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Nonlinear Regime of Propagation of Optical Pulses Phase Modulated by Double Convex Lens*

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Abstract. The optical elements introduce additional spatial phase modulation which leads to a change of the evolution dynamics of the laser pulses. In the present work we consider the linear and nonlinear propagation of laser pulse phase modulated by double convex lens. Conditions for maximal compression and self-focusing of the pulse are found.

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1 Introduction

A basic element for obtaining high intensity optical pulses in a laser system is the double convex lens. For laser source with initial power P, the focusing of the optical pulses leads to reduction of the transverse size (the spot) $r_\perp$ and to significant amplification of the intensity I which is proportional to $I = P/r_\perp^2$. In the present work is examined the impact of a double convex lens with different focusing distance f on the evolution of optical pulses in a nonlinear dispersive medium. The nonlinear regime of propagation in a medium with normal and anomalous dispersion is investigated. Conditions for maximal compression and self-focusing are found.

2 Basic Equation

The scalar paraxial (3D+1) amplitude equation which describes the propagation of optical pulse in a nonlinear dispersive medium is

$$i\frac{\partial A}{\partial z} = \frac{1}{2}\Delta_\perp A - \beta\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A\,, \tag{1}$$

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where $A(x,y,z,t)$ is scalar amplitude function, characterizing the pulse envelope, k_0 is the wave number, $\beta = z_{\text{diff}}/z_{\text{disp}}$ is a dimensionless parameter which gives the ratio between the dispersion and the diffraction length of the pulse, $z_{\text{disp}} = t_0^2/k''$ is the dispersion length, $z_{\text{diff}} = k_0 r_\perp^2$ – the diffraction length, $\gamma = k_0^2 r_\perp^2 n_2 |A_0|^2$ is the nonlinear constant and $\Delta_\perp = \dfrac{\partial^2}{dx^2} + \dfrac{\partial^2}{dy^2}$ is the transverse Laplace operator.

3 Lens as Phase Corrector on Propagation of the Optical Pulses

The influence of the double convex lens on the phase of the optical pulse is examined in [1,2]. The lens has a behavior of a quadratic phase corrector when the laser beam passes through it. The additional spatial phase, which the optical pulse obtains, is

$$\Phi(x,y) = \left(\frac{\pi}{\lambda_0 f}\right)\left[(x^2+y^2)\right], \tag{2}$$

where λ_0 is the carrier wavelength, and f is respectively the focal distance. We investigate the linear and nonlinear propagation of laser pulses in two basic types of isotropic media: a) Gas medium (air), in which the dispersion is a relatively small ($\beta \ll 1$); b) Solid medium (fused silica), in which the ratio between the diffraction and the dispersion lengths can be of the order of $\beta \approx 1$. Thus, as initial condition in our investigation we use the following modulated Gaussian pulse:

$$A(x,y,t,0) = \exp\left\{-\frac{x^2+y^2}{2r_\perp^2} - \frac{t^2}{2t_0^2}\right\}\exp\left\{i\left(\frac{\pi}{\lambda_0 f}\right)[(x^2+y^2)]\right\}. \tag{3}$$

4 Linear Regime

The evolution of laser pulses in linear regime is governed by the equation

$$i\frac{\partial A}{\partial z} = \frac{1}{2}\Delta_\perp A - \beta\frac{\partial^2 A}{\partial t^2}\,. \tag{4}$$

As a beginning, we investigate two linear regimes of propagation of optical pulses, modulated initially by a convex lens with focus $f = 3$ cm.

a) In Figure 1 is presented the propagation of the pulse in medium with small dispersion (air) $\beta = 0.00005$ and diffraction lengths of $z_{\text{diff}} \simeq 3$ cm. Due to the relatively small dispersion at these distances the longitudinal size (t projection of pulse) is preserved and only the transverse size is enlarged by Fresnel law.

b) In Figure 2 propagation of the pulse in solid medium (fused silica) with $\beta = 0.5$ is shown. The focus of the lens prevents the initial diffractive broadening. The dispersion leads to a significant increase of the time size of the pulse.

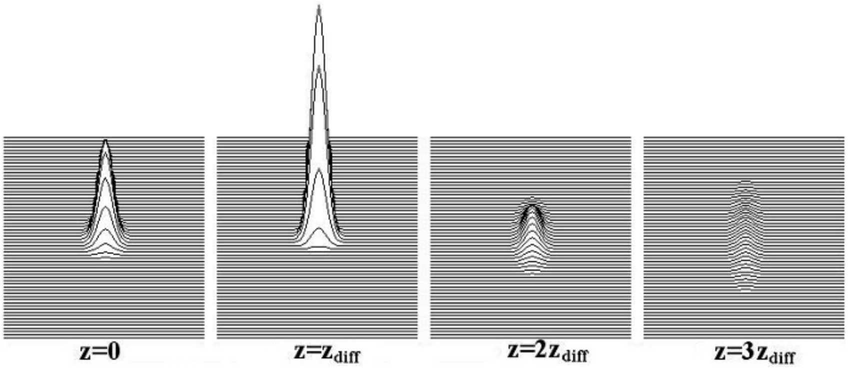

Figure 1: Plot of the side (x, t) projection of the intensity $|A(x, t)|^2$ a 1 ps Gaussian pulse at $\lambda = 800$ nm, with initial spot $r_0 = 300$ μm. We investigate the case when the ratio between the diffraction and the dispersive length is very small $\beta = 0.00005$. The evolution of the pulse shows focusing on 3 cm and a typical Fresnel diffraction on distance of three diffraction lengths. Due to the relative small dispersion at these distances the longitudinal size (t projection of pulse) is preserved and only the transverse size is enlarged.

