Decelerating chirped soliton formation at femtosecond laser pulse propagation in a medium with one-photon absorption and gold nanorods

V A Trofimov and T M Lysak

Lomonosov Moscow State University, Moscow 119992, Russia

E-mail: vatro@cs.msu.ru

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Abstract
We demonstrate the possibility of decelerating chirped soliton formation at femtosecond pulse propagation in a medium with gold nanoparticles. We take into account the dependence of one-photon absorption on the nanorod aspect ratio and time-dependent nanorod aspect ratio changing due to nanorod reshaping because of laser energy absorption. The soliton formation occurs due to laser radiation trapping by the nanorod reshaping front. We show analytically that a chirp induced by the negative phase grating is crucial for this trapping.

Keywords: nanorods, one-photon absorption, self-similar propagation, femtosecond pulse

1. Introduction
In recent years, thin films doped with noble (gold or silver) metal nanoparticles have attracted attention as recording media due to their strong nonlinear response resonance to the frequency of incident optical radiation, electric field polarization in the range of optical frequencies, and nanoparticle aspect ratio changes due to reshaping or photothermal melting [1–6]. This is why the investigation of nanoparticle optical response dependence on the nanoparticle aspect ratio and nanoparticle orientation and local environment has been the subject of numerous papers in recent years [7–12]. The other very important problem is the investigation into the physical mechanisms for nanorods reshaping at temperatures less than the bulk melting temperature [13–16]. Various models to explain photothermal reshaping of nanosized nanoparticles have been proposed up to now [13, 14, 17–19].

For the problem of data-storage based on the use of nanoparticles, a self-similar mode of laser pulse propagation is of great importance. This is due to the fact that the laser radiation spectrum distortions, caused by nonlinear refraction and absorption, can induce false recording or writing of information. Indeed, nanoparticle reshaping because of laser energy absorption leads to the laser pulse spectrum changing due to pulse chirping. A self-similar or soliton mode of nonchirped laser pulse propagation in homogeneous and layered media has been the subject of numerous studies in recent years [20–26]. However, such a propagation mode for a chirped pulse has not yet been sufficiently investigated.

In our previous papers [27, 28] we considered femtosecond pulse propagation in a medium containing nanorods under the conditions of both the nanorod ellipticity (aspect ratio) changing and the dependence of two-photon absorption (TPA) on the nanoparticle aspect ratio. In particular, in [27], using the density matrix formalism, we derived the equation set that describes the femtosecond pulse propagation under such conditions, and demonstrated the possibility of superluminality [29, 30] effect realization and soliton formation at the femtosecond pulse propagation in such medium, and also discussed a physical mechanism for soliton...
formation and light acceleration if a positive phase grating is induced by laser radiation. In [28] we showed that the appropriate frequency chirp of an incident laser pulse, propagating in a medium with nanorods, is crucial for self-similar mode occurrence in a medium with TPA or multi-photon absorption under conditions of pure amplitude grating or positive phase grating induced by laser radiation. Unlike paper [28], below we consider unchirped incident pulse propagation in a medium with one-photon absorption and a negative phase grating. Moreover, while in [28] the self-similar pulse propagation was determined by the chirp of the incident pulse, in the present paper we demonstrate that the soliton-like propagation of laser radiation is due to the self-trapping of laser radiation by the nanorod reshaping front. Our attention in the present paper is focused on the formation of the decelerating soliton. The corresponding approximate soliton is developed and the computer simulation results are compared with analytical results. It should be mentioned that we have earlier developed an approximate description of laser pulse propagation in a medium with nanorods and TPA.

2. Problem statement

We consider femtosecond laser pulse propagation in a medium with nanorods, taking into account the aspect ratio (ellipticity) of nanorods changing due to their reshaping because of one-photon absorption of optical energy. In the framework of a slowly varying envelope of a wave packet, this process can be described by the following dimensionless nonlinear equations [27]:

\[
\frac{\partial A}{\partial z} + iD\frac{\partial^2 A}{\partial t^2} + f(\varepsilon)(\delta_0 + i\xi)A = 0,
\]

\[
\frac{\partial \varepsilon}{\partial t} = -\delta(\varepsilon)|A|^2,
\]

