ions form a two-level system with transition forbidden in the electro-dipole approximation of a one-quantum process, but permitted for a two-quantum process like SRSS.

In this paper, we present computer simulations for the generation and amplification of intense individual attosecond pulses through SRSS, utilizing initial laser pulse durations ranging from 2.5 fs to 10 fs. We have investigated SRSS of laser pulses specifically for the cases where the initial pulse contains one, three, and four optical cycles (within the Full-Width-at-Half-Maximum (FWHM) of the intensity profile of the laser pulses (780 nm)). In all cases, the amplitudes of the resulting attosecond pulses are significantly greater than the amplitude of the initial pulses. We find that the efficiency of self-compression and "self-amplification" depends sensitively on the initial duration of the laser pulse, or rather the number of optical cycles initially present in the laser pulse. The result is also sensitive to the optical path length of the medium wherein saturation of the self-amplification occurs. We demonstrate that the production of attosecond pulses, when the initial pulse contains either three or four optical cycles (FWHM) can be considerably enhanced by adjusting the intensity to make the initial pulse a 4π-pulse rather than a 2π-pulse as in SIT for SRSS. In this case, the 4π-pulse splits into two 2π-pulses and one of these evolves into a very sharp and intense peak at the others expense. The splitting of the 4π-pulse into two propagating 2π-pulses also takes place in a single-quantum [33,34], double-quantum [35,36] and ordinary Raman transition SIT [37,38], but in contrast with these situations [33-38] the 2π-pulses in SIT for SRSS are nonstationary in both shape and spectrum. However, the total laser pulse energy is conserved [18-21]. In this case, the trailing edge of the laser pulse is enriched with high-frequency components into which the energy from the front of the pulse is transferred, and the pulse field is dramatically compressed.

2. BASIC EQUATIONS

We will consider the propagation of a laser pulse with a duration which satisfies the condition

$$\tau^{-1} > \Omega\ , \tag{1}$$

where $\hbar\Omega = \epsilon_2 - \epsilon_1$ is the difference in level energies participating in the regime (1) of the SRSS in the medium. When the field spectrum encloses the spectral bandwidth of a resonant Raman transition as required in inequality (1), the intensity of the laser pulse that is necessary for the realization of the nonlinear SRSS regime decreases dramatically. In this case, the laser pulse contains a wide range of frequency components with comparable high amplitudes to stimulate the Raman resonance. This means that the field of the laser pulse as well as the polarization of the medium can be represented by intact semiclassical waveforms rather than by the photon interaction picture [17-19]. We will consider the stimulated Raman scattering within the framework of a semiclassical model [28,29,39], when the dynamics of the laser pulse field is described by the wave equation

$$\frac{\partial^2 \mathcal{E}}{\partial z^2} - \frac{1}{v^2}\frac{\partial^2 \mathcal{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P_{nl}}{\partial t^2}\ , \tag{2}$$

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where v is the speed of the laser pulse arising from the linear contribution to the polarization, and P_{nl} is the nonlinear contribution to the polarization, caused by stimulated Raman process. The Raman-active medium is described by a two-level model where the direct single-quantum transitions between the levels are forbidden in the electro-dipole approximation, but permited for two-quantum prosess like the SRSS. The frequency of the Raman transition Ω is considered to be much less than the central frequency ω_o of the initial laser pulse field $\mathcal{E}$. The average value of a polarizability $< \alpha >= Sp(\alpha\rho)$ and the difference of the level populations $w = \rho_{22} - \rho_{11}$, where α is the operator of polarizability of the medium and ρ is the density matrix, are described by the equations [28,29,39]:

$$\frac{\partial^2 < \alpha >}{\partial t^2} + \frac{2}{T_2} \cdot \frac{\partial < \alpha >}{\partial t} + \Omega^2 < \alpha > = - \mid \alpha_{12} \mid^2 \frac{\Omega}{\hbar} \cdot \mathcal{E}^2 \cdot w \ , \tag{3}$$

$$\frac{\partial w}{\partial t} + \frac{(w - w_o)}{T_1} = \frac{1}{\hbar\Omega} \cdot \mathcal{E}^2 \cdot (\frac{\partial < \alpha >}{\partial t} + \frac{< \alpha >}{T_2}) \ , \tag{4}$$