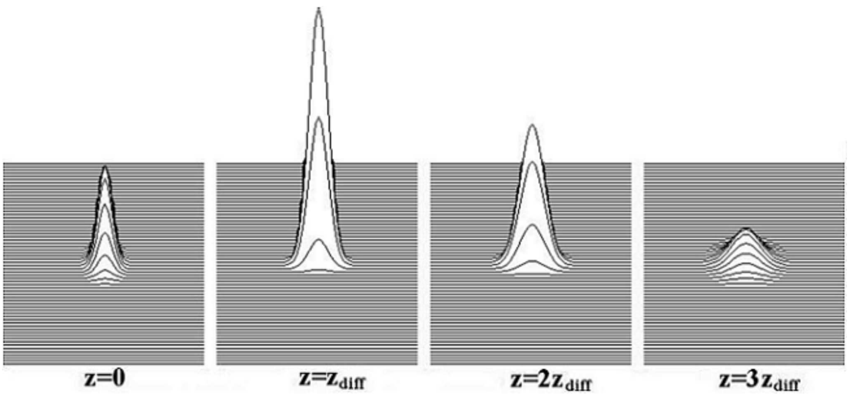

Figure 2: Plot of the side (x, t) projection of the intensity of the same pulse as in Figure 1. Now the propagation of this initially modulated optical pulse is in a solid medium with normal dispersion $\beta = 0.5$. The focus of the lens prevents the initial diffractive broadening. The dispersion leads to a significant increase of the time size of the pulse.

5 Nonlinear Regime

In this Section nonlinear regime of propagation in solids of optical pulses with intensity near the critical for self-focusing ($\gamma = 2.2$) is investigated. Two basic

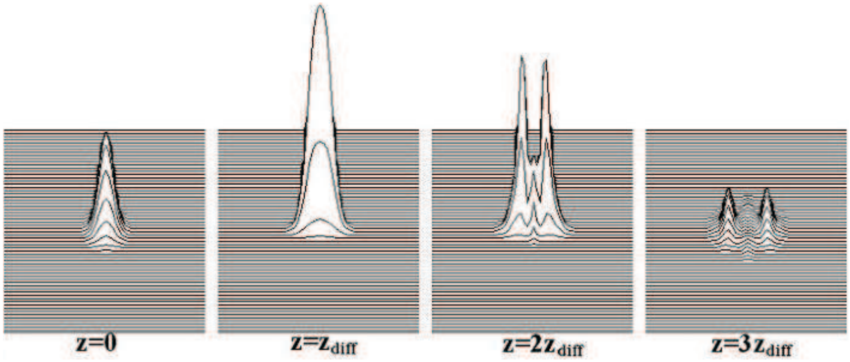

Figure 3: Nonlinear propagation of initially spatially modulated optical pulse in medium with normal dispersion $\beta = 0.5$ and coefficient of nonlinearity $\gamma = 2.2$. Plot of the side (x, t) projection of the intensity $|A(x,t)|^2$.

cases are presented:

a) Positive dispersion: In Figure 3 propagation of phase modulated pulse in a medium with normal dispersion $\beta = 0.5$ and coefficient of nonlinearity $\gamma = 2.2$ is presented.

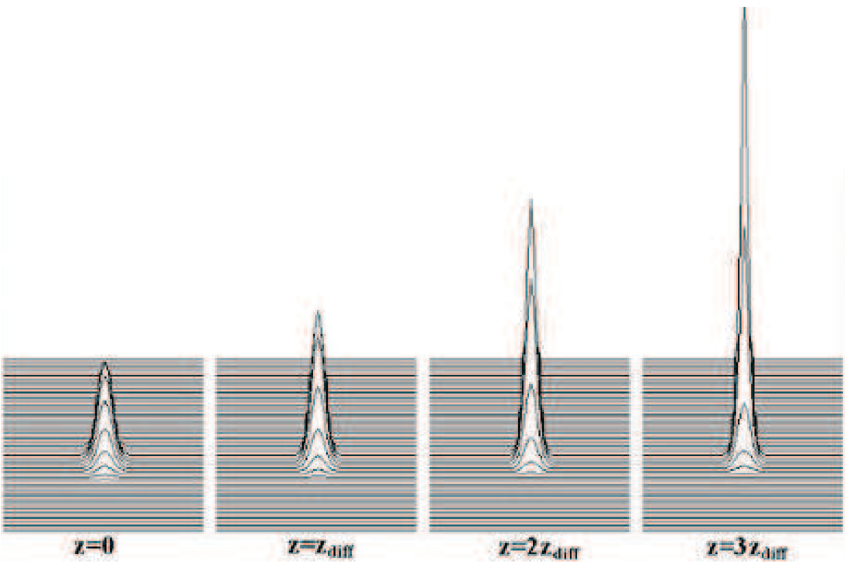

Figure 4: Propagation of an initial modulated optical pulse in medium with anomalous dispersion $\beta = -0.5$ and coefficient of nonlinearity $\gamma = 2.2$. Plot of the side (x, t) projection.

The nonlinear phase modulation has the same sign as the frequency modulation obtained by the positive sign of the dispersion. Due to this effect pulse expands significantly in time and splits into two parts.

b) Negative dispersion: In Figure 4 the propagation of the phase modulated pulse in a medium with anomalous dispersion $\beta = -0.5$ and coefficient of nonlinearity $\gamma = 2.2$ is presented. Significant compression and a self- focusing is observed.

6 Conclusions

In this paper we investigate different evolution dynamics of propagation of a phase modulated by lens laser pulse. In nonlinear regime optimal conditions for self-compression and self- focusing are found.

References

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