Self-similar Shape Mode of Optical Pulse Propagation in Medium with non-stationary Absorption

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Abstract. We discuss laser pulse propagation with the self-similar shape in a medium with instantaneous nonlinear absorption. We consider two cases of the laser pulse propagation. First one corresponds to problem of laser-induced plasma generation in silica under action of TW laser pulse. The second one corresponds to femtosecond laser pulse propagation in medium with nanoparticles of noble metals. In both cases the mode of the self-similar shape of pulse is of interest. We discuss also a physical mechanism of non-linear acceleration or slowing-down for laser pulse propagation in a medium with nanoparticles. The last phenomena are important, in particular, for a problem of data processing of all optical method. We used analytical approach for considered problem as well as computer simulation.

1. Introduction
Soliton or soliton-like profile of laser beam or shape of laser pulse plays big role in modern nonlinear optics and attaches great attention of various scientist (see, for example [1-20]). We want to stress that in our opinion, investigation of a laser beam propagation mode with self-similar profile (or shape) is actual problem if such investigation is made for a medium with non-linear absorption because powerful laser system produces high intensive laser pulse, for which a multi-photon absorption takes place due to plasma formation under its propagation.

In our previous papers [21-26] we have investigated the possibility of laser pulse propagation with self-similar profile in a medium with two-photon absorption (TPA) or multi-photon absorption and also taking into account a presence of either cubic nonlinear response of a medium (self-focusing or de-focusing) or resonant nonlinearity or both nonlinearity together. In all cases under consideration we have found out a propagation mode with the self-similar profile of laser beam. To achieve this aim we formulate the problem as corresponding eigenvalue nonlinear problem. Obviously, certain simplification has to be made because of continuous decreasing of maximal intensity of the laser beam due to nonlinear absorption. Earlier we have applied this approach for finding the soliton solution of various problems of nonlinear optics [27-31].

It should be stress, that in contrast to previous papers we consider below a possibility of self-similar shape mode of laser pulse propagation if a medium response is non-instantaneous.
Consideration is provided for two problems. The first one is laser pulse propagation in medium with TPA and taking into account self-action of laser pulse due to time-dependent generation of free electrons. The second problem is a propagation of laser pulse in a medium with nanorods. In both cases we show that there is some distance of laser pulse propagation along which the shape of laser pulse changes in self-similar mode.

2. Laser pulse propagation in a medium with nanorods

Below we consider a femtosecond laser pulse propagation in a medium with nanorods, taking into account the aspect ratio (ellipticity) of nanorods changing due to their melting because of multi-photon absorption (MPA) of optical radiation. In the framework of slowly varying envelope of wave packet, this process can be described by the following dimensionless nonlinear equations

\[ \frac{\partial A}{\partial z} + iD \frac{\partial^2 A}{\partial t^2} + \delta_0 + i\tilde{\delta}\Delta (\varepsilon - 1)|A|^{2(k-1)} = 0, \quad 0 < z \leq L_z, \quad 0 < t < L_t. \]

\[ \frac{\partial \varepsilon}{\partial t} = -\tilde{\delta} (\varepsilon - 1)|A|^{2k}. \]

(1)

with initial and boundary conditions for complex amplitude and aspect ratio of nanorods

\[ A(z,0) = A(z,L_z) = 0, \quad 0 \leq z \leq L_z, \quad A(0,t) = A_0(t), \quad 0 \leq t \leq L_t, \quad \varepsilon(z,t = 0) = \varepsilon_0, \quad 0 \leq z \leq L_z. \]

Above \( A \) is dimensionless slowly varying envelope of electric field pulse, normalized on the maximum value of square root from the incident pulse intensity (\( z = 0 \)). The nanorods are melting under the action of laser light. As a consequence, their aspect ratio (\( \varepsilon = a/b \)) is varied, where \( a \) and \( b \) are major and minor axes of nanorods, \( \varepsilon_0 \) is its initial value. Parameter \( k \) is the number of photons, involved in the absorption. E.g., \( k = 1 \) is one-photon absorption (OPA), \( k = 2 \) is two-photon absorption (TPA) and so on. Variable \( z \) is a dimensionless longitudinal coordinate, along which the optical radiation propagates; \( t \) is a dimensionless time in the system of coordinates moving with a pulse, time is measured in the units of \( \tau_p \) - duration of the incident pulse; the dimensionless duration of laser pulse is denoted as \( \tau_p \); \( L_t \) is a dimensionless time interval, during which the laser pulse interaction with nanorods is analyzed, \( L_z \) is a dimensionless length of nonlinear medium.