where $\mid \alpha_{12} \mid$ is a value of the matrix element of the polarizability corresponding to the Raman transition with frequency Ω. The parameter T_2 is the dephasing time or the time of Raman coherence, and T_1 is the population relaxation time. Since we will consider coherent interactions only ($(\tau \ll T_2, T_1)$), we can neglect the terms related to the relaxation times and in Eqs. (3) and (4). The nonlinear dipole moment related to stimulated Raman process is $d = \alpha \cdot \mathcal{E}$. The nonlinear contribution to the polarization of the medium included in Eq. (2) is given as

$$P_{nl} = N \cdot < \alpha > \cdot \mathcal{E} \ , \tag{5}$$

where N is the number density of Raman-active particles. For further consideration, it is convenient to introduce an angle of rotation of the material variable [17-19]:

$$\varphi(t, z) = \frac{\mid \alpha_{12} \mid}{\hbar} \cdot \int_{-\infty}^{t} \mathcal{E}^2(t', z) dt'. \tag{6}$$

The quantity $S(z) = \varphi(+\infty, z)$ is the integral over the entire pulse of the two-photon Rabi frequency of the stimulated Raman process.

The numerical solutions of Eqs. (2) - (4) in the case of a coherent interaction for a laser pulse with $S(0) = 2\pi$ and for various $\beta \cdot z$, where $\beta = 2\pi N \mid w_o \mid \cdot \mid \alpha_{12} \mid v\,\Omega/c^2$, were carried out in previous works [40-42]. [The quantity β^{-1}, which has the dimension of length, can be interpreted as the length of coherent SRSS.] The results for the 2π-pulses and $\beta \leq 1$ show that when the medium is initially unexited ($(w(0, z) = w_o = -1, < \alpha(0, z) >= 0)$), less than one part in ten thousand of the pulses energy is scattered in the reverse direction. It is therefore a very good approximation to introduce a reduced wave equation [17-22]:

$$\frac{\partial \mathcal{E}}{\partial z} + \frac{1}{v}\frac{\partial \mathcal{E}}{\partial t} = -\frac{4\pi v}{c^2}\frac{\partial P_{nl}}{\partial t} \ , \tag{7}$$

which describes only the forward scattering of the field. It should be noted that for single-quantum SIT, the transition from Eq. (2) to Eq. (7) was earlier shown to be appropriate [13-15]. When $\tau^{-1} >> \Omega$, the laser pulse energy is altered by the law [17,19]

$$\frac{dS}{dz} = \beta(1 - cosS) \ , \tag{8}$$

which is practically the same as for the case of a coherent two-photon interaction of a field with a resonant medium [35]. A laser pulse with $S(0) = 2\pi$ can propagate through medium ($\beta \cdot z \approx 1$) in the SIT at SRSS regime [17,19,20]. Propagation of the pulses with $S = 2\pi$ leads to effective self-broadening of the spectrum and the generation of a spectral supercontinuum due to the SRSS [18-21]. It should be noted that the possibility to satisfy the phase matching conditions automatically [43-45] is one of the important and interesting features of nonlinear processes related to resonant SRS. In the case of the SRS satisfying condition (1), the conditions for phasematching in the nonlinear process of SRSS are explicitly satisfied [44].

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3. RESULTS OF NUMERICAL SIMULATION

We investigated the dynamics of a laser pulse having initially a Gaussian shape given by

$$\frac{\mathcal{E}(t,0)}{\mathcal{E}_o} = \sin(\omega_o t)\exp\{-2\ln 2\cdot(\frac{t}{\tau_o})^2\}, \tag{9}$$