where \(A(z, t)\) is a dimensionless complex amplitude of laser radiation, measured in units of square root from incident pulse maximal intensity; \(\varepsilon(z, t)\) is the nanorod aspect ratio, which is determined as \(\varepsilon = L/W\), where \(W\) is the width and \(L\) is the length of the nanorod, or equivalently as \(\varepsilon = a/b\), where \(a\) and \(b\) are the major and minor axes of an ellipsoidal nanorod. As a rule, the aspect ratio varies from 1 to 9 [12]. Variable \(z\) is a dimensionless longitudinal coordinate, along which the optical radiation propagates, and it is measured in the units of laser pulse dispersion length; \(t\) is dimensionless time in the system of coordinates moving with the pulse; time is measured in the units of the incident pulse duration. Parameter \(D\) is equal to plus or minus unity in our notations, depending on the wavelength of laser radiation in the general case. Below we consider a medium with normal dispersion for the chosen wavelength of laser radiation. Therefore, second order dispersion (SOD) leads to pulse spreading. Nevertheless, we serve this parameter for generality and will make computer simulation for its other value to illustrate the influence of SOD on laser pulse propagation. Function \(f(\varepsilon)\) describes the dependence of the one-photon absorption (single-photon absorption) process on the nanorod aspect ratio \(\varepsilon\). Parameter \(\delta_0\) characterizes the laser energy absorption on the pulse dispersion length. Parameter \(\delta\) characterizes a part of the energy released due to the excited level relaxation, which is spent on nanorod reshaping. Thus, this parameter describes the part of absorbed energy released due to non-radiative energy level transitions. Coefficient \(\xi\) characterizes the laser pulse self-action due to the detuning of the carrier frequency of the wave packet from the frequency corresponding to the energy transition of the substance at which its excitation occurs: \(\xi = \theta_0, \theta = (\omega_p - \omega_21)T_s\). Here \(\omega_p\) is the laser pulse frequency, \(\omega_21\) is the frequency of transition between the substance energy levels, \(T_s\) is a transversal relaxation time. The case of \(\xi = 0\) corresponds to optical pulse propagation in a medium with pure amplitude grating. It means an influence only of one-photon absorption on the laser pulse propagation. In the opposite case \(\xi \neq 0\), the phase grating is also induced by the laser radiation. It should be stressed that, in our notation, the positive sign of the parameter \(\xi\) (this case is named by us as positive grating) corresponds to pulse compression and laser pulse decompression occurs at the negative sign of this parameter (this case is named by us as negative grating). It is necessary to stress that the nanorod aspect ratio (ellipticity) depends on the \(z\)-coordinate parametrically, as follows from equation (2).

We consider the laser radiation propagation far from the absorption resonance of nanorods to the incident radiation frequency (figure 1). This means that the absorption coefficient is far from the maximum of its dependence on the nanorod aspect ratio. So we approximate the dependence \(f(\varepsilon)\) by the function

\[
f(\varepsilon) = \varepsilon - 1,
\]

which is valid far from the response resonance of the gold nanorod absorption coefficient calculated in the dipole approximation for \(\lambda = 800\) nm [31] using the Boyd and Shen.
shape factor expression [32]:

\[ f(\varepsilon) = \frac{\varepsilon_2/A^2}{A + \varepsilon_m + \varepsilon_2^2}, \quad (4) \]

\[ A = \left[ 1 - \frac{\varepsilon_0 Q'_{i}(\xi)}{Q_i(\xi)} \right]^{-1}, \]

\[ Q_i(\xi) = \left[ 1 - \left( \frac{1}{\varepsilon} \right)^2 \right]^{\xi - 1/2}, \]

\[ Q'_{i}(\xi) = \frac{dQ_i(\xi)}{d\xi}. \quad (5) \]

In formulas (4) and (5) \( \varepsilon_m \) is the dielectric permittivity of the medium and \( \varepsilon_0 + i\varepsilon_2 \) is the complex dielectric permittivity of the nanorod. The dependence \( f(\varepsilon) \) in formula (3) approximates the dependence of formulas (4) and (5) quite well for the physical parameters under consideration (\( \varepsilon_0 = 22.4 \), \( \varepsilon_2 = 1.8 \) for Au at \( \lambda = 800 \) nm and \( \varepsilon_m = 3 \)) if the aspect ratio varies from 1 to 2 (figure 1). For the other values of the aspect ratio changing an approximation of \( f(\varepsilon) \) using the Gaussian function can be used.