Parameter \( D \) characterizes the group velocity dispersion (GVD). Parameters \( \delta_0 \) and \( \tilde{\delta} \) characterize the absorption of laser light. Coefficient \( \xi \) characterizes self-action of laser pulse due to detuning of the carrier frequency of wave packet from the central frequency of the absorption spectrum. The case of \( \Delta = 0 \) corresponds to optical pulse propagation at pure amplitude grating of the medium. It means an influence only of light energy absorption on the laser pulse propagation. In opposite case (\( \Delta = \pm 1 \)), the phase gratings are also induced by laser radiation. It should be mentioned that under consideration the positive sign of parameter \( \Delta (\Delta = 1, \) this case is named by us as positive grating) corresponds to pulse compression and at negative sign of this parameter (\( \Delta = -1, \) this case is named by us as negative grating) the decompression of laser pulse occurs.

We consider the mode of laser pulse propagation with self-similar shape [26]. This mode takes place, if the following equality is valid

\[ \frac{\delta_0^2}{D(1+\Delta^2)} \left( \frac{k-1}{2k} \right)^2 \left( \frac{\xi}{\delta_0} + \left( \frac{\xi}{\delta_0} \Delta + \left( \frac{\xi}{\delta_0} \right)^2 + \frac{4k}{(k+1)^2} \right)^2 \right) = 1. \]

(2)
Obviously, the parameter k must be greater than 1. In this case the complex amplitude of incident light is defined as

\[
A(z = 0, t) = A_0(t) = ch^{-1/(k-1)} \left( \frac{t - L / 2}{\tau_p} \right),
\]

\[
\cdot \exp \left\{ -i \frac{k + 1}{2(k - 1)} \left[ \frac{\xi}{\sigma_o} \Delta \right]^2 + \frac{4k}{(k + 1)^2} - \frac{\xi}{\sigma_o} \Delta \right\} \ln \left( ch \left( \frac{t - L / 2}{\tau_p} \right) \right), 0 \leq t \leq L_I. \tag{3}
\]

To verify our assumption about a validity of the self-similar shape of laser pulse under its propagation in a medium with nanorods, we use computer simulation based on the conservative finite-difference scheme. For qualitative estimation of the laser pulse propagation we calculate a deviation \( \tau_c \) of pulse center from the initial one as follows

\[
\tau_c(z) = \int_0^{t_L} (t - L / 2) |A(z, t)|^2 dt \int_0^{t_L} |A(z, t)|^2 dt
\]

and full width at half maximum (FWHM) pulse duration \( \Delta \tau \), measured at half maximum intensity level.

Below we consider only pure amplitude grating (\( \Delta = 0 \)), which means that we do not take into account the laser pulse self-action due to detuning between the carrier frequency of the wave packet and the central frequency of the absorption spectrum. Hence, the value of \( \xi \) does not matter. Additionally, we choose the initial aspect ratio of nanorods being equal to \( \varepsilon_0 = 2 \).

While the light propagates along the medium, its intensity decreases due to nonlinear absorption. Moreover, in the case of significant melting (\( \delta \sim 1 \)), the center of the pulse shifts into the area with less aspect ratio of nanorods. So, to estimate self-similarity of the pulse shape at various sections we use the following procedure. First, we renormalize pulse shape at maximum intensity (this procedure is not a rule). Then, we are comparing a calculated intensity shape of the pulse with the intensity distribution of the incident pulse, taking into account the pulse center shifting:

\[
A_{app}^2(z, t) = ch^{-2/(k-1)} \left( (t - L / 2 - \tau_z(z)) / \tau_z(z) \right), 0 \leq t \leq L_I, \tag{5}
\]

We determined parameters \( \tau_z \) and \( \tau_c \), using minimization of the functional:

\[
J(z) = \frac{1}{2} \int_0^{t_L} \left( I(z, t) - (A_{app}(z, t))^2 \right)^2 dt . \tag{6}
\]

Here \( I(z, t) = |A(z, t)|^2 / |A_{max}(z, t)|^2 \) is intensity of the laser pulse normalized on its maximum value in the section under consideration.