where $\mathcal{E}_o$ is the initial peak field amplitude and ω_o is the initial frequency of the laser field that propagates through the medium, initially unexcited (i. e., $w(0,z) = w_o = -1, < \alpha(0,z) >= 0$). The dynamics of the field of the 2.5-fs pulse with $S = 2\pi$ and containing initially one optical cycle within the FWHM of intensity (at 780nm), and containing initially three optical cycles (τ_0 =7 fs, at 780 nm) are shown in Figs. 1 and 2, respectively. The energy of the 2π-pulses is conserved when propagating in the conditions of SIT for SRSS (see Eq. (8) and [19]). But in contrast to single-quantum [33,34,46], double-quantum [35,36] and ordinary Raman SITs [37,38], the 2π-pulses with SRSS are nonstationary both in shape and in spectrum (see Figs. 1, 2 and [18-22]). The field on the leading edge of the pulse transfers the medium to the excited state, and the amplitude of the pulse's leading edge decreases (Figs. 1, 2). The wavelength of this portion of the field is shifted toward the red (continuous Stokes shifting). The field of the following portion of the laser pulse causes a coherent transfer of the medium to the initial state, resulting in an increase in amplitude to the trailing part of the pulse. The wavelength of this portion of the field is shifted toward the blue (continuous anti- Stokes shifting) (Fig. 1, 2). During this process, the overall energy of the laser pulse is conserved, but a large share of the energy is moved (or pumped) into the higher-frequency band. For the laser pulse containing one optical cycle, this nonlinear transformation of the field causes self-compression of the pulse to a duration as short as τ = 0.23 fs (half optical cycle (FWHM) after passing through an optical length of βz =0.9 (Fig. 1(d)). At the same time, the "self-amplification" results in a factor of three increase in peak intensity. The 7-fs pulse containing three optical cycles undergoes self-compression to a duration as short as τ = 1.2 fs (one optical cycle (FWHM)) after passing through an optical length of βz =0.8 (Fig. 2(d)). This duration is about one optical cycle of the new shifted center wavelength which is a factor of two less than the original. The self-amplification results in a growth in the peak intensity of a factor two. It is significant that the efficiency of the self-compression and self-amplification is greatest when the initial duration is shorter as seen in Figs. 1, 2. However, as will be shown below, an alternative scheme for high-efficiency self-compression and self-amplification through SRSS is able to accommodate somewhat longer initial pulse durations.

The dynamics of the field of 4π-pulses ($S = 4\pi$) containing initially three (τ_0 =7 fs FWHM, 780 nm) and four optical cycles (τ_0 =10 fs FWHM, 780 nm) within the FWHM is shown in Figs. 3 and 4, respectively. The splitting (or pulse breakup) of the 4π-pulse into two pulses (see Figs. 3(b,c,d) and 4(b,c,d)) is characteristic of all types of SIT [33-38,46], and is also evident here for the SIT at SRSS. In this case, the forward pulse is compressed into a half-cycle electromagnetic field (τ =0.23 fs in Fig. 3(d), and τ =0.37 fs in Fig. 4(d)). From Fig. 3 and Fig. 4 the general trend can be seen that the efficiency of the self-compression and self-amplification improves for shorter initial laser pulses. Also, as seen from Fig. 2 and Fig. 3 the efficiency of the self-ompression and self-amplification in case of 4π-pulses is remarkably better than for the 2π-pulses, albeit on only one of the resulting double peak. In addition, we find that the saturation for the 4π-pulse with initially three optical cycles take place after passing through an optical length of about βz =1 (Fig. 3(c,d).

SRSS (as well as SRS) of laser pulses can be realized in different media and quantum states (see, for examples, [12-23, 28-30]), but most purely the above two-level model of the SRSS can be realized in the ions of the noble gases. SRSS can be realized at transitions between fine structure $^2P_{3/2}$-$^2P_{1/2}$ levels of the Ne^+, Ar^+, Kr^+, Xe^+ ions. For example, in Ne^+ the ground state $^2P_{3/2}$ and the neighboring excited state $^2P_{1/2}$ form a two-level system where the frequency transition is $\Omega/2\pi c$ = 780,4 cm^{-2}, and the transition is forbidden by parity in the electro-dipole approximation for one-quantum process, but permited for two-quantum process like SRSS. All other levels are removed on $\Delta >$ 212045 cm^{-3} [32]. A similar situation exists in the ions of the other noble gases. Since a 10-fs pulse has a spectral bandwidth no less then 3336 cm^{-1} the transition frequency is easily contained within the spectrum of the pulse (as well as of dulses having a duration less than this), i.e., the conditions for SRSS are satisfied. Furthermore, all attosecond pulses with durations from 0.8 fs to 0.16 fs have spectral band no more then 210000cm^{-1}, i.e., for such attosecond pulses the two-level approximation for SRSS should work very good.