In computer simulations we consider the incident Gaussian pulse propagation

\[ A(z = 0, t) = A_0(t) = \exp\left( -\left( t - L_t/2 \right)^2/\tau^2 \right), \quad 0 \leq t \leq L_t, \quad (6) \]

where \( \tau \) is a dimensionless pulse duration. The aspect ratio initial value is

\[ \varepsilon(z = 0, t) = \varepsilon_0. \quad (7) \]

### 3. Soliton-like solution

To confirm and explain the processes of decelerating soliton formation we derive an approximate soliton-like solution for problems (1) and (2). With this aim, let us represent the complex amplitude in a soliton-like form

\[ A(z, t) = B(z) \exp(-i\zeta(z)), \quad B(0) = B_0, \quad t_0(0) = t_0, \quad \tau_0(t) = \tau_0. \quad (8) \]

Functions \( B(z) \), \( s(z, \zeta) \), \( t_\zeta(z) \) and \( \tau_\zeta(z) \) describe the soliton amplitude, phase distribution, pulse center and its duration, respectively, with their initial values \( B_0, t_0 \) and \( \tau_0 \) for the time moment \( t = 0 \). It should be kept in mind that, obviously, the soliton appears after the laser pulse propagates along a certain distance. Therefore, the initial values of the introduced parameters do not coincide with the incident pulse position.

From equations (1) and (2) we get the equations with respect to amplitude and phase distribution evolution of the soliton:

\[ \frac{d \ln B}{dz} + i\zeta \left( \frac{d \ln \tau_s}{dz} + \frac{1}{\tau_s} \frac{dz}{dz} \right) - 2 \frac{D}{\tau_s^2} \frac{\partial^2 \zeta}{\partial \zeta^2} = 0, \quad (10) \]

\[ \frac{d \partial \zeta}{\partial z} = \frac{\partial \zeta}{\partial z} \left( \frac{d \ln \tau_s}{dz} + \frac{1}{\tau_s} \frac{dz}{dz} \right) - \frac{D}{\tau_s^2} (2\zeta^2 - 1) - \frac{D}{\tau_s^2} (2\zeta^2 - 1) = 0, \quad (11) \]

\[ 1 \frac{\partial f}{\partial \zeta} = -\delta B^2 c \chi^{-2} \zeta. \quad (12) \]

Obviously, the last equation has a solution

\[ f(z, \zeta) = f_0 \exp(-\delta B^2 \chi^{-2} \zeta + 1). \quad (13) \]

We see that this function is asymmetric in time at each section of the medium, dependent on the non-dimensional parameter \( \delta B^2 \chi^{-2} \), characterizing nanorod reshaping. Therefore, both the amplitude distribution and the phase distribution will also be asymmetrical functions in time.

To consider the influence of the second order derivative from the pulse phase (which means to take into account a pulse chirp) and pulse center shifting, let us represent the pulse phase \( s(t, \zeta) \) as

\[ s(z, \zeta) = a(z) + b(z) \zeta + h(z) \ln(c h(z)), \quad (14) \]

where \( a_0 \), \( b_0 \) and \( h_0 \) define the pulse phase distribution for the time moment \( t = 0 \). Function \( a(z) \) describes a soliton phase shift. Function \( b(z) \) describes the evolution of the current frequency of the soliton along the propagation coordinate. And, finally, function \( h(z) \) describes a pulse chirp evolution. This means that a pulse frequency changes with time. In this case, it is usually said that the pulse possesses a chirp or there is a chirped pulse [34]. It is very important to stress that propagation of a chirped pulse can essentially differ from features of an unchirped laser pulse propagation. Note that the pulse phase distribution under consideration corresponds to the ‘classical’ soliton phase distribution if the chirp is absent \( h(z) = 0 \).

A detailed analysis shows that if we neglect the third term in (14) and write the pulse phase in the form \( s(z, \zeta) = a(z) + b(z) \zeta \) only, a contradiction always appears. This contradiction follows from equations (10) and (11) where the coefficients at the independent variables are different from zero. Therefore, it is necessary to take into account a non-zero value of function \( h(z) \) in the phase distribution (14), at least.