Fig. 1 shows evolution of laser pulse, having the self-similar shape (3) at the input section (\( z = 0 \)), along the coordinate \( z \) for parameters \( k = 2, \tau_p = 1, \delta_0 = 3\sqrt{2} \) and \( D = 1 \). For clarification of nanorods influence on laser pulse propagation, in Fig. 1a the evolution of the pulse shape in a homogeneous medium (\( \delta = 0 \)) without nanorods is shown. Figs. 1b,c illustrate laser pulse propagation features under moderate melting (\( \delta = 10 \)) or strong melting (\( \delta = 50 \)), correspondingly. Let us note, that these values of parameter \( \delta \) satisfy the relation (2), so the laser pulse shape changes in a self-similar mode up to section \( z = 0.6 \) for a homogeneous medium (\( \delta = 0 \)), for example. Then, a distortion of the pulse shape takes place near the pulse edges. Nevertheless, up to the section \( z = 1.0 \)
the pulse shape can be approximated by the inverse hyperbolic cosecant of the second degree (6) with high accuracy: the value of the functional \( J \) does not exceed \( 5.8 \cdot 10^{-3} \) (see Fig. 2 d).

Opposite to the homogeneous medium, the soliton–like shape of a laser pulse undergoes a compression up to 1.5 times at the initial distance of propagation in the medium with nanorods (Fig. 2a, b). In this case, the pulse center shifts towards the area of time increasing. However, the pulse center shifting becomes negligible if the absorption (\( \tilde{\delta} \)) becomes strong, or, equivalently, if strong increasing of incident light intensity takes place. For the medium values of parameter \( \tilde{\delta} \) (\( \tilde{\delta} = 10 \)), a slight asymmetry of the pulse shape is well seen, which becomes negligible for high value of \( \tilde{\delta} \) (\( \tilde{\delta} \geq 50 \)) (let us compare with Fig. 1b,c). Nevertheless, similar to the pulse propagation in a homogeneous medium, the pulse preserves its shape up to the section \( z = 1.0 \) with enough high accuracy – the value of the functional \( J \) does not exceed \( 6.6 \cdot 10^{-3} \) (see Fig. 2d). Of course, this accuracy is worse than for in the case of the homogeneous medium, especially at the beginning of the pulse propagation distance, due to the pulse asymmetry.

![Fig. 1. Pulse shape at different sections for \( \tilde{\delta} = 0 \) (a,d); 10 (b); 50 (c) and \( k = 2 \), \( \tau_p = 1 \), \( \delta_0 = 3 \sqrt{2} \) and \( D = 1 \). Fig. 1d shows evolution of the pulse shape for unchirped incident pulse, propagating in a homogeneous medium (\( \tilde{\delta} = 0 \)).](image-url)

To emphasize an influence of the pulse chirp, in Fig. 1d the evolution of the incident unchirped pulse
\[ A(z = 0, t) = A_0(t) = c h^{-\frac{1}{k-1}} \left( \frac{t - L_z/2}{\tau_p} \right)^k, \quad k = 2 \]

ing a homogeneous medium (\( \tilde{\sigma} = 0 \)) is shown. As it is well seen, the pulse duration increases and its maximal intensity decreases much faster than it happens in the case of initially chirped pulse (compare corresponding curves in Fig. 2a,b). Preservation of the pulse shape is also much worse: the value of the functional (6) in some sections up to ten times exceeds its value for the incident chirped pulse (Fig.2c).