It is important to note that we show, in this paper, the exact solutions of the full system of the Eqs. (3)-(5) and (7), without the requirement $\tau^{-1} \gg \Omega$. This requirement, however, was used to derive Eq.(8) from Eqs. (3)-(5), (7) by neglecting the term $\Omega^2 < \alpha >$ in Eq. (3) [17]. For strong fields, where $S(0) \sim 2\pi$ or greater, and for optical lengths

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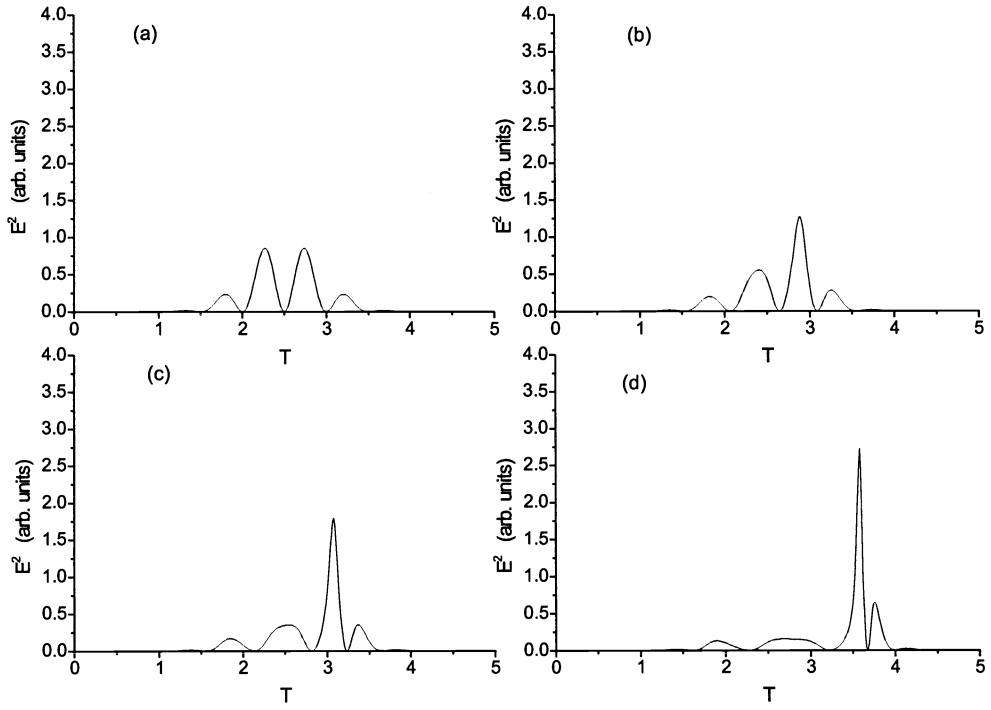


Figure 1. Temporal profiles of the pulse fields $E^2 = (\mathcal{E}/\mathcal{E}_o)^2$ vs $T = t/\tau_0$ for (a) the initial Gaussian 2π-pulse containing one optical cycle (FWHM) and after passing $z \cdot \beta$ = (b) 0.23 ; (c) 0.46 ; (d) 0.92 .

of $\cdot z \sim 1$ and more, Eq. (8) no longer holds, as has been shown by the numerical simulations of the Eqs. (3)-(5) and (7) [20]. For the strong fields that we have investigated in this paper, the frequency of the Raman transition Ω depends on the fields, and we can introduce only an effective β that, being proportional to Ω, is also a function of the field strength. For instance, Ω is function of intensity I, according to the well-known dynamic Stark effect (see, for example, [98,41]). Because we have the exact solutions of the full system of the Eqs. (0)-(5) and (7), this dependence on the Raman frequency and β from laser fields is contained automatically in the results.