Then, we expand the exponent on the right-hand side of equation (13) into a power series with respect to the exponential argument \( \delta B^2 \chi^{-2} \zeta \) and substitute (13) and (14) into equations (10) and (11). We need to take into account the first three elements of the exponent (13) expanding into a power series, because, in the opposite case, we do not get enough
equations to determine all independent variables. Thus, equating the coefficients at zero power of \( t h \zeta \), \( \xi h \zeta \) and \( t h \zeta ^2 \) in equation (10) and \( t h \zeta ^2 \) in equation (11), we get equations for the soliton amplitude \( B(z) \), duration \( \tau(z) \) and chirp \( h(z) \):

\[
\frac{d \ln B}{dz} + \frac{D}{\tau^2} h + \delta_0 \xi_0 \exp(-\delta B^2 \tau) = 0, \tag{15}
\]

\[
-3D h + 1/2 \delta_0 \xi_0 \delta^2 B^2 \exp(-\delta B^2 \tau) = 0, \tag{16}
\]

\[
\delta_0 h^2 - 3\xi_0 h - 2\delta_0 = 0. \tag{18}
\]

If optical radiation absorption is present (\( \delta_0 = 0 \)), then the non-zero solution of equation (18) is

\[
h = \frac{3\xi_0 / \delta_0 \pm \sqrt{9(\xi_0 / \delta_0)^2 + 8}}{2} = \frac{3\theta + \sqrt{9\theta^2 + 8}}{2}, \tag{19}
\]

which means that a pulse chirp should also be present. Moreover, according to equation (19) two types of soliton can occur depending on the sign of \( h \): the negative sign of \( h \) corresponds to an accelerating soliton, while the positive sign of \( h \) to a decelerating soliton. Note that we investigated accelerating soliton formation in [27]. However, a decelerating soliton was not found in a medium with TPA.

To find the soliton amplitude \( B(z) \), we get from equations (15)–(17) the following equation

\[
\frac{d \ln B}{dz} + \frac{D h}{\tau^2} (\delta B^2 \tau_0) + 6 \frac{(\delta B^2 \tau_0)}{\tau^2} = 0. \tag{20}
\]

The solution of this equation can be written in the explicit form

\[
B = \left( B_0 \exp(-4Dh / \tau_0^2) \right)^{-1} \left( 1 - \exp(-4Dh / \tau_0^2) \right). \tag{21}
\]

The first term describes the maximal intensity decreasing for a positive value of \( h \) (or increasing for a negative value of \( h \) due to the influence of medium dispersion. The second one corresponds to the maximal intensity changing because of laser energy absorption by nanorods. Formula (21) illustrates very well the difference between unchirped (\( h = 0 \)) and chirped (\( h \neq 0 \)) pulse propagation. We see that, dependent on a chirp sign, the maximal intensity of the pulse can decrease or even increase in a medium with nonlinear absorption. Equation (21), together with equations (16) and (19), gives the values of amplitude \( B \) and pulse duration \( \tau \) at each section of the medium.

Then we equate the coefficients at \( t h \zeta \) in equation (10) and \( \zeta \) (using power series near the soliton center \( \zeta = 0 \)), \( t h \zeta ^2 \) and other terms of equation (11), which do not contain \( t h \zeta \) and \( \zeta \), in equation (11) and obtain the equation with respect to the linear part of the pulse phase \( b(z) \):

\[
\frac{db}{dz} + (\xi - h \cdot \delta_0) \xi_0 \delta B^2 \exp(-\delta B^2 \tau) = 0, \tag{22}
\]

the soliton center \( t_s(z) \):

\[
\frac{dt}{dz} = -2D/\tau_s - \delta_0 \xi_0 \delta B^2 \exp(-\delta B^2 \tau_s) = 0, \tag{23}
\]

and the time-independent part of the soliton phase \( a(z) \):

\[
\frac{da}{dz} = \frac{1}{\tau_a} \frac{d}{dz} + \frac{D}{\tau_a}^2 B^2 - \xi_0 \exp(-\delta B^2 \tau_a) = 0. \tag{24}
\]

Therefore, all parameters for soliton-like shape (8) and the pulse phase distribution (14) can be computed. If the soliton amplitude remains the same for a large trace of propagation (it takes place, for example, if laser energy depletion is weak), then equations (22) and (23) provide quadratic dependence of the soliton center \( t_s(z) \) shift along the \( z \)-coordinate:

\[
t_s(z) = t_0 + \left( \frac{2D}{\tau_0} b_0 + \delta_0 \xi_0 \delta^2 B^2 \exp(-\delta B^2 \tau_0) \right) z
\]

\[
- D(\xi - h \cdot \delta_0) \xi_0 \delta B^2 \exp(-\delta B^2 \tau_0) z^2. \tag{25}
\]

It is important to stress if we do not use power series of \( t h \zeta \) then we get \( \frac{db}{dz} = 0 \) instead of (22). As a result, the linear dependence for the soliton center \( t_s(z) \) evolution follows from (23) and this contradicts the computer simulation results (see section 4 below). The second remark refers to a power series of the exponent (13). If we take into consideration only the first term of this series (which means constant absorption in time) then we can get parabolic dependence of the pulse center on the longitudinal coordinate and the direction of its displacement will be defined only by the parameter \( \xi \). However, as we mentioned above, we get a contradiction from equations (10) and (11).