Fig. 2. Evolution of the maximal intensity (a), FWHM pulse duration (b), deviation of the pulse center from its initial position (c), functional \( J \) (d) along z-coordinate for various values of parameter \( \tilde{\sigma} \) (for solid lines the values of \( \tilde{\sigma} \) are depicted in the Figs.) and \( k = 2, \quad \tau_p = 1, \quad \delta_0 = 3\sqrt{2} \) and \( D = 1 \). Dashed lines correspond to a propagation of the incident unchirped pulse in a homogeneous medium.

Computer simulation have shown that a self-similar mode of the pulse propagation under three- and four-photon absorption is similar to the case of TPA (let us compare Fig.2,3,4). Nevertheless, some qualitative differences take place. Because we chose the same absorption coefficient (\( \delta_0 = 3\sqrt{2} \)) as it was for TPA, then we have to decrease the pulse duration in accordance to the equality (2). Therefore, we chose \( \tau_p = 0.6389 \) for three-photon absorption and \( \tau_p = 0.5118 \) for four-photon absorption. Together with \( D = 1 \), these values allow self-similar propagation of the incident pulse in the form (3) if we deal with a homogeneous medium. One can stress, that in all cases the FWHM pulse
duration remains approximately the same. This fact allows revealing the influence of photon number involved in the process of light absorption on the self-similar propagation of laser radiation.

In comparison to the process of TPA, increasing the number of absorbed photons leads to a less weak decreasing of the light intensity while the pulse propagates in a homogeneous medium (Fig.3a,4a). This is obviously a consequence of increasing the number of photons involved in absorption. Indeed, if the intensity decreases less than 1, the multi-photon absorption results in smaller absorption. In a like manner to TPA, the presence of nanorods in the medium leads to focusing of the chirped pulse at the initial part of propagation because of the reflection of the pulse from the gradient of absorption grating induced by changing of the nanorod aspect ratio. In the case of MPA, focusing of the laser pulse becomes slightly stronger with the growth of the number of photons.

![Fig. 3. Evolution of maximal intensity (a); FWHM pulse duration (b); deviation of pulse center from its initial position (c); functional $J$ (d) along z-coordinate for various values of $\delta$ (solid lines, value of $\delta$ is shown in the Fig) and three photon absorption ($k=3$), $\delta_0 = 3\sqrt{2}, \tau_p = 0.6389$ and $D=1$. Dashed lines show a propagation of the incident unchirped pulse in the medium without absorption ($\delta_0 = \tilde{\delta} = 0$).](image)

The most remarkable fact is a significant decreasing of deviation of the pulse center from its initial value. As it is well seen from Fig. 2c, 3c, 4c, the deviation at the medium exit is up to 5 times less for $\tilde{\delta} = 10$ and up to 2.5 less for $\tilde{\delta} = 50$. This is also because of the weaker absorption due to increasing the photon number under the absorption of laser energy, if the maximal intensity decreases less than 1. Nevertheless, similar to the case of TPA, the pulse center deviation from its initial position is greater for $\tilde{\delta} = 10$ than for $\tilde{\delta} = 50$. Unfortunately, multi-photon absorption leads to distortion of self-similarity shape of the pulse. Remember, that for medium wuth TPA, the functional value does not exceeds 0.01
despite the strength of nanorod melting (Fig.2d). Approximation of the pulse shape, calculated from computer simulation, by the inverse hyperbolic cosecant of the corresponding degree in the case of strong melting is better than for medium strength melting. In the case of three-photon absorption, the functional value exceeds 0.01 for some sections of z-coordinate and it exceeds 0.02 somewhere in the case of four-photon absorption. For all the cases, approximation of the laser pulse shape along the initial part of its propagation is much better for homogeneous medium. Nevertheless, along the last part of laser pulse propagation, the approximation of the laser pulse shape is the best for the strong melting ($\delta = 50$).