It is notable that if the SRSS is realized through a real level, as opposd to a virtual level, the cross section of the SRSS is increased considerably. For example, the measured SRS cross section on electronic transition $4P_{3/2}$ - $5P_{3/2}$ in potassium atoms [26] is ($\sigma \simeq 4.8 \times 00^{-21}\mathrm{cm}^2$) 8 orders of magnitude higher than for the vibrational transition of typical SRS media as molecular benzene. It is well known that the cross section of the two-photon resonant processes is directly proportional to the intensity of the pulse [28].

For example, it has been found experimentally that in Xe there are two-photon excitations having stimulated Raman processes with a two-photon Rabi frequency $S(0)/\tau_o \simeq 10 \cdot I(W/cm^2)$ and effective cross section $\sigma_{eff}(cm^2) \simeq 10^{-28} \cdot I(W/cm^2)$ [50]. This means we will have $S(0) \simeq 4\pi$ and $\beta = \sigma_{eff} \cdot N \simeq 10^3 cm^{-1}$ for $\tau_0 = 10$ fs, I = $10^{14} W/cm^2$, and $N = 10^{17} cm^{-3}$.

Finally, we have calculated the effect of a plasma on coherent lengths. The estimates that we used for the density of ions was $\sim 10^{17} cm^{-3}$, then the density of free electrons is $\sim 10^{17} cm^{-3}$. In this case, the electron plasma frequency is $\omega_p \sim 10^{13} s^{-1}$ and, for example, for frequency that equals the third harmonic ω_3 ~267 nm (remembering that the spectrum of our attosecond pulse is a supercontinuum) the coherent length is $L_c = 1.1$ mm ($L_c = 2/(3k_1 - k_3)$, and for $\omega_j \gg \omega_p$ the wave number of the j-th harmonic is given by $k_j = (1 - (\omega_p/\omega_j)^2)^{1/2} \omega_j/c$, j=1,3)(see, for example, [39]). For a frequency that equal to the 11-th harmonic (ω_{11} ~73 nm) the coherent length $L_c = 0.47$ mm. These coherent lengths are much longer than for the SRSS lengths used in our paper.

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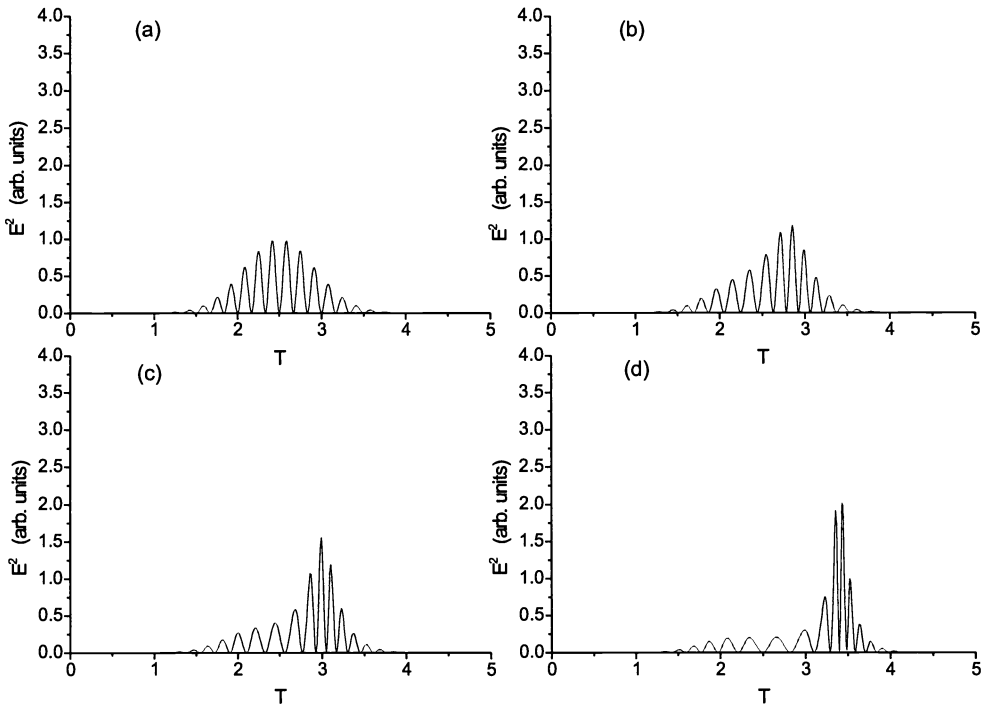


Figure 2. Temporal profiles of the pulse fields $E^2 = (\mathcal{E}/\mathcal{E}_o)^2$ vs $T = t/\tau_0$ for the (a) initial Gaussian 2π-pulse containing three optical cycle (FWHM) and after passing $z \cdot \beta =$ (b) 0.2 ; (c) 0.4 ; (d) 0.8 .