4. Computer simulation results

We analyze the incident Gaussian pulse (6) propagation in a medium with one-photon absorption, negative phase grating with dimensionless strength \( \xi = -5 \) induced by laser radiation, absorption parameters \( \delta_0 = \{0.05, 0.1, 0.2\} \), \( \delta = 5 \), dispersion \( D = 0 \) and initial aspect ratio \( \xi_0 = 2 \). These dimensionless values provide the dimensionless detuning parameter \( \theta = (\omega_p - \omega_d) T_L = \xi/\delta_0 = \{100, -50, -25\} \), which corresponds to the frequency detuning from \( \approx 0.5 \omega_p \) to \( \approx 0.1 \omega_p \) for carrying laser radiation frequency \( \omega_p \approx 2360 \) THz (\( \lambda = 800 \) nm) and transverse relaxation time \( T_L \) of about \( 10^{-13} \) s [33]. Figures 2–5 show these results.

Due to the negative phase grating induced by laser radiation and nonlinear absorption for nanorod reshaping, the pulse center shifts into the area of time increasing, and a decelerating soliton is formed (figure 2). Unlike the case described in [27] for a positive phase grating, no pulse splitting occurs in the case under consideration. The mechanism for decelerating soliton formation is the following.

Under laser pulse propagation, the nanorod reshaping front, which is the area of aspect ratio significant change, is formed in the vicinity of the pulse front (figures 2(b) and 3). A negative phase grating \( \xi < 0 \) produces a positive chirp at the pulse front, which adds to the positive chirp produced by the SOD of a medium. The pulse back possesses only a
positive chirp produced by the SOD of the medium, because a weak phase grating is induced at the pulse back due to a nanorod aspect ratio value close to unity (figure 3). As a result, the wave separation is much stronger at the pulse front, and the fast waves (lower frequency waves [34]) are concentrated at the pulse front where they are absorbed. Slow waves (higher frequency waves [34]) are concentrated at the pulse back, and they are not absorbed because the nanorod shape at the pulse back is close to a sphere \((\varepsilon \approx 1)\). So, the pulse loses fast waves, while slow waves remain in the pulse. Therefore, the pulse spectrum gradually shifts into the area of slower waves (the pulse central frequency blue-shifts, figure 4). Moreover, the nonlinear absorption of fast waves prevents the spectrum from broadening, in particular.

The law for the pulse center shifting follows from equations (19) and (25). Indeed, the positive value of \(h\)

\[
h = \frac{3\xi/\delta_0 + \sqrt{9(\xi/\delta_0)^2 + 8}}{2},
\]

which follows from equation (19), satisfies the inequality \(h > 3\xi/\delta_0\). Therefore, the coefficient at the term \(z^2\) in equation (25) is positive

\[
\frac{D}{2}(\xi + \sqrt{9\xi^2 + 8\delta_0^2})_0\delta\partial^2_0e^{\exp(-\delta B_0^2)}.
\]

Assuming the constant value of the soliton amplitude, we obtain from equations (25) and (27) the quadratic law of the pulse center position with the \(z\)-coordinate changing. Figure 2(b) confirms this law. Indeed, for the considered set of parameters, the soliton shape at section \(z = 10\) near the pulse center can be approximated quite well by the function

\[
I_0e^{\chi^2/(\tau - \tau_0)/\tau_{ap}},
\]

which corresponds to representation (8) with \(\tau_{ap} = 0.5, I_0 = 0.446, \tau_0 = 80.82\). For this set of parameters, the coefficient at the term \(z^2\) in equation (25), calculated for the parameters of the approximation (28), is equal to 0.366, while the coefficient at the term \(z\) is equal to 0.0365. The maximal intensity position \(t_c(z)\) for the left sub-pulse, obtained in computer simulations, can be approximated by the following parabolic dependence (shown by the dashed line in the lower panel of figure 2(b))

\[
t_c(z) = 50 + 0.3z^2.
\]

Therefore, both calculated coefficients at the terms \(z^2\) and \(z\), belonging to analytical consideration, are in a good agreement with the corresponding coefficients at the same terms in equation (29).