![Graphs](a) ![Graphs](b) ![Graphs](c) ![Graphs](d)

Fig.4. Evolution of maximal intensity (a); FWHM pulse duration (b); deviation of pulse center from its initial position (c); functional $J$ (d) along z-coordinate for various values of $\delta$ (solid lines, value of $\delta$ is shown in the Fig.) and four-photon absorption ($k=4$), $\delta_0 = 3\sqrt{2}, \tau_p = 0.5118, D = 1$. Dashed lines show a propagation of the incident unchirped pulse in the medium without absorption ($\delta_0 = \delta = 0$).

3. Laser pulse propagation in medium with time-dependent free electron concentration.

Below we consider laser pulse propagation in a medium with time-dependent free electron concentration under the TPA of laser energy. This process is governed by the following set of dimensionless equations:

$$\frac{\partial A}{\partial z} + iD \frac{\partial^2 A}{\partial t^2} + i\alpha p A + \delta_0 \left| A \right|^2 A = 0, \quad 0 < z \leq L_z, \quad 0 < t < L_t,$$

$$\frac{\partial P}{\partial t} + \frac{P}{\tau} = q \left| A \right|^4.$$

(7)
These equations are solved with zero-value boundary conditions

\[ A(z,0) = A(z,L_z) = 0, \quad 0 \leq z \leq L_z \]  
and initial condition for free electron concentration

\[ \rho(z,0) = 0, \quad 0 \leq z \leq L_z, \]

and initial distribution of complex amplitude

\[ A(0,t) = A_0(t), \quad 0 \leq t \leq L_t. \]  

(8)

(9)

Above, \(\rho(z,t)\) is a free electron concentration. Parameter \(\tau\) characterizes a free electron relaxation time; parameter \(q\) is proportional to squared intensity of incident laser pulse.

As it is well-known, sign of the parameter \(D\) can be positive or negative in dependence of laser pulse wavelength. We will take this into account by changing of the sign for parameter \(\alpha\), which describes changing of a medium refractive index. In our notation its positive sign corresponds to laser pulse compression at positive value of parameter \(D\). We choose below this sign of \(D\) for definiteness.

We follow the propagation of incident laser pulse with self-similar shape. In the case of a medium with TPA (pure absorption grating) and without free electron generation, such shape is defined as

\[ A_0(t) = e^{i\sqrt{2} \cdot \ln(ch(ct))}/ch(ct), \quad c = \sqrt{\frac{\delta}{3\sqrt{2}D}}. \]  

(10)

The main question under consideration is the following: what distance of the pulse propagation with self-similar shape is? It depends on the problems parameters. We fixed value of the following parameters: \(D=0.25, q=1\) and changed other parameters: \(\tau = 0.1, 0.5, 0.75, 1.0\), \(\alpha = 0, \pm 5, \pm 10, \pm 20, \pm 30, \pm 40\), \(\delta_0 = 3, 4\). It should be emphasized that the absorption coefficient influences on occurring the self-similar mode of the laser pulse propagation in a strong way. So, if the

![Fig.5. Evolution of the pulse shape along z-coordinate for \(\delta_0 = 3, \tau=0.1, \alpha = 10\) (a), -10 (b).](image-url)
absorption coefficient is equal to 4, then the amplitude grating affects mainly on the pulse propagation. If this parameter is equal to 3, then self-action of the laser pulse due to refractive grating influences essentially on taking place of the self-similar mode. As an example, in Fig. 5 we show evolution of the laser shape for its propagation in medium with nonlinear response induced self-compression of optical pulse (Fig. 5a) or its self-decompression (Fig. 5b). We see that in Fig. 5b the pulse shape remains the same up to distance that is equal to 0.7 dimensionless units. This Figure illustrates also a positive role which plays self-decompression of laser pulse if nonlinear absorption takes place. As it is well-known, without nonlinear absorption such regime of the laser pulse propagation can not appear.

4. Conclusion
We showed that the self-similar mode of laser pulse propagation takes place in a medium with its time-dependent response. The distance, along which the laser pulse shape preserves its self-similarity, depends on the interaction parameters. If laser pulse propagates in a medium with nanorods, under certain conditions the soliton appears in the area of the front of nanorod melting.

The mode of laser pulse propagation with its self-similar shape takes place also for laser radiation interaction with plasma.

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