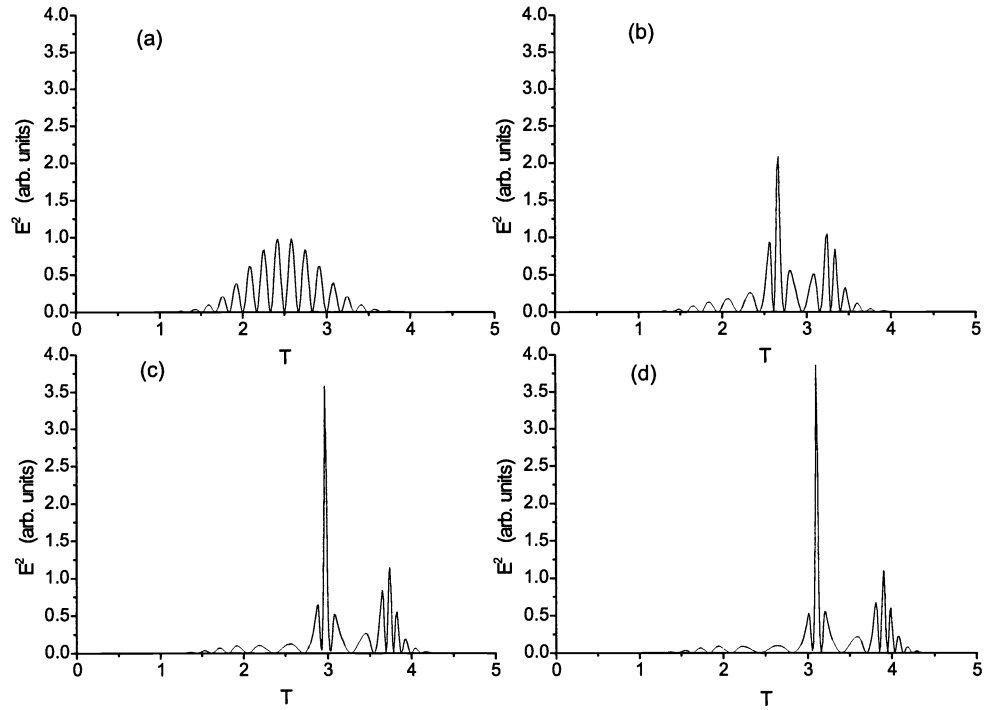


Figure 3. Temporal profiles of the pulse fields $E^2 = (\mathcal{E}/\mathcal{E}_o)^2$ vs $T = t/\tau_0$ for (a) the initial Gaussian 4π-pulse containing three optical cycles (FWHM) and after passing $z \cdot \beta =$ (b) 0.25; (c) 0.5; (d) 1.