A few words about the pulse intensity oscillations (figure 5(a)) occurring at the pulse propagation. When we discussed above the maximal intensity evolution (formula (21)), we mentioned that the intensity changing depends on the pulse chirp. In figure 3 we see clearly the change in the pulse chirp in a sequence of the medium sections: at the beginning of the pulse propagation \((\xi = 0.5, 1, 1.5\) in figure 3) we see a negative chirp of the pulse. In these sections, the pulse maximal intensity increasing takes place. Then, a pulse chirp changes its sign; it becomes positive \((\xi = 2, 2.5\) in figure 3) and the maximal intensity of the pulse decreases (figure 5(a)). After that the pulse chirp changes its sign once again \((\xi = 3.5\) in figure 3) and the pulse intensity increases. At the last stage of the laser pulse propagation, the chirp of the pulse is positive and, as a consequence of this, the maximal intensity decreases along the \(z\)-coordinate \((z = 5, 10\) in figure 3).

Why does a negative chirp of the pulse appear? Obviously, at the laser pulse propagation, an amplitude grating (due to laser radiation absorption \(\delta_0\)) and a negative phase grating (due to the negative \(\xi\)) are induced by laser radiation. As the nanorod reshaping front is formed, the negative phase grating appears only at the pulse front, where \(\varepsilon > 1\). At the other part of the pulse, the nanorod shape is close to a sphere \((\varepsilon \approx 1)\), that is why no laser radiation absorption takes place and no phase grating is induced. At the pulse front, the frequency chirp produced by the negative phase grating adds to the chirp produced by the SOD of the medium (see figure 3), while at the pulse back, a positive chirp is produced mainly by the SOD of the medium [34]. A negative chirp is formed in the central part of the pulse due to
Figure 3. Soliton shape (blue lines), aspect ratio distribution (red lines) and frequency chirp (green lines) at different sections of the incident Gaussian pulse propagation in the medium with negative phase grating $\xi = -5$ and $\delta_0 = 0.2$, $\delta = 5$. 
the amplitude grating (figure 5, \(z = 0.5\), for example). Thus, the central part of the pulse undergoes compression.

As the pulse compresses, its duration decreases and the intensity grows; the influence of the negative phase grating is enhanced as well as the pulse spreading due to the medium dispersion. Therefore, the frequency chirp of a pulse changes from negative to positive in the whole pulse area (figure 3, cf. \(z = 1, z = 1.5\) and \(z = 2.5\)). This leads to the pulse maximal intensity decreasing and the pulse duration growing. Then, in the area of the nanorod reshaping front, a negative chirp appears due to the amplitude grating. Therefore, the intensity increases and the pulse compression is repeated, but in a weaker form, because a part of the pulse energy was already absorbed and the pulse spreads due to SOD. At the section \(z = 5\), the chirp of the pulse area becomes positive with a clear kink in the pulse front. Further pulse propagation occurs with a slow intensity decreasing along the \(z\)-coordinate.

It is worth noting that, for smaller absorption parameter \((\delta_0 = 0.05)\), the third period of damping oscillations is clear in figure 5(a).

The influence of the absorption parameter \(\delta_0\) on the deceleration soliton formation is shown in figure 5. The larger \(\delta_0\) is, the faster the maximum intensity decrease and the larger the soliton deceleration velocity. The soliton deceleration velocity increasing with \(\delta_0\) growth is also confirmed by equations (19), (25) and (27). Indeed, as follows from (27), the coefficient at the term \(z^2\) in equation (25) is positive and increases with \(\delta_0\) growth, thus making the soliton deceleration larger for larger values of \(\delta_0\).

5. Conclusions

The possibility of the formation of a novel type of soliton, a decelerating chirped soliton, was demonstrated in a medium containing gold nanorods and with one-photon absorption. The soliton is formed due to the pulse chirp, which is caused by the negative phase grating at the pulse front. As a result the trapping of laser radiation by the nanorod reshaping front occurs and the soliton slows down. This slowing down becomes more pronounced for larger laser energy absorption on the pulse dispersion length. To explain the observed processes we derived an approximate solution for the problem under consideration. Our analytical consideration confirmed the numerical simulation results.

It should also be mentioned that one of the methods for slowing down light in media with metal nanoparticles was recently proposed in [35]. This method is based on saturable absorption near plasmon resonance in a pump-probe regime. In our paper, we predict the slowing down of light at single light pulse propagation due to the self-trapping of laser radiation by the nanorod reshaping front.
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