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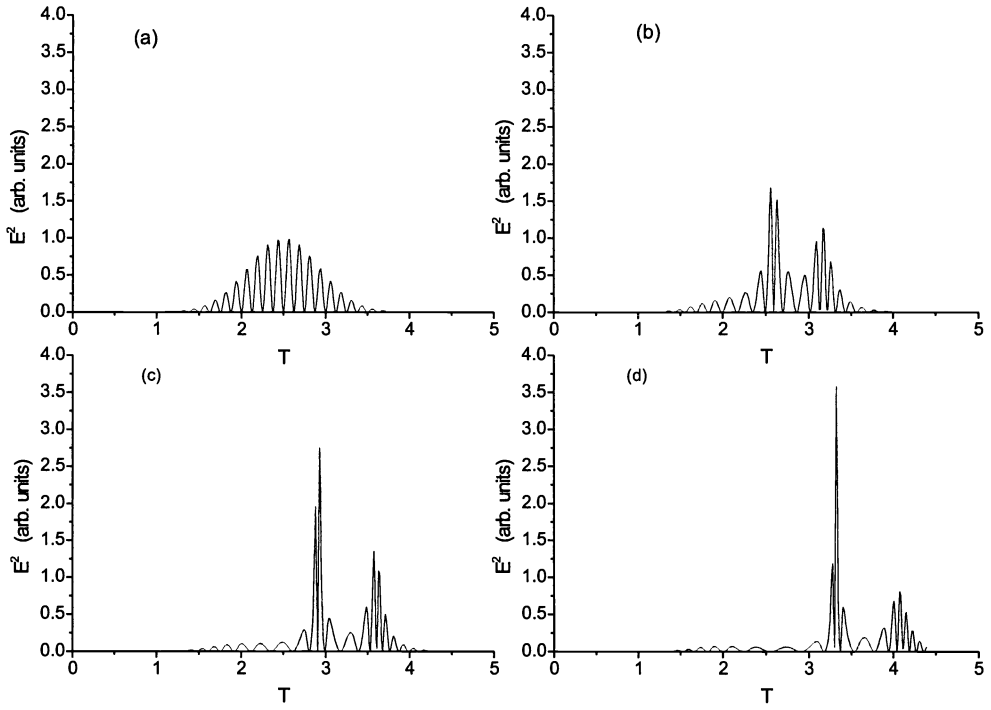


Figure 4. Temporal profiles of the pulse fields $E^2 = (\mathcal{E}/\mathcal{E}_o)^2$ vs $T = t/\tau_0$ for (a) the initial Gaussian 4π-pulse containing four optical cycles (FWHM) and after passing $z \cdot \beta =$ (b) 0.31 ; (c) 0.62 ; (d) 1.24.

4. SUMMARY AND CONCLUSIONS

We have investigated by means of computer simulation the possibility of self-compression and self-amplification of laser pulses containing several oscillation periods of the field under conditions of SRSS. The simulations show that in the regime of SIT with SRSS the nonlinear transformation of 2π-pulses causes an increase in the peak intensity of the later portion of the laser pulse, while conserving the overall energy in the pulse. A continuous spectral shifting of the increasing portion of the field towards higher frequencies accompanies the effect. The leading edge pumps the Raman quantum transition coherently, decreasing its intensity and shifting its spectrum towards lower frequencies. As the energy is deposited on the latter portion of the pulse, a self-compression and a kind of self-amplification takes place as a spike of concentrated energy builds. The efficiency of this process improves as the duration of the initial laser pulse decreases. It is also a nonlinear function of the optical propagation length. The self-compression and self-amplification phenomenon is considerably enhanced by going to 4pi-pulses. In this case, the initial laser pulse splits into two pulses and one of these then undergoes dramatic compression with an accompanying increase in intensity. This scenario is able to accommodate somewhat longer pulses, which are closer to a regime that can be realized experimentally at present. We have shown, for example, that a significant portion of a 10 fs (FWHM), 780 nm, pulse can be transformed into a pulse of width 0.33 fs. This yields a peak intensity approximately four times greater than the initial pulse intensity. The propagation of pulses for the conditions of SIT at SRSS is nonstationary both in shape and in spectrum. Nevertheless, the laser pulse energy is conserved as it is converted into a higher-frequency band. A laser pulse having initial duration in the range of 11 fs or less easily encloses within its spectral band the Raman transitions on the fine structure $^2P_{3/2} - {}^2P_{1/2}$ levels of Ne^+, Ar^+, Kr^+, Xe^+ ions which satisfy the conditions for SRSS. In this case, we have show that it is possible to generate attosecond pulses as short as 0.16 fs in Ne^+. To our knowledge, no other scheme proposed to date suggests such a high generation efficiency for individual attosecond pulses. In addition, our scheme is less experimentally complicated in comparison with other schemes.

As for the measurement of attosecont, a number of methods have been proposed recently (see, for example, M.Ivanov et al. in [8], as well as [51-53]).

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